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Forest Production for Tropical America

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Initial Foreword

Loss of tropical forests today ranks at or near the top of the forestry agenda in almost every region of the world. The Western Hemisphere contains more than half the world's moist tropical forests, mainly in the Amazon Basin but also in neighboring regions of South and Central America. Thus, it is timely to introduce the first comprehensive book on tropical forests and forestry in the New World.

This is an exhaustively researched book, one that is likely to influence the tone and content of tropical forestry in the New World for years to come. While the emphasis is on the American Tropics, the author has reviewed forestry practices in all the world's tropical regions.

The breadth of the book is immense. Beginning with a characterization of forests in tropical America, the author reviews the socioeconomic values of the forests, their biology and silviculture, and management of secondary forests and plantations. He concludes by discussing agroforestry, future research needs, and the goals for implementation of improved forestry practices by both governments and the public.

For me, two highlights deserve special mention. The first is the sensitivity with which the author treats the interrelationship between environmental and developmental concerns in tropical forests. And the second is the emphasis he places on the silviculture and management of secondary forests, an area of his personal research and one that shows high promise in forested regions that are beginning to recover from the first generation of exploitation.

This book summarizes what we know about tropical forestry. Its impact will be greatly enhanced with publication of a low-cost edition in Spanish, widely available to students, professional foresters, and interested citizens in Latin America.

A few heartfelt words about the author. I have known Frank Wadsworth personally for about half his professional career. Everyone knows him as a warm human being, scientifically and professionally at the top of his field, and a most articulate spokesman for tropical forests everywhere. I can think of no more fitting climax to a lifetime of work in this field than the publication of this book.

Robert E. Buckman
Deputy Chief for Research (Ret.)
U.S. Department of Agriculture
Forest Service

June 30, 1986

(Dr. Buckman instigated and inspired this book and wrote this foreword before his retirement from the Forest Service.)

Final Foreword

The current generation of tropical forest managers faces serious challenges, now and into the future. The tropical forest resource itself is threatened and the socioeconomic complexities are pervasive and diverse. Global trends in the tropics include increasing rates of deforestation and land degradation. Populations and standards of living are increasing, as are the demands for wood, biological diversity, and other associated services and uses. While some users of the resource expect forest exploitation to continue, others expect absolute preservation or one of the countless intermediate alternatives. To deal with these and associated problems, managers will need to understand the dynamics of the forest systems and the importance of dealing with the human dimension in resource trade-offs. Research, training, and technology transfer will certainly be part of the process if we want to leave the tropical forests improved for the next generation.

Professionals of the 21st century will benefit from the research and experience of Dr. Frank H. Wadsworth, who is a pioneer of tropical forest management. When Dr. Wadsworth arrived in Puerto Rico over 50 years ago, he found a deforested island, badly in need of rehabilitation before it could provide quality environments for its inhabitants. Since that time Dr. Wadsworth has not only conducted research and practiced management in the tropical forests of the Caribbean islands, but also has traveled the whole tropical world and participated in the development of tropical forestry institutions all over Latin America. He has personally trained hundreds of Latin American foresters in the classroom and in the field.

In this book, Dr. Wadsworth brings together a lifetime of practical experience and combines it with a comprehensive review of the literature about tropical forest management. He calls attention to the work of many other pioneers whose fundamental contributions are forgotten by those interested only in the most recent literature. It is a practical book that focuses on the ecological relationships of tropical forests. Beyond the scientific literature, the book contains knowledge accumulated from real experience by the inquisitive and creative Dr. Wadsworth—the one who had the foresight to establish long-term tree growth plots soon after he arrived in Puerto Rico in 1942.

There can be no better tool for the training of a new cadre of tropical foresters than this accumulated wisdom by the person who, decades ahead of others, dealt with the trends described above, and who can claim success in the rehabilitation of degraded forest lands in the Caribbean islands. This book was initially supported by Dr. Robert Buckman, former Deputy Chief for Research of the USDA Forest Service, who saw the value of synthesizing and sharing this important information. This book arrives at a time when the world is in need of identifying the proper balance between the need to use forests and the requirement to preserve them for generations to come. Thank you, Dr. Wadsworth, for blazing a clear path for all of us to follow as we continue, as we must, to seek a balance between people's needs and resource use.

Robert Lewis
Deputy Chief for Research
USDA Forest Service
Washington, DC

May 30, 1997

Ariel E. Lugo
Director, International Institute of Tropical Forestry
USDA Forest Service
Rio Piedras, PR

Acknowledgments

This book is the product of several years of effort by a host of workers. The scope was defined by *Forestry Abstracts* from which came a foundation of literature references. These led to a concentrated review of forestry literature from the Tropics of the Eastern Hemisphere at the unsurpassed library of the Oxford Forestry Institute in England. Through expert assistance, it was possible to peruse some 2,000 references and obtain copies of many for subsequent study. One result was that virtually all significant material found and included in the bibliography herein is now to be found in the library of the International Institute of Tropical Forestry in Rio Piedras, Puerto Rico. In the search, procurement, retrieval, and referencing of this large fund of information, the author's primary debt is to the librarians of the institute, JoAnne Feheley and Gisel Reyes, whose indefatigable efforts to find and obtain needed information, usually on the basis of incomplete descriptions, have been, in my view, nothing less than heroic.

Chapter 4 was reviewed by Dr. Peter Murphy of Michigan State University and Dr. T.C. Whitmore, ecologist of Cambridge University. Chapter 5 was reviewed by John Wyatt-Smith, retired forester with long experience in Malaysia and Africa; Dr. John J. Ewel, Director of the Institute of Pacific Islands Forestry in Hawaii; and the late Ian Hutchinson, formerly of the Department of Renewable Natural Resources, Centro Agronómico Técnico de Investigación y Enseñanza, Turrialba, Costa Rica. The entire manuscript was reviewed by Dr. Charles Larson, retired dean of the College of Environmental Sciences and Forestry, State University of New York at Syracuse, and the late Dr. Steven Preston, former Dean of the School of Natural Resources, University of Michigan. These reviewers offered advice and suggestions on concepts and policies as well as technical detail. A deep debt of gratitude is owed to these individuals for poring over a long manuscript and promptly responding; however, deficiencies in the final product are entirely the author's responsibility.

Editorial review of the entire manuscript was contracted to Mary Elaine Lora, Susan Branham, and Robert Wray, retired USDA Forest Service editor. The author acknowledges a special debt to each, not only for improved clarity of the text but also for suggestions on organization.

From within the Forest Service, assistance without which the manuscript would never have been finished was provided in the form of reviews by editors under the supervision of Carol Lowe and the corresponding, seemingly endless revisions requiring monotonous retyping, initially without benefit of a word processor. Fortunately, thereafter it was possible to index both the bibliography and the text as a whole by the use of a computer. A final, detailed, technical and format review was an extremely welcome contribution from J.L. Whitmore of the Forest Management Research Staff, USDA Forest Service, Washington, DC.

The author acknowledges a more basic debt of gratitude to the Forest Service itself, through which the acquisition and interpretation of the information presented were made possible during a professional career that included opportunities to attain some personal familiarity with the Tropics and the fascinating forests and forestry of the region.

Introduction

This book is intended as a reference for those who are to make tropical American forests productive: the students in the forestry schools of the region. There has been a serious lack of a general reference as to what is already known about forest production that might be applicable within the American Tropics. The present book, which is to be translated, is intended to reduce that deficiency.

This book focuses on the potentialities of the forests. An imbalance between forest productivity and human demands is now so widespread it affects all living species on Earth. Yet past attempts to manage and culture these forests suggest that their sustainable productivity and resulting utility could be far above anything yet reported.

This book is concerned primarily with wood production. Without the direct economic returns possible therefrom, the other, less tangible benefits that accrue from forests are in jeopardy in the face of developmental pressures driven by more attractive direct financial incentives. Nevertheless, multiple benefits from forests are inseparable, so the goal should be to make forests productive for all purposes. Forest production, then, as here defined refers to *all* the values of forests, including those primarily esthetic.

The text emphasizes two vital relations. One is that forestry is ecological. Forest managers must be oriented to accept ecological information fundamental to goals and practices. A rift between the two disciplines that exists elsewhere must not intensify in tropical America. Forest production is forestry, not ecology, but intimacy between the two disciplines is mutually vital. The second relation emphasized in the book is that in productive forest management the animal component is as crucial as the plants. The value of animals to forest ecosystems goes far beyond their physical attraction.

Personal convictions that surface in the text include the following:

- Social acceptance is fundamental to the success of forest production, but so is technical excellence.

- Single-use forests do not exist, and optimum forest-use integration maximizes none.

- Economic production is prerequisite to conservation of forests.

- Sustainability, the primary goal of forestry, is no more difficult technically in the Tropics than elsewhere.

- Tropical forest production is better served by quality human resources than by mere financial expenditure.

- User-oriented tropical forestry research must not be subordinated by that which is purely scientist oriented.

As a reference source for students, this book differs from the multitude of books appearing on tropical forests. Emphasis is more on what has been experienced than on what is new. Applicability is as important as clean-shoe esoterica. Citations go to first published sources rather than more recent restatements. The culmination of literature citations prior to 1980 is not due to omission of recent substantive sources.

Much of the apparently applicable tropical forestry experience is little known in tropical America. Many fundamentals came to light long before the present generation of forest managers. Moreover, nearly all the early findings appeared in the Eastern Hemisphere. Widely distributed journals then were few. What was published was not in languages vernacular in most of tropical America.

The text cites forestry experience from sources so distant as to appear outwardly superfluous. There is also a mixture of experimental data and interpreted observations unsupported by today's rigid scientific standards. Some of this mixture is conflicting and appears questionable. The author neither offers apologies for such inconsistencies nor presents subjective conclusions therefrom. The book is no definitive manual of practices but rather only suggests what might work if tested. The intent is to arouse in alert students curiosity to dig deeper and confirm or correct on the basis of local findings. For upon such curiosity and a capacity to enlighten the local social context that dictates the level of management hangs the fate of our tropical forests and of the Tropics itself!

A geographical note: The information reported herein appeared over nearly a century from throughout the world. During this period the names of many source countries changed. To provide consistency and maximum contemporary utility, the names of countries have all been updated to the present.

Chapter 1
The American Tropics, a Forest Region

The American Tropics (neotropics) is that portion of the Western Hemisphere lying between the Tropic of Cancer and the Tropic of Capricorn, the parallels of latitude at the greatest north and south declinations of the Sun (23° 27′) from the Equator. It has a land area of about 16.5 million km^2, about 11 percent of the Earth's land area (Anon. 1990a, 1993a).

Within the Tropics worldwide, the land area is about equally divided between the equatorial (inner) Tropics (11° 43′ N. to 11° 43′ S.) and the outer Tropics. The Western Hemisphere contains less than a third of the tropical land. Of this amount, 70 percent is in the Southern Hemisphere and 61 percent is equatorial (fig. 1–1; table 1–1; Baumgartner and Reichel 1975).

Forests that are "physiognomically tropical" extend beyond the geographic Tropics of America, notably in northern Mexico, southern Florida, southeastern Brazil, and northeastern Argentina (Baur 1964b).

The climate and physiography of the American tropical region as well as the forests themselves are described in this chapter. Sources of the climate and regional features precede a discussion of climatic classifications of forests. Under physiology, the geological source of the present physiography and the characteristics and major classes of soil are described. The forest description begins with the genesis of the forests, their present extent and location, and their classifications, finishing with a description of the extensive forests of the Amazon basin, mangrove forests, and cerrado.

Climate

The climatic Tropics is a band of varying width on either side of the climatic Equator, a line that connects points relatively uniform in humidity and temperature. The climatic Equator deviates from the geographic Equator because of a lack of uniformity in the distribution of land, oceans, and orographic influences. Tropical climatic conditions, sometimes termed "subtropical," may be extended beyond the geographic Tropics by cyclone systems.

Climate is the greatest force affecting the natural distribution of vegetation. Thus climate similarities or differences are a key to explaining the degree to which forest productivity varies from place to place and the corresponding probability that measured results in one place may apply to another. The description of the climate of tropical America that follows draws on Trewartha (1968).

Solar Radiation. The greatest determinant of climate is solar energy. Each day, tropical America is bathed somewhere by the Sun's rays from vertically overhead. Some 30 percent of the radiation received at the upper edge of the Earth's atmosphere over the Tropics (fig. 1–2; Gentilli 1968, cited by Trewartha 1968) is lost through reflection, chiefly because of clouds. Of the radiation not reflected, about 30 percent is absorbed as it passes through the atmosphere before reaching the Earth's surface. The amount so lost is least where the Sun is directly overhead and more where the atmosphere is penetrated at an angle. Angularly incident radiation is also less effective because it is diffused over a larger area of ground surface. These losses are further increased by reductions in day-length as latitudinal distance from the position of the Sun increases. Daily insolation levels at the Earth's surface for the months of June and December are shown in table 1–2 and figures 1–3 and 1–4.

Solar radiation at the Earth's surface in the outer Tropics is greater than in the equatorial Tropics because of greater cloudiness near the Equator. The radiation at latitude 10° is about 6 percent greater than at the Equator; at latitude 20°, it is about 10 percent greater (Budyko 1962, Trewartha 1968). For example, inner Amazonia on the Equator receives less than 120 kcal/cm2 of solar radiation per day, whereas the eastern Sahara, at latitude 20° N., receives more than 220.

The reflective capacity of the Earth's surface, termed "albedo," varies with the nature of the land surface. For grasslands, it may be 15 to 30 percent; for bare ground, 7 to 20 percent; and for forests, 3 to 10 percent (Trewartha 1968).

If the annual vegetative period of the Tropics were only as long as that of the Temperate Zone, the Tropics would be at a disadvantage with respect to potential photosynthesis (Best 1962) because daylight in the summer is markedly shorter in the Tropics than in the Temperate Zone. The ratio of tropical to temperate average daily radiation is approximately 1:1.5 (Best 1962). Moreover, sufficient water to grow crops in the Tropics is generally available only during the monsoon season when radiation is less than in the growing season in the Temperate Zone.

Temperature. Normal temperatures in tropical America vary somewhat from summer to winter (fig. 1–5). More than half the region's land area experiences mean temperatures above 25 °C in the summer, and less than a

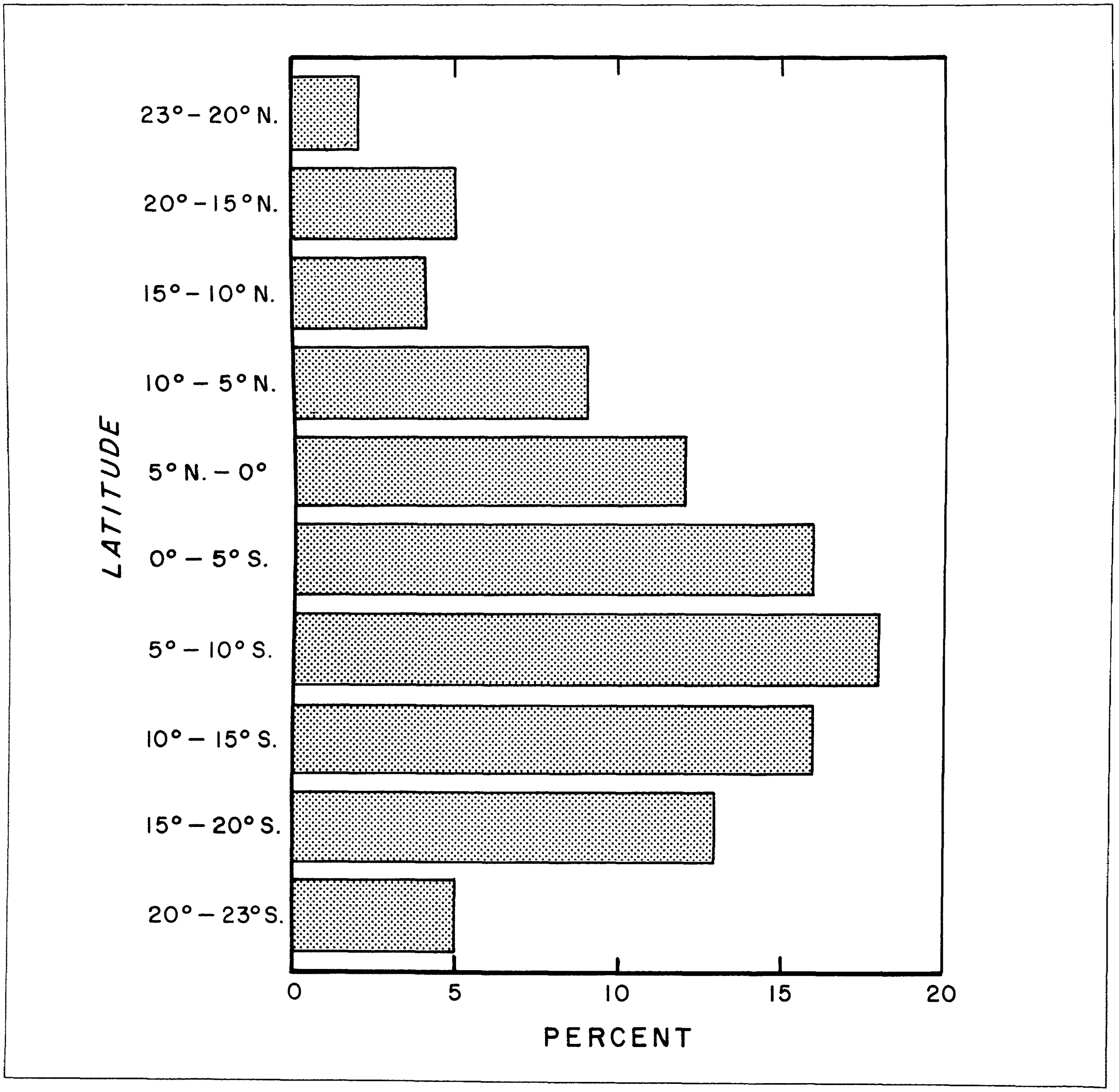


Figure 1–1.—*Percentage of land at different latitudes in the American Tropics (Baumgartner and Reichel 1975).*

Table 1–1.—Equatorial (inner) and outer tropical land areas

Location (latitude)	Tropical land areas (%)
Equatorial Tropics (0° to 11° 43′)	
North	22
South	39
Outer Tropics (11° 43′ to 23° 27′)	
North	10
South	29
Total	**100**

Source: Baumgartner and Reichel 1975.

fifth of the region is cooler than 15 °C all year (Anon. 1975b, 1979b).

Proximity to the sea produces maritime climates in part of tropical America. Since turbulence leads to slow warming and cooling of water surfaces, the climates of oceanic islands and exposed coasts are relatively uniform. Oceanic surfaces probably do not change in temperature more than 1 °C between day and night. Continental areas far from the sea experience much greater daily and seasonal extremes. Webb and others (1980), analyzing data from 319 weather stations in tropical and subtropical America, found that below 1,000 m in elevation, the lapse rate is a change of 1 °C for every 278-m change in altitude, whereas between 2,000 and 3,000 m, a change of 1 °C occurs every 189 m. They also concluded that the rate of change decreases with distance from the Equator. At latitude 0° a rise of 204 m in elevation reduces temperature 1 °C, whereas at latitude 25° N., it takes a 276-m change to reduce temperature 1 °C. Their findings are summarized in table 1–3; a few examples appear in table 1–4.

Nearly the entire region is free of frost. Major exceptions are the Sierra Madre in Mexico, the high Andes, and southern Brazil.

Wind. Winds in the Tropics are seasonally variable. Surface winds as a whole are easterly. The winds of tropical America generally blow from north of due east in the Northern Hemisphere and south of due east in the Southern Hemisphere throughout the year. The trade winds are strongest near 10° N. and S. latitudes (fig. 1–6). However, there are many exceptions to the seasonal uniformity of wind direction and much remains to be learned about tropical wind movements. Westerly winds are not rare, and the "doldrums"—prevailing calms and light, variable winds attributed to the zone of convergence of the easterly trade winds from the Northern and

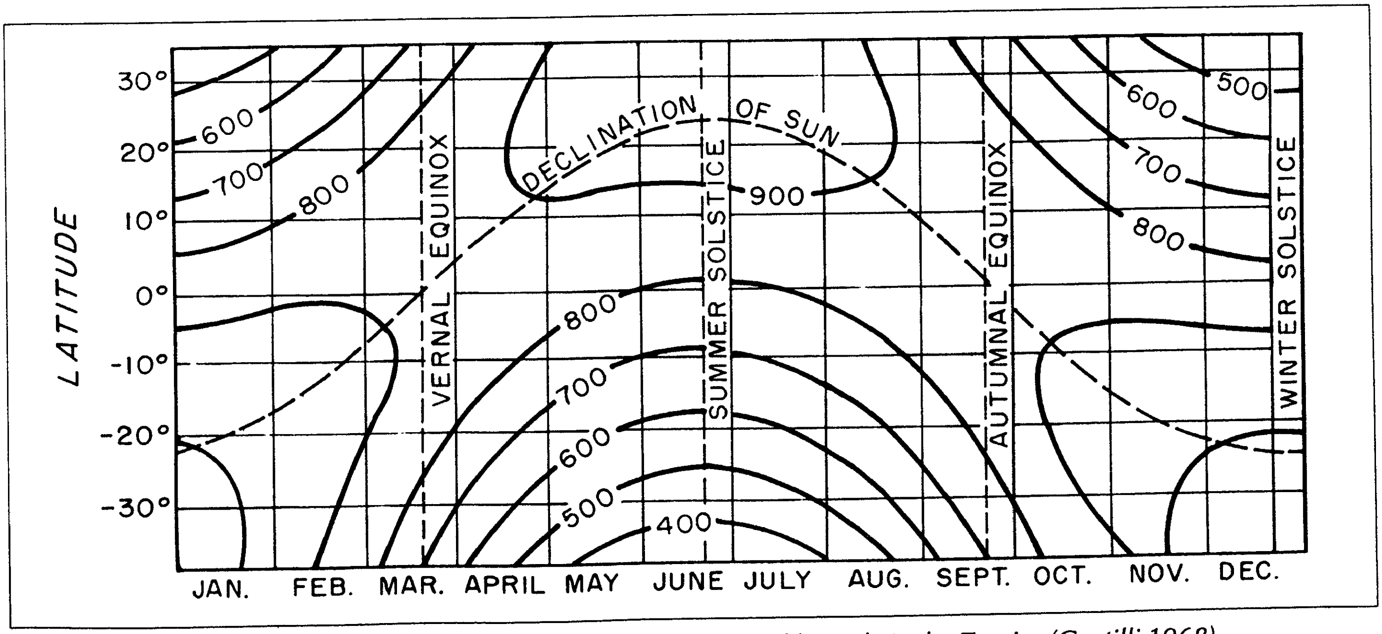


Figure 1–2.—*Mean surface solar radiation as affected by season and latitude in the Tropics (Gentilli 1968).*

Table 1–2.—Daily insolation losses at the Earth's surface for June and December by type of loss and latitude

Type of loss and resultant insolation	Equator	Tropic of Cancer	Tropic of Capricorn
Equinox			
(June—Sun over Equator)			
Loss due to angularity	0	8	8
Loss through atmosphere	39	39	39
Effect of day-length	0	0	0
Resultant surface insolation	61	53	53
Northern solstice			
(December—Sun at 23° 27′ N.)			
Loss due to angularity	8	0	33
Loss through atmosphere	39	39	33
Effect of day-length	0	49	-4
Resultant surface insolation	53	70	30

Source: Gentilli 1968.

Southern Hemispheres—are common. Weather in this region is extremely localized.

The seacoasts of tropical America are subject to land and sea breezes caused by seaward drift of air that has been cooled by more rapid night radiation over land than over sea and, conversely, landward drift during the day caused by the rise of more rapidly heated air over land. These sea breezes may reach storm intensity and are particularly strong on dry, tropical coasts adjacent to cool, ocean currents. Similar diurnal and nocturnal mountain and valley winds also occur due to these temperature differentials.

Violent cyclones or hurricanes enter tropical America each year. They usually approach from an easterly or southeasterly direction through (or just to the north of) the Caribbean Sea, affecting the West Indies and the Atlantic slope of Central America and Mexico. Tropical hurricanes may also reach the west coast of Central America and Mexico from the Pacific Ocean, entering from a northwesterly direction. These hurricanes develop wind speeds up to 250 km/h or more. Roughly circular in outline, they may attain 600 km in diameter and affect a single area for days. Precipitation totaling 1 m or more may accompany such storms.

Moisture. For the Tropics as a whole, cloudiness is greatest near the Equator. The worldwide average for latitudes 0° to 10° is 52 to 56 percent (Brooks and Hunt 1930). Cloud cover is 40 to 46 percent for latitudes 10° to 20° and declines to 34 to 38 percent in the 20° to 30° latitudinal range.

Rainfall in tropical America is typically either convectional, caused by cooling of rising air above the warm land surface, or orographic, caused at least in part by upthrust effects of highlands. The generation of orographic rainfall is illustrated in figure 1–7.

Rainy "seasons" characterize most of the Tropics. These generally result from the unstable air common to the intertropical front, a zone of convergence between permanent cells of moist equatorial air in each hemisphere. This zone migrates northward and southward each year, generally being found in the hemisphere experiencing summer (figs. 1–8, 1–9). The saying that rainfall "follows the Sun" is illustrated well by de Martonne's chart (fig. 1–10).

Mean annual precipitation for all tropical land masses worldwide varies by latitude (Brooks and Hunt 1930, Meinardus 1934). The amounts are generally lower than those for America alone because vast tropical areas of the Eastern Hemisphere are relatively rainless. Precipitation over the oceans is much greater in the equatorial Tropics where large-scale lifting of warm, humid air is of major climatic significance.

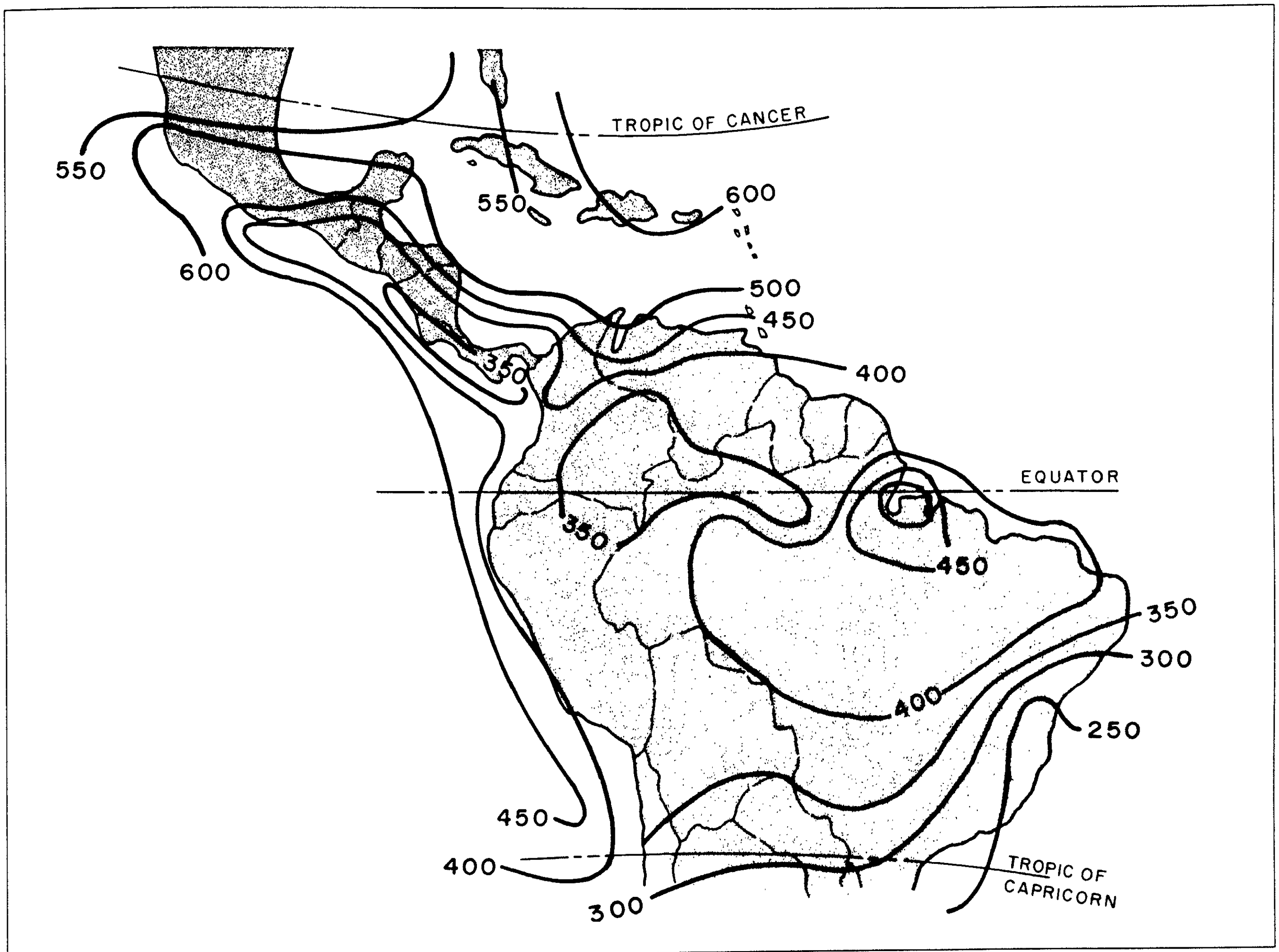


Figure 1–3.—*Mean daily solar radiation (calories/cm²) received at the Earth's surface in June (Landsberg 1961).*

The mean annual precipitation over the region ranges from less than 40 cm in a few isolated areas to more than 320 cm (figs. 1–11, 1–12; Anon. 1975f, 1979f). About 70 percent of the area receives 160 to 320 cm/yr. Monthly precipitation of 10 cm or less slows the biological activity of many plants. Much of the area in tropical America receives less than 10 cm during part of the year, between December and April north of the Equator and between May and September south of the Equator. About 64 percent of the region experiences dry months with less than 5 cm of precipitation (Anon. 1975a, 1979g).

Precipitation in the region may vary widely from year to year, especially in the dry climates of northwestern Mexico, northeastern Brazil, coastal Peru, western Bolivia, and northern Chile. In these areas annual rainfall in any specific year may average 40 percent below or above the mean. In the rest of tropical America, this variation ranges from 10 to 20 percent (Biel 1968). The seasonal rainfall patterns (fig. 1–13) affect the types of forest vegetation present and the adaptation of individual tree species to different regions.

The evaporation capability of the air is proportional to the atmospheric saturation deficit, which is a measure of the degrees that vapor pressure is below saturation. More commonly used for this purpose is relative humidity, a measure of the percentage of vapor pressure in the air. Actually, saturation deficit and vapor pressure are better indicators than relative humidity of moisture stresses on plants because they take into account current temperature and pressure (Longman and Jenik 1974). In the moist

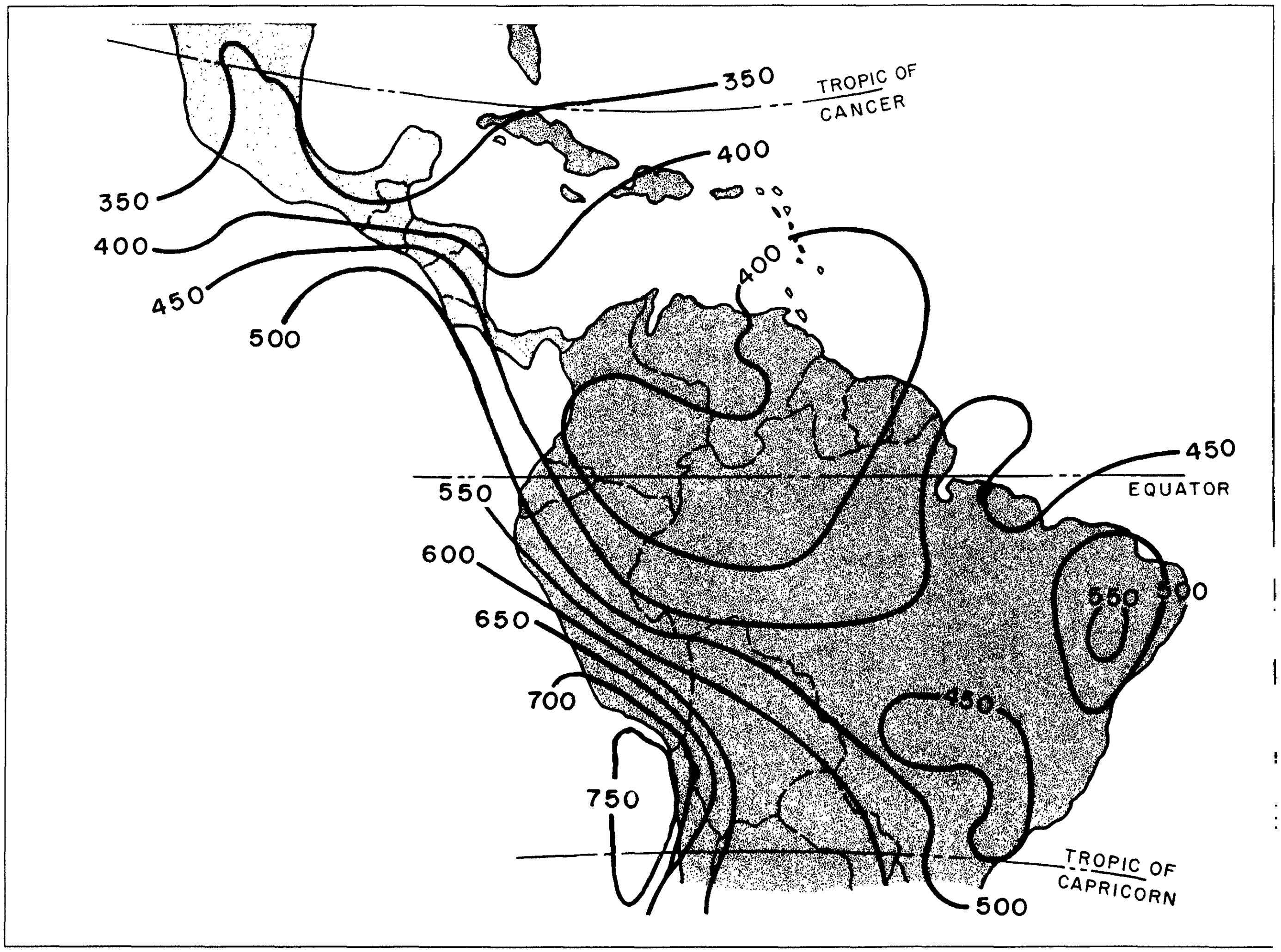


Figure 1–4.—*Mean daily solar radiation (calories/cm²) received at the Earth's surface in December (Landsberg 1961).*

Tropics, relative humidity may fall to 70 percent at midday in the forest canopy, but at the soil surface it is generally higher than 90 percent. At night, the humidity is generally higher than 95 percent (Longman and Jenik 1974). Twenty-four-hour means range between 70 and 85 percent.

Probably more than half the Earth's evaporation takes place within the Tropics (Trewartha 1968). Evaporation decreases slightly at the Equator due to heavy cloudiness there. Potential evaporation, or that which would take place with unlimited amounts of water, averages 120 cm/yr at latitudes 0° to 10° and 130 to 140 cm/yr for latitudes 10° to 20° (Schwerdtfeger 1976).

Regional Climatic Features. Tropical America is characterized by distinct subregional climatic features. Descriptions of these appear in appendix A and draw heavily on Garbell (1947) and Schwerdtfeger (1976).

The classification of climates of significance to vegetation is fundamental to the recognition of distant but similar climates to guide land use and forest practice. These classifications are particularly useful in interpreting the extent to which research results may be expected to apply in a distant area. Climatic classification has been undertaken since the mid-19th century, chiefly by biologists (Thornthwaite and Hare 1955). By 1875, the idea that climates might be classified according to vegetation

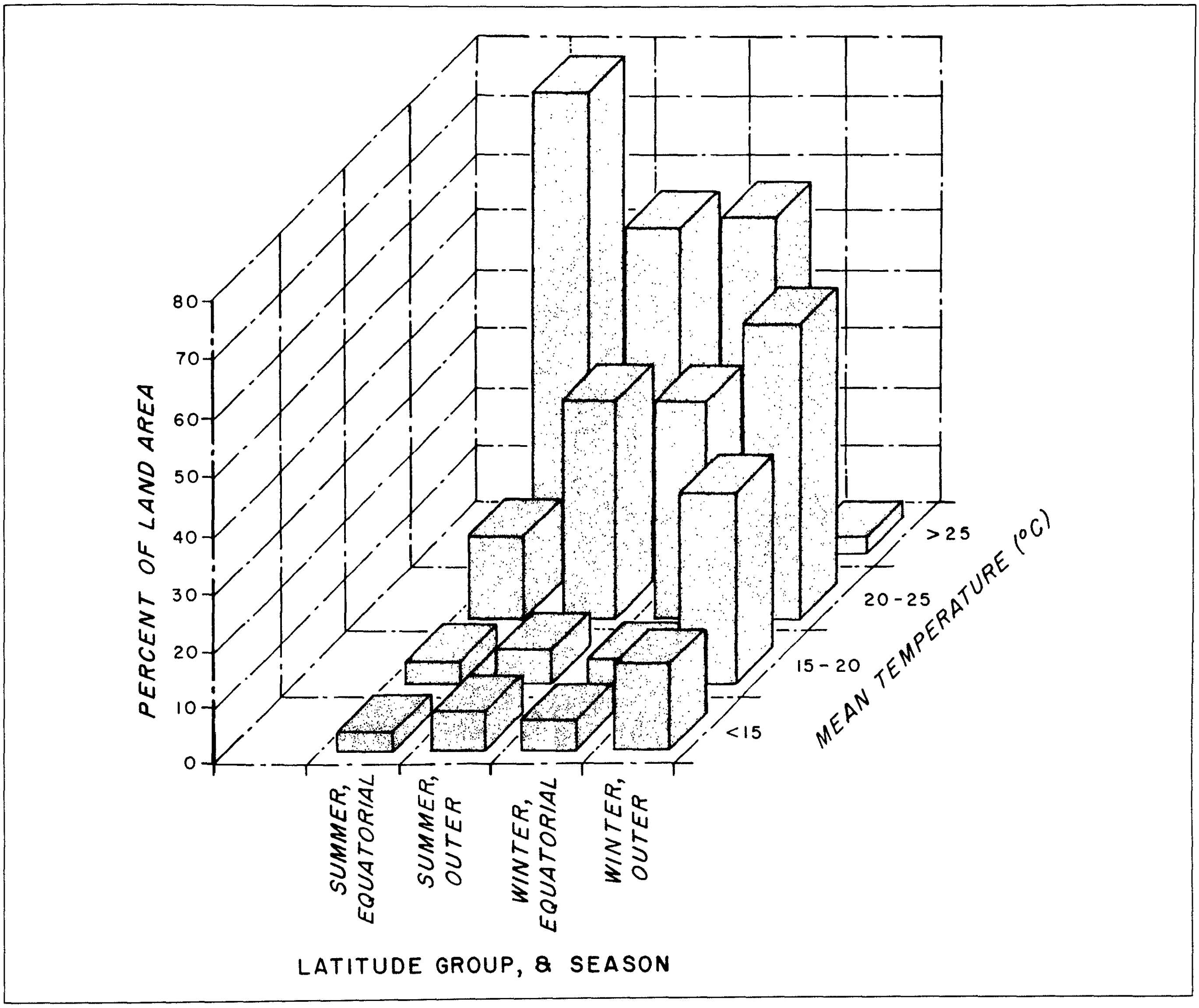


Figure 1–5.—*Land area of tropical America by latitude and mean temperature (Anon. 1975b, 1979b).*

type was well established. Yet today no one classification system is currently accepted worldwide, and new, local classifications continue to appear. A record of major classifications applicable to the Tropics is to be found in appendix B.

The climatic classifications described in appendix B show different attempts to integrate temperature and moisture in terms significant to vegetation and thus lead to its broad classifications as well. At best these systems distinguish only widely different vegetation; additional sources of differences in forest structure and particularly composition are local soil, topography, and degree of isolation. Greater refinement for purposes of management calls for descriptions of forest associations and types.

Physiography

Three-fourths of the land in tropical America lies below a 500-m elevation (fig. 1–14; Anon. 1979f). In contrast,

Table 1–3.—Mean temperature relative to altitude and latitude (°C)

Altitude (m)	Latitude 20° N.	 0°	 20° S.
0	25.8	27.2	23.1
1,000	22.8	23.1	19.9
2,000	17.2	18.1	16.3
3,000	10.8	12.2	12.1

Source: Webb and others 1980.

nearly half the land in the eastern Tropics lies above 500 m. The following physiographic description draws heavily on Sanchez (1976).

The most outstanding physiographic feature of tropical America is the mountainous Cordillera near its western edge, extending throughout North, Central, and South America, including the Sierra Madre Oriental in Mexico and the Cordillera Oriental of Colombia and Venezuela. The highest peaks are Popocatepetl in Mexico (5,400 m), Huila in Colombia (5,800 m), Chimborazo in Ecuador (6,300 m), and Huascaran in Peru (6,800 m). In addition, extensive plateaus from 1,000 to more than 3,000 m characterize central Mexico, southeastern Venezuela, the southern half of the Guianas, and Brazil south of latitude 5° S. In contrast, extensive lowlands less than 500 m in elevation are found to the east of the Cordillera on Mexico's Yucatan Peninsula, in the Llanos of the Orinoco in Venezuela, and in the basins of the Amazon and the upper Rio Paraguay, extending southward from the southern Matto Grosso into Paraguay. Elevations in the West Indian islands range from the extensive lowlands of central Cuba to mountainous areas in eastern Cuba (2,000 m), Jamaica (2,300 m), and Hispaniola (3,200 m). The Lesser Antilles are nearly all mountainous, with many peaks higher than 1,000 m.

The Cordillera arose late in the Cretaceous period (65 to 135 million years ago) and has undergone subsequent modifications, including probably three periods of volcanism. The high peaks on the Mexican plateau (Popocatepetl, Ixtaccihuatl, etc.) arose during the Miocene epoch (10 to 25 million years ago), when volcanism affected all of Mexico. Volcanic activity resumed in this area and began in Central America in the Pliocene epoch (600,000 to 10 million years ago) and has continued to the present. The marine deposits of the Yucatan Peninsula were laid down during the Pleistocene epoch (12,000 to 600,000 years ago).

Most of western Mexico and the mountainous areas of Central America and central Hispaniola and Puerto Rico have been above sea level since the Cretaceous period (Schuchert 1935). Cuba and the Yucatan were largely submerged during the Pleistocene epoch. The central Lesser Antilles, which have the most active volcanoes at present, may have appeared as early as the Miocene epoch, but the islands to the north and south of these are of Pliocene and Pleistocene origin.

In the northern Andes, the Pliocene epoch was a time of vast volcanic eruptions and mountain construction. The plateaus to the north and south of the lower Amazon are of Mesozoic (65 to 230 million years ago) or Paleozoic

Table 1–4.—Mean temperature change with elevation at different locations in the Western Hemisphere

Location	Latitude	Difference[a] Elevation (m)	 Mean temperature (°C)	Rate of change (m/°C)
Alvarado/Desierto de los Leones, Mexico	18° N.	3,190	13.6	235
Barinas/Mucuchies, Venezuela	9° N.	2,820	16.0	176
Cobija, Bolivia/ Cerro de Pasco, Peru	11° S.	4,200	17.8	236
Chaco Mission, Paraguay/ La Quiaca, Argentina	20–22° S.	3,340	14.7	227

Source: Webb and others 1980.

[a] Difference in elevation and mean temperature of the two locations listed in the first column.

Figure 1–6.—*The easterly trade winds prevailing throughout the region shape the crown of this sentinel standing on the windward coast of the island of Saint Lucia.*

(280 to 600 million years ago) origin and are the oldest structures of the region (Schuchert 1935). The extensive lowlands of South America are Tertiary and Quaternary deposits (within the past 65 million years).

The moist conditions and the limitations of agricultural productivity have left extensive forests on the steep slopes of the uplands of tropical America, local exceptions notwithstanding. At the other extreme, because of similar difficulties for successful agriculture, extensive lowlands in the Yucatan Peninsula, the coastal plains of Central America, and the Amazon Basin also remain largely forested.

No summaries of topography were found for the region as a whole but an Empresa Brasileira de Pesquisa Agropecuaria (EMBRAPA) study (Cochrane and Sanchez 1981) for the central lowlands of tropical South America showed the relations given in table 1–5.

Soils

Information given here draws heavily on descriptions of the formation, classification, and properties of the soils of the Tropics by Mohr (1944), Sanchez (1976), and Young (1976).

Formation. Seven factors significantly affect soil formation: climate, parent material, relief, drainage, organisms, time, and human activity (Young 1976). Profile depth, stoniness, and soil texture affect the properties of the soils that are formed. Climate helps determine the organic component, the reaction, and the base saturation; the parent material influences soil texture; relief influences soil depth and stoniness.

Young uses Koeppen's (1936) system of climatic classification for soil relationships because of its simplicity. Young contrasts soil formation processes in different climates. In a rain forest (Koeppen's Afl), weathering is intense, with complete breakdown of all minerals other than quartz. Leaching throughout the year produces acid soils with low base saturation. Dry seasons of up to 3 months duration do not retard these processes significantly.

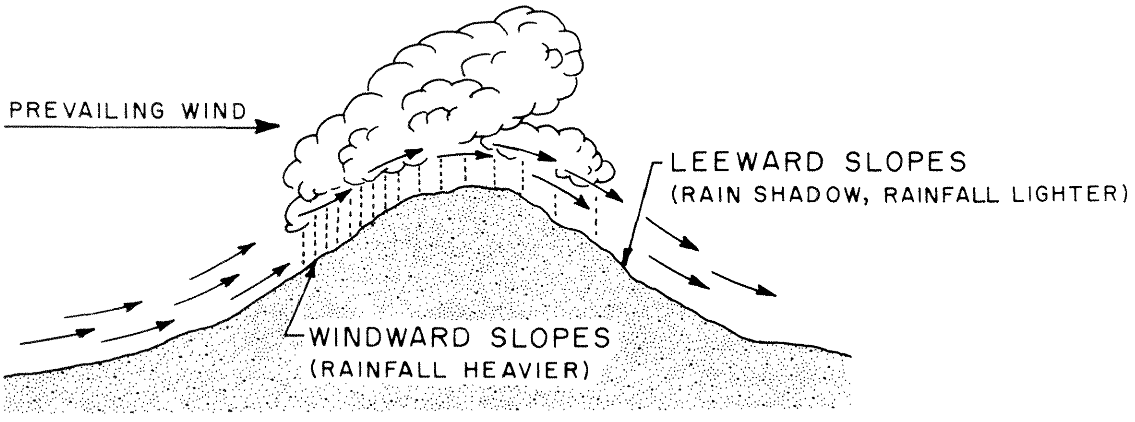


Figure 1–7.—*Rainfall contrasts on windward and leeward slopes (Beard 1949).*

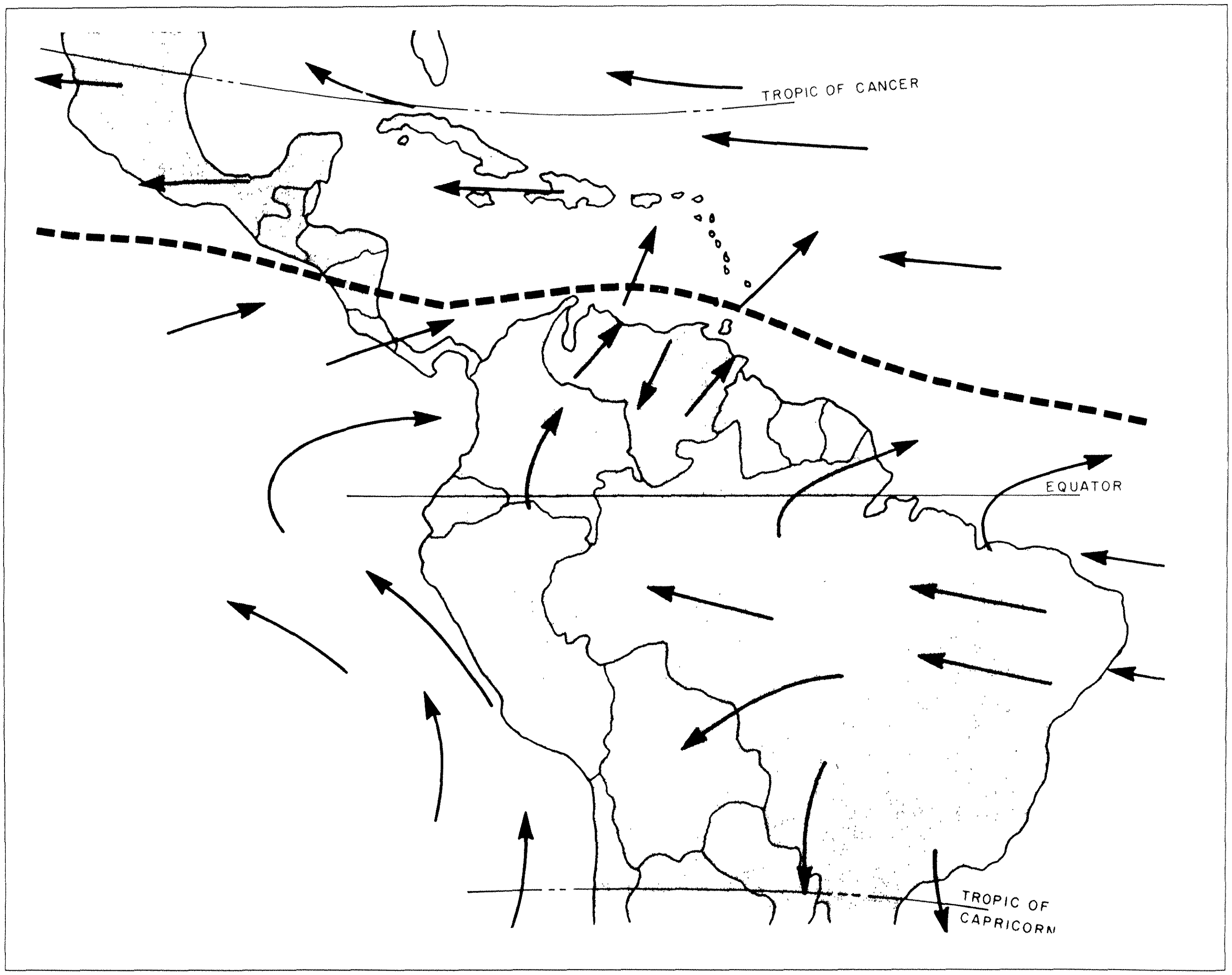


Figure 1–8.—*Surface windflow pattern during the northern solstice; dashed line equals the convergence zone (Garbell 1947).*

In the rain forest-savanna transition zone (Am), leaching is less intense; therefore, acidity is less and base saturation (content of calcium [Ca], magnesium [Mg], potassium [K], or sodium [Na]) is higher. The moist savanna (Aw) soils are leached but may dry to wilting point to a depth of more than 1 m. Acidity ranges from a pH of 5.0 to 6.0 and base saturation from 40 to 60 percent. In the dry savanna (CWa) where rainfall is concentrated within a 5-month period, the wilting point may reach a depth of 2 m. Base saturation rises to between 60 and 90 percent. Both fertile and infertile soils are widespread.

In the semiarid climates where mean annual rainfall is below 60 cm, calcium carbonate is not leached and accumulates in the lower soil horizons. A clearly developed humic topsoil may accumulate. Lithosols are common on slopes, and saline soils are common on low-lying sites.

In areas that are subtropical because of elevations of 900 to 1,600 m (as in central Africa), the zonal soils are humic Latosols. At higher elevations, organic matter increases substantially. In subtropical, humid areas

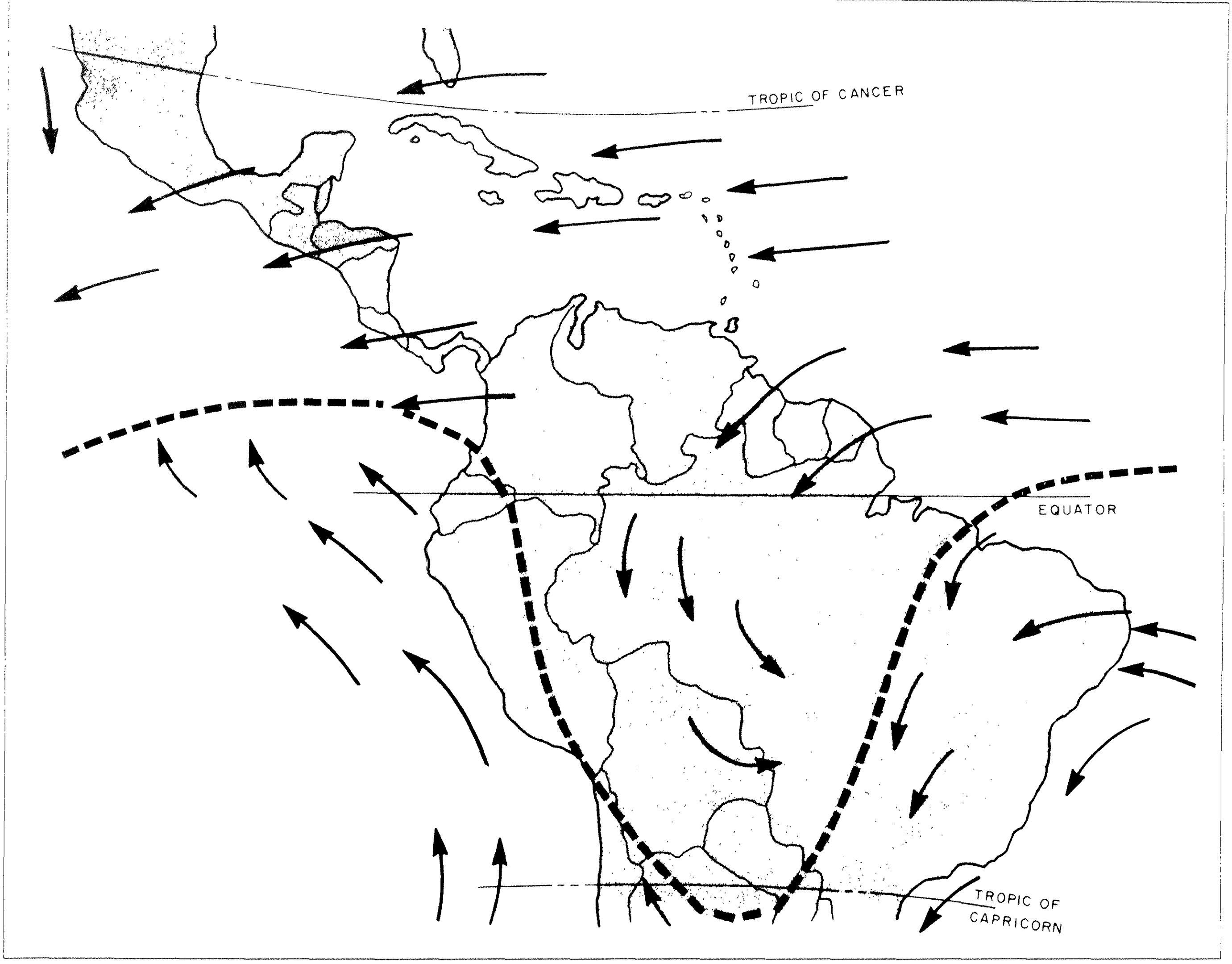


Figure 1–9.—*Surface windflow pattern during the southern solstice; dashed line equals the convergence zone (Garbell 1947).*

adjacent to the Tropics, leached red-yellow podzolic soils are common.

Soil formation in the Tropics is largely related to water and its amount, changes, and movements in the soil. Most weathering and leaching of tropical soils are a result of moisture combined with high temperature.

Rainwater dissolves carbon dioxide from the atmosphere and thus is already a weak solution of carbonic acid before it reaches the earth. Its acidity increases as it comes in contact with the carbon dioxide in the soil air and takes organic substances into solution. As soil acidity increases further, the soil solution becomes an increasingly more powerful leaching agent. Typical soil conditions in the Tropics described below are adapted from Young (1976).

- *Lowland rain forest, free drainage.* Rapid downflow of soil water throughout the year. High rates of weathering and leaching.

- *Lowland rain forest, impeded drainage.* Wet throughout the year. Subsurface has laterally, generally downward throughflow. Conditions conducive to reduction except for intermittent oxidation at the surface.

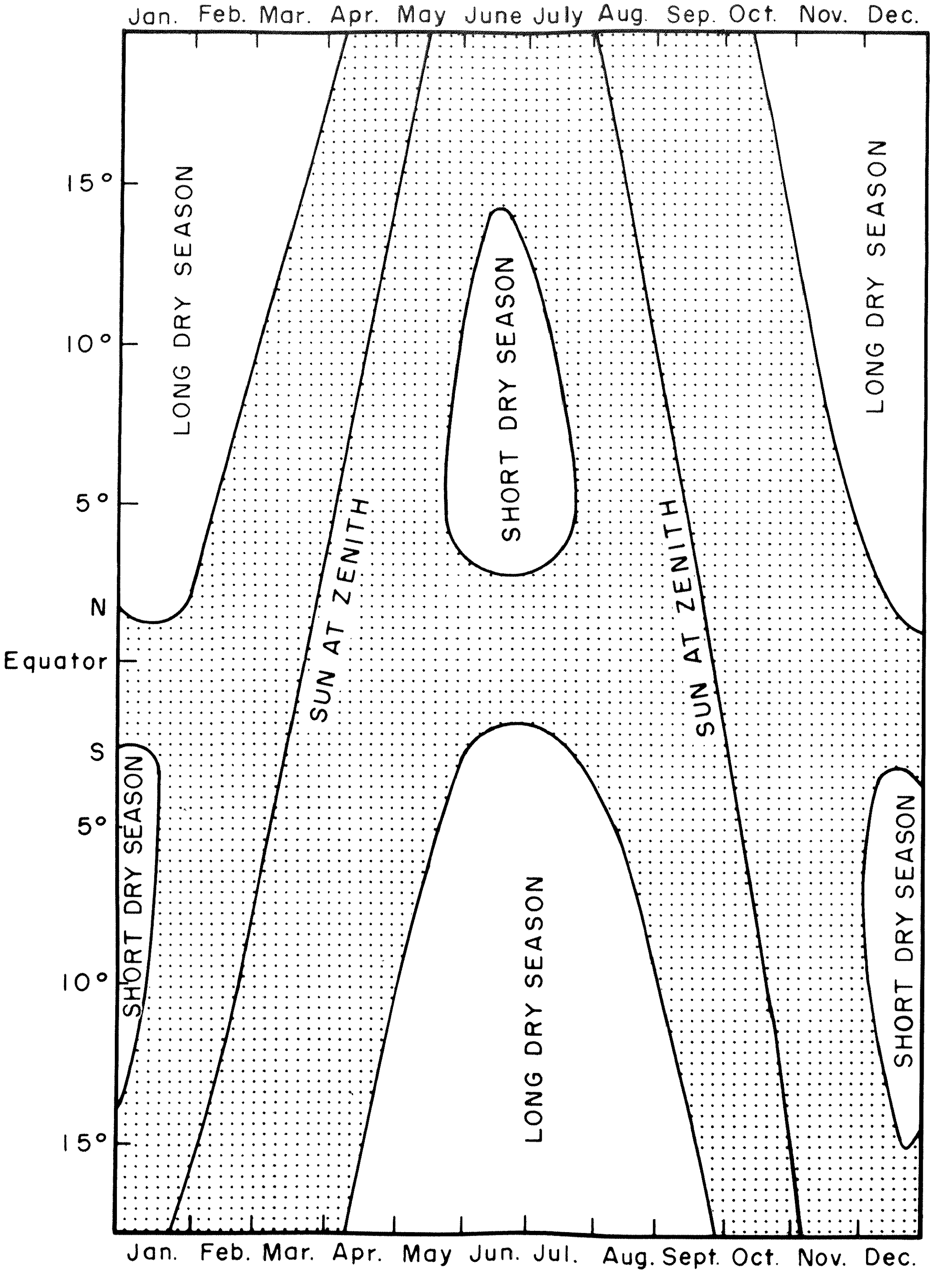


Figure 1–10.—*Wet and dry seasons in the Tropics in relation to latitude (adapted from E. de Martonne, cited by Richards 1952).*

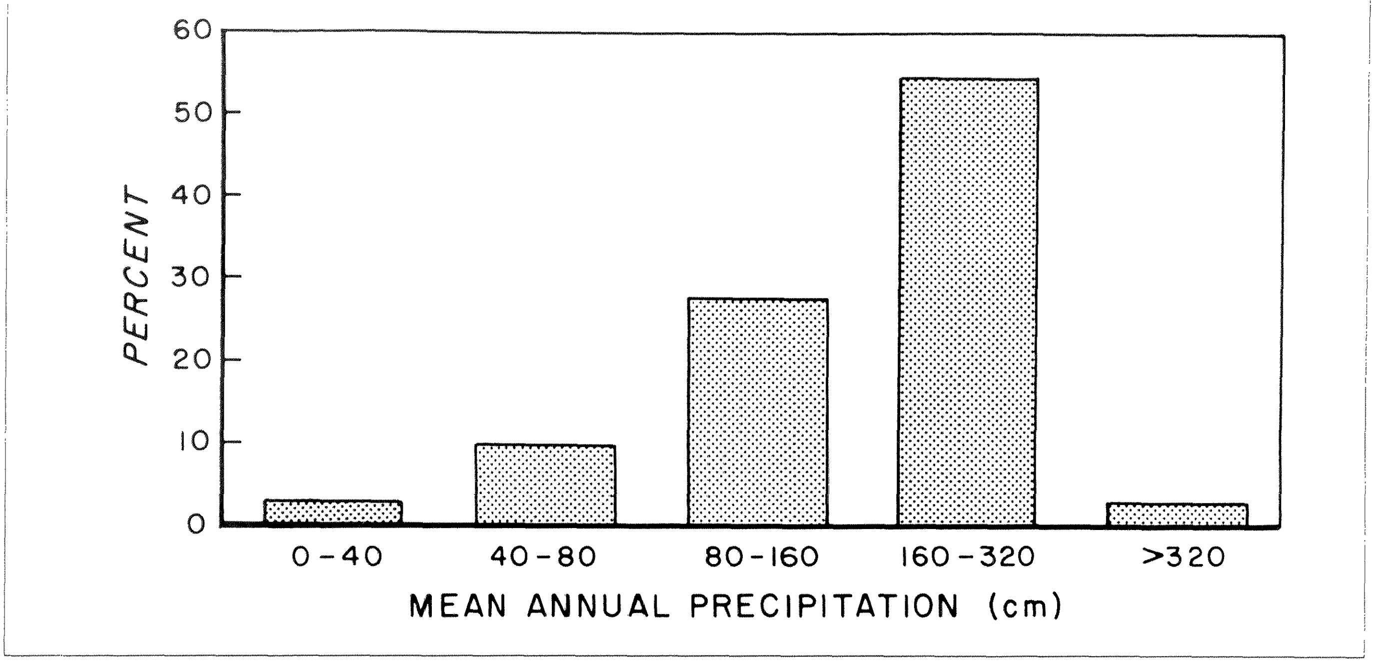


Figure 1–11.—*Land areas of tropical America by precipitation levels (Anon. 1975h, 1979f).*

- *Savanna, free drainage.* Moist during wet season with downward flow. Static in the early dry season and becoming dry 1 to 2 m in depth in the late dry season. Weathering of bedrock is rapid but slowed within the profile during the dry season. Leaching in the wet season alternates with precipitation of dissolved substances in the dry season.

- *Savanna, high water table.* Wet in the wet season and at depth throughout the year. Upper horizons alternately wet and dry. Reduction during the wet season alternating with dry-season precipitation of dissolved substances.

Little is known about absolute rates of soil formation. Both rock weathering and profile development are involved; the latter process is much more rapid than the former. Young (1969) estimated rock weathering sufficient to produce 1 m of regolith (unconsolidated material that overlies solid rock) generally would take 20,000 years but thought rates in the humid Tropics would be higher. Profile development in the Tropics may take place in 100 years or less.

Parent Material. Mineral soils originate from the three classes of rock: igneous, sedimentary, and metamorphic. Igneous rocks have solidified from a liquid state. Sedimentary rocks developed from materials transported and deposited by water or air. Metamorphic rocks are usually of igneous origin, but they have been subjected to such prolonged high pressure and temperature that their characteristics are altered.

Igneous rocks that solidified deep in the Earth are plutonic. Those that solidified en route to the surface are intrusive. Those that solidified after they reached the surface are volcanic. Because all igneous rocks may arise from the same magma (molten rock), their composition is generally similar: they commonly contain quartz (SiO_2) and feldspar (SiO_2, Al_2O_3, and K_2O or Na_2O). The quartz resists weathering as do those feldspars rich in SiO_2.

Sedimentary rocks differ in particle size from coarse sand to fine clay and in composition from calcareous to volcanic materials. Metamorphosis may produce a variety of new minerals. Based on soil parent material, Young distinguishes crystalline and sedimentary rocks and unconsolidated materials. Igneous and metamorphic rocks of similar composition are grouped together, because there is no clear difference in their effect on pedogenesis.

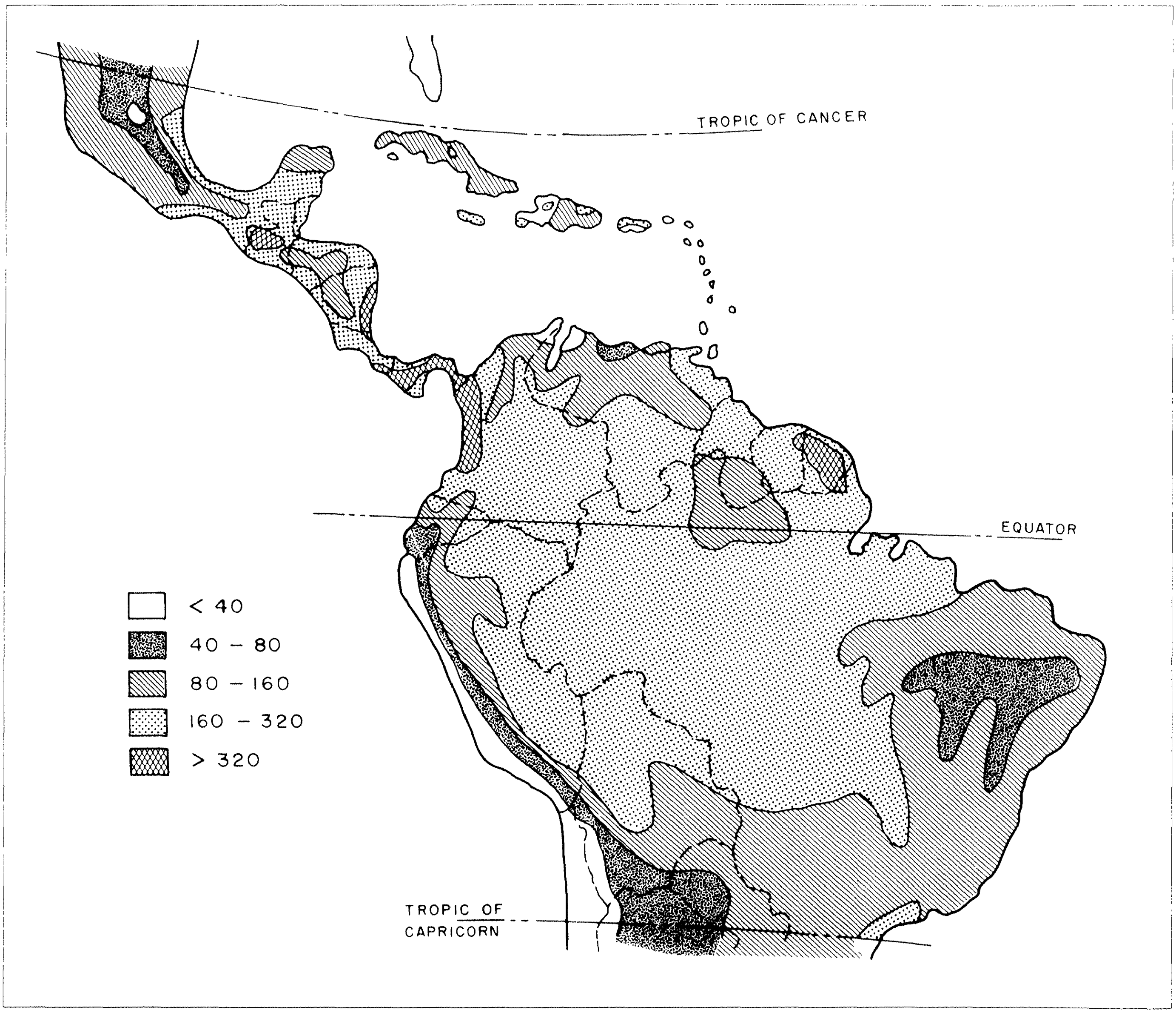


Figure 1–12.—*Mean annual rainfall (cm) in the neotropics (Anon. 1975h, 1979f).*

Rock composition ranks with rainfall as one of the two main causes of soil differentiation in the Tropics. The main variable in the composition of parent material is silica; felsic rocks contain 66 percent or more, intermediate rocks contain 55 to 66 percent, and basic rocks less than 55 percent. Rock composition determines which products are supplied to the soil solution through weathering.

Felsic rocks are a poor source of Ca, Mg, K, iron (Fe), and manganese (Mn). Residues of weathering include quartz and kaolinite; all weatherable minerals are readily dissolved. Basic rocks, in contrast, retain weatherable minerals in the lower parts of the profile, thus providing a continuous source of new weathering products, such as Ca, Mg, and K, to the soil solution. Soils developed from rocks of felsic or intermediate composition are so extensive as to be termed zonal soils.

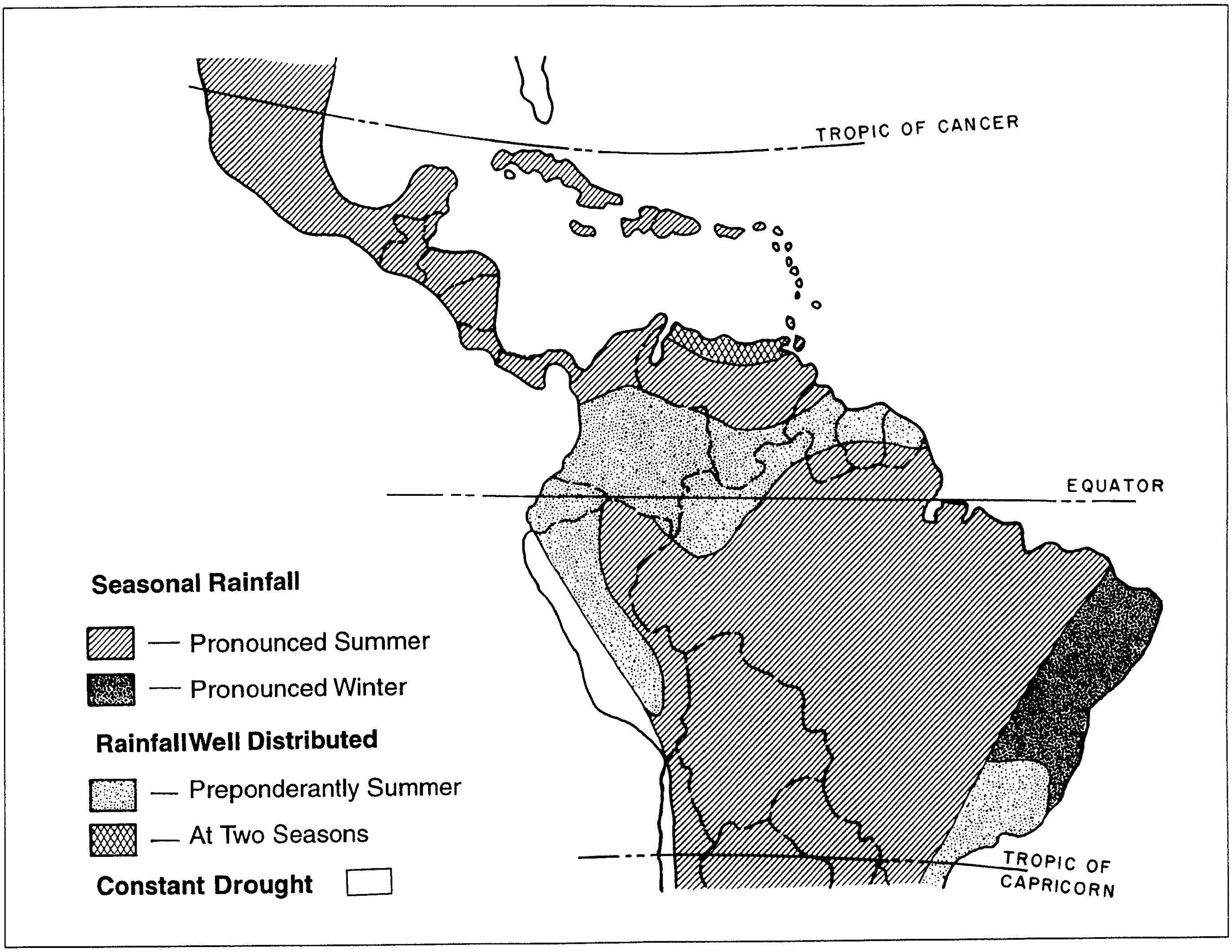


Figure 1–13.—*Seasonal rainfall patterns in tropical America (Biel 1968).*

Limestone soils in the Tropics are intermediate in fertility between the felsic and basic soils. In humid areas, they are generally acid Latosols, whereas in the semiarid zones they generally are Vertisols.

Felsic crystalline rocks are mainly granites and gneisses, the most extensive types of parent material in the Tropics. The resulting soil is either sand or sandy clay. In humid climates, these rocks are low in weatherable materials and high in permeability and are thus subject to strong leaching, which produces an acid reaction and low base saturation. Fertility is low. At the other extreme, basic igneous rocks yield clay soils that retain weatherable minerals. Fertility is adequate to sustain continuous cropping.

Sedimentary rocks weather more slowly than felsic crystalline rocks. Sandstones may give rise to sandy soils. Fine-grained sedimentaries, except shales, weather more deeply. Soils derived from shale have poorer physical but better chemical properties than those from sandstone. They also have higher available water capacity and higher nutrient levels.

Topography not only directly affects soil formation but also influences climate and drainage, which in turn

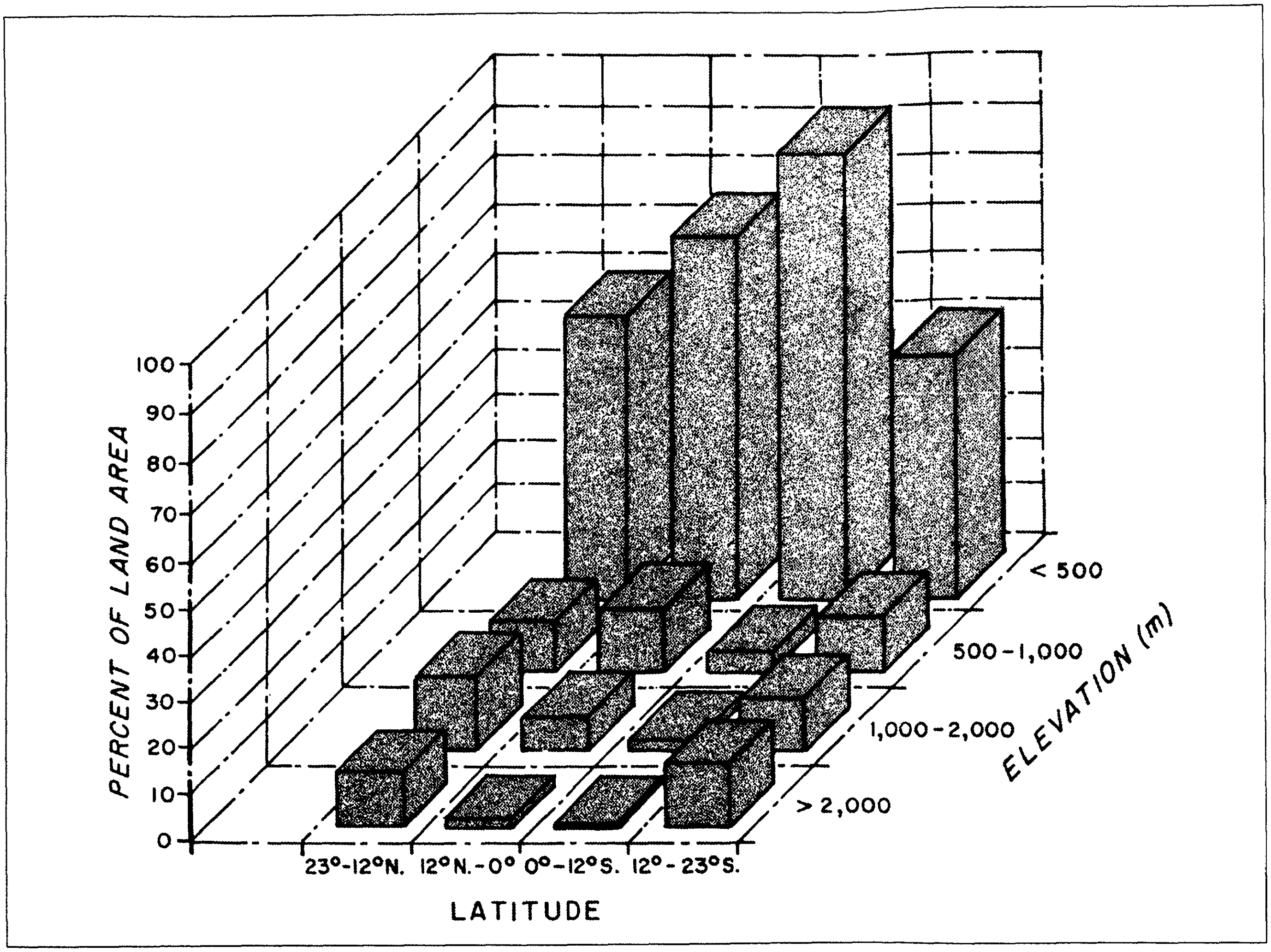


Figure 1–14.—*Percentage of land area of tropical America by latitude and elevation (Anon. 1979b).*

affect soil formation. Temperature change with elevation produces elevational soil zones that differ particularly in organic matter content. Elevation affects rainfall, especially on windward slopes. Relief also has a great effect on soil drainage.

Steepness of slope affects soil formation both directly and indirectly. The steeper the slope the greater the erosive power of water. Apparently the weathering rate is not affected by slope, so the imbalance of weathering and erosion on steep slopes results in thinner soil there than elsewhere. On the other hand, on gentle slopes the longer residence time of the soil may lead to a highly weathered (and thus infertile) surface soil, whereas, on

Table 1–5.—Topography of tropical South America

	Area	
Topographical type	Millions of hectares	Percent of total land area
Flat, poorly drained	170	21
Well drained		
Slope 0–8 percent	497	61
Slope 8–30 percent	116	14
Slope >30 percent	36	4
Total	**819**	**100**

Source: Cochrane and Sanchez 1981.

the steep slopes, the shorter residence time of the soil means it is less weathered and may contain more minerals. These differences are common knowledge among shifting cultivators, who may get their best yields on steep slopes.

Drainage. Drainage is critical to soil properties. Poor drainage commonly results in the reduction of Fe compounds in the absence of oxygen (O) and their partial reoxidation and precipitation.

Soil water may be free in soil cavities, adhering to soil particles, hygroscopically combined, chemically combined, or in vapor. It enters mostly from above in the form of rainfall and dew, from the side on the surface, or from below by ascent of ground water. Soil water leaves by evaporation, transpiration, or lateral or gravitational flow. Evaporation and transpiration increase generally with rainfall and with saturation deficit of the atmosphere. Under forests, soil moisture 1 m deep or more may be less than on bare land because of draft by the vegetation (Henry 1931, cited by Mohr 1944).

Young (1976) quotes the Food and Agriculture Organization (FAO) Manual on soil drainage classes as follows:

- *Very poorly drained.* The water table remains at the surface for most of the year, and frequently there is standing water. Applied to swamps.
- *Poorly drained.* The water table is at or near the surface for much of the year. Soils exhibit gleying in the topsoil. Applied to sites that, although not swamps, suffer from poor drainage.
- *Imperfectly drained.* Waterlogged for significant periods. Applied to soils with a clearly mottled B horizon. Crops sensitive to drainage impedance cannot be grown.
- *Moderately well drained.* The profile is wet for short periods, and the soil is mottled to some depth. These soils are freely drained for most purposes but show slight indications of temporary impedance.
- *Well drained.* Excess water is removed from the profile freely but not rapidly. No mottling is present.
- *Somewhat excessively drained.* Water drains through the profile as rapidly as added. Applied to sandy soils.
- *Excessively drained.* Water is removed from the profile very rapidly. Applied to stony soils on steep slopes.

Soil Organic Matter. Differences between weathered rock and the soil derived from it (and, in fact, much of soil fertility) may be considered largely biological (Jacks 1963). Organic matter in tropical soils increases erosion resistance and root penetration, augments cation exchange capacity, and constitutes a store of nutrients. The nutrient content and exchange capacities of most tropical soils are largely held in the organic complex within the top 20 cm of mineral soil.

The plant-soil system contains four stores of organic materials: living vegetation, dead vegetation, soil humus, and soil organisms. Carbon (C) is commonly used as a measure of organic matter. About half of oven-dry dead vegetation is C.

Organic-matter content of the soil may remain relatively constant beneath forests, but it is potentially unstable because the rates of humidification of litter and root exudations and of humus oxidation are both rapid relative to net storage in the soil. Nye and Greenland (1960) show that annual cycling rates for humidification and oxidation are each equal to about 2.5 percent of soil humus storage in lowland rain forests.

Young (1976) states that soil organic matter generally varies directly with rainfall and inversely with temperature. He estimates that a topsoil 10 to 20 cm deep contains 3 to 5 percent organic matter in zonal soils under lowland rain forests. Under moist savannas, the organic matter content averages 2 percent and under dry savannas, about 1 percent. Under rain forests, the layer of leaf litter may range in thickness from two leaves to 5 cm. At elevations of 1,500 to 3,000 m, the humic horizon is thicker and may contain 5 to 10 percent organic matter. Organic matter levels of the principal tropical soils compare favorably with those of the same general classes in the Temperate Zone. In many instances, the nitrogen (N) content of tropical soils is greater than that of Temperate Zone soils (Sanchez and others 1982).

Soil organic matter (humus) is supplied from rainwater and the resultant humidification of vegetative litter and root exudations. It is lost through oxidation to the atmosphere, erosion, leaching, and root uptake.

Lowland rain forest soils have topsoil C contents of 1 to 3 percent, or 3 to 9 kg/m^2. The turnover period for soil humus under rain forests is 20 to 50 years. The turnover period for dead litter is less than 1 year, decomposition being 1 to 3 percent per day. Once litter is humidified, however, the loss may be only 2 to 4 percent per year (Nye 1963). For savannas, the turnover period for soil humus is 40 to 50 years.

Both animals and plants affect the soil, but the major impact is from vegetation, primarily dead plant material. Biomass may be 300 to 900 or more tonnes per hectare in tropical rain forests, 60 to 100 t/ha in moist savanna woodlands, and 30 t/ha in dry savannas. Wood may make up 92 to 96 percent of this biomass in rain forests and about 88 percent in savannas. The overall productivity of the vegetation, reflected by turnover rates, is significant to the supply of soil organic matter. Rates range from 30 t/ha/yr in rain forests to 10 t/ha/yr in moist savannas and 5 t/ha/yr in dry savannas. For lowland tropical environments, topsoil organic matter is directly related to these productivity rates. Typical organic matter contents are 2 to 5 percent under rain forests and 1 to 2 percent in the savannas, levels not much different from those of the Temperate Zone (Kanehiro 1978).

Vegetation strongly affects soil moisture. In rain forest climates, leaf litter maintains a stable microclimate at the soil surface favorable to evergreen species. Under savannas and steppes, this cover decreases greatly during the dry season, accentuating the seasonal contrast.

Weathering. Vegetation also increases the weathering rate, modifies N mineralization, and increases fertility as a result of N fixation. Plant remains also increase the activity of soil fauna, which, in turn, affects soil formation.

Soil formation is a slow process, so time is critical. Mohr (1944) recognized five stages of soil weathering:

- Beginning—unweathered parent material
- Juvenile—weathering begun but still much unweathered material
- Virile—weathering more advanced but still much unweathered material
- Senile—unweathered material occurs only sporadically
- End—soil weathered out.

Mohr differentiates chemical from physical soil weathering. The former can occur only in the presence of water. What is dissolved in the water is very important. In nature, water never occurs in pure form. The purest water is rainwater that falls after the initial part of a shower has washed the atmosphere of its acidity. Water containing carbon dioxide is generally acidic; water containing calcium bicarbonate is alkaline. Water emanating from forests in which detritus (loose material such as rock fragments or organic particles) is being decomposed on the surface is generally acidic.

Soil formation is further affected by the predominant direction and velocity of water movement. Three general conditions have been cited (Mohr 1944): (1) continuous downward movement, (2) alternating upward and downward movement, and (3) upward movement. The first two are the most common. One result of such movements is the development of horizons within the soil. Some horizons lose constituents through leaching, whereas others may be correspondingly enriched.

Erosion significantly affects soil formation. The erosive power of water is a function of its speed and volume. Erosion resistance is determined by the weight of soil particles and their cohesiveness. These two factors are inversely related to particle size. Thus, coarse, sandy soils are loose and erosive; clay soils (composed of small, light particles) are cohesive, but once detached, the particles are easily transported by water.

Past human influences on the soils have been less evident in tropical America than in the Eastern Hemisphere. Some of the consequences of exploitation and culture of soil resources have been changes in organic matter content, nutrient levels, reaction, and moisture regime, and increases in runoff, erosion, sedimentation, compaction, salinization, and pollution.

Soil weathering in the Tropics is chiefly chemical and consists of the breakdown of primary minerals and the synthesis of secondary ones. Chemical weathering is inseparably related to leaching because elements released by weathering are subject to leaching and the intensity of leaching affects the types of secondary minerals found.

The ubiquitous presence of organic acids in the soil solution affects the susceptibility of different minerals to weathering (fig. 1–15). At any pH level, leaching tends to be selective (Lucas and Davies 1961). According to

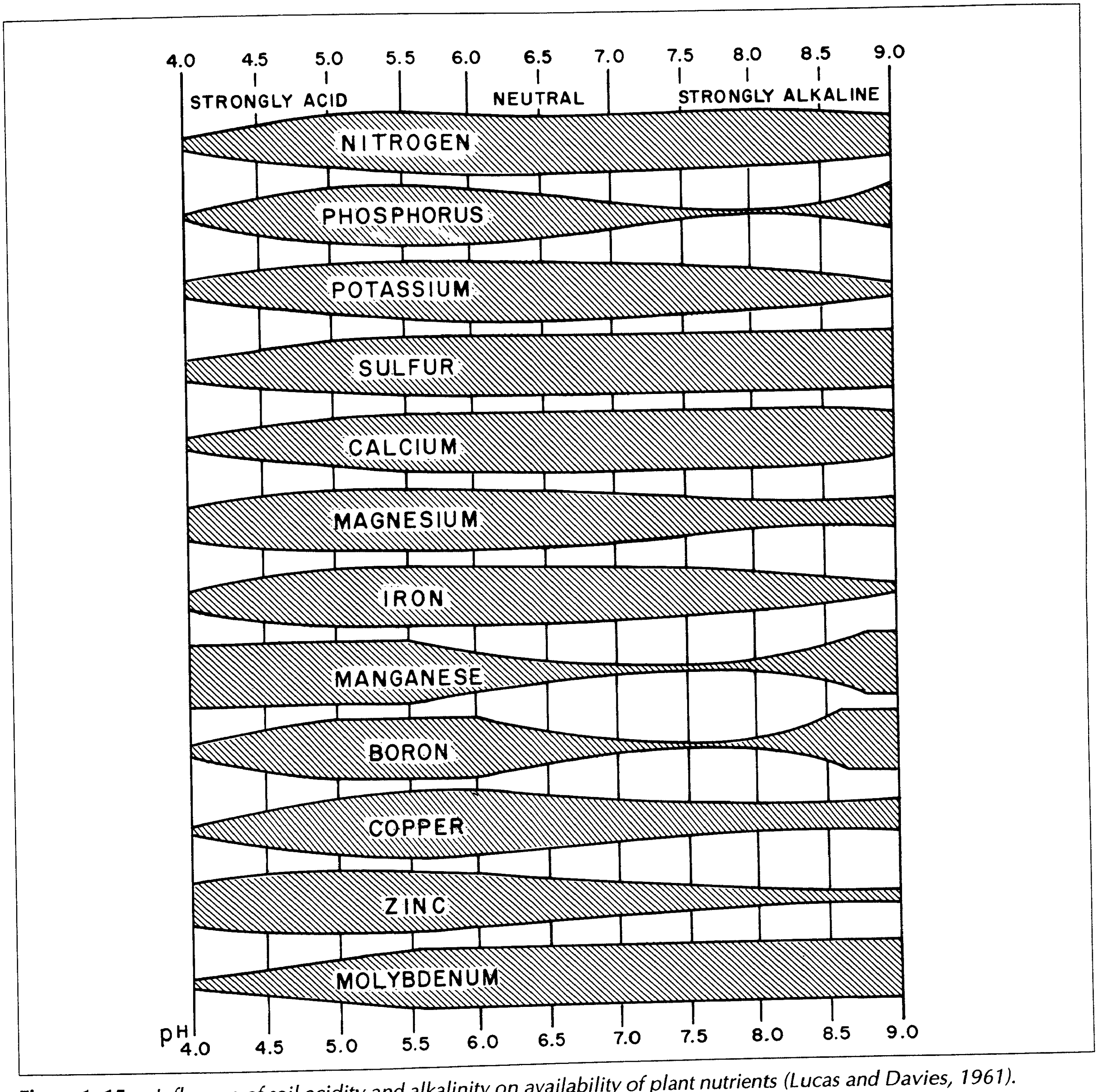


Figure 1–15.—*Influence of soil acidity and alkalinity on availability of plant nutrients (Lucas and Davies, 1961).*

Young (1976), soluble salts (chlorides and sulfates) are 30 to 100 times more mobile than the exchangeable bases (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}), which, in turn, are 5 to 10 times more mobile than silica in forms other than quartz, and these are 5 to 10 times more soluble than quartz and sesquioxides.

The soils of the Tropics are predominantly reddish brown or yellowish red. In lowland humid areas, they are high in clay content and low in silt, and the B horizon is blocky in structure. In the rain forest zone, soils are very friable, due to clays consisting almost entirely of kaolinite and sesquioxides. The A horizon of many tropical soils is darker than other horizons because of the presence of humus. Dark soils, however, should not generally be considered rich in humus. Mottled coloring is a common result of drainage impedance. Generally, clay content decreases with elevation and dryness of climate. Savanna areas commonly have a sandy topsoil.

Soil Classifications. The variation in geological history and climate in tropical America has produced a wide variety of soils. The only valid generalization about these soils, other than their common location, is a lack of marked seasonal soil temperature variation.

The following descriptions of the major soil orders of tropical America are taken largely from Aubert and Tavernier (1972) and Sanchez (1976) and are related to groups already described by Young (1976). The percentage of tropical America covered by each soil group is cited by Sanchez (1976) from Drosdoff, based on a map by Aubert and Tavernier (1972).

Oxisols. Oxisols are principally mixtures of kaolin, hydrated oxides, and quartz and are low in weatherable minerals. They are usually deep-red or yellow soils of excellent granular structure and have uniform properties throughout their depth. They are well drained, but low in fertility.

Oxisols occur in humid areas on very old tablelands where weathering products have been protected against erosion for long periods. Oxisols depend mostly on the amount and quality of organic matter for retention of cations. Without added fertilizer, they can support only tree crops, shifting cultivation, or extensive grazing.

Mountain Soils. These soils can vary greatly within short distances because of changes in elevation, relief, parent material, temperature, and moisture.

Inceptisols. Inceptisols are young soils without accumulations of translocated materials other than carbonates and silica. Some Inceptisols are in river floodplains and in areas of rock outcrops. An important subgroup of these soils evolved from volcanic ash into an amorphous clay. When combined with organic matter, they have a high waterholding capacity. At a low pH, these soils may have a low cation exchange capacity. Their potential productivity varies widely; at best, they may be excellent agricultural soils.

Ultisols. Ultisols are soils with subsurface horizons of clay and a low base supply. They are usually deep red or yellow, well drained, with less desirable physical properties than Oxisols but with more weatherable minerals (and thus slightly better fertility, although still low).

Ultisols characteristically form under forest vegetation in climates with slight or pronounced seasonal variations in moisture supply. In the humid Tropics, they have a low cation exchange capacity. Bases not held in the plant tissue are depleted. A few Ultisols contain plinthite, a soft, clayey material that hardens into ironstone if exposed to wetting and drying.

Alfisols. Alfisols have subsurface horizons of clay and a medium-to-high base supply. They are similar to Ultisols except for greater fertility. Alfisols characteristically form under forest or savanna vegetation in climates subject to seasonal droughts when evapotranspiration exceeds precipitation and stored soil moisture is depleted.

Entisols. These recently developed soils have no pedogenic horizons. Included in this classification are rock outcrops, dunes, and alluvial sediments. Entisols range from unproductive sands to periodically flooded alluvial sediments that are among the most productive soils in the world.

Aridisols. As the name implies, these soils are common to dry regions. They are never moist for as long as 90 consecutive days.

Mollisols. Mollisols have nearly black, humus-rich surface horizons and a high base supply. Some are usually moist, others usually dry.

Fertility of Tropical American Soils. According to Sanchez (1976), citing the President's Science Advisory Committee, 51 percent of the soil types in the Tropics are Oxisols, Ultisols, and Alfisols, highly weathered and leached. Another 17 percent are dry sands and shallow soils. Fourteen percent are Aridosols; other soils make up the remaining 18 percent.

The FAO/Unesco soil survey of 1971 showed that more than 8 million km^2 (about 56 percent) of tropical America have soils that may be too poor for farming or grazing but are capable of producing forests. Oxisols are stable aggregates that drain gravitational water as sands do and resist compaction and erosion. However, they may be droughty and highly leached. Ultisols and Alfisols may have a sandy topsoil that is subject to compaction, runoff, and erosion; thus tillage is seriously detrimental, especially on steep slopes.

Organic matter content of tropical Oxisols is higher than the red color suggests. In moist tropical climates, organic C is added and decomposed five times faster than in the Temperate Zone. Organic matter benefits the soil by recycling most of the N and sulfur (S), maintaining cation exchange capacity, blocking phosphorus (P) fixation, improving structure, and forming complexes with micronutrients.

The total P content of a soil reflects the intensity of weathering. In highly weathered soils, organic P may account for more than half the total soil P. Most tropical Oxisols and Ultisols are too deficient in P for cropping. Phosphorus management is complex in soils with a high fixation rate. Sulfur deficiencies are also widespread throughout the Tropics, especially in Oxisols, Ultisols, and Alfisols, and in young volcanic and sandy soils.

In forested areas, the soil and forest may have a remarkably closed nutrient cycle, producing lush vegetation even on soils of low native fertility. In Mexico, Central America, and the Caribbean, soils of fair-to-good natural fertility were found to outnumber soils of low natural fertility (Anon. 1971c, d). The main limitation to productivity in this region is steepness. However, many lowland areas are grossly underutilized. With minor adjustments in traditional practices, these soils can be much more productive.

In South America, soil is generally low in natural fertility (Anon. 1971a). More than 90 percent is too poor for farming. Approximately 50 percent of the continent's soil is Ferralsols (Oxisols), Acrisols (Ultisols), and Arenosols that are low in cation exchange capacity and exchangeable bases. About 20 percent of the continent is so dry that farming without irrigation is risky or impossible. Ten percent is poorly drained, and another 10 percent is composed predominantly of Lithosols on steep slopes.

Forests

Tropical America's climate and soils are conducive to the natural development of forests. Ford-Robertson (1971) defines forests as "plant communities predominantly of trees and other woody vegetation, growing more or less closely together." The definition of trees from the same source excludes shrubs, which, although perennial and woody, generally lack "a single well defined main stem." Lesser classes of forests include scrub—areas of "small or stunted trees and/or shrubs, generally of unmerchantable species," woodland—areas where trees are characteristically short-boled relative to the depth of their crowns and form only an open canopy, tropical savanna woodland—areas with an undergrowth mainly of grasses, and tree savanna—areas where the trees are only irregularly scattered (Ford-Robertson 1971).

Vegetation Genesis. The origin of forests in tropical America is a response to the geological changes that formed the region. These are described in appendix C.

During the glacial period (21,000 to 13,000 years ago), the vegetational belt of the Andes was lowered by as much as 1,500 m because of cool, dry conditions, when the mean temperature was possibly 6 to 7 °C lower and precipitation less than half that of the present day. By 10,000 years ago, however, forests had ascended to at least 2,850 m in elevation. By 6,000 years ago, the temperature had risen to possibly 2 °C higher than it is today, so species of *Cecropia* and *Acalypha* grew several hundred meters above their present upper limit. About 3,000 years ago, the temperature fell to the present level, and the forests again receded below 2,850 m in elevation.

Concurrent with the cooling that began 3,000 years ago, grasslands in the western Llanos of Colombia were apparently being invaded by *Byrsonima spp.* and other forest plants (Wijmstra and van der Hammen 1966). Studies in the lower Magdalena Basin (Wijmstra 1967) indicate significant changes in precipitation in the upper or lower watershed during the past 2,000 years. From 1100 to 1500 A.D., forests and marshes were being replaced by savannas with *Byrsonima, Cecropia, Ficus,* and genera of Ulmaceae. Precipitation cycles may have been as short as 250 years.

Evidence of significant vegetational change during glacial periods has also been found in Central America

(Graham 1973, Martin 1964). Some 36,000 years ago, the forests in Costa Rica were 650 m lower, and paramo (moor) was found at 2,400 m instead of *Quercus* and *Alnus.* Some of the tree species now growing in the uplands were apparently then near sea level.

Glacial-period recession and interglacial advances of the Guiana coastline also were significant in the development of present-day forests of that region. Pollen diagrams from near Georgetown, Guyana, (van der Hammen 1963; van der Hammen and Wijmstra 1964; Wijmstra 1969, 1971) show sequences of *Rhizophora,* a seacoast mangrove genus; *Avicennia,* a landward mangrove genus; fresh water swamp trees; and upland vegetation such as species of *Byrsonima* and *Curatella.*

Fragmentary evidence from the southern Amazon Basin (van der Hammen 1972, 1974) indicates that an area of Rondonia now densely forested was open savanna some time during the past 10,000 years. All current equatorial rain forest areas seem to have been strikingly different 14,000 to 20,000 years ago (Flenley 1979). Mountain vegetation was of types now found at higher elevations, and lowland vegetation was of types typical of areas with a pronounced dry season.

Past hypotheses to explain the richness of the biota of the Tropics have leaned heavily on a presupposed constancy of a warm, moist, favorable climate. Current knowledge, however, suggests that, in terms of microclimate at any one location, such constancy must have been the exception. Pollen findings in the region show no evidence that forest communities have been stable for as long as 500 years, which is, indeed, no longer than the lifespan of some of the present-day trees.

The rain forest, therefore, has not been a paragon of stability. Its great diversity cannot be explained by long-term stability because these forests have existed in a state of equilibrium with their environment at most only a few tree generations (Flenley 1979). So the wealth of species is now explained as a result of—rather than in spite of—past environmental changes (Vuilleumier 1971).

Amazon biota illustrate this point. Although the Amazon flora were derived from families and genera that occur outside the region, most species are confined to Amazonia (Prance 1978). This internal speciation is attributed mainly to the succession of environments during the glacial period. As recently as 15,000 years ago, there was a significant climate difference between the uplands and the valleys of the region during warm periods. Savannas that are now discontinuous but have common genera (such as *Byrsonima* and *Curatella*) bear witness to widespread savannas of recent origin (Prance 1978). Speciation is believed to have been favored by the isolation of humid mountain forests and dry valley savannas.

Forest Extent and Location. The distribution of forests in tropical America has been changing continually over long periods in the past, but the rate of change has been almost imperceptible since the "discovery" of America. So, the extent and location of areas that, without human interference, would be forested can be determined from current climatic and edaphic conditions. The extent and location of natural forests also indicate the geographic limits within which forest growth continues to be suitable ecologically and, consequently, where forests would appear to be one rational land use.

Nonforested areas of the region (fig. 1–16) include the Mexican highlands, grassland savannas and marshes, the Llanos of the Orinoco, the Guiana highlands, the campos, the Matto Grosso swamps, the Andean uplands, and the Pacific coast of South America (Hueck 1972). These areas have not borne forests in recent years and do not appear capable of doing so, at least not without the environment being "made over" at great expense.

At least 70 percent of tropical America is environmentally suited for some type of forest. The largest consolidated natural forested area of the American Tropics is the Amazon Basin, an area of 6 million km^2, 98 percent of which was forested when European explorers arrived (Pires 1974).

The FAO forest inventory (Anon. 1993b) recognizes six forest formations: rain forest, moist deciduous, dry deciduous, dry, desert, and montane. Table 1–6 presents the 1990 inventory in these categories. The two deciduous zones and the dry and desert areas have been combined. It is seen that the forests of tropical America make up slightly more than half the tropical forests of the world. About a third are in Africa, and less than 20 percent are in the Asia-Pacific region. Of the tropical rain forests of the world, 63 percent are in America. Within tropical America, 87 percent of the forests are in South America. About half are classified as rain forests; these and deciduous forests making up 86 percent of the total. Forests in 1990 covered only 56 percent of the zones

Figure 1–16.—*Shaded areas on map indicate portions of tropical America, including savannas, that are naturally without forests.*

Table 1–6.—Tropical forest formations by zones (thousand km²)

Zone	Rain forest	Moist and dry	Dry/desert	Montane	Total
Central America	124	152	22	383	681
Caribbean	357	85	0	29	471
South America	4,062	3,155	5	807	8,029
Tropical America (total)	**4,543**	**3,392**	**27**	**1,219**	**9,181**
Africa	866	3,437	620	353	5,276
Asia/Pacific	1,774	829	31	472	3,106
Tropics (total)	**7,183**	**7,658**	**678**	**2,044**	**17,563**

Source: Anon. 1993a, 1993c.

listed by FAO (table 1–6), suggesting that at one time the rain forests and deciduous forests together covered 92 percent of the land.

The present forest area of the region reflects centuries of human occupancy, beginning possibly as early as 20,000 years ago. In 1492, the region was at least partially settled, ranging from a population of more than 20 million in Mexico to a sparse population (which may have been denser earlier) in the Amazon Basin (Bennett 1975). Shifting cultivators temporarily removed wild vegetation from vast areas of tropical America, creating grasslands and vegetation mosaics. However, the native population decreased drastically in the 150 years following arrival of the Europeans, allowing forests to reclaim many areas. More recently, the trend reversed again and deforestation has accelerated due to increasing numbers of landless rural people and the expansion of beef production.

The FAO forest inventory (Anon. 1993b) shows one impact of past human intervention into tropical forests, that of deforestation (table 1–7). It is seen that 44 percent of the former forests have been removed. Of the former montane forests only 28 percent remains. Forest loss has been even greater in Africa and the Asia-Pacific region. The forest areas remaining in 1990 (Anon. 1993b) are listed in table 1–8.

Lanly and Clement (1979) inventoried "operable" forests, those containing commercially desirable wood accessible enough to be harvested. They estimated that 5.13 million km², or 78 percent of the region's closed forests fit this definition in 1975. Of this amount, 85 percent is in South America, and 5 percent is coniferous.

Environmental Influences of Forests. Tropical forests produce more water vapor and carbon dioxide than forests outside the Tropics because infrared emission, saturation vapor pressure, and plant productivity increase with temperature. In contrast, albedo and emission of some pollutants from tropical forests are less than the global mean. Of all these, the emission of carbon dioxide, which persists in the atmosphere, probably has the most influence outside the Tropics. However, the radiation that vaporizes water in the Tropics is also transported outside the region in the form of latent heat, becoming part of the global thermal balance after the water vapor condenses.

The water vapor produced within the humid Tropics contributes greatly to the global hydrological balance. The hydrological cycle is the disposal of rainfall through vegetation to the soil, streams, lakes, and the ocean and the return to the atmosphere of the moisture through evaporation and transpiration (fig. 1–17; Holzman 1941).

Some 58 percent of the global water vapor comes from the 37 percent of the Earth's surface within the Tropics (Baumgartner and Reichel 1975). Of the water vapor from the region, 15 percent arises from the 30 percent of the surface that is land and 85 percent from tropical seas. Tropical land surfaces supply about 9 percent of the world's water vapor (Baumgartner and Reichel 1975).

The moist Tropics receives three times the global average annual precipitation of 75 cm. Similarly, evapotranspiration from tropical vegetation is nearly three times the global average (120 cm versus 46 cm). Annual runoff from tropical land averages 88 cm as compared to 27 cm for the world as a whole.

Table 1–7.—Annual tropical deforestation, 1981–90

Region	Rain forest	Deciduous	Dry/ desert	Montane	Total	Area per 1,000 people
			Thousands of hectares			
Central America	240	277	51	544	1,112	10.6
Caribbean	59	43	0	23	125	3.8
South America	1,639	3,463	12	1,055	5,172	27.9
Tropical America (total)	**1,938**	**3,786**	**63**	**1,622**	**7,409**	**20.6**
Africa	471	3,103	327	289	4,100	9.7
Asia/Pacific	2,162	1,122	32	584	3,900	2.8
Tropics (total)	**4,541**	**7,921**	**422**	**2,525**	**15,409**	**7.0**
			Percentage of deforestation in 1985			
Tropical America	0.3	0.3	2.1	1.2	0.8	
Global Tropics	0.6	1.0	0.6	0.9	0.8	

Source: Anon. 1993a.

The major rivers of the region, the Amazon and the Orinoco, carry 20 percent of all surface water discharge of the Earth (Anon. 1978a). Some parts of the uplands of tropical America receive as much as 600 cm of rainfall annually, 500 cm of which runs off; the rest is dissipated through evapotranspiration. The Amazon Basin receives an average of about 350 cm of precipitation, discharges 200 cm, and evapotranspires 150 cm (Anon. 1978a).

Tropical forests are also significant in the world's carbon balance. The natural forests of the Tropics were estimated in 1990 to average 169 t of biomass per hectare (Anon. 1993b). For tropical America the average is 185 t/ha. Tropical forests contain 30 percent or more of the carbon dioxide contained in the world's atmosphere and about a sixth of the world's organically bound C (Anon. 1978a). The carbon balance in the biosphere is a product of (1) assimilation and fixation of carbon dioxide by plants and (2) release of carbon dioxide by respiration of living organisms and oxidation (burning) of inflammable organic remains. Tropical forests fix some 15 to 20 billion tonnes of C annually (Lieth and Box 1972, Woodwell 1970), at least 25 percent of the Earth's total (Bolin 1970). Through photosynthesis they release some 55 million tonnes of O per year, an amount presumably equaled by respiratory consumption (Brunig 1971).

The influence of tropical forests on climate cannot be reliably measured yet because changes in atmospheric composition cannot be predicted and forest influences cannot be correlated with structural or site properties or the productivity of various forest types (Anon. 1978a). Far-reaching global influences of tropical forests on climate have been suggested in simulation studies by Potter and others (1975). Between latitudes 5° N. and 5° S., forest land produces much lower albedo (0.07 versus 0.25), less runoff, more evaporation, slightly higher surface temperature and precipitation, greater absorption of solar energy, greater convective activity, more warming of the middle and upper tropical troposphere, lower tropical lapse rates, and higher global temperatures than deforested land. Also, tropical forests induce part of the precipitation that falls as far away as latitude 85° N. and 60° S. (Anon. 1978a).

What effect deforestation of the Amazon Basin would have on the atmosphere is not clear (Newell 1971). It might reduce the available potential energy and heating at middle atmospheric levels at low latitudes. This could counteract the "greenhouse effect" expected if the carbon dioxide content of the atmosphere rises and constrains radiation outward from the earth.

The climatic effects of forests are chiefly local. Forests efficiently absorb visible and infrared radiation. Their reflectivity is 5 to 10 percent lower than that of other soil covers. The high energy intake of forests is expended primarily in evapotranspiration. Water vapor cools the

Table 1–8.—Natural forest cover in the Tropics, 1990

Country or continent	Total forest area (thousand ha)	Percentage of land area	Forest land per capita (ha)
Central America			
Costa Rica	1,428	28	0.5
El Salvador	123	6	—[a]
Guatemala	4,225	39	.5
Honduras	4,605	41	.9
Mexico	48,586	26	.5
Nicaragua	6,013	51	1.6
Panama	3,117	41	1.3
Total	**68,097**	**28**	**.6**
Caribbean			
Antigua and Barbuda	10	22	0.1
Bahamas	186	19	.7
Belize	1,996	88	11.0
Cuba	1,715	16	.2
Dominica	44	59	.5
Dominican Republic	1,077	22	.2
French Guyana	7,997	91	86.9
Grenada	6	16	.1
Guadeloupe	93	55	.3
Guyana	18,416	94	17.7
Haiti	23	1	—[a]
Jamaica	239	22	.1
Martinique	43	40	.1
Puerto Rico	321	36	.1
St. Kitts and Nevis	13	37	.3
St. Lucia	5	7	—[a]
St. Vincent	11	27	.1
Suriname	14,768	95	36.6
Trinidad and Tobago	155	30	.1
Total	**47,118**	**68**	**1.4**
South America			
Bolivia	49,317	46	6.7
Brazil	561,107	66	3.7
Colombia	54,064	52	1.7
Ecuador	11,962	43	1.1
Paraguay	12,859	32	3.0
Peru	67,906	53	3.0
Venezuela	45,690	52	2.3
Total	**802,905**	**60**	**3.3**
America	918,120	56	2.3
Africa	527,586	27	1.3
Asia/Pacific	310,597	35	.2
Total (continents)	**1,756,303**	**37**	**.7**

Source: Anon. 1993a.

[a] Less than 0.05 ha per capita.

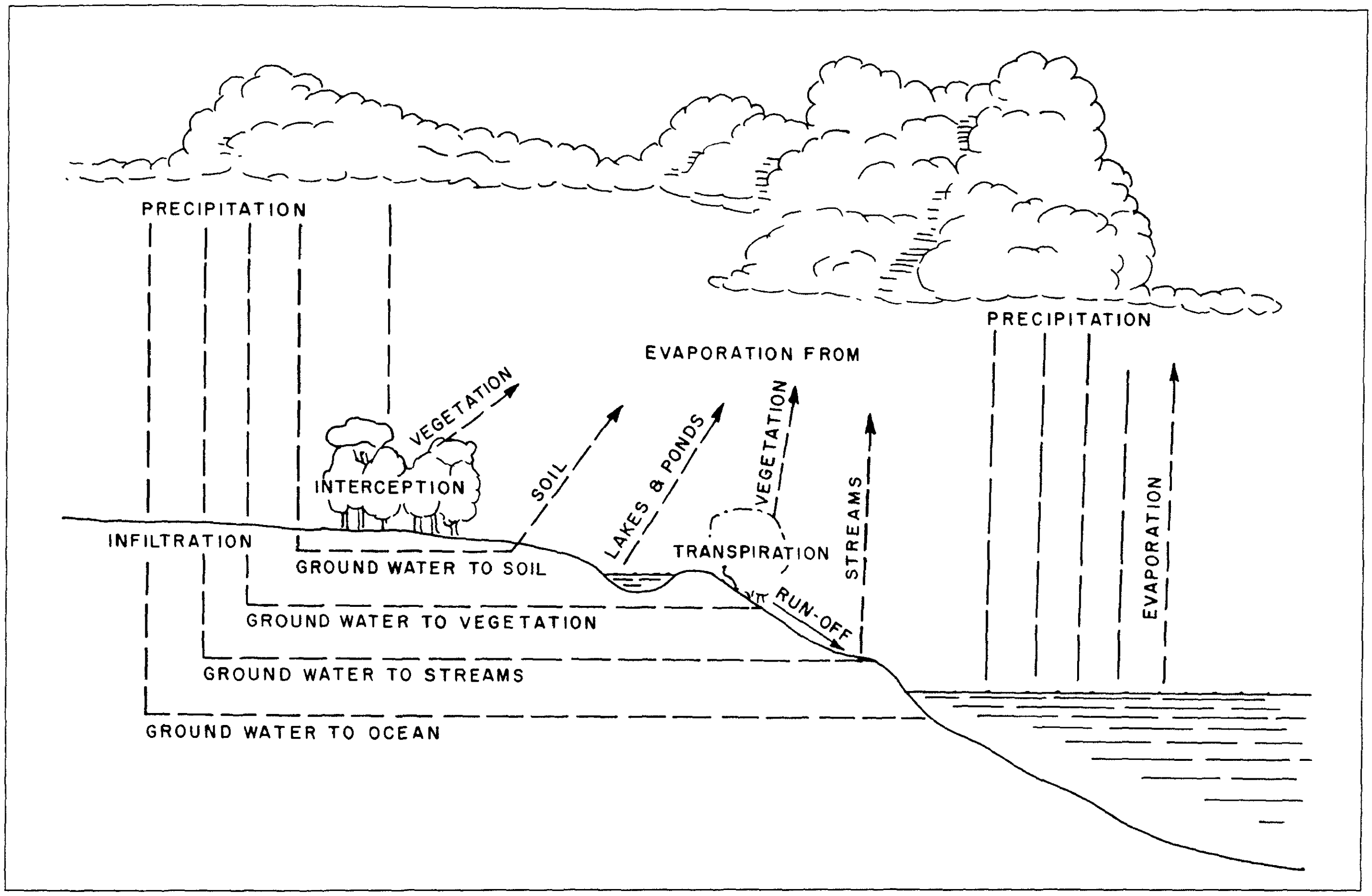


Figure 1–17.—*The hydrological cycle (adapted from Holzman 1941).*

air above forests, thus reducing convection. The water balance of the Tropics is sensitive to latitude. For the outer Tropics, annual evapotranspiration averages 65 cm, or 76 percent of the precipitation. For the equatorial Tropics, annual evapotranspiration averages 109 cm, or 62 percent of the precipitation.

At least as important to plant life as the amount of precipitation is its seasonal distribution. In most of the Tropics, the dry season coincides with the cooler months. The difference between rainy and dry seasons is more pronounced inland, especially on plains, than it is along the coasts and on the mountains. Most deserts within the Tropics occur at the borders and are tropical continuations of extensive subtropical deserts. The existence in the Tropics of both ombrophilous plants (requiring continuous moisture) and ombrophobious plants (not requiring continuous moisture) is significant to the selection of species for forest production. Ombrophobious species may survive in constantly moist climates, but they generally grow slowly except in open, sunny situations. Many of these species have delicate, pinnate leaves.

Insolation (solar radiation received) is as important as atmospheric temperature to living organisms, particularly in continental dry areas. However, the effects of insolation are especially important in humid areas because stomata remain open, through which moisture continues to be released. The high insolation in the Tropics results in shade flora that are distinct from flora that grow in direct sunlight.

Ferns (Polypodiaceae) are most abundant in humid tropical forests, especially in mild, cool, mountain climates. Conifers are also generally found on high mountains outside lowland tropical climates.

Monocotyledons are prominent in tropical vegetation. In dry areas, palms (Palmae) may be widely scattered, but in swampy areas they may grow in dense groves.

Bamboos (Gramineae) are common, growing in pure stands, scattered among other trees, or comprising part of the undergrowth. The Araceae, including fleshy vines such as *Philodendron*, are common in wet forests, as are the Scitamineae, including *Musa* and *Heliconias*. Other plants showing great diversity from place to place are the orchids (Orchidaceae) and bromeliads (Bromeliaceae).

The occurrence of several orders of dicotyledons reflects variations in the vegetation within the Tropics. The Amentaceae are mostly in the higher mountain regions. The Polygoninae, including the Piperaceae, are limited to the warmer and wetter parts of the Tropics. The Magnoliaceae of the order Polygoninae, important in the Temperate Zone, are limited in the Tropics to high mountains. The Citiflorae, including families such as Clusiaceae, Ochnaceae, and Dipterocarpaceae, are limited to the warm Tropics. Other groups exclusively warm-tropical are the Columniferae, with the Bombacaceae and Sterculiaceae, and the Terebinthinae, with prominent families such as the Meliaceae, Burseraceae, and Anarcardiaceae. Among the Aesculinae, the Malpighiaceae are limited to the warm Tropics. Of the Umbelliflorae, some families, such as Umbelliferae and Cornaceae, occur only in the highlands, whereas the Araliaceae also grow in the lowlands. Of the Saxifraginae, the Cactaceae are prominent in dry regions but occur also in wet areas as epiphytes or lianas. The Myrtiflorae are exclusively warm-tropical but include species of the uplands (Melastomataceae) and some in tidal swamps (Combretaceae and Rhizophoraceae). Of the Rosiflorae, some families, such as Chrysobalanaceae, are exclusively warm-tropical in distribution, whereas others (Rosaceae) are limited to the mountains. The Leguminosae include trees, shrubs, herbs, and climbers, some in humid and others in dry regions. Other orders preeminently warm-tropical are Diospyrinae (Ebenaceae and Sapotaceae), Tubiflorae (Cordieae), Personatae (Bignoniaceae), Labiatiflorae (Verbenaceae), and Companulinae (Rubiaceae).

Schimper (1903) recognized not only a general tendency of plant groups to segregate by broad climatic zones within the Tropics but also the effect of seasonal climatic changes on plant growth. He noted that plants experience alternating periods of repose and activity relative to certain functions. Where the climate is not seasonal, the alternation of rest and activity results from internal causes. Even evergreen woody plants in continuously wet climates exhibit alternative periods of rest and activity.

Where seasonal climatic differences are marked, flowering coincides less with the season of the year than with the climatic season. During most of the flowering period, vegetative development is retarded. Where there are dry seasons, woody plants blossom most abundantly during or immediately after the dry spell.

Leaf fall among woody plants is extremely variable, even in seasonal climates. Some plants lose their foliage before the end of the rainy season. Some shed their leaves at the beginning of the dry season. Others do so gradually during several months. Still others remain in full leaf until the new leaf buds open. And mixed among these may be evergreen trees never totally out of leaf.

Schimper (1903) observed that the influence of soil character on the differentiation of flora is much more pronounced in periodically dry regions than in constantly humid ones. He recognized that paucity of alkali, lime, P, Mn, and S—all essential to vegetation—is widespread in tropical soils. He further noted that in seasonal climates the most drought-resistant forest types—thorn-forest, thorn-bush, and thorn-scrub—develop on calcareous soils.

Schimper also pointed out that hygrophilous evergreen forests develop along the shores of lakes and rivers in regions that elsewhere are grasslands or xerophilous forests. He distinguished between open vegetative growth along rocky and sandy shores and littoral woodlands (mangroves) above and below high tide.

Appendix D presents the development of a number of attempts to classify and describe tropical vegetation. Each classification has some limitations. Each is an attempt to quantify differences between forest types in mathematical or physiognomic terms. None reflects significant differences with precision. For purposes of forest management, a classification framework at the formation level, within which edaphic and compositional variants exist, is precise enough to predict more widespread applicability of results from place to place. Until something better is derived, Holdridge's life zones (1967) may be as precise as is needed, provided edaphic variants are recognized and described.

Chapter 2
The Environment for Forest Production

The environment for making tropical forests productive depends on forest values, appropriate land, and production goals. This chapter deals principally with the physical environment for forest production and its development for that purpose. The recent rise in social concern for forests brings to the forefront a distinct feature of the environment that will be dealt with mostly in chapter 10. It is necessary here, however, to recognize that making tropical forests productive for human wants on the scale needed in the future calls for forest modification and plantations. It is imperative that such practices are acceptable socially. This requires that they meet the standards of silviculture in perpetuating the productivity of the basic resource, the soil, and that the public understands what is being done and why and accepts all the probable consequences. Without such understanding and acceptance, forest production will not be effective or even applied on a scale adequate to meet future needs.

Forest Values

The initial evolution of *Homo sapiens* is believed to have taken place on the margin of a tropical or subtropical forest (Leakey 1964, cited by Longman and Jenik 1974). Tribes later turned to forests to gather food and to take refuge during intertribal conflicts. For eons, forests have been slowing water movement and thus precipitating sediments, capturing nutrients, and building the soil upon which tropical peoples depend for subsistence. Forest-created agricultural potential dictates the level to which a human culture can develop (Meggers 1954). The presence or absence of forest cover may decide the ultimate fate of a human society (Sartorius and Henle 1968). Tropical America without forests probably could not have supported human life.

The largest forest area in tropical America, the Amazonian lowlands, has been inhabited only a few millennia (Sioli 1973). Human inhabitants evidently came as hunters and fishermen, collected wild food plants in the uplands, and adopted agriculture to some degree (Sternberg 1968). Since numbers were few, the tribes could satisfy their needs without seriously affecting the forest ecosystems. Exploitation was concentrated along the water and in *varzea* (seasonally flooded) forests. The rivers were so large that their waters completely digested human waste, and in many areas river water, at least until recently, still could be drunk without danger of intestinal infection (Sioli 1973).

The population of tropical America is not only as large as it probably has ever been—399 million in 1990 (Anon. 1993b)—but its growth has been very rapid, increasing at an average annual rate of 2.7 percent (Anon. 1976k). The mean population density, 18 persons per square kilometer, is similar to that of tropical Africa (16 persons per square kilometer), but much less than that of the tropical Asia-Pacific area (82 persons per square kilometer) (Anon. 1993b).

Forests and the Human Environment. In earlier times, the tropical forest provided a favorable environment for human habitation. Those areas closest to water and natural food sources were generally forested. Then, as population increased and tribal competition for these resources appeared, the forest provided refuge and security. It is still so used by the remaining indigenous peoples in tropical America. Tropical forests provide (in addition to wood) thatch, basketing, cordage, ornaments, canoes, starch, oils, plant and animal foods, glues, pigments, rubber, condiments, medicines, and poisons (figs. 2–1, 2–2; Levi-Strauss 1952).

Humans have only begun to discover the forest's importance as creator and conserver of an environment vital to

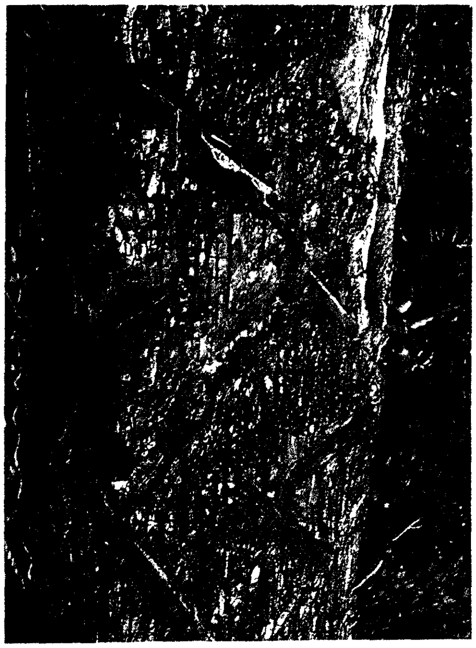


Figure 2–1.—*The trunks of virtually all chicozapote trees* (Manilkara zapota) *in Mexico and Central America have been tapped repeatedly for their latex as a base for chewing gum.*

Figure 2–2.—*Mangroves provide a locally accessible, highly productive source of straight poles for construction.*

human survival (Poore 1976b). The forest is a reservoir of genetic capital. Within it lie hidden secrets about natural materials, the ultimate utility of which is unknown, as well as opportunities for their preservation, production, and utilization. Knowledge of the many species harbored in forests, as well as their occurrence, behavior, and potential benefits, is essential for the full use of these resources. But, in many areas, such knowledge has declined with the transition from primitive forest peoples to modern societies. Many of the forests have been destroyed before their potential utility was even fully recognized.

The forests absorb and productively utilize solar radiation. They ameliorate microclimate by reducing extremes of temperature and available moisture. Significant effects on macroclimate (carbon balance with the atmosphere) have been postulated (Woodwell 1970) but have not yet been verified (Newell 1971). Forests absorb particulates and noxious substances from the atmosphere (Cliff 1973). They reduce noise levels. They may harbor organisms capable of causing epidemic diseases and pests deleterious to human society, but they also harbor other organisms that in nature provide means for preventing or controlling such outbreaks. Forests also go almost unheralded as effective, if limited, repositories for human wastes (van der Ploeg and Vlijm 1978). Near centers of high-density urban congestion, natural forest systems, such as mangroves, have been deliberately used to digest and recycle wastes. In summary, the forests of the Tropics serve as a giant and resilient buffer that minimizes environmental extremes and, within limits, compensates for aberrations caused by human intervention (fig. 2–3).

People are just beginning to understand the web of life in forest ecosystems—the interrelationships among species. This new knowledge will prove vital to the preservation of many species and to their sustained propagation under human management (Budowski 1976).

Animal life plays an essential, if subtle, role in maintaining the well-being of the forest. Many tree species would disappear were it not for the pollination and seed dispersal functions of animals. Also, the decomposition of forest litter is partly the work of microfauna. The additional roles of animals in preserving a balance among the less conspicuous components of the forest are probably vital to the welfare and restorative powers of forest ecosystems.

Forest animals provide social benefits as well. To hunters, primitive or modern, the fauna are an important source of food or sport. Throughout tropical America, most mammals and birds are forest dwellers. In the Amazon Basin, some farmers are said to rotate their cultivated fields on a 20-year cycle (although the soils are actually rejuvenated in 12) to allow more advanced successional vegetation for the benefit of game (Posey 1982). Along major rivers, edible aquatic animals may largely depend not only on the stability of the banks provided by tree roots but also on the food provided by forest litter falling into the water. Animal life in tropical

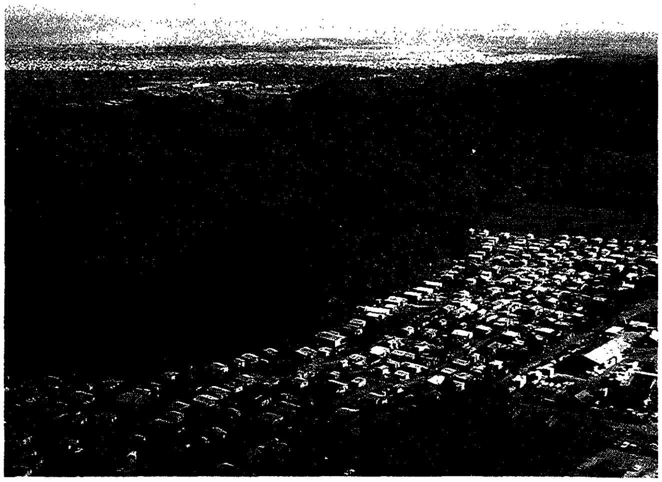


Figure 2–3.—*Despite urban sprawl, forests remain a valuable companion in northern Puerto Rico.*

forests is esthetically far more attractive than its current use for human enjoyment would suggest. Even so, it is becoming the primary source of public concern for the conservation of tropical forests.

Tropical forest ecosystems are highly efficient in the use and conservation of energy and other resources and have developed intricate mechanisms for preventing and repairing damage. They are a challenging and promising field for scientific study. Studies of forest ecosystems should yield knowledge that will further human progress on many fronts.

Forests and Water. The significance of forests to water supplies is commonly attributed to some direct effect of forests on the amount of rainfall. The magnitude of this effect remains in doubt, in part because only a few studies have been attempted and in part because of the difficulty of eliminating variability due to either place or time. Results suggest that any such effects are mostly local. The finding that much of the rainfall in the western Amazon Basin is water transpired by the forests to the windward (Villa Nova and others 1976) may suggest—but does not prove—that the rainfall would have been less had it been transpired from vegetation other than forests or evaporated from unforested areas.

Actually, the most important effect of forests on rainwater is its disposition once the rain reaches the forests. Part is intercepted by the forest canopy and evaporates. Interception by rain forest canopies varies widely with the density of the canopy and the intensity and duration of the rainfall. For short, light showers, all water may remain on and evaporate from a dense forest canopy. Measurements over time suggest that, under closed forests, about 15 to 20 percent of the rainwater is held in the canopy (Kline and others 1968, Lawson and others 1981). Whether such "lost" water benefits the ecosystem or not has been debated. Its evaporation cools the vegetation and the air, presumably reducing the draft on soil water for transpiration. Moist vegetation is darker in color than dry vegetation, and therefore absorbs more solar energy, suggesting that at least part of the energy required would not otherwise have been available for the ecosystem's needs (Satterlund 1972). Moreover, the diffusion of intercepted water requires less energy than transpiration.

In the Brazilian Amazon, studies have shown that 62 percent of the water goes to evapotranspiration, and 90 percent of this is due to a delicate energy balance (Villa Nova and others 1976). Because the hydrological cycle is so intimately related to the presence of forests, general deforestation can lead to serious consequences.

Litter that accumulates on the forest floor absorbs the physical impact of torrential downpours and releases the water gently to the mineral soil beneath (fig. 2–4). This "cushioning" action largely prevents the water from becoming turbid with suspended surface soil particles and thus clogging soil pores beneath. In addition, the decaying litter enriches the water entering the soil and supports organisms that produce porous upper soil layers. These processes are the most obvious ways forests enhance water supplies (fig. 2–5). The draft on soil water is greatest under forests with their deep-rooted trees and high rates of transpiration. Between storms porous forested soils again become highly receptive to new water.

Storm water, generally received in torrents, may carry away the litter and surface soil if it cannot promptly percolate into the soil. Such percolation generates the lifeblood of the Tropics. It supplies the forest above it, and it follows subterranean pathways to reappear gradually but continuously in springs that feed streams that in turn safeguard and support aquatic life, commerce, irrigation, and urban life downstream (fig. 2–6). It is this intimate relation between forests and usable water that makes the Tropics habitable. Thus, tropical forests provide soil protection, a high soil infiltration rate, and, where soil is deep, substantial detention storage (Pereira 1967).

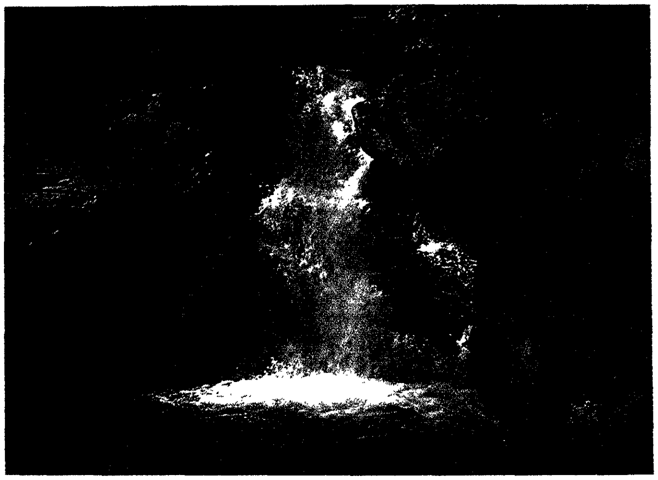


Figure 2–4.—*Forests have an unexcelled capacity to promote rainwater infiltration into the soil, ameliorating floods, and gradually releasing a constant flow that is free of sediments.*

Figure 2–5.—*The delayed release of rainwater from forested soils of the uplands maximizes the value of downstream water impoundments that are vital to urban centers.*

Even after water enters streams, it may continue to be affected by riparian forests. Tree growth on streambanks stabilizes the soil. When floods occur, the forest litter may support aquatic life important as a source of human food. Flooded streamside forests slow water movement, and thus precipitate sediments, capturing nutrients and building up the level of streambanks. At river mouths, estuaries, and along relatively protected seacoasts, mangrove forests retain sediments and provide habitats for important terrestrial, amphibious, and marine fauna.

Figure 2–6.—*Montane highway construction and deforestation immediately show the effectiveness of the former forest in preventing sedimentation of this river in Sarawak.*

Many rivers separate nations or run through more than one nation. Therefore, forest benefits to streamflow become an international concern and expand the self-interest of all nations into a web of interdependence.

Forests and Soil. The relations between forests and tropical soils are an outgrowth of forest-water relations. Humic acids picked up by rainwater as it passes through the forests accelerate weathering of parent rock and other soil-forming processes. The forest floor (by absorbing the shock of intense rainfall) and the dense and deep tree-root systems minimize landslides. Studies show the superiority of forest over other types of vegetative cover in this function (Lawson and others 1981).

The effectiveness of forests in controlling erosion varies with the climate, slope, soil condition, and the character of the forest. The densest forests, which permit few living plants in the ground layer, may be less protective than more open forests with herbs, grasses, or young trees to hold the litter in place on slopes or where floodwashing otherwise would occur. Trees that are excurrent in form, particularly palms, tend to concentrate throughfall as stemflow. As much as 10 percent of the rainfall may reach the soil beneath rain forests in this manner (Lawson and others 1981). This stemflow may be rich in particulates washed from the tree bark and thus provide nutrition at the base of the tree, but the concentrated flow downslope from that point can, in extreme cases, cause severe erosion. Where these problems become serious, they can be ameliorated by silvicultural practices.

Forests and Agriculture. It has already been pointed out that forests safeguard agriculture in the Tropics. In much of tropical America, the harvesting of wood from forests is an integral activity of farmers, providing products for either local consumption or distant markets. The employment provided by wood use and production is in tune with the traditions and needs of forest regions and essentially benefits rural people. Nearly all the soils capable of sustained (or even intermittent) agriculture are a heritage from forests, which have enabled soil building. The results are particularly impressive on the most productive agricultural soils of the region—valley bottom soils that are level, workable, and (at least initially) fertile. An example of the usefulness of such soils is to be seen in the floodable varzea in Amazonia, used to produce short-term crops (Sioli 1973). If these bottomlands are diked to reduce flood damage, they cease to receive the nutrients that formerly were supplied from forests and forest soils upstream (fig. 2–7). Thus, for continued cropping of such areas, canals must be constructed to introduce water that contains sediments (Sioli 1973).

Tropical forests benefit agriculture in other ways. They tend to be the only residual source of native varieties of food plants, not only those now in production but also many others that may eventually prove useful. These attributes are of growing value as the production of food, forage, and fiber must be intensified. Native varieties of plants are now being sought out, conserved, and bred into crops for anticipated advantages.

Mixed natural forests, unlike agricultural crops, are rarely subject to epidemics. Evolution and coevolution of hosts, predators, and parasites in primary forests long since have produced equilibria that minimize fluctuations in the populations of individual species within the systems. Lands formerly forested harbored organisms that could become pests when the land is farmed. But these forests also contained control mechanisms for these pests. However, if epidemics do occur, maximum use of biological controls is desirable, usually for financial as well as environmental reasons. Thus, the presence of native forests within agricultural regions may facilitate such controls and in that way foster food production. Unfortunately, optimal location, extent, shape, and management techniques for forests to provide biological controls for pests in nonforested areas are not yet known.

Forests adjacent to farm crops also harbor insects and other animal life vital to pollination of crop plants. Insects pollinate most cultivated vegetables, fruits, and flowers (Biswas and Biswas 1976).

The importance of forests as a source of soils for farming is nowhere more clearly demonstrated than in the shifting cultivation systems and related practices that keep alive almost the entire rural population of the Tropics, some 630 million people (fig. 2–8; Nair 1980). The essential element of shifting cultivation is that after a cropping period, the land is fallowed, generally in woody growth, for 1 to 20 years or more. During this period, the soil productivity for another cropping period is restored beneath a recovering forest, enabling farmers with little capital and only the most primitive tools to subsist on crops produced by soils whose fertility is depleted very rapidly (Watters 1971). The fallow period restores the soil partly through addition of nutrients from weathering and rainfall. In addition, the rapid development of secondary forests during the fallow period protects the formerly exposed soil from erosion, rapidly restores soil porosity, and captures nutrients that might otherwise leach out.

Figure 2–7.—*The most productive soils for agriculture were accumulated beneath former forests, and trees on the hills and borders continue to protect the environment for farming.*

Figure 2–8.—*Old-growth tropical forests are felled and commonly burned rather than harvested because they are remote from markets, and the purpose is not to obtain their wood but rather to use their soil for food production.*

Some of these nutrients are then made available to the next farm crop when the forest is felled and burned. The effectiveness of the practice is shown in the repeated cropping of some of the poorest soils of the Tropics, where slopes and physical and chemical soil properties do not favor continuous agriculture of any kind.

Artificially established tree crops, such as coffee (fig. 2–9), cocoa, oil palm, and rubber (fig. 2–10), have also improved and maintained productive soil conditions. Unlike conventional cultivated or pastured crops, these do not "wear out" the soil, at least not as quickly. Some areas have been in continuous production for 50 years or more. One practice has been to plant these crops under a tree overstory. The presence of a light tree cover (either tree corps or tree shade over other crops) fosters maintenance of the soil and constrains the development of understory crops to a level commensurate with available nutrients. Cultivating tree cover is a wise investment, because it may greatly lengthen the cropping period on land that would otherwise require fertilizers and costly soil-conservation measures.

These effects of forests on agriculture are not confined to the humid Tropics. In dry areas, tree corps may draw on moisture at depths below those used by food crops while their litterfall reduces evaporation of soil water near the surface. Litter also provides nutrients that may not otherwise be available at the surface. The use of a sparse tree layer (particularly legumes) over corps in dry areas is common.

Figure 2–9.—*Tree crops such as coffee commonly replace forests, and if well managed, may persist for many years.*

Figure 2–10.—*Tapping latex for rubber remains an important forest industry in tropical America.*

Forests as a Source of Products. Biologically, forests convert energy and nutrients into assimilate, a process termed "gross primary production." When respiration is deducted, the remaining growth in roots, stems, branches, and leaves is termed "net primary production." Net primary production in the tropical forests (above ground only) ranges up to 30 t/ha/yr (Anon. 1980e). Timber plantations, on the other hand, may yield up to 60 t/ha/yr (Oudshoorn 1974).

Wood is one of the most useful of the world's raw materials. It is versatile, widely available, and relatively low in cost. Compared to most alternative materials, wood is superior in its strength-to-weight ratio, more workable, and more attractive in appearance. It is also warm to the touch.

Manufacturing steel requires 87 times as much energy per tonne as does processing wood; aluminum, 45 times as much (Makhijani and Lichtenberg 1972). Moreover, wood products are biodegradable, presenting no major environmental disposal problems. Such advantages have led to wood consumption, at least formerly, roughly equal in weight to that of all metals, cement, and plastics combined, even in the United States (Cliff 1973).

Three broad categories of wood materials are used industrially: (1) solid wood not structurally altered, (2) fiber, the complex of cellulose in the walls of hollow cells, and (3) chemical components of cellulose, lignin, and extractives.

Worldwide production of wood products in 1992 was estimated at 3.477 billion m^3, an increase of 19 percent during the decade (Anon. 1993b). Of this 3.477 billion m^3, 380 million, or about 11 percent, were produced in tropical America, an increase of 20 percent during the decade (table 2–1). Of this increase, 74 percent was for fuelwood and charcoal, a proportion unchanged in the last decade. Exports of all forest products from the countries of the region in 1992 were valued at US $2.2 billion, up 126 percent in current dollar value.

Of the industrial products of the region, nonconiferous sawn wood production reached 13.9 million m^3, with exports worth US $215 million in 1992 (fig. 2–11). Of greater economic significance was paper and paperboard production, totalling 9.8 million t and exports valued at US $867 million. This is a 10-year increase in production of 40 percent and a fourfold increase in export value, in current dollars. Wood pulp production increased 56 percent to 6.1 million t in 1992, with exports worth US $698 million (table 2–1).

However, tropical America consumes more sawn wood, veneer, and plywood than it produces. In 1982, the developing countries of America produced only 3 percent of all wood exported from such countries worldwide and a negligible portion of the sawlogs and veneer logs, but 19 percent of the sawn wood and 34 percent of the veneer sheets (fig. 2–12; Anon. 1984a).

The leader in the production of fiber products in the American Tropics has traditionally been Brazil. This country produced 2,900,000 t of pulp and 3,200,000 t of paper in 1982 and 6,100,000 t of pulp and 9,800,000 t of paper in 1992 (Anon. 1993b).

An indication of the economic significance of tropical forests is the record of the Indian Forest Service, which historically has been one of the most effective public forestry agencies in the world. This agency is concerned with many forms of public assistance other than the mere sale of timber; nevertheless, between 1950 and 1960, it yielded revenues more than 50 percent greater than its expenditures (Anon. 1960d).

Forest production, as defined here, reflects the harvest of much old-growth timber, which is a natural heritage rather than a product of human effort (fig. 2–13). This heritage is being eroded in many places. However, with management and culture, continued production is not only possible but in some places has already been remarkably successful.

Table 2–1.—Production and export of wood products in tropical America, 1982–92

Wood product	Production 1982	Production 1992	Exports 1982	Exports 1992
	Thousand m^3		Thousand US$	
Roundwood	316,500	379,900	—[a]	—[a]
Fuelwood/charcoal	233,200	280,400	—[a]	—[a]
Processed products	—[b]	—[b]	977,500	2,214,600
Sawn wood (nonconiferous)	13,100	13,900	202,300	214,900
Wood-based panels	3,900	4,100	179,100	279,700
Veneer sheets	300	400	59,500	52,900
Plywood	1,500	1,500	62,800	127,300
	Thousand tonnes			
Wood pulp	3,900	6,100	278,500	698,100
Paper and paperboard	7,000	9,800	216,700	866,900

Source: Anon. 1993a.

[a] Information not available.

[b] Units not additive.

Figure 2–11.—*Timber from tropical lowlands is largely extracted by rivers as is seen in Panama.*

The development of processes that use mixed tropical woods in the manufacture of pulp and paper has already reduced tropical America's imports of these costly forest products. The problems that remain in expanding cellulose use are more economical than technical (Kyrklund and Erfurth 1976). One prospect is more complete utilization of natural stands. Another is that the faster growing, lighter woods of the region's natural regeneration may prove as good as (or better than) the mix from first cuttings in natural stands for pulp. The feasibility of plantations in most parts of the region depends largely on cellulose markets for intermediate-sized thinnings or for short-rotation crops.

Next to the soils, the water they conserve, and the nutrients they hold, the most important commodity of tropical forests certainly has been fuel. More than 1.5 billion people worldwide depend on wood for cooking and warmth (Anon. 1977b). It is estimated that in Latin America wood consumption for fuel ranges from 0.36 to 1.03 cubic meters per person per year (Arnold and Jongma 1979). In 1974, this meant a total of 240 million m^3, one-eighth of the world's total consumption of fuel wood. This amount was 82 percent of the wood consumed for all purposes within the region (Arnold 1978). Wood provided 20 percent of Latin America's entire energy consumption in 1974. The developing countries collectively have untapped energy potential in their forests, which, if managed well, might supply all their energy requirements and provide a surplus for export (Earl 1975). An early prediction that, if only 5 percent of the deforested land in developing countries were planted to rapidly growing tree species, the world would have no risk of wood scarcity may still be valid because deforested land may be increasing as rapidly as wood needs (Sartorius and Henle 1968).

Wood is principally cellulose and lignocellulose, made up of about 50 percent carbon (C), 6 percent hydrogen

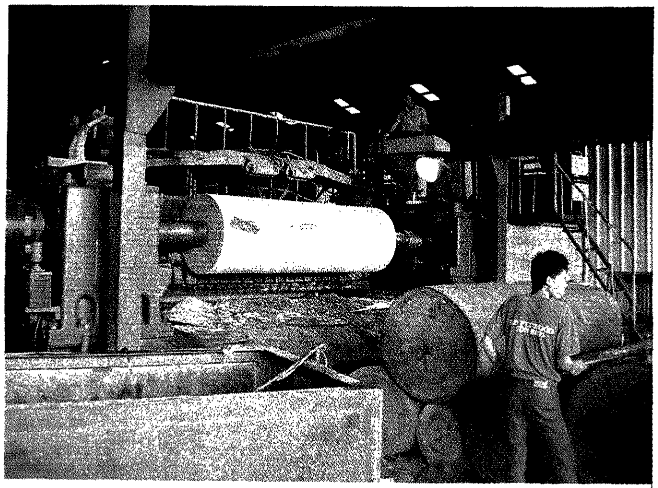


Figure 2–12.—*The large trees with attractive, medium-weight woods provide one of the most valuable products of tropical forests, veneer, being made here from a dipterocarp in Sarawak.*

Figure 2–13.—*The harvest of tropical timber typically is concerned solely with immediate profit, at the expense of any immature trees that might provide future crops.*

(H), and 44 percent oxygen (O) (Earl 1975). Its calorific value is 4.7 kcal/t oven-dried and 3.5 air-dried. There is remarkably little variation among species. In comparison, calorific values are 6.9 kcal/t for bituminous coal and 9.8 for fuel oil.

Wood is the cheapest fuel available in most of the region. No storage is required, yet, it can be stored for a long period. Its production is labor intensive, which may or may not be an advantage. Its removal can be so complete as to deplete forests, requiring management discipline. Its bulk is great, a problem in transportation and storage (Earl 1975).

An analysis of the fuelwood situation some years ago in tropical America showed the following areas to be experiencing acute shortages: Haiti, eastern Brazil, El Salvador, coastal Peru, and the Bolivian altiplano (Anon. 1981f). Less critical deficits existed in northern Mexico, Honduras, Cuba, Jamaica, Dominican Republic, the Andean slopes from Colombia to Bolivia, and Trinidad.

In extensive deforested areas in the Eastern Hemisphere, fuelwood production in forest plantations has proved successful. A favorite species is *Casuarina equisetifolia,* a tree of rapid growth and dense wood. In Madras, India, this tree, on a 4-year rotation, yields 200 to 250 t/ha of dry wood (Kaul and Gurumurti 1981). In Dahomey, now Benin, the fuel needs of a dense population in a poorly forested region have been supplied by plantations of *C. equisetifolia* along the seacoast (Buffe 1962).

Future demand for wood fuel seems assured because satisfactory substitutes are generally lacking. One foreseen development is greater efficiency in fuelwood use. Cooking in the open consumes five times as much fuel as cooking in an enclosed stove (Arnold and Jongma 1979). Simple improvements in stove design may save yet another 70 percent. Another option is conversion of wood waste to charcoal. Fuelwood plantations, successful for decades in India and elsewhere, can also concentrate production and succeed if they are in keeping with the traditions and knowledge of the people.

The inflexibility of fuelwood markets is to be seen in heavily populated India, where 80 percent of the rural energy requirement is still met from noncommercial sources. Of this amount, 64 percent is firewood, used mostly for cooking. In fuel-scarce areas, fuelwood plantations are preferable to any substitute forest crop. The consumption, about 0.6 tonne per person annually, is at least as great as in much more heavily forested tropical America (Kaul and Gurumurti 1981). Cooking rice in India has cost about 17.5 percent of the food energy content of the rice itself (Revelle 1981).

Charcoal derived from wood has a calorific value of 7.1 kcal/t, comparable to coal (Earl 1975). It burns almost smokelessly, and much of its energy is emitted as radiant heat. Its low bulk density makes it fragile and necessitates special transportation and storage. A danger of carbon monoxide poisoning exists from its use in confined areas (Earl 1975). Nevertheless, charcoal is a common fuel in the region's urban areas. It is used industrially in the region as well.

Charcoal manufacture is particularly suited to rural tropical society. It may be pursued profitably on a small scale. The ratio of capital to labor is low, so it creates more employment than most industries. It utilizes common skills and requires little managerial or supervisory expertise. Its rural location contributes to the urban/rural economic balance (Earl 1975).

Wood from forests will be at least as important to the Tropics in the future as it has been in the past. Forested tropical countries are importing timber products, but the developed world may soon have little wood to export to them. The demand for all types of wood, including that suitable for such uses as fuel and chemical feedstocks, can be expected to increase in developed countries. Countries with abundant raw-material stockpiles can be expected to move into a better bargaining position (Mitchell 1978). Substitution of other materials is not likely because there is not enough cheap energy to make substitutes. Between 1980 and 2000, the demand for products from tropical woods was predicted to increase 110 percent worldwide, 180 percent within the Tropics, and 220 percent in tropical America (Pringle 1976).

Consequences of Overuse. Overexploitation of tropical forests is common, primarily because of the tradition of free use. Where forests are plentiful, their profligate use has been neither illegal nor locally recognized as wasteful (Hardin 1968). Established use traditions become thought of as rights, generally before either the public or government foresees ultimate disaster.

Overexploitation is serious because tropical forests are intrinsically fragile. Outwardly, forests on moist sites show remarkable powers of recovery from disturbances, rapidly regenerating in fields left after cultivation and closing gaps in the tree canopy. Forests subjected to selective logging or infrequent shifting cultivation may not change sharply in general appearance. In a quantitative sense, they may appear to endure well even what appears to be abusive treatment. Their complexity, however, results from a web of interdependence among components that have coevolved. Disturbing the delicate balances among organisms, even by cautious, selective harvesting might eventually so simplify the ecosystem as to deteriorate its stability and reduce its capacity for self-restoration. In the pure sense, primary tropical ecosystems, once substantially modified, are thought not to be retrievable (Gomez-Pompa and Vazques-Yanes 1972). Even if a long subsequent period of complete protection were afforded, long-term changes in climate and other influences could be expected to preclude restoration of an essentially identical primary forest.

One of the subtlest consequences of human intervention in tropical forests is the gradual loss of biodiversity. This might result for example, from direct harvesting of all mature (seedbearing) *Cedrela* trees or mature game animals. Even more subtle would be the deterioration of habitats or inadvertent favoring of enemies of certain species. Because habitat requirements, parasitism, and predation are not well understood, such damage may be undetected. If as many as 10,000 individuals may be needed to conserve the gene spectrum of a species (Poore 1976a), obviously the decline of a species, particularly one sparsely distributed, might be indiscernible until long after its population falls below that level.

The effect of wood removal on diversity cannot be measured purely in terms of changes in the number of plant species. Animal species may be strongly affected by some plants that biologists recognize as ecological "keystones." Keystone plant species may provide food for animals during periods when other, preferred foods are not available. Evidence indicates that as little as 1 percent of the plant species might tide over most of the fruit-eating wildlife of moist forests, suggesting that timber removal geared to conserve certain keystone species might not reduce the capacity of the forest to feed many forms of wildlife. It remains to be seen, however, whether the keystone species, if their proportion of the forest increased, could be safe from pests and diseases, and if other requirements of animal populations, such as reproductive habitat, would persist regardless of how the rest of the forest was treated.

Another, more apparent consequence of overexploitation is a decline in the forest's capacity to produce marketable timber through removal of the best timber trees and damage to those remaining. Usually, harvesting also results in erosion from abandoned, unstabilized roads and skid trails. Continual overexploitation reduces wood yields for both exports and local needs.

The overuse of forests is readily evident where cultivators so rapidly deteriorate the soil that they cannot recrop the area within a reasonable period. On parts of the terra firme (upper terrace) of the Amazon, for example, cultivation for 2 years followed by a 10-year fallow period permits only one more traditional crop (Sioli 1973). Cropping decreases soil infiltration, reducing the recharge of soil water and increasing floodflow. Erosion and landslides may result. Overuse of forest land has in some areas progressively shortened the fallow period to a point where fallowing suffices neither to restore soil fertility nor to regenerate a usable forest crop (Anon. 1977b). Restoration is then seen as impractical, so the people either have to leave or continue a marginal existence. The ultimate result can be a vast, unproductive waste. Such conditions are forerunners of famine, epidemic disease, and civil strife, examples of which already exist in Africa and elsewhere (Poore 1976b).

In central Tanzania, gathering fuelwood for an average family now occupies 250 to 300 days a year of one person's time (Anon. 1977b). An extreme situation is in the Punjab of India where only 1 percent of the demand for firewood can be met by local forests. Under these conditions, the rural people, although fully aware of the impact on food production, are forced to use dung, maize stalks, and other agricultural residues for cooking fuel (Sagreiya 1946a, Singh and Randev 1975).

As recent world events illustrate, the consequences of extensive deforestation may be far reaching. The desertification underway in Africa south of the Sahara is thought to emanate from brush fires, branch lopping for forage, deforestation, overgrazing, and trampling of vegetation by animals (Delwaulle 1973). It has resulted in deterioration of the remaining natural vegetation and crop yields. This, in turn, has led to mass migration of the inhabitants.

Land: Forest Versus Nonforest

Setting rational goals for forest land use calls first for consideration of the priorities and requirements of nonforest land uses and then an assessment of the several major forest uses. A schematic diagram for the identification of forest and nonforest land and its development is seen in figure 2–14.

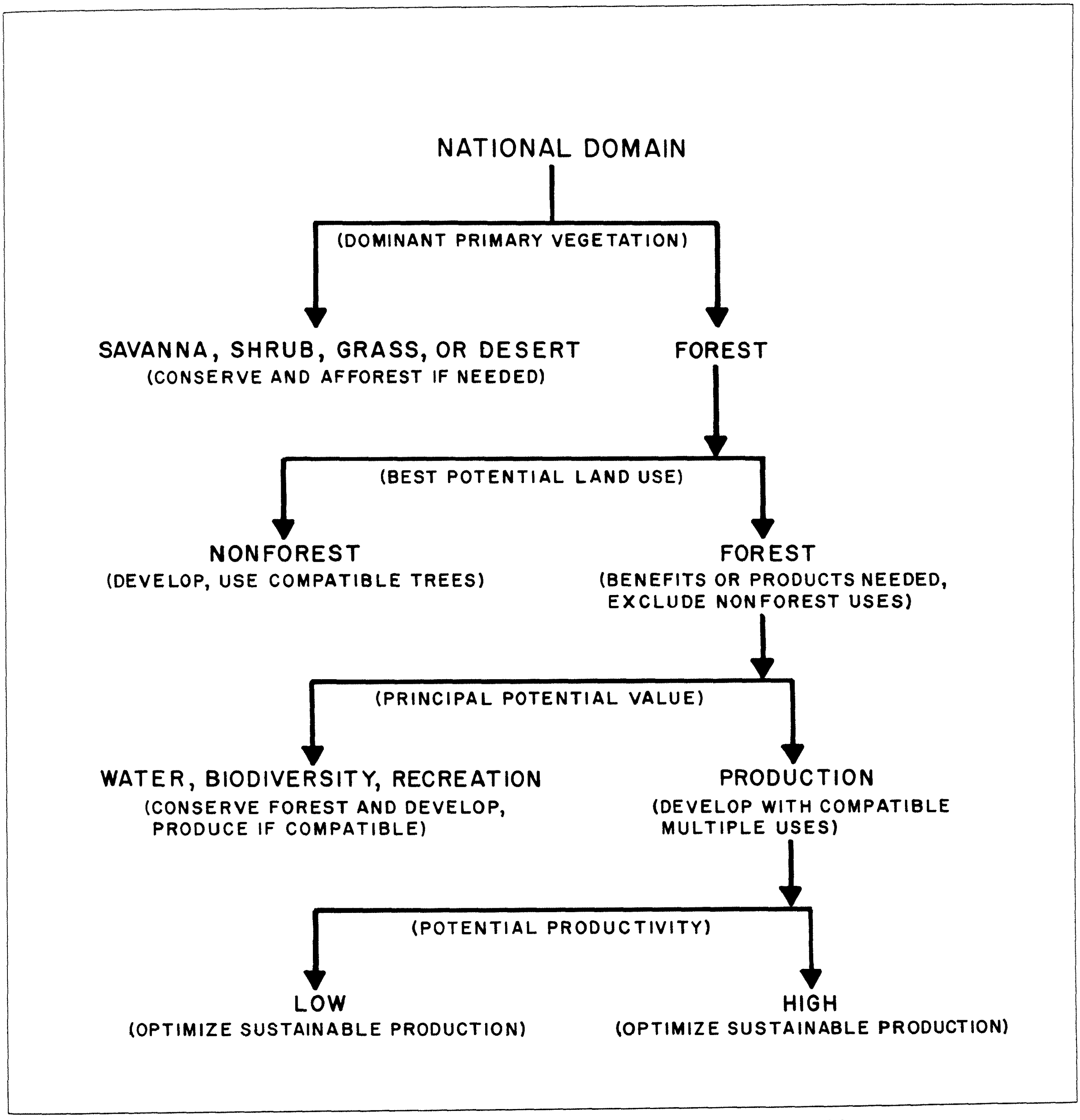


Figure 2–14.—*Schematic sequence for the identification and treatment of lands for trees and forests.*

Forest Versus Agriculture. Food production offers more obvious and earlier returns than does forest production. Population growth is not everywhere being matched by increases in food production, as seen in table 2–2 (Anon. 1993b).

A consequence of this trend is continued deforestation to exploit the soil and the plant nutrients recycled from the forest vegetation. The population agriculturally active in the region increased between 1980 and 1982 by more than 2 million persons (Anon. 1993b). Land dedicated to permanent and temporary agriculture increased by more than 65 million ha between 1970 and 1991 (Anon. 1993b). Irrigated agriculture, mostly dependent on forest water, increased some 2 million ha between 1981 and 1991.

The hardest part in securing land for long-term forest production is protecting it from food and forage production. Forests grow best on land that is also the most productive for food and forage. Yet, the deforestation of this land for farming may appear necessary even where the farming practices themselves may not have been successful or lasting.

Any comparison between food or forage crops and wood crops is usually biased against forests because agricultural values are both tangible and immediate, whereas many forest values are not. Moreover, agricultural research has led to intensification of production methods that have no equal in forest production. Unlike the farmer's field, forests contain many poor quality or unmarketable trees and generally none that have been improved genetically. Forest stocking is not precisely controlled; neither are nutrient supplies, weeds, insects, or diseases. If agriculture had these handicaps, it would not be economically attractive either. Correcting these deficiencies in the culture of coffee, a tree crop, increased yields in Puerto Rico at least twelvefold (Wadsworth 1962). Cassava yields on red-yellow Podzolic soils of the humid Tropics, have been increased nearly 60 percent purely by a modest application of NPK fertilizer, and soil properties were improved as well (McIntosh and others 1980).

Food production is declining in more than half the countries of tropical America (Anon. 1993b). Therefore, there are strong arguments that level, well-watered land with deep, workable soils should be used for food and forage production. However, if all such land were managed at top productivity and fully protected from wide fluctuations in river flows by forests in the uplands, most countries could produce most of their needed food and forage and still dedicate large areas to wood production and other forest benefits.

Unfortunately, the best soils of the region are not fully productive. Consequently, less suitable land has been pressed into service. Because the nutrients contained within the trees are released when they are felled, soils

Table 2–2.—Food production in tropical America, 1972–81

Country	Per capita food production index	Country	Per capita food production index
Brazil	115	Guatemala	92
Bolivia	114	Honduras	91
El Salvador	112	Peru	90
Colombia	110	Panama	84
Ecuador	110	Dominican Republic	84
Jamaica	110	Suriname	83
Mexico	101	Cuba	81
Venezuela	99	Guyana	68
Paraguay	94	Haiti	67
Costa Rica	93	Nicaragua	62

Source: Anon.1993a

Note: Per capita food production index in 1969–71 was 100.

too poor for continuous cultivation can still be so used temporarily (fig. 2–15). The area of such marginal land required to sustain a given yield is far greater than that in use at any one time, because, after one or two crops, the land must be fallowed for several years before it can be recropped. But in mountainous areas, severe erosion resulting from this practice may ultimately preclude even tree crops. In Cuba, for example, a country largely forested when "discovered," conversion to agriculture has left only 16 percent of the island forested in 1990 (Anon. 1993a). More than 80 percent of the island of Puerto Rico was deforested for the same purpose (Murphy 1916). Without special incentives, farmers hesitate to adopt practices that would allow continuous field cultivation even where fallowing has obviously been degraded by reducing its period and where the advanced technology has already been developed and proven (Ward and Cleghorn 1964).

The prospect of greater financial returns from the production of food and forage than from timber on the best land has led to widespread deforestation in the Tropics, much of it a result of deliberate colonization and rural development schemes. Such schemes are usually successful in deforestation but less so in providing continuous support for settlers from farming. The result on extensive areas is the near abandonment of land that was once covered by luxuriant forests. This record justifies not relinquishing to agricultural exploitation all forested land that superficially appears suited to it. Intensifying agriculture on land already deforested would be more rational.

Figure 2–15.—*Recently deforested slopes in Sarawak are commonly converted to plantations of black pepper vines, a cash crop.*

In most cases, the amount of forest destroyed and the density of the rural population are directly related (Poore 1983). Urbanization is apparently associated with less deforestation. In areas with low population densities, such as the central Amazon, the forest is less threatened than in more densely populated Central America. South Asia is seen as a hopeful exception. There intensive forest management, community forestry, and high-quality intensive agriculture allow a denser rural population to be supported with less forest destruction.

Holdridge (1959) points to climatic features that limit food and forage production more than wood production. He concludes that agriculture is most successful where rainfall and evapotranspiration are about equal, in the "moist" and "dry" life zones as opposed to the "wet" and "very dry" zones (appendix B). He says that in the wet zone, fertility is hard to maintain because of leaching and erosion. In the very dry zone, water becomes limiting. He points out that shifting cultivation is possible where permanent agriculture is not, but that it may yield too little to support permanent communities.

Tosi (1975) considers Holdridge's moist forest life zone optimal for agriculture and animal husbandry. However, even here, dry seasons may range up to 7 months, and a dry period of only 2 to 4 months is enough to cause moisture deficiency in unirrigated field crops and pasture grasses. Tosi further points out that in the wet forest and rain forest life zones, water surpluses are so great that leaching drastically reduces soil fertility. Even pasturing is low in productivity because of livestock treading on waterlogged soils. In the generally well-watered Amazon, rice and corn culture is questionable because they rely heavily on capital and machine inputs in an area of unskilled farmers (Smith 1978). The multilayered polyculture of 13 species of plants used by the Caribs under these conditions is less risky (Smith 1978). However, it presents no prospective supply of products adequate for urban markets.

On poor land, the advantages of trees over other crops become overwhelming, a fact especially apparent where poor soils result in low yields and short cropping cycles. Permanent tree crops are recognized by some agricultural experts (Alvim 1981) to be most appropriate where rainfall is high and soils are poor. Their most important ecological advantage over annual crops is their protective value.

Alvim (1981) also pointed out that tree crops demand fewer soil nutrients and tolerate greater soil acidity and aluminum toxicity than farm crops. Their lower nutrient demand, he said, not only seems due to mineral recycling—a function that annual plants cannot perform efficiently—but also to the fact that the products harvested from perennial crops usually have a lower nutrient content than those from annual crops.

Alvim listed only five perennial agricultural crops that can be recommended as appropriate for the Amazon Basin: rubber, oil palm, cacao, sugar cane, and black pepper. Other tree crops that might be considered include guarana, achiote, palm fruits, palm hearts, and copaiba timber. Alvim believes that the potential land requirements for all of these would be perhaps 1 percent of the basin, leaving nearly all the area for timber crops. Perennial crops, however, in leading to fragmentation of land use, may pose a far more serious danger to the security of forests than subsistence farming and annual crops (Gordon 1961).

On marginal land, wood production differs from grazing in the following ways: (1) it requires more capital per unit of labor and land area, (2) it produces a greater revenue per unit of area, (3) it employs more persons per land unit, and (4) it is more sensitive to the rates of interest charged on capital (Johnston 1966).

Pasture management on the poor soils of the moist Tropics has been questioned. Simulation tests of yield prospects in the Amazon Valley led to doubts that any of the systems popular or promoted at present can assure sustainable yields (Fearnside 1979b). In drier climates, pasturing is not only marginal but may irreversibly set back the forest, as 1.7 million ha of lalang grass in Indonesia resulting from forest burning will attest. Reforestation of such areas has proved difficult.

On land best suited for agriculture or other land that must be used for food crops, there may still remain some out-of-the-way places where productive forests can be grown. As an example, in the Punjab, where 80 percent of the land is farmed, 4 percent is forested (Singh and Randev 1975). This area, totaling 100,000 ha, includes 42,000 ha in narrow strips along railway lines, roads, drains, and canals. Another 22,000 ha are in small blocks along rivers. The remaining 36,000 ha are scattered over plains and hilly areas. More than half of this forest land is preserved for its protective value only. Only 0.15 ha per capita is available to produce wood for human use.

The relentless invasion of shifting cultivation and pasturing into forests on progressively less stable and less productive soils has been accompanied by growing human misery and loss of future productivity of the land for agriculture and possibly also for forests (fig. 2–16). As a consequence, the search has begun for alternatives that will assure sustainable yields. Studies under what may be favorable conditions in central Brazil (Watters 1974) have shown that a village of 145 people that had not moved for 90 years required 5,500 ha of forest, or 38 ha per capita. Cultivating in the forest may require less labor to produce a specific unit of food than cultivating grassland soils or operating a permanent field system of agriculture (Ward and Cleghorn 1964). However, land for forests may no longer be available to this extent in most of the Tropics.

One suggested alternative, termed "agroforestry," includes growing farm and forest crops concurrently or alternately on the same land, the subject of chapter 8. Concurrent crop integration includes the already extensive and time-tested plantations of coffee, cocoa, and fruits under tree shade and the use of such conventional tree crops as rubber, oil palm, and coconuts over food or forage crops, including tree fodder. Good management

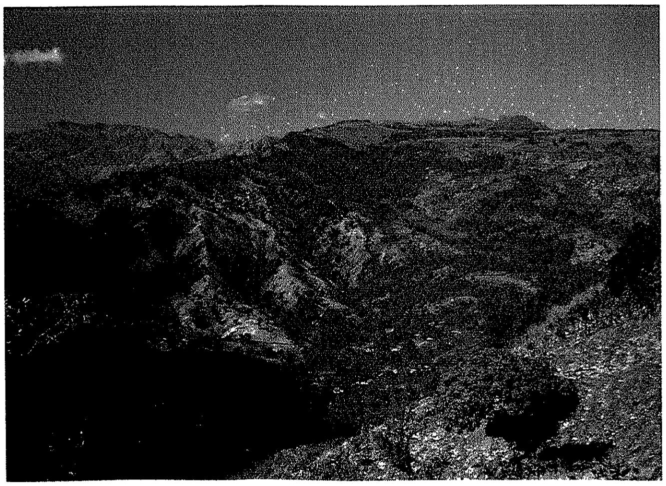


Figure 2–16.—*Extreme overuse of formerly forested slopes produces degraded land such as is seen here in Haiti.*

of a tree story over food or forage crops may help stabilize agricultural production by lengthening or augmenting the productivity of the cropping period or reducing the length of the fallow. Even small gains of this nature should prove popular with farmers and reduce the need for felling more natural forests. A secondary gain could be the production of wood from the trees.

Sequentially integrating farm crops with wood is the century-old taungya system of starting timber plantations by initial intercropping with food plants. Such plantations may be primarily for tree crops other than wood and may or may not be so spaced as to permit continued farming or forage production beneath the trees, depending upon the site's potential for the two types of crops.

Agroforestry is especially useful for land otherwise marginal for agriculture. Some 49 million km^2 of land in the Tropics (65 percent of the total) was said to be in a "wasted" condition in 1979 (King 1979a). About 630 million people (35 percent of the total population of the developing countries) depend on this land for subsistence. Agroforestry is a means to produce both food and wood from such land.

In identifying land to be dedicated to forest production, agroforestry could be of great significance. Agroforestry does not promise all the benefits of closed forests, but if stable agroforestry could replace shifting cultivation, it could clarify the boundaries between closed forests and farms. Even if it were to employ all 630 million people, agroforestry would undoubtedly prove most rewarding on the better "waste" lands, so secondary forests might remain as such. Tosi (1975) warned that new settlement should be confined almost totally to the humid (moist forest) zones; only under special soil conditions would perhumid (wet) areas be suitable for sustained agriculture or grazing.

The volume and quality of wood that might be produced by agroforestry are unpredictable at this early stage of experimentation. Sources of uncertainty include site adaptability and yields of timber species under agroforestry (as opposed to pure timber production), the significance (if any) of fruit trees in meeting wood requirements, and the fact that agroforestry will be accepted by those who apply it only if wood remains a by-product of food or forage production.

Land-Use Capabilities. The selection of land for forest production should be based on the properties of the land itself and the requirements of different land uses. A first step in good land-use planning is the development and application of a system of land evaluation. Young (1976) specified that such a system should do the following:

- Evaluate land for specified uses
- Consider alternative uses that are physically possible and economically and socially beneficial
- Take into account both production and other benefits and inputs or necessary costs
- Consider environmental effects
- Permit evaluation in stages, according to the purposes and intensities of surveys
- Be versatile, applicable to both large and small land areas
- Produce permanent results, not unduly affected by current economics
- Permit revision
- Present results simply to inspire confidence from the nonspecialist.

Poore (1976b) said success in land-use planning depends on recognizing public interests and ranking them skillfully. Resolving conflicts is essentially political. He recommended a logical sequence of steps in planning: (1) identify the main areas of public interest, (2) examine land in relation to its importance to each of these areas, (3) compare values, and (4) settle conflicts. He pointed out that the test of any action should be its lasting effect on human well-being. He sees two complications in assessing effects: (1) many of these effects take time to become evident and (2) the effects may take place far from the point of cause.

The development and application of land-evaluation systems in tropical America are in their infancy. The climatic, physiographic, and edaphic parameters basic to land-use decisionmaking are not mapped everywhere and are not generally well understood. Mapped data have been the basis of most land-use allocation proposals in the region. Moreover, land evaluation and planning are long-term processes that generally can be done only in stages. But there is great pressure to make decisions quickly to meet immediate needs. Such has been the case in the Temperate Zone as well. Therefore, Young's (1976) provision that the planning system allow for revision as new information becomes available is of critical importance.

Two types of criteria are used in land-use planning: (1) those that are physical and essentially constant and (2) those that are social and subject to change over time. Specific criteria to help determine whether land should be dedicated to forest production and, if so, the benefits or products most appropriate include the following:

- The physical environment
  - Climate—particularly the quantity and uniformity of rainfall
  - Soil—particularly its depth (water-holding capacity) and susceptibility to erosion
  - Physiography—particularly scenic values, slope, contribution to potential water use or floods downstream, and accessibility
  - Presence and quality of existing forests and features comparatively scarce elsewhere.
- The prospective social environment
  - Traditional land-use pattern and practices
  - Prospective need for forest benefits, including those of both the adjacent population and tourists
  - Prospective human pressures on the land for food production, on downstream water, and on the wood supply, including export prospects.

Applying one of the above criteria, Holdridge (1959), as has been pointed out, observed that rainfed agriculture is most successful where rainfall and potential evapotranspiration are about equal. Dubois (1971) applied another when he based his recommendation for the production of annual crops, perennial crops, pasture, rubber, cacao, oil palms, and timber or for shifting cultivation on the severity and periodicity of flooding in the Amazon Valley. Holdridge (1976), on the basis of foreseeable social pressures, listed land in Costa Rica most likely to lose its forests as: (1) fertile alluvial plains subject to no dry season (the Caribbean lowlands), (2) fertile arable land with a long dry season, and (3) mountainous land on the Pacific slope subject to drought and fire.

Plath and van der Steenis (1968), using available data on climate, soils, and slopes, classified land capabilities in Central America (table 2–3). From this tabulation, it is apparent that only 38 percent of the land should be farmed. The rest includes areas that may be needed for residential, commercial, and industrial purposes, but most of the area would best be left forested. Plath's category for "extensive cultivation" in humid areas would appear to correspond to those areas where shifting cultivation is sustainable. The portion of the subregion now subject to shifting cultivation is certainly much more extensive than this, covering a large area of the land classed as unsuitable for agriculture.

Table 2–3.—Land capabilities in Central America

	Area	
Land-use category	(million km^2)	(%)
Suited for sustainable agriculture		
Most favorable climate		
(tropical humid)		
Intensive cropping		
Annuals	16	3
Perennials	4	1
Subtotal	20	4
Extensive cropping		
Annuals	6	1
Perennials	38	8
With trees	24	5
Subtotal	68	14
Total	**88**	**88**
Less favorable climates	103	20
Total (suited for agriculture)	**191**	**38**
Unsuited for sustainable agriculture		
(mostly suited for forests)		
Climatically	115	23
Otherwise	193	39
Total	**308**	**62**
Total land area	**499**	**100**

Source: Plath and van der Steenis 1968.

The agricultural land capability classification system of the U.S. Soil Conservation Service (Norton 1939) has been tested in tropical America. The system is based on soil productivity, drainage, and erodibility. A study of the Andean region and part of the Amazon and Orinoco Basins in Colombia (Cortes 1977) showed only 20 percent of the land suited for annual crops. An additional 30 percent was land either level or gently sloping with poor drainage or land that was excessively stony, steep, or erodible. This left 50 percent of the land suitable only for forests, native pastures, and other natural vegetation to protect watersheds and wildlife.

McKenzie (1976) estimated that 5 percent of Venezuela's land is suited for annual crops, 32 percent for pastures, and 62 percent for managed forests. Independently, Luna (1976) concluded that 39 percent of the country should remain in forests. Of this amount, 31 percent (12 percent of the country) should be kept primarily for its noncommodity benefits and 69 percent (27 percent of the country) for wood production.

In 1978, Kudela estimated that 25 percent of Cuba should remain forested (only 13 percent was then so covered). In Puerto Rico, half the total land area has been recommended for forest (table 2–4; Birdsey and Weaver 1982, Wadsworth and Schubert 1977).

A common conclusion reached by these studies of land-use capabilities is that important areas that should be left forested have been or are being deforested and either overused or abandoned. The disparity between the ideal identified by these studies and reality should not relegate such studies to oblivion. There are important benefits from knowing what is desirable. Even where increasing population is making the disparity worse, it may be possible to direct degradation to land where the least resources are at stake and to restore forests where such land has been abandoned after clearing. Reforestation can be focused on areas where maximum aggregate values will accrue.

An important feature of the Puerto Rico study was identifying land where there is least controversy between government development agencies and landowners as to its use. Another was a liberal allowance for infrastructural (urban, industrial, and commercial) land-use expansion. Fortunately, this generous allowance proved to be minor relative to the entire land area. Finally, the allocation made to farming was limited by a realistic assessment of prospective markets for crops, so there remains on this heavily populated island a large area available potentially for forests. Theoretically, more than a quarter of the island is available for noncommodity benefits and yet is still able to satisfy, with proven technology, well over half the demand for forest products projected 25 years hence.

Land-Use Control. The long period generally needed to produce forests and forest crops requires that investments be made where they will not be lost through arbitrary changes in land use. The social and intangible nature of forest benefits justifies government participation to foster this stability. The well-being of entire nations and their cultures are at stake. The people as a whole have a clear

Table 2–4.—Prospective land use in Puerto Rico

Land-use category	Highest sustainable use	Land area (thousand km^2)	Land area (%)
Urban	Residential, industrial, commercial	100	
Agricultural cropland	Food and forage cropping	345	
Other rural land			
Mangroves, swamps	Protective forests	10	1
Rainfall >250 cm/yr	Protective forests	43	5
Rainfall 100–250 cm/yr			
Slope >60%	Protective forests	68	8
Slope <60%	Productive and protective forests	202	23
Rainfall <100 cm/yr	Protective forests	122	13
Subtotal		**445**	
Total		**890**	**1**
Summary of forest use			
Protective only		243	27
Protective and productive		202	23

right and responsibility to participate in decisions affecting the future of their nation's forests.

A logical outgrowth of this philosophy has been public reservation of forests, particularly those valued for more than their immediately exploitable wood resources. Forests have been reserved in most tropical countries of the world, including those of tropical America. In west Africa, for example, between 1929 and 1950, more than 600 forest reserves were set aside in 9 countries, totaling 146,000 km^2, or 2.4 percent of the land area (Bellouard 1952).

However, Gordon (1961) has warned of the dangers of legally reserving forested land that later proves to be better suited to production of food or forage. He points out that forest land reservation and protection have generally been left up to governmental forestry agencies. He concluded that foresters may be deluding themselves if they believe that most of the land reserved in the past for forestry is going to remain so dedicated in the future.

The problems inherent in reservation in advance of social conviction are illustrated by experience in Venezuela. In the western Llanos, some 9,370 km^2 of forest was reserved in 1950 (Veillon 1977). Because much of the land is flat and seasonally well watered, it has been increasingly subject to trespass for cultivation and grazing (Luna 1973). Government efforts to control this practice without engendering hostility have not been effective. The State has had to allot part of one reserve for agriculture. Trespassers were allowed to sell their crops and new violations continued. The Turen Reserve was almost gone by 1973 (Luna 1973). The total reserved forests had, by 1975, declined by one-third to 6,270 km^2 (Veillon 1977). Yet, more than half of the deforestation has been in the premontane zone where protection of headwaters for rivers is needed. It was then predicted that about half the forests remaining in the reserve would be gone by the year 2000 (Veillon 1977). In tropical America, the wet and moist forest remaining in 1992 was estimated at 6.80 million km^2, a reduction of 22 percent from the original 8.73 million km^2 (Anon. 1993b).

In summary, forest land, if defined as land that should be dedicated to forests regardless of whether or not it is presently forested, constitutes an important part of every country in tropical America. This includes all land capable of growing forests that is not needed now or in the near future for other purposes. In most countries, deforestation, rational and irrational, is leaving forests only on land that must remain forested for reasons other than their wood productivity, such as the following:

- Areas incapable of serving other purposes
- Spectacular scenic areas already in use for recreation or tourism
- Rainy, steep, upper watersheds, particularly where existing water use is crucial
- Floodable areas, tidal coasts, and thorn woodlands.

Collectively, these forests may not be sufficiently extensive or productive to supply needed products (nor should they necessarily all be so used). To the degree that they can provide forest benefits, they constitute an environment that may be stable, because their continuation as forests may be required for more than one purpose. But because these areas tend to be marginal for forest production as well as for agriculture, additional land may be required for forest commodities. More favorable land then merits research to determine its potential forest yields.

Public reservation of forests does not guarantee forest production. Past reservations in the region commonly have been unprotected, forgotten, and lost. Much land best suited to forests is privately owned, occupied, and too costly for the government to acquire. So incentives are needed if private landowners are to conserve, manage, or reforest appropriate land. Such incentives must assure continued forest production. This objective can be partly met using forests intermixed with farmlands. Crucial to success will be good prospective markets and a public extension effort to involve landowners and rural communities.

Forest Land: Use Allocation

The intensified management prerequisite to increased and sustained production of forests should result in many benefits other than increased product yield. Intensive culture and plantation management require technical skill, and most of the earnings can go into the pockets of rural dwellers, counteracting the drift of people to towns. Likewise, much of the wood processing can be left to intermediate technology within the rural areas. A study in Australia showed that employment in the logging and sawmilling of plantation products provided continuous employment for 6 to 26 persons per 10,000 m^3 of product (Greig 1979). For administration and service to forest recreationists alone, 4 to 7 persons are employed per 100,000 visitor-days. Worldwide, the harvesting and processing of industrial wood and related silviculture plus peripheral services supported some 75 million persons in 1963 (Sartorius and Henle 1968).

Managing productive forests in the future will be progressively more complex, concerned with the conservation of natural ecosystems, species survival, a favorable flux of energy and materials and organic turnover, landscape values, and the multiple consequences of human activities in forests (Ovington 1974). Moreover, important as economics should be in making decisions, the way of life of individuals, families, and tribes, whose heritage is rooted in the forests and related lands, must be respected. It is only by making full use of the inherent skills, characteristics, beliefs, and prejudices of the local people that the general productivity of the land can be improved (Beresford-Pierse 1962).

Our concern here is with forest production, so a logical starting point is to identify those areas that are appropriate for such production. The importance of this step has often been overlooked; however, it is not a simple process. The selection of land must start with a review of the objectives it is to serve. A list of the major purposes of forests that might guide the selection has been adapted from Poore (1976b): (1) support of indigenous peoples, (2) advancement of scientific study, (3) preservation of germplasm, (4) soil and water conservation, (5) public enlightenment, (6) public recreation, (7) biological controls, and 8) production of commodities such as wood.

All tropical forests serve more than one of these purposes. However, most areas are not qualified to serve several equally well. The different purposes are not fully compatible, so providing certain forest benefits limits opportunities for providing others in the same area. Initial uncertainties usually concern how much land is needed for each purpose and how many purposes can be served concurrently on the same area. No one fixed policy can guide all these decisions. Because the process should focus on long-term objectives, it is wise to avoid, minimize, or postpone irreversible decisions that may foreclose options that later might prove superior. Constraints later found to be unnecessary or excessive could easily be liberalized, and any temporary loss of use should be a minor cost.

The dedication of land to forests should be as liberal as is practical for all foreseeable benefits. Throughout the Tropics, too little is known as to what kinds of forests best serve each purpose and how much forest area will eventually be needed for each. Meanwhile, the more land conserved, the more surely future requirements can be met. Ideally, there should be a margin of safety to compensate for possible misjudgments. Compatible multiple uses should be projected for each area.

Land use can be planned rationally by integrated resource analysis (Norton and Walker 1982). A region may be divided into land units, each internally homogeneous as to climate, soil group, slope, vegetation or habitat type, or accessibility. Each may then be assessed as to its capability to provide foreseeably needed benefits. Land capabilities may be represented in a series of maps, with suitability of each land unit for each kind of land use superimposed. When overlaid, these maps present a composite image showing where compatible uses can be integrated and where incompatible uses least impinge on each other. Currently this process is being revolutionized by geographical information systems that sort and overlay different land characteristics electronically.

Application of sound land-use principles to an undeveloped area is illustrated in guidelines recommended for the Amazon (Dubois 1979): (1) until the ecosystems are better known, maintain the largest possible area under protection in unmodified condition, (2) concentrate efforts on consolidation of areas already colonized, (3) limit new settlements to areas of greatest fertility, (4) use production systems that simulate nature, and (5) within settlement areas, determine the suitability of parts of the area for forests.

Forest-Dependent Cultures. The forest resources that must be accommodated first are those most vulnerable to irreversible deterioration from misuse. Indigenous cultures that are forest dependent and individually unique (and therefore vulnerable) are to be found throughout much of tropical America. Areas where tribal customs are integral with the forest, relying heavily on traditional use of areas, soil and plant and animal resources, seasonal migration, and transportation routes, should be recognized as critical to the preservation of such cultures. Those peoples generally are rich reservoirs of information about food plants, medicines, and sustainable life-support strategies as well as social concepts that should be preserved and might prove useful elsewhere. Interaction between forest tribes and the outside world almost invariably erodes delicate balances that traditionally have been worked out between the tribes and their natural environment (Poore 1976b). Therefore, outside uses of such areas, including even recreational and scientific visitations, may have to be rigidly controlled if such cultures are to survive.

Scientific Study. The second most fragile forest resource, organic diversity, outwardly may appear of little value. Benefits from the study of ecosystem diversity and dynamics are only beginning to appear and are proving far reaching. The most fundamental information they yield concerns the interactions within living systems as a whole and between their individual components and the environment-coevolutionary development, interdependence, and symbioses that have guided and could continue to guide human society in its quest for more durable and harmonious ways to live in tropical environments.

Manifestations of evolutionary progress that may be vital to ecosystem welfare can best be discerned in forests where codevelopment of organisms has progressed with minimal disturbance by human intervention. In such environments, because of long relative stability, ecological cause-and-effect relationships are best developed and in evidence. Thus, self-sustaining areas of least-disturbed forests of each major land unit (climatic and edaphic) ideally should be preserved unmodified for nondestructive scientific study. Such areas must remain free of human disturbance throughout an indefinite sequence of studies. They must be large enough to be self-contained and ideally protected by surrounding buffer zones to preserve rare species and migrant animals. For such complex ecosystems as tropical moist forests, self-containment may require either larger reserved areas than might be anticipated (Terborgh 1976) or continuous adjacent forests. Unmodified forest areas also serve as benchmarks for monitoring long-term global changes. In some countries and regions, it is clearly too late to establish ideal reserves of this magnitude, even if public opinion could be promoted to support them. Under such conditions, the reservation of representative climatic and soil areas, even with drastically modified forests or none at all, can nevertheless be in the public interest because, given time, these should gradually revert to forest ecosystems with many of the characteristics of those formerly undisturbed.

Preservation of Biodiversity. A third benefit of native forests is the variety of genotypes of useful or potentially useful species they contain. Many plants and animals critical to the well-being of natural ecosystems—plants that produce food, medicines, and other useful extracts and animals that are esthetically attractive or used as a food source—are distributed sparsely through large expanses of tropical forests and their disappearance must be prevented. Difficulties here are in knowing *a priori* which species will be of greatest future importance, the degree to which they are endangered or significantly different in genotypes, and where in the forest their genotypes occur. For most of the region, neither this knowledge nor the methods to ensure the preservation of all genotypes is at hand; therefore, if rare but possibly useful species are to be preserved, their location and evaluation are urgent. Evaluation may, in fact, be never ending, because new potential values of natural materials continue to be discovered. The preservation of rare species may be partially effected by judiciously selecting forest areas to be reserved, but because this natural condition may be only fortuitous and thus uncertain in the future, early determination of the habitat requirements of critical species is essential to enlightened forest management everywhere. Properly integrated, forest areas allocated for nondestructive, scientific study might be compatible with those used by forest-dependent cultures and those dedicated to preservation of biodiversity.

Soil and Water Conservation. A fourth forest benefit, soil and water conservation, has been widely documented. The significance of forests to erosion and infiltration is illustrated by data from three storms in Cuba on slopes of about 20 percent (table 2–5) (Herrero and others 1975). Particularly impressive is the sharp contrast in erosion among the forest, grassland, and cultivated areas. Although infiltration was about the same in ungrazed grassland and forest, it was lower in cultivated areas.

The superiority of forests in holding soil and infiltrating rainwater is greatest on steep slopes, on loose soils, and under high rainfall intensity. The benefits of forest cover vary also with the magnitude of downstream economic impacts of erosion and floods. Forests for soil and water conservation are thus of high value in rainy areas, but they may also be crucial to soil stability in dry climates where showers, although infrequent, may be intense. Particularly critical are those watersheds serving areas of actually or potentially irrigated floodplain agriculture, usable lowland aquifers, and urban and industrial water sources. Forests for soil and water conservation may also be used for other purposes if their basic protective capacities are not seriously impaired.

Table 2–5.—Vegetation influences on erosion and infiltration in tropical forests in Cuba

Vegetation	Rainfall intensity (mm/min)	Rate of erosion (kg/ha)	Rate of infiltration (mm/min)
40-year broadleaf forest	3.3–3.5	10.4	3.4–3.5
40-year pine forest	2.0–2.3	2.2	2.0–2.3
Ungrazed grassland	3.3–3.5	7.3–115.6	3.3–3.5
Cultivated cassava, 3 months old	2.1–2.3	1,591–4,874	1.7

Source: Herrera and others 1975.

The importance of forests to the borders of river courses is especially evident along the Amazon, where widespread deforestation in some areas has so deteriorated the water that former aquatic organisms have disappeared and disease vectors have spread (Sioli and others 1969). Good silviculture, however, can prevent such consequences. Forest areas allocated for soil and water conservation need not be unsuitable for forest-dependent cultures, preservation of biodiversity, and nondestructive scientific study.

Public Enlightenment. The full benefits of forests will never be realized without the understanding and support of the general public, including even people remote from the forests. Public understanding cannot be expected without some degree of firsthand knowledge of forests and their benefits. Special provisions are needed to influence people to visit forests that demonstrate these benefits. Appropriate forests need to be identified, maintained, and developed to serve this purpose. Special attention is required to attract youth, particularly students. Ideally, forest visitation, instruction, and investigation should be incorporated into educational curricula. What may be needed is a network of educational forest areas representative of the range of forest benefits and sufficiently close to population centers to facilitate public visitation, such as exists in Puerto Rico (fig. 2–17). These areas should demonstrate the benefits of enlightened management. Visitors should learn about such forests on foot, so the area need not be large. Forest areas allocated for public enlightenment should be so managed as to be fully compatible with preservation of biodiversity and soil and water conservation.

Public Recreation. Camping in, exploring, and visiting forest areas of scenic beauty and favorable climate are all recognized therapies for increasingly frenetic urban life. The term "vacation" means literally to vacate, or get away from, the routine. For that purpose, extensive forests are desirable to provide adventure as well as less strenuous recreation, but they need not all be forests otherwise unused. They must be reasonably accessible to population centers, and a small part of the area, preferably on the periphery, may provide basic facilities for accommodating visitors. One product of forest recreation will be greater public appreciation of forest benefits and forestry needs. Forest areas allocated for public recreation, properly developed, should be compatible with soil and water conservation and public enlightenment (fig. 2–18).

Commodity Production. The need for tropical forests to supply wood and other products is shown in recent wood consumption statistics for the region (table 2–6). An increase in use of more than 20 percent in wood and 13 percent in pulp and paper products took place from 1982 to 1992 (Anon. 1993b) and is likely to continue. Although the FAO figures are imprecise, they suggest a slight decline in wood use per capita from 1.00 to 0.96 m^3 and in pulp and paper products from 45 to 42 kg. Forest land selected for production must be capable of producing repeated crops of trees of good form and growth where topography and access facilitate harvesting and marketing. The forest area required to meet increasing demand may be only a small portion of the total forest area but must increase over time or be made increasingly productive, or both. At the very least, forest land dedicated to wood production should be adequate to meet projected future needs based on the productivity that can be expected from forseeably intensive management.

In selecting land for wood production, practical limits of productivity must be recognized. For example, in Bolivia, the best mahogany forests are in the lowlands, but these areas are also clearly suitable for agriculture and

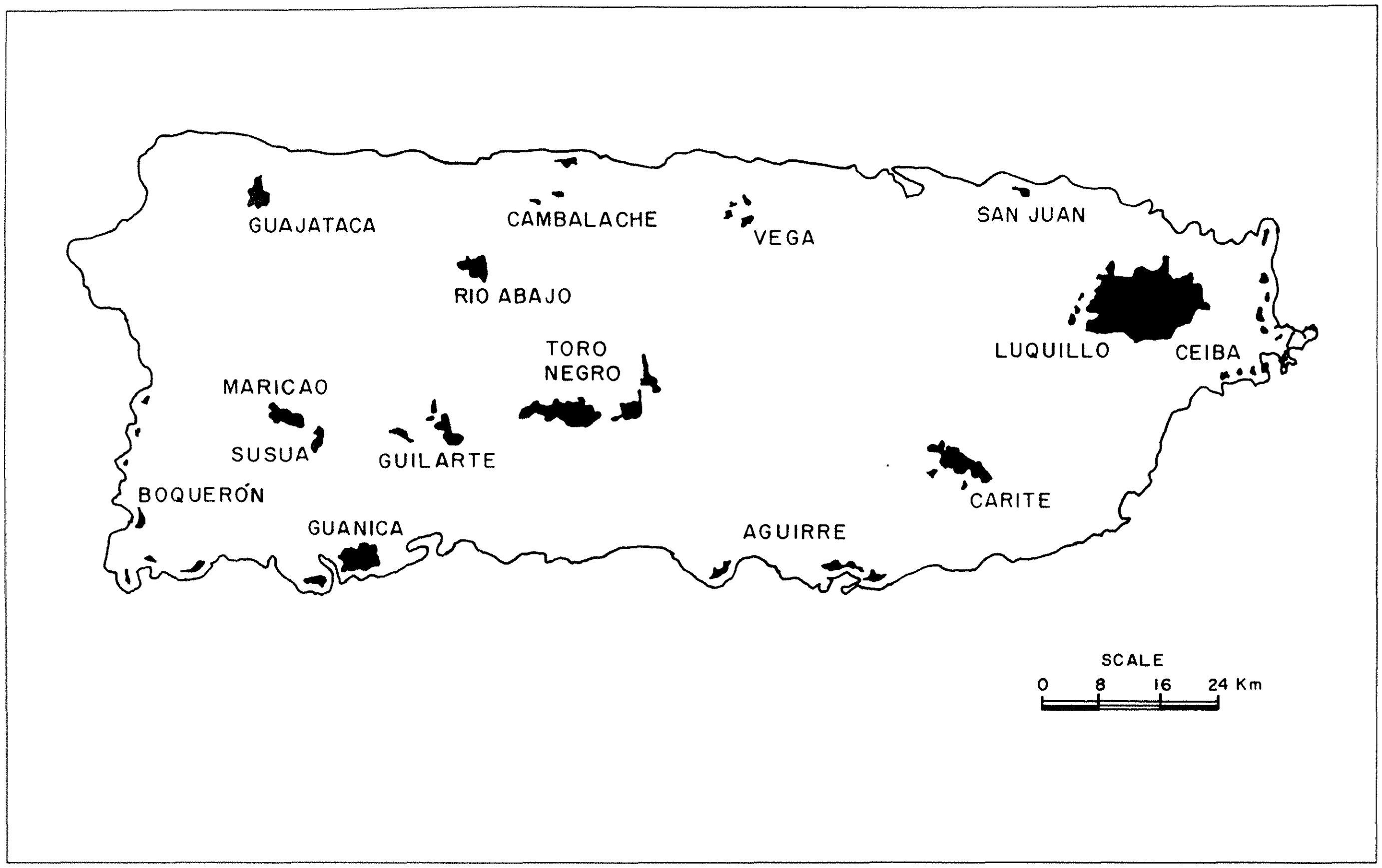


Figure 2–17.—*The public forest reserve system of Puerto Rico, representing diverse climates, soils, and ecosystems.*

possibly best used for that purpose (Scott 1961). At the other extreme, Brazil's dry forest land, the so-called "campos cerrados," considered by Beard (1953) to be a result of extremes of flooding and dryness on impoverished senile Latosols, shows evidence of water 2 to 3 m below the surface (Denevan 1965, Ferri 1961, Rawitscher 1950, Young 1976). Barring fire, it may thus be possible to establish forests there. Their potential timber productivity would of course need study.

Intermediate examples are the various soil conditions of the Amazon. Dubois (1971) recommended that the mangroves be used to produce tannin; the tidal varzea be used for timber, palm oil, rubber, and cocoa; the seasonal varzea for timber and forage; and the shallow soil *facies* of *igapó* (long-term flooded forest) for timber. On terra firme, Dubois proposed a combination of timber, perennial food crops, pasture, and shifting cultivation. Crops such as Brazil nuts would be grown in addition.

The production of forest commodities, because it calls for modifying the forest, may conflict with the preservation of biodiversity and public recreation. However, properly integrated, it should be compatible with forest-dependent cultures and soil and water conservation.

Integration of Forest Uses. Assessing the optimum potential benefits of tropical forests may appear futile in view of the social difficulties inherent in halting further uncontrolled felling of state-owned forests for shifting cultivation and other forms of agriculture. Only rational goals should guide land-use planning. So planning must expose the nature and magnitude of any sacrifices of forest area that may have to be made to accommodate important (or inevitable) nonforest land uses, as well as those inherent in shifts among forest uses.

Because no land area can produce all the desired benefits, the role of individual forests must be determined by

Figure 2–18.—*Enjoyable forest recreation can be provided with simple facilities at natural beauty spots such as in this forest in Puerto Rico.*

Table 2–6.—Indicative wood consumption in tropical America, 1992

	Wood product consumption	
Region	Wood products (million m³)	Pulp, paper, and paperboard (million tonnes)
Mexico	23.1	4.3
Central America	31.2	.6
Caribbean	11.9	.6
Tropical South America	315.2	10.8
Total	**381.4**	**16.3**

Source: Anon. 1993a.

Note: Consumption is derived by adding imports to production and subtracting exports.

compromises. Each possible use yields different benefits accruing over different periods, and many forest benefits are difficult to quantify economically. One axiom is to assign a high value to those that are unique or require forests and, that once modified, would never again serve their original purpose. These areas in most need of total protection from destructive outside influences (tribal lands, virgin ecosystems, and areas with rare species) may not be those that promise highest immediate economic returns.

The incompatibility of different forest uses suggests that no one benefit would be maximized, even on those areas where it seems most appropriate. For example, forest production may have to be less than maximized to preserve soil, water quality, and animal habitats.

Production Policies

The primary productivity, biodiversity, and long-term stability of natural ecosystems may be unexpectedly compromised by human intervention. How this can be accommodated without permanent loss of these values is a major ecological challenge (Farnworth and Golley 1973). The complexity of this issue must not be lost on the forestry profession. Meyer and others (1961) concluded many years ago that in few other fields of resource management are goals as difficult to achieve, or the problems as complex, or efforts as far reaching as in the management of forests. The fundamental reason for human intervention in forest production is that nature requires too long a time to produce certain values useful to humans.

Laurie (1962) referred to the great homage that has been paid to *biocenosis,* the biological balance and harmony that exist in natural forests but that are not ideal for producing useful forest products. Proper silviculture is seen as a compromise between a close following of nature and adherence to short-term economic considerations (Smith 1962). A managed forest composed mainly of useful tree species may be widely different from the climax association; yet, it may be more vigorous, more productive, and safer from injury (Smith 1962).

Treatments to immediately increase yields, such as regulating stand composition, stand structure, or density, reduce the degree to which forests utilize sites (Spurr 1961). But treatments that affect site productivity or a stand's genetic potential are effective only over long periods.

Balanced production of both economic and cultural forest values calls for finesse in underdeveloped areas because of the perceived desperate need for early financial returns. Two opposite approaches to integrating these goals have been proposed (Dawkins 1964b). One is to manage commercial forests for their other values also. The other approach is to develop wood production in forests that must be preserved primarily for noncommodity values.

Policies must reflect the broad scope of forest production needed in the Tropics. One policy concerns the relative emphasis placed on forest products and services. It may seem desirable to produce as much of the local timber requirement as possible to minimize importation costs. However, there is generally also a need to preserve representative ecosystems, natural wildlife habitats, or scenic forests for recreation and tourism, goals not fully compatible with maximum timber production. The solution, eventual if not immediate, does not lie in geographic separation of forest uses but in their integration. The proper balance means some degree of compromise, depending upon the extent of forest land available. No general rule applies; rather, each country's needs must be considered independently.

A second policy concerns the degree to which forest production is to serve domestic or foreign markets. The apparent advantages of supplying the local market may be partly offset by opportunities to export fine timbers offering greater net return. On the other hand, for national security reasons, heavy dependence on trade for both sources and markets may be precarious; therefore, the optimum solution here may be a political decision in which economic returns are but one factor.

A third policy concerns the relative emphasis on public or private forest production. In most countries of the region, the forests have largely passed from public to private ownership; the government serves mainly as a stimulus to private production. On land marginal for farming, the direct returns from wood crops and related employment, once technology has been developed, may also prove financially attractive. But the public has a stake in other forest values, whether or not visibly economic, such as soil rehabilitation and biodiversity. Any remaining publicly owned forest area, however small, may be invaluable as a reserve for social ends that do not interest private landowners and for demonstrations of diversified forest management for these same landowners.

A fourth policy concerns the degree to which multiple uses can (or must) be made of tropical forests. It is impossible to manage a forest for any one of its values without contributing to or detracting from some others. Yet, there may be a big advantage of managing for integrated uses over managing for one economic goal even at some financial cost. The former approach is most attractive for public forest owners; the latter is appropriate for private forests.

A fifth policy concerns trends in yields. A basic tenet of forest management is stability of yields. If current yields are below their potential, it may be possible to increase them to help provide future local timber requirements or nationally important exports. However, any future production goals should not exceed sustainable levels. Harvesting beyond a sustainable rate is justifiable only in time of emergency or some imminent catastrophe that endangers the crop. Normally, removals during the first cycle, even when a large overburden of overmature trees is harvested, should not exceed the expected sustainable yield.

The arguments for setting a sustainable yield as a maximum are legion. Present trends in the rate of product removals from tropical forests show no signs of decline. Failure to ensure prospective yields now can cause far greater future shortages than any sacrifice in present consumption. Sustained yield has been criticized as vague, but it is not. What may be vague is available information to predict yield levels. Maximizing the present worth of all future net forest benefits may appear a sound basis for predicting sustainable yields, but this requires fully assessing intangible forest values and the social and economic impacts of even-flow, variable, or declining yields (Pant 1977). These values are so uncertain that a yield goal may have to be set arbitrarily at some point thought optimum. However imprecisely derived, the concept of sustained yield remains fundamental to forest management. If removals are increased, the sustainability of the increased level must be ensured.

The concept of sustained yields is nevertheless repeatedly challenged as a goal where secondary forests are not equal in quality to primary forests. Although secondary forests may yield the same quantity of products as did the primary forest, they may not yield the same quality. Moreover, with most other human aspirations in the Tropics so short term, sacrificing present consumption of tree crops to sustain distant future yields has been challenged as blatantly opposed to the realities of the developing world (Leslie 1977). However, such "realities" themselves seem out of synchrony with the future. Thus, despite a continuing decline in forest area, sustained yields must be a goal of forest production. Sustained yields are indeed the very foundation of forestry (Gentle 1987).

The principle of sustainability must not dogmatically cling to the size and composition of the original timber crops. Management must seek high yields of those products most needed in the future, not the present, including smaller trees and species not now used. Both of these changes are legitimate components of sustained future productivity.

Forest Protection. Forest production begins with the protection of existing forests. Protection does not necessarily mean preventing use of or modifying the forests. Indeed, the word "conservation" has been defined as "wise use" (Leopold 1933). Some forests, as already noted, are on land that might be better used for other purposes. Nevertheless, all forests, by their mere presence, yield some benefits. They may be the best and least expensive custodians of the land. Unless there is clearly a better, sustainable, land-use alternative, rational argument favors protecting and conserving existing forests.

Protecting forests means more than simply preventing their destruction. Most forest values are systemic, the contributions of countless organisms interacting to utilize and store up energy and nutrients that would otherwise be lost. Protection, then, means safeguarding this process even in forests in no immediate threat of removal. Harvesting the best specimens of one or more species of plants or animals can severely affect the remaining ecosystem. Adding solid, liquid, or gaseous wastes from human activities can also place forests under stress. Examples are disposal of raw sewage into swamp forests and the emission of vehicular exhaust into forests along major highways.

The precise level of protection necessary is uncertain because the requirements and resources of forests are incompletely known and probably are assessed only superficially. The diverse utility of plant resources in tropical forests is indicated by the number of species used for different purposes by peoples who have lived for centuries in the forest environment. In northwest Amazonia alone, some 1,600 medicinal and hallucinogenic plants have been found (Schultes and Raffauf 1990). Another 798 medicinal plants are described for the Caribbean region (Liogier 1990).

Other forest products include latexes, gums, fruits, nuts, canes, and honey. These have been extracted chiefly from natural forests and have received only minor attention in forest productivity efforts. Some oleoresins, such as "elemi" from *Amyris, Canarium,* and *Proteum,* are used in the manufacture of varnish and paints, plastics, and printing ink (Tongacan 1972). Gutta-percha latex from *Palaquium* and balata gum from *Manilkara* are nonelastic, decay-resistant rubbers widely used for insulating subterranean or submarine cables (Tongacan 1971). Chicle, also from *Manilkara,* an ingredient of chewing gum, has been legally protected in the forests of southern Mexico. Tannins, formerly from mangroves, have been produced intensively in plantations of *Acacia* and *Albizia* (Tongacan 1973). Rattan comes from several species of *Calamus,* mostly vinelike members of native forests (fig. 2–19). They have been propagated in India on a 15-year rotation (Ordinario 1973). The harvest of Brazil nuts is of sufficient economic importance in Brazil to merit a national law prohibiting the felling of mature trees. The value of honey and beeswax from native forests in Tanzania has been sufficient to justify preservation of large woodland areas (Tesha 1968).

A partial list of products other than wood from the forest plants of India appears in table 2–7 (Krishna Murthy 1967, 1974).

Human society will certainly want more (rather than less) forest product diversity in the future. Preservation of that diversity at its source calls for perpetual protection of representative forests as storehouses of undiscovered knowledge.

Protection involves patrolling to monitor and prevent misuse of forests. A far larger but more rewarding task is to mold public opinion to support rather than resist forest protection. This calls for a continuous broad-scale effort,

Figure 2–19.—*Several varieties of rattan come from lianas in the tropical forests of the Asia-Pacific region.*

Table 2–7.—Nontimber products derived from forests in India

Product	No. of forest species[a]	Product	No. of forest species[a]
Medicinal	1,800	Cellulose	44
Human food	280	Cover crops	26
Dyes	112	Fish poisons, pesticides	24
Fibers	100	Beverages	16
Tannin	78	Beads	13
Fatty oils	75	Green manure	11
Fodder	75	Saponins	10
Gums and resins	75	Latex	3
Baskets and canes	60	Other	>100
Essential oils	44		

Source: Krishna Murthy 1967, 1974.

[a]Number of different species used for each purpose.

using all available media to convince urban people especially that forests are beneficial not only for the production of commodities but for many other purposes.

The same degree of protection afforded existing forests may be justified on unforested forest land. Adequately protected, most such land can be expected to return to forests, some with no investment other than protection. And these new forests can control erosion, restore rainwater infiltration, store nutrients, and develop systemic benefits. Protection is needed primarily against fire and grazing and, as the trees reach usable size, against excessive removals for fuel or forage.

The Convention on International Trade in Endangered Species has classified a number of plant and animal species to be restrained from international trade except where sustainability is not jeopardized. Currently listed tree species from tropical America are: *Abies guatemalensis, Balmea stormiae, Caryocar costaricense, Dalbergia nigra, Guaiacum officinale, G. sanctum, Oreomunnea pterocarpa, Platymiscium pleiostachyum, Podocarpus parlatorei, Swietenia humilis,* and *S. mahagoni.*

Selection of Products. The products or benefits desired from forests are critical to their management. Forest production encompasses the whole realm of benefits, including such intangibles as public appreciation of recreational and educational opportunities provided by forests. Enlightened forest production must take these intangibles into account, for ultimately it depends upon, affects, and is affected by them. Forests managed as a source of ecological information may need only protection and access for research. Forests managed for rare species may be given intensive protection and made accessible for studies that could help preserve the species. Forests used for public education or recreation require safe public access, facilities to provide needed services, inventories or monitoring to quantify what is being demonstrated, and trained personnel to ensure proper and effective use of the areas.

The production of wildlife may not become a sole objective of forest management in many parts of tropical America. However, management generally should ensure the welfare of the ecosystem's wildlife. All forms of animal life perform significant, sometimes critical, roles in the forest ecosystem, still far from fully understood, (e.g., in pollination, seed dispersal, decomposition, and maintaining soil quality). Forests harbor many species of animals that would disappear unless necessary forest conditions persist.

All forests are significant to soil and water conservation. Forests can give maximum protection to the soil and capture a maximum amount of rainwater, from which they can extract a maximum of energy before they release the water that passes through them (Hoover 1962). These attributes dictate a policy of leaving some natural forests without unnecessary disturbance. In forests where commodities are to be produced, the importance of watershed protection should generally be fundamental to cultural and harvesting practices.

The most common direct use of the forest is for wood and its derivatives. In the Tropics, consumption of wood for fuel ranks first, followed by the rapidly growing use of fiber products such as paperboard and paper. Other high-use industrial wood products include utility poles and piling, construction lumber, plywood and veneers, furniture and cabinet woods, and specialty woods for novelties such as turnery items and matches.

One woody material not yet fully utilized in tropical America is bamboo. In the Philippines, bamboo has been used for house construction, carts, trellises, outriggers, scaffolding, agricultural implements, hats, baskets, rope, fish traps, matting, furniture, and paper (Fernandez 1951). Bamboo has also been used for paper in Cambodia, India, Indonesia, Pakistan, and Thailand (Doat 1967).

Forests provide fuelwood for most of the world's population. In 1992, some 1.51 billion m^3 of wood was removed from the world's forests for fuel including charcoal (Anon. 1993b). The demand in the Eastern Hemisphere is so great that plantations of *Albizia lebbek, Bauhinia variegata, Dalbergia sissoo,* and *Prosopis juliflora* have been maintained at great public expense to provide fuelwood (Misra 1960, Singh 1951). There is a long history of forest fuel production in tropical Asia, where only about 0.03 ha of forest per capita remains (Anon. 1993b).

Fuelwood is also heavily used in tropical America, particularly where the population is concentrated in dry climates. Moreover, some of the region's most extensive and best-managed plantations are those of *Eucalyptus* grown for Brazil's steel industry. Because of the rising price of imported petroleum, the potential fuel yields of Brazil's *Eucalyptus* plantations were calculated (Anon. 1979c). On a 5-year rotation, an annual yield of 12,500 t of wood per 1,000 ha is expected. This amount of wood, in turn, could yield 2.3 to 2.5 million L of ethanol, 1 to 1.8 thousand t of high-quality metallurgical coke, 2,000 t of animal feed, and 1.4 million kg of carbon dioxide.

From this calculation, it was concluded that 2 million ha of *Eucalyptus* planted in 1979 would provide enough ethanol to replace 19 percent of the country's projected petroleum consumption in 1984 (Anon. 1979e). *Eucalyptus* plantations in South Africa have been found to convert about 0.5 percent of solar energy into useful fuel (Grut 1975).

Energy requirements in the region point to increasing demands for fuelwood production. The world's total supply of energy was estimated in 1976 at 27.7 billion joules (Burley 1980c). Wood then supplied only about 1 percent of this energy (Earl 1975) but 66 percent of the fuel consumed in Africa (Burley 1980c), 29 percent in Asia, and 20 percent in tropical America.

Fuelwood supplies, limited naturally in dry forest areas, have become locally critical in almost every tropical American country. Many areas of the region are fuelwood deficient, some of them suffering acute scarcity.

Where other, more efficient, fuels are available, wood and charcoal are less frequently used. Per unit of weight, air-dry wood has less than half the caloric value of fuel oil and only two-thirds that of coal. The corresponding percentages for charcoal are 72 and 103 percent (Earl 1975). Nevertheless, in the Tropics, wood tends to be the most economical fuel because its cost is chiefly human labor. Thus, fuelwood's place in future forest production in the Tropics seems assured. Alternative fuels are rising in price more rapidly than fuelwood and generally must be imported.

Wood-energy goals involve wood quality as well as quantity. Wood's caloric value increases with its density (a correlation of +0.99 for each calorie per cubic centimeter) (Doat 1977). Extreme values found with Suriname woods were 1,940 cal/cm^3 for *Cecropia surinamensis,* which has a specific gravity of 0.42, and 5,000 cal/cm^3 for *Tabebuia serratifolia,* which has a specific gravity of 1.04 (Doat 1977).

Wood moisture content is critical to the net heat available from wood, because driving off moisture consumes heat. The net heat yield of wood with 60 percent moisture content is about a third less than that of wood with 20 percent moisture content (Murphy and others 1981). Therefore, use of green wood might nullify possible benefits from silvicultural stimulation of forest growth (table 2–8; Anon. 1980g).

Moist tropical forests may contain the heat energy equivalent of more than 50,000 L of fuel oil on 1 ha (Catinot 1974). *Eucalyptus* plantations in Brazil yielding 30 to 40 m^3/ha/yr produce an energy equivalent of 5,000 to 5,500 L of fuel oil per hectare per year.

Table 2–8.—Effects of moisture content on the heat value of wood

Moisture content[a] (%)	Heat value (kcal/m^3)	Loss due to moisture (%)
0	4,670	0
20	3,780	19
40	3,160	32
60	2,710	42
80	2,380	49
100	2,070	56

Source: Anon. 1980g.

[a] Based on dry weight.

Earl (1975) made a good case for setting national production goals for fuelwood plantations in the Tropics. He points out that where low income and meager fuel supplies prevail, financial returns from fuelwood plantations may be submarginal, but the social benefits are often very high. Because the social cost of underemployed labor may be much lower than the wages the forest authority must pay, wages are in effect a subsidy to the labor force. Producing fuelwood is labor intensive, and the wages paid to the rural sector have a ripple effect locally.

Wood's value as a fuel substitute is graphically illustrated in densely populated India, where cow dung is burned for fuel. Cow dung has a fertility value more than double its value as a direct source of heat, but it is nevertheless burned (knowingly to the detriment of the soil) because of a lack of fuelwood (Sagreiya and Venkataramany 1962). It was estimated by Foot (1968a) that replacing cow dung with wood fuel in India would require an increase in wood production of 3.4 million m^3 annually.

Sources for fuelwood depend partly on the presence of other forest industries. Where sawtimber and pulpwood are both in demand, chips for heating may sell at only 10 percent as much as an equal volume of sawtimber or 35 percent as much as pulpwood. Thus, fuel can compete for only the wood fraction not acceptable for these other uses (Murphy and others 1981). However, the industries serving these other wood outlets create low-cost residues both in the forest and from processing that may equal 50 to 70 percent of the volume of the trees felled. Therefore, statements about the economic feasibility of producing energy from wood are seldom widely applicable. Case-by-case analysis is necessary. Price changes for fossil fuels call for periodic reevaluation of the potential energy production from forests.

Next to fuelwood, the most widely used solid-wood product in the Tropics may be fenceposts. Where dairy and beef cattle are important, establishing fencepost production goals is wise. Where there is a good post market, plantations may be closely spaced to allow a large volume of posts from thinnings. Receipts from the sale of posts may assist in amortizing plantation investments. There is some advantage and need for live fenceposts, tree species that sprout readily or can become permanent supports for fencewire. But such trees generally serve only in certain fences, so the market for cut posts will persist.

The presence in tropical forests of cabinet woods of a quality rare in the Temperate Zone has led to large-scale exportation of such timbers. Because high-quality cabinet wood comes from wide boards from large-diameter logs or from veneer peeled from large logs, past silvicultural treatments have been directed toward the production of large trees. Management has aimed at spreading the harvest of primary forests over a period long enough to permit maturation of residual adolescents or a new tree crop. Growth data revealed that rotations up to 80 years would be required to produce the trees 90 to 120 cm in d.b.h. that the importers have come to expect. The famous teak plantations at Nilambur, India, have been managed on an 80-year rotation. Wyatt-Smith (1959) predicted a 70-year rotation for his Malayan uniform system. The management plan for the natural forests of Uganda also used 70 years (Dawkins 1958g).

The fact that there were only a few large trees in mixed forests that were marketable led to the question of what to do with the 90 to 95 percent of the standing volume for which there was then no market. With improved access, rising population, and more information about little-used woods, markets are appearing for many more tropical timbers. In some places, local markets exist for fiber from 90 percent of the tree species of the forests (Frisk 1979). The properties and potential uses of hundreds of tropical American woods have been studied (Berni and others 1979, Chudnoff 1984, Mainieri and others 1983). This knowledge has opened up opportunities to utilize more of the natural stands, accept more options as satisfactory regeneration, shorten rotations, and extract intermediate harvests. Particularly significant to this change has been the growth of the market for cellulose. The wood of rapidly growing genera such as *Eucalyptus* and *Pinus* is suitable for this market.

In considering short rotations, Baskerville (1966) warned that foresters must not assume that loggers will harvest the maximum volume the plantation can produce. He pointed out that all known wood manufacturing processes are linear; small trees cannot be handled as cheaply per unit of volume as large ones. Profitability is thus directly sensitive to tree size.

A special objective of tropical forest production has been to satisfy wood requirements of rural villages, a practice that began in India in 1873 (Kapoor 1961) to eliminate the use of dung for fuel. Areas have been selected for village forests where fuelwood shortages are acute and prospects for cooperation are good. Badly eroded areas and existing forests are protected from grazing, and fire and gaps are planted. Other idle land, such as roadsides, canal banks, and field boundaries, has also been put to use (Kapoor 1961). Even shade trees and garden plantings are included. Village forests usually have been 20 ha or more in area. Tree species planted include *Prosopis* spp., *Casuarina* spp., and *Dalbergia sissoo* (Kaul and Maun 1977). The success of such ventures requires winning the cooperation and participation of the local leaders (Phillips 1961).

Predictable trends in the market for forest products and the social need for forest benefits should determine national goals for the size and types of forests required. Lamb (1968c) saw a need for production goals directly related to prospective demands, including exports. He points out that tropical high forests are a source of valuable timbers that can be produced nowhere else in the world. Supplies are seriously depleted. Population pressures make it desirable in many countries to produce useful timber from every available and suitable hectare. Consumption of tropical wood is trending away from species-sensitive products toward mass processing. Nevertheless, the outstanding beauty and decorative value of tropical woods may well continue the demand for specialized tropical wood products (Erfurth 1976).

Production Goals. Forest production, as a long-term commitment, requires defining long-term goals. These may be diverse and widely separated in time. Goal setting involves some factors only indirectly related to the forests. Social, economic, and silvicultural considerations must be integrated. Until goals have been defined, no large-scale forest production venture, public or private, can be wisely directed.

The presence or absence of forest cover has in the past determined the fate of traditional societies (Sartorius and Henle 1968). The ills that beset tropical peoples are due less to any "insufficiencies" of nature than to the misdirection of society. The potential exists to ameliorate tropical deforestation and its consequences through changes that society wants. To accomplish this, forest planning must focus on goals that are broad in scope (King 1968b).

As seen by Miller (1975), forestry in 1975 stood at the threshold of an opportunity to participate in major global efforts to achieve sustainable use of living natural resources. Initiatives identified for this purpose included ensuring the protection of species and forest areas, determining conservation strategies, implementing practices that serve the needs of the rural population, and restoring depleted land.

Conservation requires legalized forest protection, but that is not enough. In South America, legally established parks and nature reserves were estimated to include 489,000 km^2, nearly three times the area so reserved in the United States (Mares 1986). Yet, it is common knowledge that much of this area is neither productive nor indeed adequately protected. *Management* is as necessary to the production of forests as is legal protection.

Forest-production goals should be coordinated globally, since the ultimate social and economic self-interest of all nations is inevitably merged with all others. Within each country, forest production must be coordinated within the context of the local economy, considering population, land, food, other resources, and traditions. The interaction of these factors will decide national goals for forest production.

The social as well as economic values of forest production are generally underestimated in national planning. The share of the gross domestic product of a country credited to timber (usually well below 10 percent) is grossly unrealistic (Sartorius and Henle 1968). Timber production and processing are multifaceted enterprises, requiring many employees and affecting related industries. Thus, investments in timber production and processing have a greater influence on the economy than is usually reflected in statistics.

Nor is the potential significance of timber production to the balance of payments of developing nations fully recognized. Developing countries suffer from trade deficits that may be exacerbated by shipping charges attributable to the use of foreign vessels. Moreover, development may be crippled by diverting foreign earnings into imports of forest products that could be produced locally. Imports are recurring expenses, whereas investment in processing of local raw materials, even if greater at the outset, may be a onetime cost. Probably no product offers a greater opportunity for domestic investment leading to a healthier national balance of payments than does locally produced timber.

Traditional comparisons of costs and benefits tend to undervalue forest production because rates for discounting over long periods are unreliable and because indirect forest benefits cannot be expressed in monetary terms. In assessing the value of forest investments, opportunities for employment and earnings must also be credited.

In developing nations, the forest economy must fulfill more extensive functions than elsewhere. Among these is maximum employment of masses of rural people at their skill level. The most desirable industry in developing countries would generate jobs quickly and use local raw materials to make products for local consumption. Employment may be more important than productivity of goods and services. Silviculture and forest regeneration normally require large amounts of manual as well as skilled labor, and they pay off by increasing or improving forest capital, the growing stock.

Production goals are also affected by the amount of the tree that is usable. This may depend upon the minimum diameter that can be utilized and the width of the useful heartwood and less useful sapwood. These considerations also affect selection of species, rotations, and pruning and thinning regimes.

Another source of diversity in forests is genetic. A wide range of genetic potential exists. Genetic manipulation can produce trees with characteristics not found in nature. Genetic modifications may result in trees that can thrive on sites now considered marginal, thus allowing an increase in productive forest area. To conserve these options, different natural genotypes of native tree populations must be preserved.

Solid-wood processing, unlike other raw-material processing, does not require complicated, expensive machinery. Because the raw material for wood processing is bulky and heavy, there is an incentive to locate industries in rural areas near forests where economic development is most needed. For products such as lumber, veneer, and particleboard, small production units that require little capital and managerial ability and take advantage of traditional skills can operate profitably. The raw-material and employment values of forest products are relatively high. For sawmill products, raw material may make up 50 to 75 percent of total production cost. Milling may employ 10 to 15 hours of labor per m^3. Plywood manufacture may employ 10 to 20 hours of labor per t and does not require high-quality woods, fresh water, or large power supplies. Moreover, forest production focused on goals for projects such as these can easily be redirected should products less demanding as to tree size and species come to the forefront in the future.

Employment is so important to developing countries that it may be better to discount competitiveness among alternatives and emphasize productivity as a forestry goal (Sartorius and Henle 1968). Competitive approaches to the opening of local resources and satisfaction of local demands may not overcome employment stagnation, but rather a need for mass employment may transcend all considerations of direct economic returns. The multiplier effect of operations connected with industrial wood processing varies from 4 to 17 (Svanqvist 1976).

Less mechanization may be desirable in the Tropics than in developed countries because mechanization usually depends on imported machinery and specialized training (Sartorius and Henle 1968). Sociological (as well as technical and economic) factors must help decide the most appropriate degree of mechanization.

Timber production and resultant local industrial development, great as their contributions may be, are inadequate social goals for tropical forestry. Forest industries in developing countries must have public support, sound planning, and adequate safeguards, and governmental forestry agencies with broad social goals and regulatory power must be developed. The alternative is haphazard mobilization in uncontrolled directions while weak forestry agencies stand helplessly by.

Silviculture. To date, tropical forests have been managed chiefly for the production of wood rather than for other products or benefits. Silviculture, including the stimulation of productivity of secondary forests and regeneration, is treated in greater detail in later chapters, but its place in forest production is reviewed here.

The culture of tropical forests originated in the practices of early tribes, records of which are not available. It seems certain that the Mayan Empire in Central America, a region of seasonally deciduous forests, must have had its policies regarding the culture of forests just as it had policies for farming. Silviculture as we know it, on the other hand, was first brought from the Temperate Zone to the Tropics in the Eastern Hemisphere in 1855 (Parker 1923).

Silviculture has always been allied with forest ecology. Foresters have helped identify forest trees and forest types and have studied their responses to site and stand conditions, both natural and imposed. If ecology was the approach, silviculture was the application by foresters. All successful foresters, from conservators who direct forestry programs to guards that patrol the forests, may be termed practicing ecologists. Most have made no record of the accumulated wisdom of their personal observations. Outstanding sources of pertinent literature include Foxworthy (1909), Watson (1928), and Wyatt-Smith (1961a) for Malaysia; van Steenis (1958) for Indonesia; Troup (1921) and Champion and Trevor (1938) for India; Aubreville (1948) for west Africa; and Beard (1944b), Holdridge (1947), Schulz (1960), Hueck (1972), de Graff (1986), and Lamprecht (1989) for tropical America. Champion and Trevor's (1938) manual of silviculture is still a unique source of ecological information about the forests of India. Forestry itself has long been termed "applied ecology" in India (Seth 1955). Almost all technical forest production information has consisted of recorded responses of trees to their environment and interpretation of those responses in terms of marketable productivity. An early manual of silviculture for the forest types of the Western Hemisphere (Fors y Reyes 1947) for the Pozos Dulces Forest School in Cuba began with forest ecology as a basis for recommended practices. For each published report, there were undoubtedly many additional conclusions reached by unsung native field personnel intimately familiar with the components and behavior of their forests.

Although forest managers may have been among the original environmentalists (Ghosh 1975), growing public sensitivity to all tampering with the natural environment has brought forest management under closer public scrutiny. Traditional forest management has included differential treatment of species, intervention into irreplaceable primary forests, clear cutting in publicly visible areas, establishment of pure plantations, introduction of exotic tree species, use of fire for hazard reduction, and use of herbicides and pesticides (Ovington 1974). Although all these practices can enhance timber production and may be acceptable under certain circumstances, none of them is publicly accepted everywhere nowadays. Managers must minimize adverse ecological impacts in preliminary planning and discuss proposals with the public in layman's terms. Otherwise, public criticism, rational and/or emotional, can be expected.

Forestry is sometimes incorrectly presented as purely exploitative, its practitioners obsessed with maximizing wood yield while merely paying lip service to safeguarding other forest values. Some appropriate forestry practices in regulating wild forests are indeed a form of conversion. But their merits have not been adequately justified before the public.

The silvicultural aspects of management go further than the application of ecological knowledge. The amount of energy fixed annually by tropical forests may be large, but it is only by applying sound silvicultural principles and practices that wood production can prosper in quantity and quality. Those responsible for developing forest crops from "seed to sawtimber" must be generalists rather than specialists. But they must also freely use the expertise of specialists in getting maximum benefits from the forest (Singh 1960). While managing the current tree crop, they must also explore the potential of increased productivity through genetic improvement.

A final aspect of forest production is direct service to agriculture, including the use of forests and trees for fodder, shelterbelts and windbreaks, and crop shade, or the utilization of swamps. Fodder production in forests has been undertaken mostly in dry areas of the Eastern Hemisphere, often in conjunction with fuel production. Both the foliage and the pods of species such as *Prosopis juliflora* are eaten by cattle (Singh 1951), whereas just the foliage of *Leucaena leucocephala* is eaten. Other fodder species that have been used in India include *Acacia arabica, Azadirachta indica, Bauhinia variegata,* and *Zizyphus jujuba* (Chaturvedi 1948).

As windbreaks, trees protect crops and thus increase harvests. For example, in Ecuador, cornfields shielded by forests reportedly increased the yield 20 percent over that of unprotected fields (Anon. 1955b). Genera used there include *Cupressus* and *Pinus.* In Peru, *Eucalyptus globulus* is commonly used as a windbreak. Species of *Erythrina* and *Inga* are widely used to provide shade in coffee plantations in Costa Rica, El Salvador, Puerto Rico, Suriname, Trinidad, and Venezuela. *Cordia alliodora* is also used in Colombia and Costa Rica. In Uganda, where swamp drainage for mosquito control is desirable but costly, plantings of *Eucalyptus* and *Senna siamea* have proved effective (Dale 1943).

Examples of Forestry Diversity. The possibilities of forest production are as diverse as the forest conditions and human needs of the Tropics. The forests themselves, as has been seen, are diverse, ranging from dense rain forests to dry scrubs and savannas. The poorest natural forests are likely to be most deserving of attention because of their role in land stability and possibly as a sole fuelwood source. Such forests have usually been further diversified by human intervention, leading to an array of successional secondary forests, differing in character, productivity, and utility.

The extent of a nation's forests itself influences production objectives. Extensive forests call for management intensities different from small forests. For example, extensive secondary forests may best be managed on a basis of natural regeneration with low input/output, providing geographically diffuse rural employment. Where native forests are less extensive, plantations may be needed for high yields per unit of forest area (Earl 1975).

The diverse structure of natural forests may also influence production. Stands may be classified as positive, neutral, or negative depending on how the number of various tree sizes relates to the de Liocourt curve (Sammi 1961) (a constant logarithmic increase in tree numbers from the largest to the smallest classes). Positive stands have an excess of small trees of merchantable species regenerating naturally. Negative stands do not; so, for them, not only must methods to ensure regeneration be devised, but goals in terms of products and yields may have to be adjusted accordingly. An example is a forest rich in *Virola* but with few or no small trees of this species. Unless regeneration of this species can be induced silviculturally, different species, possibly less useful, may be favored by merely harvesting mature *Virola.*

Local variation in the capacity of forest sites to produce different tree species, sustain rapid growth, and yield merchantable trees also affects production goals. For teak in tropical America, for example, different sites produce, at age 30, trees ranging in height from 13 to 30 m and having a mean annual growth ranging from 1 to 11 m^3/ha (Keogh 1979). The advantages of the better sites are obvious.

Environmental extremes, such as hurricane frequency or periods of high fire risk, may influence rotation lengths, tree species, stand densities, and silvicultural practices (Gane 1970).

Finally, where increasing employment is a national priority, the type of forest produced can be critical. According to one estimate, the maximum employment from naturally regenerated forests is about 1 employee for 100 to 125 ha (Svanqvist 1976). Short-rotation plantations, in contrast, can employ 1 person per 15 to 20 ha. Mixed food and long-rotation tree crops may employ 1 person per 7 to 18 ha, but with most of the labor attributable to the agricultural crop.

Experience in Malaysia has shown that forestry can attain diverse goals of national significance (Wyatt-Smith and Vincent 1962b). Among these are the safeguarding of water supplies, the prevention of erosion and flooding of agricultural land, and the supply, in perpetuity, of all forms of forest products that can economically be produced within the country and will be required for agricultural, domestic, and industrial purposes.

In South Africa, extreme measures have been necessary because large areas of the country are treeless (Anon. 1966a). Tree species suitable for timber markets have had to be introduced as well as ways of growing them at a profit. And, finally, plantation timber has had to be converted into products that compete with imports.

In Trinidad, an analysis of forest-production potential revealed some impressive possibilities for future employment (Gane 1969). Expanding tropical shelterwood treatment from 160 to 200 ha/yr could double gainful employment from forests and their products in 60 years. Increasing the planting of pine and teak from 280 to 320 ha/yr would result in even greater gains. Employment in teak production and processing would be double that in shelterwood, and employment in pine would surpass shelterwood sevenfold.

In Uganda, analysis of national wood requirements clarified goals for forestry (Dawkins 1958e). Because more wood would be needed in the future and importation was not an economical option, local production was imperative. However, plantations had proved so expensive that, no matter how productive they might become, their establishment was likely to be slow. Accordingly, the extensive natural forests were considered the primary timber source. Forestry objectives were as follows (Dawkins 1958e):

- Two percent of the forest was to be set aside to preserve its natural development
- Amenities, agriculture, and water supplies were to be protected by forests
- Wood production was to conform to protection needs and not be undertaken where preservation of nature was a goal
- Wood production was to be sufficient for the diverse needs of the country's inhabitants
- Emphasis was to be on timber for buildings and furniture, woods that were strong, easy to work, and preferably permeable
- Production efficiency was to be maximized.

The goals of forestry in tropical America must be multidimensional and highly diverse. The important thing to recognize is the imperative need for goals that are (1) firmly established and stable, (2) technologically sound, (3) socially acceptable, and (4) subject to the selection, preparation, execution, and evaluation of forestry projects and activities.

Chapter 3
Primary Forests and Their Productivity

Primary forests are those that have existed without significant human or other disturbances for longer than the lifespan of mature trees (60 to 80 years is used by FAO) (Anon. 1982c). In such relatively stable forests, functional relationships evolve that display preferences, tolerances, capacities, and interdependencies among organisms not otherwise evident. Such forests are self-sustaining and evince both ecological and economic values useful to society. In present times, during a small fraction of the last 2 million years, primary forests are believed to have approached their maximum extent (Whitmore 1982). Many are worth preserving in perpetuity. As a unique source of information on the relations between forests and their environments, primary forests and their dynamics merit thorough study by foresters. They afford important points of reference for assessing silvicultural departures.

This chapter describes those characteristics of primary forests that are significant to productivity. There has been a long history of ecological studies of such forests throughout the Tropics; some of the most thorough were those of Jones (1956) in west Africa and Schulz (1960) in Suriname. More recently, the ecology of wet forests in Puerto Rico (Odum and Pigeon 1970), the Amazon (Fittkau and Klinge 1973), the Far East (Sutton and others 1983, Whitmore 1984), and other regions have been studied.

The physical environment of forest ecosystems determines the pattern and the rate of change, and it may set limits on how far ecosystem development can go (Odum 1969). But the ecosystem itself may in turn modify the physical environment. Succession culminates in a maximum degree of homeostasis in which the ecosystem's organic responses tend to compensate for environmental changes. The primary forest provides maximum self-protection from disturbances. It also attains, relative to available energy, maximum or near-maximum biomass and interaction among organisms. Interaction may include competition, in which one of the organisms involved is suppressed; commensalism, in which one is benefitted, but none is suppressed; and mutualism, in which more than one organism benefits (Longman and Jenik 1974).

Primary forests exhibit both resilience, the capacity to absorb changes and still persist, and stability, the capacity to return to an equilibrium state after a temporary disturbance (Holling 1973).

Compared to other forests, primary forests generally achieve a relatively stable equilibrium between gross production and respiration, low gross production relative to standing biomass, high biomass relative to energy flow, low net production (yield), weblike rather than linear food chains, large volumes of organic matter, intrabiotic inorganic nutrients, high diversity, well-organized stratification and spatial heterogeneity, narrow niche specialization, large organisms, long and complex life cycles, closed mineral cycles, slow nutrient exchange rates with the environment, quality versus quantity production, developed internal symbiosis, and good nutrient conservation and stability (Odum 1969).

Valid as these concepts may be, the traditional vision of the virgin forest as being "unharmed" is unrealistic (Spurr and Barnes 1980). Disturbances (or even major disasters) are natural and frequent relative to the lifespan of most forest trees. Instability of the forest is inevitable, even in the Amazon, where climatic change and tribal intervention may have occurred within the lifespan of the oldest trees. Caution must be exercised in classifying tropical forests as primary because of the possibility of past human intervention (Catinot 1974).

The following description of ecosystems has been adapted from Odum (1972). The structural components include the climatic regime, inorganic substances involved in mineral cycles, organic compounds, autotrophic (self-nourishing) forms of life, and heterotrophic forms (nourished from others). Heterotrophic life forms include phagotrophs, or macroconsumers, which are largely animals that ingest other organisms, and saprotrophs, which are microorganisms that decompose organic matter. The living and nonliving parts of ecosystems are so interwoven that they are hard to separate.

Moist tropical ecosystems are so complex that their performance cannot be studied by traditional one-problem, one-solution investigations. To understand them, it may be necessary to use investigative systems involving mathematical modeling and cybernetics (Odum 1972).

Much recent ecological research may appear peripheral to forest productivity. It concerns information primarily of scientific interest, such as soil microbiota and understory plants, leaf-area indexes, litterfall, biomass, and gross productivity in terms only vaguely indicative of useful wood volume or growth (Harper 1977). Whereas foresters have studied forests chiefly to ascertain how much usable wood they might produce, ecologists are more broadly interested in how forests function as systems. These broader insights are at least partly of use to the forester. Ecologists have shown the added costs to society of misuse or destruction of forests, and they are explaining phenomena that heretofore were neither well understood nor studied in depth by foresters or anyone else.

The primary forest, an ecological ideal, is not an ideal for production to satisfy all human needs. Evolution tends to favor individual species more than the forest as a whole (Harper 1977). It would be surprising if activity that favored one individual against another also maximized the performance of the population as a whole as a producer satisfying human wants. Thus, production of the entire population requires compensation for some of the evolutionary advancements favoring individual fitness. An example may be the need to reduce forest density to accelerate growth rates of those trees selected for a future timber crop. Such modifications may start with primary forests but, once applied, have removed the forest under such management from the category of primary.

In 1980, the primary and old secondary forests of 76 tropical countries worldwide had an estimated area of more than 6 million km^2 (Anon. 1982a; table 3–1). They constituted about 76 percent of all potentially productive forests in these countries. In tropical America, the corresponding percentage was 87 percent. Between 1980 and 1990, some 2.4 million ha of closed broadleaf forests were logged in tropical America (Anon. 1993b) suggesting that the area of undisturbed forest in the region in 1990 was about 450 million ha.

Table 3–1.—Extent of undisturbed tropical forests in 1980

Region and no. of countries	Undisturbed productive forest[a] area (thousand ha)
America—33	454,507
Africa—37	118,450
Asia—16	99,033
Total—86	**671,990**

Source: Anon. 1982e.

[a] Undisturbed productive forests are closed primary forests or old secondary forests unlogged for at least 60 years on terrain that could support (without legal objection) production of wood for industry.

Forest Structure

Forest structure is concerned with the sizes, relative locations, and types of life forms. The description presented here applies chiefly to moist forests (fig. 3–1). A summary of structural contrasts between moist and dry, tropical and subtropical primary forests appears in table 3–2 (Murphy and Lugo 1986).

Rain forests, as defined by Baur (1964b), are generally at least 25 m tall. Semi-evergreen forests range up to 40 m; evergreen seasonal forests, to 50 m; and equatorial rain forests from 40 to 60 m. A tall tree reported from a Malaysian tropical forest, a *Koompassia excelsa,* attained 84 m (Foxworthy 1927, cited by Longman and Jenik 1974). Tropical forests tend to be shorter in dry areas and at high altitudes (fig. 3–2). In Venezuela, mean height of trees 10 cm in diameter at breast height and larger at elevations up to 3,000 m above sea level was 10 m; above that elevation, it was 5 m (Veillon 1965).

Forest Density. Forest density is measured by the number and size of the trees, stand basal area, or stocking (volume per unit of land area).

Number and Size of Trees. The number of trees per unit of forest area that have attained a certain d.b.h. is a significant measure of forest density (Schulz 1960). In primary moist tropical forests, the number of trees per unit of area is fairly uniform (table 3–3; Heinsdijk 1957, Wyatt-Smith 1949b).

Figure 3–1.—*The canopy of moist forests at low elevations is formed by broad tree crowns, as illustrated by this forest in Panama.*

Table 3–2.—Structural contrasts between moist and dry forests

Structural trait	Moist forest[a]	Dry forest[b]
Canopy height (m)	20–84	10–40
Canopy strata (no.)	3 or more	1–3
Leaf area index (m^2/m^2)	5–8	3–7
Uniformity	Uniform	Patchy
Ground vegetation cover	<10%	Low-high
Basal area (m^2/ha)	20–75	17–40
Plant biomass (t/ha)		
Stems and branches	209–1,163	28–266
Leaves	7–10	2–7
Roots	11–135	10–45
Total	**269–1,186**	**78–320**

Source: Murphy and Lugo 1986.

[a]Annual rainfall >200 cm; potential evapotranspiration/precipitation ratio normally >1.

[b]Annual rainfall 50 to 200 cm; potential evapotranspiration/precipitation ratio normally <1.

The number of trees 10 cm in d.b.h or more per unit of area varies by site. For seasonal forests, the mean is about 500 trees per hectare; for submontane forests, it is up to 1,000 trees per hectare (Baur 1964a). In Venezuela, the number varied with the altitude (table 3–4; Veillon 1965).

In primary forests, most of the trees are small (fig. 3–3). An extensive sampling of the forests of the Amazon (Heinsdijk 1957) revealed that about half the trees are consistently in the smallest class (table 3–5). In higher latitudes, this proportion is lower (Baur 1964a). Stand tables for tropical moist forests show consistency. Dawkins (1959) found great uniformity in tree numbers by sizes in primary tropical high forests and constructed a "pantropical" stand table (table 3–6).

Great numbers of trees start out, but only a few reach large size. Many, of course, are small at maturity. Each tree's fate depends on its capacity to tolerate or dominate its neighbors, depending in part on the relative capabilities of root systems to obtain water and nutrients and of the crowns to reach adequate illumination.

In large samples of primary forests, the ratio of the number of trees in each diameter class to that in the next smaller class tends to be constant throughout the range of tree sizes. The de Liocourt quotient, or ratio "q" (Amobi 1973, Harper 1977), is described in the previous chapter. If these ratios are similar throughout the range of diameter classes, the stand is considered "balanced," because mortality in each class apparently is being offset by a compensating number of trees entering the class from below. If the smaller classes exceed, in number of trees, those immediately larger by a greater ratio than that for the upper end of the d.b.h. range, the stand is considered to be "positive," in that ingrowth is apparently more than adequate for replacement. A converse trend, termed "negative," suggests that regeneration may be deficient.

Figure 3–2.—*On shallow soils, such as on these limestone hills in Puerto Rico, the forests are short, the trees having low, broad crowns.*

Table 3–3.—Number of trees per hectare in selected tropical forests

	No. of trees	
Location	D.b.h. >10 cm	D.b.h. >25 cm
Guyana	235	—[a]
Ivory Coast	214	—[a]
Malaysia	232	—[a]
Brazilian Amazon		
Madeira-Tapajos	—[a]	12–117
Tapajos-Xingu	—[a]	119–127
Xingu-Tocantins	—[a]	63–121

Source: Heinsdyk 1957, Wyatt-Smith 1949a.

[a]Not counted.

Table 3–4.—Trees 10 cm in d.b.h. and larger by altitude in Venezuela

Altitude (m)	No. of trees per hectare
50–600	133
600–1,600	184
1,600–3,000	253
3,000–3,300	189

Source: Veillon 1965.

Table 3–5.—Distribution of tree sizes in Amazon forests (no. of trees per ha)

	D.b.h. class (cm)		
Subregion	25–34	35–44	>45
Madeira-Tapajos	54–58	30–31	27–30
Tapajos-Xingu	53–55	32–33	31–41
Xingu-Tocantins	33–60	14–29	16–39

Source: Heinsdijk 1957.

Moist forests of India are generally balanced (Mathauda 1953), whereas the dipterocarp stands of the Asia-Pacific region are mostly positive, a circumstance of great significance to their culture.

In Africa, a constant logarithmic relation between d.b.h. and tree numbers was found to apply best to shade-tolerant tree species (Jones 1956, cited by Longman and Jenik 1974). With emergent light demanders, however, a deficiency of trees in the middle sizes was common and there was sometimes also a deficiency in small trees. Seedlings of even the most tolerant emergents were apparently not numerous enough to maintain current stocking, surviving only near small gaps in the canopy (Jones 1955, 1956). A bimodal distribution of tree frequencies is not unknown elsewhere (Harper 1977), with dominant and suppressed trees composing the two modes. Baur (1964b) explained the deficiency of trees in the middle sizes by different growth rates, assuming that trees pass through the intermediate sizes more rapidly than through the smaller and larger classes. Jones (1955, 1956) differed, concluding that the scarcity of midsized trees is due to discontinuous recruitment in the past.

Similarly, Schulz (1960) blamed the lack of small trees of *Goupia* in Suriname on historic events that produced irregularities in regeneration. However, he found that at Mapane, mesophytic lowland forests are, as a whole, well stocked with smaller and intermediate-sized trees.

Basal Area. The total basal area of all tree boles (with bark) at breast height per unit of area is a measure of forest density that reflects both tree numbers and size. Even without height measurements, it may be a good index of relative wood volume. In primary moist tropical forests, basal area for all trees 10 cm or more in d.b.h.

Figure 3–3.—*Primary moist forests are typically composed of many small trees beneath a canopy of a few large ones.*

Table 3–6.—Approximate pantropical stand table for high forests

D.b.h. class (cm)	No. of trees per hectare
10	247.0
20	101.0
30	42.0
40	20.0
50	11.0
60	7.2
70	4.9
80	3.5
90	2.5
>100	5.4

Source: Dawkins 1959.
Note: High denotes closed primary moist forests.

commonly ranges from 35 to 45 m^2/ha, with extremes to 70 m^2/ha (Baur 1964a). Basal area may vary with elevation above sea level. A study in Venezuela (for trees 25 cm and more in d.b.h.) showed a mean of 22 m^2/ha between 50 and 600 m in elevation, a range from 28 to 31 m^2/ha between 600 and 3,000 m, and only 18 m^2/ha from 3,000 to 3,300 m (Veillon 1965).

Stemwood Volume. Volume of stemwood—generally based on tree diameters, total or merchantable heights, and some expression of stem taper or form—indicates the potential yield of a forest. For practical purposes, limits must be realistic as to species, minimum stem diameter, and allowances for bark and defects.

Stemwood volumes attained in primary moist tropical forests typically range from 290 to 525 m^3/ha (Leigh 1975). For west Africa, a range of 275 to 425 m^3/ha has been found (Catinot 1974). The range in Puerto Rico is from 145 to 365 m^3/ha; the addition of branchwood to a 2.5-cm limit increases this range to 180 to 440 m^3/ha.

Stemwood volume, commonly measured to the 7-cm point, diameter outside bark (d.o.b.), has a relatively constant relationship with total aboveground wood volume, or stemwood plus branchwood (Dawkins 1967). An average of 1.3 as a factor to relate the two is applicable to widely differing forests. The extreme range is from 1.1 to 1.5. Stem and branchwood volume underbark has been found under some conditions to be closely correlated ($R^2 = 0.991$) with the product of tree basal area and total height (Dawkins 1964a).

The product of d.b.h. squared and height gives a good estimation of aboveground tree volume (Dawkins 1961b). For 30 trees of 9 species from the wet mountain forests of Puerto Rico, the formula

$$V = 0.0368 + 0.545\ (D^2H),$$

where V = volume outside hark, and D = diameter and H = height, both in meters, gave a correlation coefficient of 0.986, or a practical form factor of 0.6 D^2H. For some forests, a form factor of 0.7 may be closer. In Thailand, a good logarithmic relationship was found between the product of the d.b.h. squared and total height and the dry weight of the stem (Kira and Ogawa 1971).

The relation between stand basal area and stemwood volume is dictated largely by stem height. In Puerto Rico, this relation was found to vary from 6.2 to 7.0 m^3/m^2 for primary moist forests of basal areas between 20 and 40 m^2/ha (Odum and Pidgeon 1970). In Venezuela, the relation varied with elevation, averaging 8.7 m^3/m^2 for stands at 50 to 600 m in elevation, 9.7 m^3/m^2 at 600 to 1,600 m, and back down to 7.4 m^3/m^2 from 1,600 to 3,000 m (Veillon 1965).

Biomass. Recent interest in biomass as a measure of the forest resource can be attributed to three main causes (Parde 1980): (1) increased production of fiber and wood-based panel products, which are more appropriately measured in weight than in volume; (2) increased interest in the biological productivity of forest ecosystems, using dry-weight biomass as a measure; and (3) increased interest in wood energy and chemicals with the approaching scarcity of fossil fuels.

Many life forms other than trees make up biomass. Woody lianas and "stranglers" (trees that attach to other trees for support) are common in primary forests of both wet and dry climates. Other common forms include hemiepiphytic plants (plants that start on another plant), epiphytes, insectivorous plants, and geophytes. All of these are more abundant in wet climates. Biomass also includes animal life, a commonly undervalued component of tropical forests.

Unfortunately, the term biomass is not always used in the same sense, and comparisons of various biomass studies must be made cautiously. Total biomass is only partially phytomass, that portion that is plant tissue, living or dead. Although the term biomass refers to organisms both above and beneath the soil surface, difficulty in measuring or using subsurface material gives rise to the common practice of assessing only aboveground biomass. Biomass may be expressed in terms of either fresh or oven-dry weight, preferably the latter. Two variables are critical to conversions from volume to biomass: the specific gravity of the woods and their moisture contents. Oven-dry specific gravities range from 0.2 to at least 1.3 and vary by both species and site; an overall average for all woods in wet forests is possibly 0.6. Green moisture contents of woods in forests in Colombia and Panama were found to range from 48 to 67 percent (Golley and others 1975). A study of 59 species in Puerto Rico showed a range from 37 percent for *Bucida buceras* to 242 percent for *Ceiba pentandra* (Longwood 1961).

A controversy concerning the measurement of forest growth in terms of phytomass (weight) was reported in the Soviet Union, now Russia (Dylis 1971). Such a measurement was seen to reflect the demand for forests only indirectly, as systems transforming radiant energy, air, water, and minerals. Forest resources are also characterized by volume, surface, inner structure, chemical composition, and energy content. In Russia, phytomass in secondary broadleaf forests may be only one-half to two-thirds that of primary, mixed, broadleaf-spruce forests. Yet, the secondary forests are more useful to humans because more of the phytomass is in the trunks of the trees (Dylis 1971). Total biomass, oven-dry, for primary, lowland, moist, tropical forests ranges from 300 to 1,000 t/ha. For moist subtropical forests, it ranges from 400 to 450 t/ha (Bazilevich and Rodin 1966, Fittkau and Klinge 1973, Young 1976). The range is 60 to 100 t/ha for moist savannas and 30 t/ha for dry savannas.

Near Manaus in the Amazon Basin, where annual rainfall averages 180 cm, aboveground fresh-weight phytomass of a primary forest plot was found to be about 1,000 t/ha; an additional 280 t/ha was belowground (Fittkau and Klinge 1973). Animal biomass totalled only 0.2 t/ha, of which half was soil fauna.

Common formulas used for tree volume measurement can be adapted to give weights (Crow 1978). Examples are $V = a + bc^2$ and $V = ac^b$, in which a and b are constants and c is the d.b.h. (Parde 1980). For entire stands, using 5 to 10 carefully selected mean trees may be adequate. Their mean biomass may be multiplied by the total number of trees in the forest. Another method is to cut, dry, and weigh the biomass of representative forest samples and then apply the total per hectare to an entire area. Also, an array of trees of different diameters (30 or more) may be weighed to produce regression and mass tables comparable to those commonly used for volumes.

Stratification. Primary tropical forest ecosystems are complex vertically as well as horizontally. The trees and other plants, as well as the animals, may be vertically stratified. Stratification of plants seems best expressed in terms of their height at maturity, because in any one location, stratification may be obscured by the presence of immature trees. Five or more strata have been recognized in some tropical forests versus two or three in Temperate Zone forests (Richards 1952). One explanation is greater light partitioning in a tropical forest made possible by a high canopy, long growing season, and more intense sunlight because of the greater mean angle of incidence (Terborgh 1973). Other postulated explanations for and results of stratification in tropical forests (Smith, A. P., 1973) include the following:

1. Optimal use of light because leaf strata separated vertically by 50 to 70 times the diameter of the upper leaves enable lower plants to escape umbras (shadows)

2. Increased photosynthesis because openings between strata make more carbon dioxide available

3. Better pollination or seed dispersal because flyways are created between strata for insects, birds, and bats

4. Intensified selectivity and interdependence among species

5. Isolated emergent trees or groups that produce an irregular upper surface of the forest canopy, contributing to the ventilation of crowns and favoring high leaf area for the capture of more energy and water than is possible with smooth canopies

Whitmore (1981) drew attention to an appearance of stratification resulting from gap regeneration, which produced adjacent groupings of pioneers, second-generation species, and mature groups.

Horn (1971) pointed out that because only 20 percent of full sunlight is needed for tree growth, strata separated by adequate heights can coexist without unduly interfering with one another. Conceivably, they could photosynthesize twice as much as a single stratum. To be efficient, single-stratum leaves must be distributed regularly without overlap.

The number of stories in vegetation may be related to moisture and soil quality. As conditions become less favorable, there are fewer stories (Baur 1964a). An extreme case is mangrove, which commonly has but a single tree story.

Tree strata are not always recognizable. Leigh (1975) concluded that stratification exists but is impossible to distinguish objectively. Schulz (1960) regarded the classification of stories in the moist forests of Suriname as arbitrary. Baur (1964b) concluded that strata are generally discontinuous, rising beneath gaps.

To expect sharply defined strata to be clearly visible in all parts of the forest is to deny continuous regeneration of trees of all species. To conclude that strata do not exist because of the differences from place to place resulting from gap recovery seems an opposite extreme. Whatever their practical significance, strata appear to exist in most closed tropical forests if Newman's (1954) criteria for their definition are accepted: (1) omission of immature trees of higher strata, (2) tree maturity defined by no more lateral branches being shed, and (3) height of stratum considered to be that of its lower limit of permanent branching.

Richards (1983) felt that objectively demonstrable or purely arbitrary divisions of a continuum are both oversimplification. He found that mixed rain forest strata are not usually evident, although there are sometimes large numbers of trees in certain height classes. The boundaries between strata are mostly arbitrary and cannot be objectively defined. Richards concluded that it is more important to recognize foliage density variation at different levels. Foliage density is greatest in the understory.

Notwithstanding the difficulties in identifying tree strata, Baur (1964b) ascribed numbers of stories to most tropical forests. For equatorial rain forests, he listed no emergent layer but three or more tree stories and two shrub layers. For evergreen seasonal forests, he listed emergents plus three tree stories. For semi-evergreen and submontane rain forests, he listed two or three stories and in xeromorphic and swamp forests, two stories.

Five strata have been identified in primary forests northeast of Manaus, Brazil (Klinge and Rodrigues 1973). Data on their heights and fresh-weight phytomass appear in table 3–7.

Jones (1956) concluded that 21 percent of the emergent species in the rain forests of Nigeria are very strong light demanders, scarcely represented in the lower stories. Another 45 percent are abundant in the lower story but scarce in the middle story. About 32 percent decrease in abundance from the lower story to the emergent layer. Other data from Nigeria (Kio 1979) show that two-thirds of the volume of old-growth moist forests is below the upper story. This represents an incompletely tapped reservoir of wood that might be put to use.

Table 3–7.—Tree strata and phytomass, Manaus, Brazil

Stratum height (m)	Fresh phytomass	
	Mean weight (t/ha)	Percentage
24–35	190	28
17–26	400	58
8–14	77	11
4–6	16	2
2–3	5	1
Total	**688**	**100**

Source: Klinge and Rodrigues 1973.

Tree Form. Sharma (1976) examined the phytomass of trees by parts for *Buchenavia lanzan* and *Shorea robusta* in India's dry deciduous forests. In these relatively small trees, the proportion of branchwood was significantly greater in the larger size class (table 3–8). Other relationships were variable, although the bole contained more than half the total mass for all sizes.

Root Systems. The root system's portion of total tree phytomass in primary forests evidently varies with local conditions. One study worldwide indicated that roots constitute from 19 to 23 percent of the total biomass (Bazilevich and Rodin 1966). Yet, in one lowland, mixed dipterocarp forest (dominated by trees of the Dipterocarpaceae family) of Malaysia, roots made up only 7 percent of the dry weight of the trees, or 65 t/ha (Brunig 1967). In one of Cambodia's evergreen seasonal forests, roots were found to make up 16 percent of the tree phytomass (Hozumi and others 1969). In evergreen seasonal forests on terra firme near Manaus, Brazil, this percentage was 27 percent (Fittkau and Klinge 1973, Klinge and Rodrigues 1973). In dry climates, trees may develop more extensive root systems (Kozlowski 1982). Four types of root systems of dicotyledonous trees are recognized by Longman and Jenik (1974): (1) thick, horizontal roots commonly merging into large spurs or "buttresses", no taproot, (2) the same, with a taproot, (3) weak surface roots and a prominent taproot, and (4) numerous aerial "stilt" roots and a network of weaker, underground roots. Large, thick roots apparently provide both anchorage and nutrient transport, and the primary function of fine feeder roots is absorption of nutrients and water. In a Latosol near Manaus, 25 percent of the fine roots were found in the litter layer at the surface (Klinge 1973).

Conspicuous tree buttresses distinguish moist tropical forests from most Temperate Zone forests (Leigh 1975). Buttressing and "stilt" roots are especially common in swamp forests and mangroves. Buttressing is most common on upper story trees, but stilt rooting may occur anywhere. Buttressing is less common in subtropical

Table 3–8.—Percentage of phytomass by tree components for two tree species in India

D.b.h. (cm)	Percentage of total weight				Total
	Roots	Bole	Branches	Leaves	fresh weight (kg)
			Shorea robusta		
3–6	18	66	10	6	6
13–16	22	66	7	5	77
22–25	22	54	19	5	291
			Buchenavia lanzan		
3–6	25	59	6	10	5
13–16	12	75	8	5	53
22–25	11	54	30	5	184

Source: Sharma 1976.

forests at low temperatures (Baur 1964a). Although buttresses would appear to increase stability, their function has not been clearly demonstrated (Longman and Jenik 1974). A form of aboveground rooting common to moist forests is found on stranglers.

Stems. In terms of mass, stems are the largest tree component. In a primary forest near Manaus, the stems made up 50 percent of the total weight of the trees and 68 percent of the aboveground weight, or about 295 t/ha, dry weight (Fittkau and Klinge 1973, Klinge and others 1975). In the subtropical wet forests of Puerto Rico, stems may make up 58 percent of the total tree weight and 77 percent of the aboveground weight (Ovington 1972). In Cambodian evergreen seasonal forests, the corresponding percentages were 56 and 67 percent, or about 135 t/ha, dry weight. In the low miombo woodlands of Katanga, in what was formerly Zaire, the stems made up only 44 percent of the aboveground tree weight, an indication of the shortness of the stems and the branchy habit characteristic of trees under dry conditions (Malaisse and others 1972).

Klinge and Rodrigues (1973) measured the aboveground fresh weight of trees in seasonal evergreen forests along the Amazon. For trees in the intermediate layers (4 to 26 m above ground), stems were found to make up 61 to 67 percent. For trees in the layer between 24 and 35 m above ground, stems made up 73 percent. The stems of most trees in moist tropical forests are columnar and generally straighter than those of broadleaf trees in Temperate Zone forests (Leigh 1975). In a hectare of evergreen forest near Manaus, at least 75 percent of the trees had more than 8 m of straight stem, and nearly 10 percent had 16 m or more (Prance and others 1976). Taper is also less than in many other forest types (Baur 1964a). Taper measurements from a mixture of posts from wet forests in Puerto Rico yielded the following mean values:

Stem Mid-Diameter (cm)	Mean taper (cm/m)
10	1.1
20	1.4
30	1.7
40	1.9
50	2.2
60	2.5

Bark weight, measured in a mixed dipterocarp forest, was found to make up 14 percent of the total weight of the trees, or about 120 t/ha, oven-dry (Brunig 1967). Bark-thickness measurements of the stems and branches of 434 trees of 41 different tree species of subtropical wet forests in Puerto Rico showed a mean of 0.6 cm for stems 10 cm in diameter, 1.3 cm for stems 30 cm in diameter, and 1.4 cm for stems 60 cm in diameter. For stems alone, the average was 2.0 cm, with a maximum of 4.8 cm.

Branches. Branch weight varies greatly with tree height. In the evergreen forests of the Amazon, branches were found to make up about 128 t/ha, dry weight, or 21 percent of the total fresh weight of the trees and 29 percent of their aboveground weight (Fittkau and Klinge 1973, Klinge and others 1975). In evergreen seasonal forests in Cambodia, the corresponding percentages were 26 and 31 percent (Hozumi and others 1969). In the relatively dry miombo forests of what was formerly Zaire, the branches made up about 54 percent of the aboveground weight (Malaisse and others 1972).

Crow (1978) found similarity in the stem and branch weights in trees relative to d.b.h. times tree height from wet forests in Puerto Rico and Thailand. He found that the natural logarithm of oven-dry branch weight was equal to a coefficient *b* times the natural logarithm of d.b.h squared, in centimeters squared, and tree height in meters, minus a constant *c*. He found *b* and *c* to be similar for these distant forests, 1.050 and 5.521 respectively for Puerto Rico, and 1.027 and 5.116 for Thailand.

The proportion made up by the branches varies not only with tree size but also with strata. In seasonal forests along the Amazon, the proportion of aboveground tree weight in branches was 26 percent in the top layer (24 to 35 m), 31 to 34 percent in the 8- to 26-meter stratum, 23 percent in the 4- to 6-meter stratum, and 15 percent in the 2- to 4-meter stratum (Klinge and Rodrigues 1973). The ratio of branch weight to stem weight is significant to forest utilization. For evergreen forests near Manaus, the ratio was about 0.43 (Fittkau and Klinge 1973, Klinge and others 1975). But it varied among the five tree stories, ranging from 0.35 to 0.56, the highest ratio again occurring in the middle story, between 8 and 14 m above ground (Klinge and Rodrigues 1973). In the evergreen seasonal forests of Cambodia, the ratio was 0.46 (Hozumi and others 1969); in Thailand's forests, it averaged 0.29 (Ogawa and others 1965). In the miombo forests of Africa, branch weight was found to be 123 percent of the stem weight, reflecting the branchy form of the trees there (Malaisse and others 1972).

Tree Crowns. The size and shape of tree crowns influence tree productivity. The trees in the top story tend to have shallow, horizontal crowns; those in the understories have deep, vertical crowns. Zavitkovski and others (1974) conclude that in the Temperate Zone vertical extension of crowns is important to productivity, suggesting the use of Assman's (1970) crown fullness ratio (crown width to crown height) as an indicator. Crown diameter to d.b.h. ratios (Assman's growing-space index) are also significant to growth rates. In the Tropics, these ratios range from about 14 to 28; high-yielding species typically have crown diameter to d.b.h. ratios of 15 to 20; lower yielders have ratios of 25 or more (Dawkins 1963a). Assman (1970) found that the ratio of crown diameter to d.b.h. is greater for suppressed than for dominant trees; he also noted that it declines with age. Dawkins (1963a) concluded that in the Tropics as well, the ratio declines with age for shade bearers but that strong light demanders may retain a nearly constant crown diameter to d.b.h. ratio throughout life.

For many tree species of New Guinea, the ratio between d.b.h. and crown width in rain forests proved to be nearly linear, ranging between 21 and 23 (Paijmans 1970). A ratio of 22 was found for mora in Trinidad (Bell 1971) and for a group of 15 tree species in Puerto Rico (Wadsworth and others 1989). Large crown diameter to d.b.h. ratios (up to 40) are thought to explain the low volumes of timber per unit of land area produced by huge trees occurring in groups in Africa (Catinot 1974).

Foliage. Foliage makes up 2 to 5 percent of the total biomass in tropical forests (Bazilevich and Rodin 1966, Brunig 1967, Fittkau and Klinge 1973, Hozumi and others 1969, Klinge and others 1975). Leaf weight varies sharply with height above the ground. Near Manaus, Brazil, leaf weight was found to make up 1 percent of the aboveground weight of the trees in the top story, 24 to 35 m in height (Klinge and Rodrigues 1973). In the second layer, from 17 to 26 m, the leaves made up 2 percent. In the third layer, from 8 to 14 m, the proportion was 6 percent. In the fourth layer, from 2 to 3 m, it was 46 percent.

Leaves in primary evergreen forests weigh only 3 to 4 percent as much as the accumulated wood (Brunig 1967, Fittkau and Klinge 1973). However, the annual production of leaves in such forests is about equal in dry weight to the new wood produced each year (Jordan 1971a). In contrast, in Temperate Zone forests, in contrast, wood production reportedly exceeds that of leaves by 50 to 60 percent.

Leaves are the center of photosynthetic activity or productivity. Leaf area is commonly expressed relative to ground area in the same units: the leaf-area index. Studies in the Temperate Zone indicate that there is an optimum leaf-area index; productivity suffers when the index is either above or below that level (Zavitkovski and others 1974). Leaf-area indexes in primary forests range from 7 for seasonal forests to about 12 for rain forests, with extremes to 22 (Golley and others 1975, Hozumi and others 1969, Kira and others 1964). Tropical forests demonstrate similarity of leaf form and size among otherwise unrelated plant families (Leigh 1975). Leaves with entire margins and acuminate tips are prevalent in moist forests. The average length of the leaves ranges from 7 to 13 cm, and the area from 20 to 180 cm^2. Light-demanding, opportunist species in rain forests, such as *Ochroma* spp. and *Cecropia* spp., produce exeptionally large leaves. Leaf size decreases in the cool mountain areas (Baur 1964a). Compound leaves are most common in dry forests or the exposed, upper strata of moist forests. In the rain forests of Suriname, about 25 percent of the trees in the top layer have compound leaves (Schulz 1960).

Four patterns of leaf phenology in tropical trees have been distinguished (Longman and Jenik 1974): (1) leaf-fall before bud-break, the entire tree remaining leafless or nearly so for a few weeks to several months; (2) leaf-fall associated with bud-break; (3) leaf-fall completed well after bud-break; and (4) continuous production and loss of leaves.

Deciduousness, characteristic of the first three patterns listed above, may be absent or rare in rain forests (Baur 1964a). In evergreen seasonal forests, as many as a third of the trees may be deciduous, and in semi-evergreen forests, as many as a half. Deciduousness appears to be partly genetic in that the phenomenon is characteristic of some genera (*Ceiba* and *Andira*) regardless of climate. It is also partly environmental in that the timing, degree, and length of the leafless period may vary with current weather.

A relation between the percentage of deciduous trees in the forest and the number of dry months (rainfall in millimeters less than twice the temperature in degrees Celsius) was found in Venezuela (Veillon 1963). With 1 dry month, deciduousness was 20 percent; with 3 dry months, 53 percent; with 5 dry months, 81 percent; with 7 dry months, 88 percent; and with 9 dry months, 93 percent. Other adaptations that reduce desiccation include reduced number and size of leaves, sunken stomata, rapid stomata closure, and leaf waxes (Kozlowski 1982).

In Sri Lanka, leaf-fall may take place after a period of low humidity and low rainfall; the reflush after high humidity and rainfall (Koelmeyer 1959). Flushing of leaves of 150 dipterocarp species in Malaysia occurs twice each year, in April and October (Ng 1981). In dry forests some trees drop their leaves at times unrelated to the dry season (Madge 1965). One species shed twice a year: once in the middle of the dry season and once at the start of the wet season. *Alchornea* drops leaves only in the middle of the wet season.

Forest Composition

Composition deals with diversity of species in an ecosystem, measured by richness (the number of species), equitability (their respective representation), and heterogeneity (the dissimilarity in richness and equitability) (Peet 1974).

Diversity. Composition is concerned with the species makeup of the organisms that comprise the forest. A striking attribute of nearly all tropical forests is the large number of species they contain. Of the 3 to 10 million species of organisms in the world, two-thirds are limited to the Tropics, and most of these are forest dwellers (Prance 1982). Possibly 80 percent of the tropical plant species have been named, but less than 50 percent of the insects. In Amazonia alone, there may be a million species of insects. There are more than 50,000 species of higher plants. In a world where major food crops total less than 20 species, the richness of tropical forests suggests an almost completely untapped resource.

The large number of tree species in primary forests of tropical America has been reported by Gentry 1988 and by Gentry and Dodson 1987. In a 0.1-ha plot at Rio Palenque in Peru, the total number of trees, including seedlings, was 653, including 114 different species. Of trees 10 cm in d.b.h. or more, there were 52 individuals and 32 species, or fewer than 2 trees per species. In a 1-ha plot at Yamamono, Peru, the number of tree species was 285, ranking well with the most complex forests of the Far East (Whitmore 1984).

Studies in the evergreen forests of tropical South America have shown great extremes in numbers of tree species. In 0.1-ha plots in several forests of Suriname, the average number of species of trees 10 cm in d.b.h. and larger ranged from 110 to 120 (Schulz 1960). In a 3.5-ha plot at Castanhal, Para, Brazil, 179 tree species of 10 cm in d.b.h. or more were found; 70 additional species were found nearby (Pires and others 1953). A plot of terra firme forest near Manaus, Brazil, contained 51 tree species of 15 cm in d.b.h. or more on 0.25 ha, 99 species on 0.5 ha, and 179 species on 1 ha (Prance and others 1976). These are the equivalent of one species for every two trees.

Terra firme forest, which makes up about 95 percent of the vegetation along the Amazon (Gachot and others 1953), has been sampled systematically by the Food and Agriculture Organization (FAO). The FAO's inventory of Amazon forests (table 3–9) consisted of a series of east-west transects more than 3,500 km in length and 1,200 ha in area (Glerum 1960; Heinsdijk 1957, 1958a, 1958b, 1958c).

The tree species of evergreen tropical forests are not only numerous but also taxonomically diverse. Of all botanical families, 72 are composed essentially of tropical trees (Baur 1964a). Of these, 16 are found in all 3 tropical forest regions: Africa, America, and Asia-Pacific. Another 32 are in 2 regions, and 24 are confined to 1. Many genera also are represented in two or three regions. One species, *Ceiba pentandra,* is found in all three regions, presumably as a result of the mobility of its seeds.

In the American Tropics, genera with large numbers of species include the following:

Genus	*Family*	*No. of species*
Miconia	Melastomataceae	700–900
Myrcia	Myrtaceae	500
Guatteria	Annonaceae	250
Inga	Fabaceae	200–250
Psidium	Myrtaceae	150
Coccoloba	Polygonaceae	125–150
Cecropia	Moraceae	120

In the extensive FAO transects in the Amazon Valley, three botanical families predominated in trees > 25 cm in d.b.h. (table 3–10; Heinsdijk 1960). Despite the 3,500-km, east-west spectrum of the samples, most botanical groups show no marked preference for either end of the transects. A few that are best represented at the western end, in the central Amazon, are Celastraceae, Eleocarpaceae, Melastomataceae, Moraceae, Myristaceae, Nyctaginaceae, Olacaceae, and Vochysiaceae. Genera apparently more common in the lower Amazon include *Eschweilera, Manilkara, Micropholis,* and *Vouacapoua.*

Table 3–9.—No. of tree species >25 cm in d.b.h. per unit of terra firme forest in the Amazon

Subregion	10-ha unit	50-ha unit
Madeira-Tapajos	141–150	192–200
Tapajos-Xingu	100–118	142–198
Xingu-Tocantins	121–126	157–171
Tocantins-Guama/Capim	118–124	156–178

Source: Heinsdijk 1957, 1958a, 1958b, and 1958c.

Fanshawe (1952) described two forests dominated by single species in Guyana, one a type of rain forest dominated by greenheart (*Ocotea*) and the other, on white sands, dominated by wallaba (*Epirua*). Both species regenerate abundantly. They illustrate a marked tendency for single species dominance of forests on adverse sites such as these white sands (Schulz 1960). Mangroves are, for the same reason, also forests of limited diversity, composed almost entirely of one or two tree species (van Steenis 1958).

Dominant tree species tend to be: (1) well adapted to the site, (2) fairly frequent and heavy seeders, (3) relatively shade tolerant in youth, (4) capable of taking over gaps, (5) tall, and (6) fairly dense in crown (Baur 1964a).

Dominance of one or a few tree species in rain forests is more common than may be generally realized. In most rain forests, the recognition of forest types or other units depends largely on the behavior of a few key species. Species that are ecologically dominant are not always indicator species for the classification of rain forests (Baur 1964a). Ecologically dominant species, however, may be directly related to occurrence of economically important species.

The final composition of an undisturbed forest community can be ascribed to both opportunity and competition, the former selecting among the potential pioneers, the latter establishing a dynamic balance in structure and pattern (Poore 1964). One view of the rain forest is that it is a continuum of species, each with different tolerances (Schulz 1960). There may be sharp differences at the ends of a spectrum, but none in between. The concept of a continuum that is uniform may be as impossible as that of a discreetly distinct association.

The natural distribution of a plant species is not solely a response to physical conditions prevailing in the habitat. In the Tropics, competition more than physical environment controls selectivity of organisms (Dobzhansky 1950). Plants can normally exist far beyond their natural distribution areas if they are protected from competition. The natural distribution limit of a species is where (as a

Table 3–10.—Percentage of all trees >25 cm in d.b.h. by family in the planalto Amazon forest

	Location			
Family	Madeira-Tapajos (Central Amazon)	Westbank of Rio Tapajos	Westbank of Rio Xingu	Tocantins-Capui (Lower Amazon)
Burseraceae	4.2	7.0	6.0	6.1
Lauraceae	6.6	7.0	4.2	1.9
Lecythidaceae	11.5	14.5	15.2	25.8
Leguminosae	17.7	21.8	21.1	18.9
Moraceae	5.0	6.5	3.4	2.2
Myristicaceae	4.0	6.1	2.2	0.8
Rosaceae	7.0	1.1	5.8	6.4
Sapotaceae	12.8	9.2	19.7	18.4

Source: Heinsdijk 1960.

result of changing physical environmental factors) its capacity to compete is so reduced that it can be ousted by other species (Walters 1973).

Species in the same community occupy different ecological niches or specific habitats and seldom compete directly in all respects. Gause's (1934) exclusion principle states that two or more species with precisely the same living habits and requirements cannot coexist indefinitely in the same habitat because one will inevitably prove more efficient and crowd out the others. Nevertheless, each species apparently does not require a totally distinct physical niche. Species that superficially look much alike may differ in many less obvious characteristics such as lifespan, growth rate, tolerance, reproductive strategy and mechanism, phenology, and seed dispersal (Richards 1969).

Evolution tends toward digression from similar niches (Whittaker 1965, 1970). Ashton (1969) called this process "mutual avoidance." He concluded that it has reduced the gene pools of the constituent species of stable primary tropical forests but has also led toward morphological stability.

An explanation for the large numbers of tree species in tropical forests is complex. It is no longer thought due simply to the generally favorable environment for plant growth, with few extremes of either temperature or moisture. One theory was that the "low competitive nature" of such a "permissive" environment (Baker 1970b) would favor the survival of mutant forms and, thus, create diversity (van Steenis 1969). For the same reason, the species extinction rate was presumed to be low. Not only is the degree of competition assumed by this argument questionable, but there is reason to believe that a permissive environment might not have stimulated evolution of the species already present.

The role of predators in preventing domination by a few species (and, thus, favoring coexistence for many) has been expounded persuasively by Janzen (1970a) who studied tropical forests of both hemispheres. Yet, many are reluctant to view the animal component as a powerful selective force in plant evolution. Janzen postulates that the wealth of the lowland tropical flora and the relatively long distances between trees of the same species result in part from the action of predators on seeds and seedlings. He points out that any event that increases the efficiency of predation on seeds and seedlings of a given tree species may reduce the population of the adults of that species or increase the distance between new adults and their parents. Either condition will lead to a larger number of species by preventing the best competitors from becoming common enough to eliminate the others. Janzen's explanation, however, is not borne out in all cases.

Species richness (diversity) has its origin in ancient history. Speciation has been in progress ever since the continents separated. In the Amazon (and in Africa as well) climatic changes as recent as 1,500 years ago produced a drier and cooler environment that favored only isolated patches of forests. New species probably evolved in these isolated areas and increased species richness with long lifespans. Woody vines and a rich shrub flora may also have developed (Budowski 1965).

Primary tropical moist forests are rich partly because coevolution and succession have progressed to a point of relative stability in which species take advantage of interdependency with others. The major tree species, unlike those of secondary forests, are shade tolerant, especially in youth, and have long lifespans.

Ecosystems with many species are generally found in environments with little climatic fluctuation over time. Such has been the case in the humid Tropics and sub-Tropics (Stern and Roche 1974) since the Cretaceous period (Baker 1970b), and these regions largely escaped glaciation (Longman and Jenik 1974). Ashton and Brunig (1975) point out that there were some climatic changes during the Pleistocene era, especially in Africa and the neotropics, but there remained refugia for humid forests. This observation leads to the presumption that most of the species have evolved to a high degree of competitiveness. The past stability of the Tropics, according to Connell and Orians (1964), allows energy that would otherwise go into regulation of the climate to be used for more productivity, larger populations of organisms, more opportunities to form interspecific associations, and greater genetic variety.

The length of time an environment has remained stable affects the development and regulation of niches, most of which result not from variation in the physical environment but from interactions among organisms (Connell and Orians 1964). Ashton (1969) concluded that seasonal and geological stability has led to selection for mutual avoidance, increased specialization, many (but narrow) niches, and integrated systems of high productive efficiency.

Functional adaptations contribute to the coexistence of so many species. Examples are sequential specialists (those with seasonal functional strategies), interstitial species (those dependent on fringe areas between high densities of other species), and hypercontingent species (those dependent directly on relationships between at least two other species) (Colwell 1973). A small increase in the number of niches so developed might make a large difference in the number of species accommodated (Stern and Roche 1974).

Diversity may be manifest in a number of dimensions, such as microsites within a habitat, polymorphism, groupings at levels higher than species, genetic variants within species, and age (Harper 1977).

Ashton (1969) saw difficulties in relating forest composition to any specific cause. He concluded that each rain forest tree occupies a succession of microhabitats during its lifespan; therefore, it is impossible to determine whether a particular tree arrives at maturity through a process of selection, by means of a complex series of competitive hurdles alone, or in part by chance. He assumed that all three are involved and that the relative importance of each will vary, although selection always plays a crucial part.

A good discussion of the hypotheses regarding diversity and adaptive strategies in rain forests was presented in Spanish by Toledo (1976). He emphasized a need to study life cycles of more species.

An analysis of Costa Rican forests suggests that species richness does not increase with available soil nutrients; in fact, the relationship may be just the opposite (Huston 1980). Tree-species richness was analyzed in 0.1-ha plots; the significant soil nutrient parameters were phosphorus (P), potassium (K), calcium (Ca), sodium (Na), total bases, base saturation, and cation exchange capacity. No significant relation was found for available nitrogen (N), total N, organic matter, manganese (Mn), or magnesium (Mg). Correlations with precipitation, tree density, tree height, and soil fertility suggested that within the range of the 46 sites studied, the greatest tree richness occurs under poor conditions.

Whitmore (1982) postulates that the forests richest in species are those recovering from a major disturbance, in that they contain both pioneers and their successors. This is the intermediate disturbance hypothesis of Connell and Orians (1964). Disturbances of some degree are considered continuous, enabling both mature forests and all other stages to coexist (Orians 1982). Within such a mixture, there is much duplication in species tolerances.

Species diversity has commonly been considered a measure of ecosystem stability (Stern and Roche 1974). In the gross sense, there is an element of truth in this, because diverse systems of the Tropics are adapted to maintain themselves in a relatively stable environment. The rapidity with which cleared areas naturally reforest may be positively related to former species richness. However, if stability is to be taken literally, diversity and complexity beget fragility rather than stability. The probability that disturbances will greatly affect food chains, intrabiotic nutrients, biochemical diversity, spatial heterogeneity, mineral cycles, and internal interdependencies is far greater in complex ecosystems than in simple ones.

Diversity has been a powerful obstacle to the exploitation of mixed tropical forests. The percentage of tree species of commercial interest in the past has been low, and even among these, the percentage of merchantable stems (at least for lucrative export markets) has been even lower. In the rich forests of Borneo, for example, as recently as 1967, utilization was but 45 t/ha, or only 7 percent of the aboveground wood volume and 5 percent of the biomass (Brunig 1967).

Population growth within the Tropics and expansion of local markets have markedly increased the proportion of harvestable industrial wood in some areas. Carton de Colombia (Frisk 1979), for example, has utilized up to about two-thirds of the wood volume (100 species) of its mixed forests for a variety of products, including cellulose.

Species diversity is commonly expressed by the number of species per unit of land area: number of species increases as area increases. A crude measure of the "importance" of any species may be expressed in terms of its dominance, density, and frequency (Curtis and McIntosh 1950). Dominance is the proportion of the total basal area; density is the proportion of the total number of trees; and frequency is the proportion of a set of samples within which a species is found. Basal area alone was considered a good single indicator of species importance by Baur (1964a, 1964b), but Schulz (1960) believed it gives too much weight to infrequent dominants. The significance of frequency is seen in data from 2-ha plots in Brazil and Malaysia (Baur 1964a). Of 405 tree species, 166, or 41 percent, were represented by a single tree.

The diversity of tropical forests should be measured by more than the number of species present or even by any special horizontal arrangement of species. Meaningful diversity also includes the relative representation of different species.

Heterogeneity. The existence of a great number of species in the forests of the Tropics is further complicated by heterogeneity, a lack of consistency from place to place. Patchiness in species occurrence and size groups has been reported from all moist tropical forest areas. Described as "discontinuity" among the tallest trees and the herbaceous vegetation and "clumping" among the smaller trees (Fontaine 1976), patchiness has been noted particularly in regeneration, a fact of utmost significance to wood production (Baur 1964a). In Suriname, canopy dominants were observed to occur in groups, with a relatively small number of leading species found in each (Schulz 1960). Many are common among the groups, but species vary in their prominence. Patchiness in different species groups may appear in secondary forests as early as age 12 (Webb and others 1972).

Some observers have concluded that patchiness is largely a result of chance. Early studies in Nigeria indicated that emergent trees were distributed more at random than those of lower stories, and few pairs of a species occurred as common associates (Jones 1955, 1956). Observations in Suriname indicated that variations in forest composition are somewhat accidental but left doubt as to whether mixed forests are purely chance aggregates with no pattern (Schulz 1960).

Later studies in Nigeria supported the purely random theory, because many species were seen as interchangeable (despite Gause's exclusion principle), with similar physiological and ecological requirements (Longman and Jenik 1974).

Other theories for forest heterogeneity are based on intricate microenvironmental variations. Richards (1953), noting that most of the species occur over large areas, suggested that their occurrence might vary locally in response to slight changes in topography, soil, and microclimate. Webb and others (1967) concluded that the floristic composition of Australian rain forests reflects the environment with great precision and found that social cohesion within the forest is more vertical than horizontal. Each species group was seen as a functional system of interacting plants, possibly representing a skeletal ecosystem with its own microenvironment and animal organisms. Studies in Malaysian lowland forests (Poore 1968) suggested that rare species occur in associated groups responsive to soil and microenvironment, but are immersed in a matrix of commoner species with a distribution determined more by chance. Groups of species were seen to occupy distinct habitats, each differing in the narrowness of their tolerances.

Possibly the most plausible explanations of the heterogeneity of tropical forest composition lie in the infinite variety of circumstances that influence reproduction. The fact that such influences might also vary widely with time seems to deepen the mystery. An early and intriguing theory was developed by Aubreville (1948) after long observation in west Africa. Called the "mosaic" theory (Richards 1952), it suggests that only certain species may succeed others, forming a variety of contemporaneous but differing multispecies sequences.

Baur (1964b) saw in the species patchwork a result of the nature of overstory mortality. The death of a single mature tree that remains standing stimulates only gap opportunists, not all secondary species. If the tree falls over, creating a large opening, an even-aged stand of secondary species enters. Poore (1968) concluded that in Malaysian forests the distribution of the common species is determined primarily by relations among flowering, fruiting, dispersal agents, and gap formation.

Longman and Jenik (1974) describe three characteristics of primary forests, following, that tend to confirm reproductive factors as one cause of heterogeneity:

1. Mature stands with an unbroken canopy of large trees, lianas, and vines, with rare grasses and forbs covering only a small proportion of the soil and with seedlings and small trees scattered irregularly

2. Gaps, commonly caused by falling trees, normally covering less than 5 percent of the forest area, with luxuriant development of climbers and ground herbs and with germination of dormant seeds and accelerated seedling growth

3. Thickets, resulting from a former gap, with dense, tangled masses of living and dead climbers, low light intensity beneath, and no herb layer.

Ashton (1969) concluded that because distribution of tree species within the forest varies with size of recent openings and their proximity to seed sources, single visual counts may be misleading as to the responsible factors. Such counts may merely record the consequences of historic and catastrophic events and subsequent difficulties in the reestablishment of certain species, none of which may still be readily discernible.

It is evident then that the wealth of species in tropical moist forests cannot be explained easily. Such wealth is not simply due to an absence of competition, for competition appears to be fierce, probably intense enough to offset the region's favorable environment for rapid plant growth. Indeed, stand basal areas are no greater in tropical rain forests than in Temperate Zone forests. The probability is that during a long period of stability, growing intimacy and interdependency among species have favored diversity.

As with trees, small mammals in tropical ecosystems are unequally distributed among species (Fleming 1975). One to three species are usually dominant, yet the biomass may be concentrated in a few other (not necessarily abundant) species. Rare species make up a greater proportion of the birds of tropical forests than of temperate forests. Mixed moist tropical forests with little environmental seasonality favor extreme specialization in the food habitats of birds (Harper 1977).

Nutrient Cycling

Primary forests are known for large accumulations of organic matter, concentrations of several nutrients primarily within the biota, closed nutrient cycles, slow rates of nutrient exchange between organisms and the environment, and good nutrient conservation (Odum 1969). These attributes generally contribute to stability, which underlies sustained production.

Nutritive elements can be classified into three groups: nonmetallic—N, P, S, and boron (B); light metals—K, Ca, and Mg; and heavy metals—iron (Fe), Mn, copper (Cu), zinc (Zn), and molybdenum (Mo) (Assman 1970).

Nutrients come from surface and subsurface minerals and from the atmosphere and are loosely held and readily available in humus and clay soil fractions (Assman 1970). In the moist Tropics, the uptake of mineral-derived nutrients by forests may reach 2 t/ha/yr (Bazilevich and Rodin 1966).

The physical and chemical composition of an undisturbed moist forest at Kabo, Suriname, is summarized in table 3–11 (Anon. 1980a). The preponderance of N is

Table 3–11.—Biomass and principal nutrients in an undisturbed moist forest at Kabo, Suriname

Component	Dry phytomass (t/ha)	Nutrient (kg/ha)				
		N	P	K	Ca	Mg
Leaves	10	170	9	112	66	21
Branches	105	532	44	361	542	60
Stems	231	767	53	521	811	115
Roots	26	289	13	122	47	40
Subtotal	**372**	**1,758**	**119**	**1,116**	**1,466**	**236**
Litter[a]	48	365[c]	25[d]	45[e]	227[e]	59[e]
Soil organic matter[b]	129	7,869[c]	20[d]	113[e]	173[e]	83[e]
Total ecosystem	**549**	**9,992**	**164**	**1,274**	**1,866**	**378**

Source: Anon. 1980a.

Note: N = Nitrogen. K = Potassium. Mg = Manganese. P = Phosphorous. Ca = Calcium.

[a] Includes standing dead wood.

[b] To a depth of 170 cm.

[c] Total N content.

[d] P-Bray I: available P.

[e] Exchangeable cations.

impressive, making up three-fourths of the total phytomass. Also notable is the fact that only 20 percent of the N is in the aboveground phytomass.

Only about 0.3 percent of the world's N is in living organisms, humus, and seabottom compounds (Wollum and Davey 1975). Nearly all the rest, 97.8 percent of the total, is in rocks; only 1.9 percent is in the atmosphere. In the Temperate Zone, the addition of N from the atmosphere to the earth's surface is 4 to 10 kg/ha/yr (Wollum and Davey 1975). Recycling of N, unlike that of other nutrients, may be 6 to 10 times greater in tropical forests than in Temperate Zone forests (Laudelot and Meyer 1954).

Forests obtain N partly from the atmosphere, especially during heavy storms, but chiefly through biological fixation, which is attributed to blue-green algae (in participation with lichens) and bacteria (Wollum and Davey 1975). Such fixation may amount to 20 to 40 kg/ha/yr. Nitrogen is also fixed in moist forests by microorganisms in the phyllosphere, the contact layer between the leaves and the atmosphere.

Better known, however, is the input of N into forests through microbe-root relations of some legumes. Raised as crops, legumes may fix up to 200 kg/ha/yr of N. The process requires the minerals Mo, Ca, Fe, and Cu. In natural forests, N fixation by legumes has scarcely been studied. One large sample of leguminous plants indicated that as many as 90 percent have nodules, suggesting N fixation but not proving it (Wollum and Davey 1975). In west Africa, leguminous trees are fairly common, but many have no N-fixing nodules on their roots.

Nonleguminous, nodulated plants, both angiosperms and gymnosperms, also exist in tropical forests. Among the angiosperms are 10 families, 15 genera, and 113 species, including *Casuarina* and *Alnus* (Wollum and Davey 1975). Nonleguminous, N-fixing plants are generally less active than legumes.

As a reservoir of total N, the forest floor is more important than the mineral soil. The N content of most surface soils ranges from 0.3 to 0.4 percent by weight, generally decreasing with depth (Wollum and Davey 1975). However, most of the N reaching the soil is probably immobilized by organisms that convert elemental N to forms that are usable by plants but that require N themselves to grow. Thus most of the N in and on the soil is unavailable to plant roots. Much may be tied up in undecomposed humus and must undergo changes that release ammonia (Wollum and Davey 1975).

Rainwater both brings and transports nutrients as it passes through the forest, generally carrying far more than it had initially by the time it reaches the forest floor. In a lowland rain forest in Malaysia, 98 percent of the nutrients added by rainfall reached the ground as throughfall and the rest as tree stemflow (Manokaran 1980). How much of these nutrients in solution might be lost is not known, because the water was not assessed below the root zone, where much of the water-borne minerals would probably be absorbed by roots before escaping. Indications of changes in the nutrients carried in rainwater in the La Selva forest in Costa Rica are summarized in table 3–12 (McColl 1970).

A major source of nutrients is recycled litterfall: the leaves, branches, and other dead vegetation that accumulate on the forest floor. Litterfall is thought by some to relate directly to gross productivity. Its amount varies widely from place to place. In Panama, litterfall biomass was found to range from 0.7 to 4.6 percent of the aboveground standing crop (Golley and others 1975). In Costa Rica, 58 percent of the total was leaves, 38 percent branches, and 4 percent flowers and fruits.

In the Western Hemisphere, rates of litterfall range from 7 t/ha/yr for mora forests in Trinidad (Cornforth 1970a) to 10.2 t/ha/yr for Colombian rain forests (Bray and Gorham 1964) and 21.9 t/ha/yr for the Amazon (Stark 1971).

This wide range in litterfall rates may actually reflect differences in forest productivity, but because the rates seem inconsistent with wetness of climate, there apparently are also differences in the dryness of the litter samples weighed or in the degree to which small branchwood may have been included. The published reports of these studies do not describe methods in sufficient detail to permit direct comparisons.

Litter, whatever its accumulation rate, is critical to the future of the forests. Although plants withdraw nutrients from leaves before dropping them (Tanner 1977), there is a residue of nutrients in litter that is a major source for the ecosystem (table 3–13; Cornforth 1970a, Klinge 1977, Nye 1961). The data in this table are not directly comparable. For example, the Brazilian dry season, although less than half the year in length, may produce more than half of the annual leaf-fall. Relatively high amounts of N and Ca were being recycled in all areas.

Treefall is another significant source of nutrient cycling, although it has been measured less than litter. Tree mortality in a natural forest leads to replacement of overmature, suppressed, and diseased trees by more vigorous competitors. Tree mortality has been estimated at about 1 percent per year for all tree sizes (Leigh 1975). A life table drawn up for the palm, *Prestoea montana,* shows that less than half the trees 2 m tall make it to 3 m; of those that do, less than a third make it to 4 m; and of those, only 2 percent make it to 12 m (Bannister 1970). Standing dead trees are commonly decomposed by insects and fungi and recycled by nearby tree roots that may penetrate decadent wood before dead trees fall.

Coarse litter of 10 cm in diameter or more, including treefall, may be as significant to recycling as fine litter. In

Table 3–12.—Nutrient changes in rainwater at La Selva, Costa Rica

	Nutrient content				
Location	N (pp/m)[a]	P (pp/m)	K (meq/L)[b]	Ca (meq/L)	Mg (meq/L)
Rainfall	0.110	0.000	0.006	0.008	.010
Throughfall	.220	.030	.018	.013	.007
Stemflow	.980	.104	.050	.040	.006
Soil solution at 8-cm depth	.310	.000	.022	.126	.193

Source: McColl 1970.

Note: N = Nitrogen. K = Potassium. Mg = Manganese. P = Phosphorous. Ca = Calcium.

[a] Pp/m = parts per million.

[b] Meq/L = milliquivalents per liter.

Table 3–13.—Nutrient content of litter in forests of three tropical countries (kg/ha)

Source	Nutrients				
	N	P	K	Ca	Mg
Ghanaian rain forest	199	7	68	206	45
Brazilian seasonal forest (5-month dry season)	56	1	6	14	2
Mora, Trinidad	60	3	11	65	15

Source: Cornforth 1970a, Klinge 1977, Nye 1961.
Note: N = Nitrogen. K = Potassium. Mg = Manganese. P = Phosphorous. Ca = Calcium.

a mature rain forest in Nigeria, the annual weight of treefall was found to be about 11.2 t/ha/yr, or 6 percent more than litterfall (Nye 1961). Nutrient content of this treefall, compared with that of litterfall, contained per unit of weight only 17 percent as much N, 38 percent as much P, 8 percent as much K, 37 percent as much Ca, and 16 percent as much Mg. This appears to verify that the nutrient content of stemwood is generally lower than that of branches, bark, and foliage.

Rainwash, including throughfall and stemflow, has already been mentioned as a vehicle for the transport of nutrients. In Nigeria, rainwash was found to transport 12.3 kg/ha/yr of N, 3.7 kg of P, 220 kg of K, 29 kg of Ca, and 18 kg of Mg (Nye 1961). In Malaysian rain forests, leaching of K, Ca, and Mg directly from the canopy was found to be a source of nutrients almost as great as litter (Kenworthy 1971). Nye (1961) found that in rain forests in Ghana, significant amounts of P and K may be washed out of the canopy by rain (table 3–14).

Table 3–14.—Nutrient cycling in a Ghanaian rain forest (kg/ha/yr)

Process	Nutrient returned				
	N	P	K	Ca	Mg
Litterfall	159	5.8	54	164	36
Treefall	29	2.3	5	65	6
Rainwash	10	2.9	175	23	14
Total	**198**	**11.0**	**234**	**252**	**56**

Source: Nye 1961.
Note: N = Nitrogen. K = Potassium. Mg = Manganese. Ca = Calcium. P = Phosphorous.

Losses of certain nutrients from a primary forest ecosystem in Papua New Guinea (table 3–15) illustrate the nutrient conservation capacity of the ecosystem (Turvey 1974). Only a small fraction of available nutrients is being lost to streamflow. If the ecosystem is stable, these losses are presumably being replaced largely from weathering of the substrate.

Litter decomposition in the Amazon is attributed largely to fungi (Fittkau and Klinge 1973), whereas arthropods may be more significant elsewhere (Madge 1965). Termites are ubiquitous and undoubtedly a major factor in litter decomposition throughout the Tropics. Madge considered the earthworms present in Nigerian rain forests to be of little importance to litter decomposition.

Anderson and Swift (1983) questioned the widely held belief that plant litter decomposes rapidly in the humid Tropics and that a major portion of the ecosystem nutrient capital is in phytomass, thus leaving soils with a low organic-matter content. Citing the occurrence of widespread Podsols containing more than 60 percent of the N and P capital in deep humus horizons (Klinge 1966), they question broad generalizations. They conclude that decomposition rates are not purely a function of moisture and temperature and that the relative balance of nutrients and active decay organisms may cause sharp variations from place to place anywhere in the Tropics or Temperate Zone. Three groups of variables (Swift and others 1979) are responsible for these variations: microorganisms, litter quality, and the physiochemical environment (Anderson and Swift 1983).

Under conditions favorable for decomposition, litter accumulates beneath moist lowland forests only after seasonal pulses of leaf-fall. Golley and others (1975) found that in premontane wet forests, litter present in

Table 3–15.—Nutrient losses in a primary forest ecosystem in Papua New Guinea (kg/ha)

Content	Nutrient				
	K	Ca	Mg	Na	Si
Total in ecosystem	7,166.0	237.0	6,233.0	6,981.0	14,684.0
Annual flux					
Rainfall input	0.8	0.0	0.3	8.4	0.0
Streamflow loss	14.9	24.8	51.0	66.0	288.1
Net loss	14.1	24.8	50.7	57.6	288.1

Source: Turvey 1974.

Note: K = Potassium. Mg = Manganese. Si = Silicon. Ca = Calcium. Na = Sodium.

May was more than half gone by November and more than 80 percent gone by February. Exceptions are swamps where decomposition is partly anaerobic and slower than elsewhere and forests at high elevations where lower temperatures slow the process. Under tropical montane conditions, humic topsoil may reach 5 to 10 percent of total biomass (Young 1976).

In Nigerian rain forests, litter decomposed in 4 or 5 months during the wet season, but decomposition was essentially arrested during the dry season (Madge 1965). Early estimates in what was formerly Zaire (Laudelot and Meyer 1954) showed that litter decomposed in miombo and other dry woodlands in 2 to 3 years.

During a 5-month dry season near Manaus, Brazil, the percentages of mineralization were 62 percent for N, 85 for P, 79 for K, 33 for Ca, and 35 for Mg (Klinge 1977). A tendency for Ca, Fe, Mn, and Cu to accumulate in old litter was found, suggesting that they are taken up more slowly than other nutrients (Stark 1971).

Mycorrhizae (composite structures of nonpathogenic soil fungi on tree roots) are thought to be present on most tropical trees and to form hyphae capable of increasing absorption and translocation of nutrients from the soil into the roots (Bakshi 1968). The fungi utilize carbohydrates and probably other growth-promoting substances from the root cells. The mycorrhizal association increases the effective nutrient-absorbing surface and may increase disease and drought resistance as well as the uptake of water and nutrients. Mycorrhizal plants are best suited to exploiting the Oxisols and Ultisols, where P is largely immobilized. Such soils are extensive in the Tropics (Menge 1981).

The most common form of mycorrhizae in tropical forests is endotrophic (growing mainly inside the cortical root cells with only a few hyphae outside the root). The more readily visible ectotrophic mycorrhizae form a compact sheath (or mantle) around rootlets, creating a network between cortical cells and the surrounding soil (Mikola 1969). Ectotrophic mycorrhizae are found on the Caesalpinaceae, Dipterocarpaceae, and Pinaceae families and *Eucalyptus* spp. Many mycorrhizal fungi are not highly host specific.

Mycorrhizae are especially common on surface roots in poor soils. In the primary forests on poor sandy soils of Amazonia, most trees are believed to be mycorrhizal (Stark 1971, Went and Stark 1968). Stark (1969) theorizes that when the lakes that once covered much of Amazonia dried up, the forests that developed may have lacked mycorrhizal roots. But then, as soils became poorer through leaching, mycorrhizal species took over.

In summary, it appears that nutrient cycling is the lifeblood of tropical forests. The nutrient supply in established forests is predominantly from recycling rather than from atmospheric fallout or weathering of substrate. Thus, primary forests are largely self-generated, requiring the residual nutrients arising from mortality of organisms for growth and renewal. Any significant interruption of the natural process of nutrient recycling in primary tropical forests will lead to deterioration. To thwart jeopardizing productivity, nutrient levels should be monitored and may have to be replenished.

Tree Growth

Trees grow through photosynthesis, mostly carried on within the leaves. Chemically, the process is expressed as (Bonner 1962):

$$6\ CO_2 + 6\ H_2O + 10\ (+)\ \text{quanta plant}^{plant} \\ > (CH_2O + \text{more plant}) + O_2$$

Of the two known photosynthesis pathways, tropical trees generally use the one designated C_3. This C_3 photosynthesis is efficient at low light levels but calls for transpiration of about double the quantity of water the C_4 pathway requires, and is sharply constrained by even slight moisture stress (Longman and Jenik 1974). Another critical limitation of the C_3 pathway is its photorespiration, which is greater in the light than in the dark (Chartier and others 1973). Respiration also increases with temperature and at high temperatures (particularly at night) may consume much of the photosynthate.

Living plants respire whether or not there is enough light for photosynthesis. In the dark, they thus consume oxygen (O_2) and produce carbon dioxide (CO_2), whereas, in the light, with photosynthesis offsetting respiration, the opposite is true. Protection from wind may even deter photosynthesis because of a lack of circulation of CO_2.

Evidence in the Temperate Zone indicates that shade leaves may photosynthesize faster than sun leaves (Helms 1976). On the other hand, the most shaded, oldest foliage can be below the light-compensation point much of the time and, where respiration rates are high, can drain a tree's carbohydrate resources.

Assimilation, also accompanied by respiration, is the storage of photosynthate energy in complex molecular combinations in tree roots, wood, bark, leaves, flowers, and fruits. The apparent assimilation rate is the net consumption of CO_2. The net assimilation rate is that of the increase in dry matter per unit of leaf area. With an equal leaf area, assimilation will be much less on a poor site than on a good-quality site (Assman 1970).

Growth in dry weight thus requires photosynthetic activity exceeding the respiratory load of the whole plant. Only a small part of the energy stored by photosynthesis benefits tree growth. The respiratory burden may become so great that even an efficiently photosynthesizing plant may not grow (Harper 1977). A balance between photosynthesis and respiration is one of the major features of stable primary forests. As stability approaches, energy is increasingly relegated to maintenance (Odum 1969). Furthermore, as a forest matures, gross production decreases relative to standing biomass, and gross production and respiration approach each other, so that net production is also low (Odum 1969). Thus, changes in mature forests are mostly qualitative rather than quantitative. For example, in an old montane forest in Puerto Rico, the simple maintenance needs of leaves and roots and soil respiration absorb nearly all available photosynthetic production (Odum 1969). In another instance, Catinot (1974) reports that of 43 t/ha/yr of synthesized dry material examined in Ivory Coast, 95 percent was consumed in respiration, leaving only 5 percent for growth.

Assimilation depends on the nutrients that the plant absorbs. The chief elements determining the geochemistry of the biological cycle of ash constituents and N are silicon (Si), N, and Ca; the second group is K, Mg, Fe, and aluminum (Al); and the third group consists of Mn and S (Bazilevich and Rodin 1966).

Assimilation is accompanied by transpiration of large volumes of water. Production of a gram of organic dry substance may require transpiration of 200 to 1,000 g of water, depending on local conditions (Assman 1970). Assimilation increases with light intensity. Assimilation in the early morning hours may be 10 times as effective per gram of water transpired as later in the day. During normal weather in the Tropics, the rate of assimilation varies during the day, with the highest rate occurring before noon. Rates of assimilation normally drop at midday, apparently because of increased respiration or water stress.

The driving force for transpiration is the gradient in vapor pressure from the leaf to the air when the stomata are open (Whittaker and Woodwell 1971). The evaporating power of the air is determined by its saturation deficit and rate of movement (Schulz 1960). The fall of water potential in the leaf resulting from evaporation losses is the impetus that moves water through the xylem and across all membranes. Evaporation of water through the stomata draws up water and soil nutrients from the roots, thanks to the cohesion of water molecules in the thin vessels of the xylem (Leigh 1975). Transpiration for 20 different tree species in the Venezuelan Amazon was found to range from 2.7 to 1,180 l/d (Jordan and Kline 1977). Evapotranspiration (rainfall less runoff and percolation) measures the simultaneous availability of water and solar energy, the most important rate-limiting resources in photosynthesis. Thus, it has been found to be a highly significant predictor of net annual aboveground productivity of mature terrestrial plant communities (Rosenzweig 1968). Evapotranspiration in lowland rain forests ranges between 120 and 190 cm/yr (Leigh 1975), about the same as that from an open water surface (Kenworthy 1971).

The potential transpiration rate from dense vegetation that completely shades the ground, is of uniform height, and never short of water is determined by radiation and air movement rather than by species or stand density (Harper 1977). Uneven canopies, particularly in arid regions, produce wind turbulence that may result in a higher transpiration rate than that from a smooth canopy.

Light is fundamental to assimilation efficiency. Fifteen to 25 percent of total solar radiation is lost through reflection and transmission (Rosenberg 1974). Of the remainder, only about 40 percent is in the visible spectrum useful for photosynthesis, between 4,000 and 7,000 nm (angstrom). Of the usable sunlight, regardless of intensity, the chloroplasts of the leaves absorb from 60 to 80 percent (Bonner 1962). However, light saturation of a typical leaf occurs at about 0.1 to 0.2 full sunlight.

A great part of this energy is used to evaporate water (Chartier and others 1973). The basic efficiency of photosynthesis is 105 kcal stored from 520 absorbed, or 20 percent (Bonner 1962). Thus, a leaf that absorbs 80 percent of full sunlight but that can use only 20 percent of that, with a processing efficiency of 20 percent, is operating at an overall efficiency of 5 percent. Under favorable conditions and good management, forest crops thrive on no more than 2 percent of the energy of visible light (Bonner 1962). Such efficiencies are not to be expected generally in nature, although for brief periods in the Temperate Zone growing season, 5 percent has been attained. Common limiting factors are deficiencies in nutrients and water. Under high illumination, CO_2 deficiencies may constrain photosynthesis efficiency by 50 percent, maximum efficiency being near 10 percent of full light (Bonner 1962). Photosynthesis efficiency depends also on the crown portion that receives enough sunlight for photosynthesis. Overall tree growth may peak in full sunlight, even though photosynthesis of individual leaves may peak well below it (Schulz 1960). Understory leaves tend to have more chlorophyll than canopy leaves (Horn 1971). Four-year growth of a mixture of dipterocarps in natural forests of Sarawak shows the significance of light (table 3–16; Bryan 1981).

Sunlight passing through a forest canopy, particularly when the leaves are in motion, is fragmented into light flecks before reaching the forest floor. In some rain forests and evergreen seasonal forests, these sunflecks make up as much as 50 to 70 percent of the total light reaching the ground (Baur 1964a). Sunfleck light may increase light intensity several hundred times what mean shade density would indicate (Schulz 1960). Furthermore, such light supports vegetation of the lower strata more than its brightness suggests (Evans 1966, cited by Longman and Jenik 1974).

Forest trees differ in "tolerance," which outwardly appears to be the capability to survive and grow under low light intensities. Many canopy trees that live completely exposed at maturity have at their outset withstood years of deep shade until openings occurred that were adequate to stimulate their growth. However, tolerance involves more than shade because suppressed trees, in all but the wettest forests, must also withstand serious water stress induced by larger nearby trees during dry periods. In contrast, seeds of intolerant trees may not even germinate, and if they do, the seedlings may not survive on the shady forest floor.

The allocation of the assimilate within plants has not been well studied. Three-quarters of the photosynthate may be used up in respiration, as seen in a rain forest in Thailand (table 3–17; Kira and Shidei 1967). Of the

Table 3–16.—Light effect on mean annual 4-year d.b.h. growth of dipterocarps in Sarawak (cm/yr)

	Illumination		
D.b.h. class	Full overhead light	Some overhead light	Sidelight only
10–14	0.72	0.44	0.26
30–34	.78	.56	.51
50–54	.95	.53	—[a]

Source: Bryan 1981.

[a]Not available.

Table 3–17.—Energy allocation in a Thai rain forest

Parameter	Phytomass (t/ha/yr)	Energy allocation (%)				
		Roots	Stem	Branches	Leaves	Total
Gross production	123.2	6.0	16.5	31.8	68.9	100.0
Respiration	–94.6	–4.5	–10.6	–15.4	–46.3	–76.8
Net production	28.6	.3	2.8	10.4	9.7	23.2
Litterfall	–23.2	—[a]	—[a]	–9.2	–9.6	–18.8
Mortality	–1.2	–.1	–.7	–.2	—[b]	–1.0
Net growth	4.2	.2	2.1	1.0	1.0	3.4

Source: Kira and Shidei 1967.

[a] Not applicable.

[b] Trace.

remainder, as much as 85 percent may be lost through litterfall and tree mortality, leaving only a small amount for biomass growth. This tally illustrates the low level of assimilate actually allocated to the production of wood. The cost is high, but presumably such production is sustainable.

The allocation of assimilate in trees varies with stimuli such as increased light or growing space. Allocation to the roots, branch terminals, and stem diameter generally takes place in that order (Assman 1970). Growth rings, a reliable indicator of stem growth rates in the Temperate Zone, are not reliable for most species in the Tropics. Most tropical trees do not produce clearly discernible rings, and those produced are generally of unknown periodicity. Growth rings may arise from any of the following anatomical characteristics (Chowdhury 1962):

- Woods that are ring-porous or semiporous (only about 1 percent of tropical trees)

- Less predominant vessels in earlywood than in latewood

- Radially flattened, thick-walled fibers in extreme latewood contrasted with tangentially flattened, thin-walled fibers in the earlywood

- Initial parenchyma cells (found in many families)

- Terminal parenchyma cells (found in one family only).

A study of 60 Amazonian trees disclosed 26 to have no rings at all. Another 22 had clear rings, but these are not known to be annual (Alvim 1964). Rings may be found in the wood of both deciduous and evergreen trees. There appears to be no relation between the deciduousness of trees and the formation or clarity of growth rings (Chowdhury 1940).

Height growth of tropical trees begins early but diminishes when trees have reached only a third to a half of their maximum stem diameter (Dawkins 1963b). In the Temperate Zone, this is true especially in light-demanding species (Assman 1970). Gap opportunists, such as *Cecropia,* given adequate sunlight, may grow to 10 m in height in 2 years (Schulz 1960).

In primary forests, the topmost trees may be vigorous, or they may have already begun declining in diameter growth, although not necessarily in basal area growth. Canopy trees in middle strata may still be accelerating in growth and may not achieve full vigor until they are much older and larger.

Rapid diameter growth reported for individual trees has suggested a potential for increasing tropical forest production through cultural treatment. An analysis of the diameter growth rates of a mixture of tree species in the rain forests of the Indian Ghats showed that of those 10 cm in d.b.h., some attained 19.5 cm in 10 years (Mathauda 1953). In the rain forests of Nigeria, the most rapidly growing, emergent trees, with a d.b.h. of 101 cm, were estimated to be only 35 years old (Jones 1956). Several dominant species of west Africa, such as *Aucoumea, Chlorophora, Nauclea, Terminalia,* and *Triplochiton,* reportedly are capable of 1 to 2 cm of diameter growth annually for 80 years or more (Catinot 1974). In what was formerly Zaire, a 7-year record showed that *Macaranga, Musanga,* and *Ricinodendron* are capable of more than 2 cm of diameter growth per year (Hombert 1958). Exceptional, exposed trees in the subtropical wet forests of Puerto Rico may grow at the rate of 2.5 cm/yr in diameter (Wadsworth 1958).

However, mean rates of diameter growth in primary forests are far below these extremes. In the rain forests of the Indian Ghats, mean diameter growth rates were reported to be only about 0.3 cm/yr (Mathauda 1953). In Nigerian rain forests, the mean growth rates of even overstory trees of *Khaya grandifoliola, Pycnanthus angolensis,* and *T. scleroxylon* were found to be only about 0.7 cm/yr, suggesting that 80 years would be necessary to attain 60 cm in d.b.h. (MacGregor 1934, Webb 1964). For *Afzelia africana,* more than 100 years would be required. For trees of 100 cm in d.b.h., the indicated life cycle, based on the mean growth rate, is 135 years (Jones 1956).

In primary subtropical wet forests in Puerto Rico, where both understory and overstory trees were measured, a tree of 10 cm in d.b.h. with average growth was estimated to be 80 years old, whereas one of 50 cm was 260 years (Wadsworth 1958). A summary of the 25-year d.b.h. growth of more than 500 trees in a secondary subtropical moist forest in Puerto Rico gave a mean of 0.12 cm/yr and extremes of 0.04 and 0.58 (Weaver 1979b). Even the dominant and codominant trees were growing only about 0.4 cm/yr. In nearby lower montane rain forests, the corresponding estimates were about 400 and 1,200 years for trees to reach 10 cm and 50 cm in d.b.h. These probably are overestimates, because surviving competitors presumably grow faster than the average.

Jordan (1971b) suggests that tree growth in primary tropical forests is slower than that in the Temperate Zone because of less selective evolutionary pressure toward maximizing efficiency of wood production where solar energy is abundant. Catinot (1974) counters that such comparisons generally use managed forests in the Temperate Zone, to which unmanaged tropical forests cannot be fairly compared.

All such broad generalities about diameter growth, even within species, seem to obscure as much as they reveal. The d.b.h. growth variation within any plot, species, or size class is so wide that means are difficult to interpret. A tenfold difference was found between the slowest and fastest growth recorded over 24 years for 43 trees of the same species *(Dacryodes excelsa)* and of about the same initial d.b.h. (10 to 20 cm) (Wadsworth and others 1989). Diameter growth rates of *Ceratopetalum* trees in the same plot and of the same d.b.h. class ranged from 1 to 6 mm/yr (Baur 1964a). *Manilkara,* generally considered slow growing in Puerto Rico, may outgrow *Cecropia,* a rapidly growing pioneer, when both are in a closed forest.

Primary forests, by definition, are products of natural (as opposed to human) influences that favor the ecosystem as a whole over the individual organism. One result is that stand density reaches a level that creates intense competition among individual trees, none of which grows unconstrained. Where forest basal area exceeds 32 m²/ha (commonly attained in primary forests), individual tree growth is slow (Dawkins 1959, cited by Ovington 1972). Mean growth is generally derived from a mix of trees growing in different microenvironments, under different degrees of suppression, of different sizes, possibly of different ages, and with different histories of competition. In addition, the growth of some of these trees may reflect effects from causes no longer discernible. So, it is no wonder that individual tree growth in nature varies markedly and generally is far below potential.

The relative importance of different growth constraints is hard to assess. There probably are multiple causes, and those due to competition are difficult to assess. Their effects may persist for decades after the visible evidence of the cause is gone. A tree may also influence its neighbors in many ways other than direct competition for light, moisture, or nutrients. It may produce and release chemical inhibitors (allelopathy); it may shelter pests, carry pathogens, or attract birds or mammals that harm neighboring trees.

One of the most unmistakable constraints on the growth of rain forest trees is shade. The canopy trees absorb 80 to more than 90 percent of the total solar energy (Dawkins 1961b). Maximum assimilation rates and the compensation point between assimilation and respiration are both higher for sun leaves than for shade leaves. Although shade leaves respond more to weak illumination than sun-nurtured leaves, the difference is less than compensating (Chartier and others 1973). Any crown that is higher than neighboring trees has a significantly greater production potential (Assman 1970).

Leaf angles bear out the constraining influence of illumination on the well-being of tropical trees. In the crowns of emergent trees, the leaf angles are more vertical than in the main canopy below (Williams and others 1972). Light saturation occurs at a low intensity; leaves exposed perpendicularly to the Sun's rays may use radiation incompletely. Leaf angles that result in light interception somewhat below saturation can be much more efficient.

Diameter-growth comparisons among tropical trees are complicated by the lack of synchrony in their growth, sometimes even among neighboring trees of the same species (Harper 1977). The time of diameter-growth initiation and the flushing of buds may vary without apparent correlation with external factors (Chowdhury 1940, Longman and Jenik 1974). Eighty percent of the trees in a study of lowland forests in Malaysia were intermittent growers, and nearly all of these were evergreen (Alvim 1964). Only 20 percent were both evergreen and evergrowing. Even among the evergrowing species, growth rates varied during the year. A study of 21 tree species near Belem, Brazil, showed 17 to be clearly periodic in their growth (Moraes 1970). In Nigerian lowland rain forests, five principal timber species were found to grow only seasonally (Amobi 1973). Studies in the wet forests of Puerto Rico showed some species to be more seasonal in diameter growth than others (Murphy 1970).

An early study indicated that cambium cells of deciduous trees do not divide during the leafless period, only after the new leaves unfold. A study of six forest tree species in latitude 30° N. in India (Chowdhury 1939) yielded the following results:

- Diameter growth of the trunk followed foliar development by as much as 2 to 3 months.
- Trees of the same species differed by 1 to 3 weeks in the commencement of growth, unrelated to aspect or spacing.
- Some species had two growth periods.
- No direct correlation could be found between temperature, rainfall, or humidity and commencement and cessation of growth. Hereditary differences were suggested.

In a seasonal climate in western Costa Rica, 12 of 25 upland tree species gained all of their stem growth during the rainy season (Daubenmire 1972).

Growth behavior also varies with the period of the tree's life. Some trees increase their growth rates until they have reached the canopy and their crowns are expanding. After they reach about 60 cm in d.b.h., their growth rate may decline (Jones 1956, Keay 1961, Schulz 1960). Yet in Nigeria, some of the large rain forest trees are capable of increasing their basal-area growth continuously to ages as advanced as 140 years (Webb 1964). Rapid stem-diameter growth through the 30- to 60-cm d.b.h. range has been suggested to explain the paucity of trees of middle sizes in African primary forests (Baur 1964a). Relating diameter growth rate to size is confounded by crown position in the canopy (dominance). These anomalies prompted measurement of tree growth in terms of basal area rather than diameter (Banks 1962, Schulz 1960).

These reports on diameter growth are indicative, but it should be recognized that the use of mean diameter growth is seriously biased. It assumes either that trees are all the same diameter or that their diameters increase throughout life in proportion to their size. Neither is true. Diameter growth is usually much less in large trees than in small ones, yet the wood volume growth in the larger trees may be greater. Use of basal-area growth eliminates much of this bias. Even more bias is eliminated by using basal-area growth as a percentage, which reflects approximately how much a tree grows relative to its root and crown space (as indicated by its stem basal area). Nevertheless, there is still a tendency for this measure to favor small trees over large (Baur 1964a).

Other variations in individual tree growth arise from differences between tree species in the maximum size or age class. The light demanders are initially rapid growers, particularly in the intermediate size range (25 to 60 cm in d.b.h.) (Baur 1964a). But many are short lived, and so the large specimens may not be growing, despite their crown positions.

Past events may well have affected the relative size of two neighboring trees, but they may also be different genetically. Assman (1970) (presumably referring chiefly to the Temperate Zone) attributes much of the variability in tree growth to genetically fixed characteristics, concluding that survival and vigor are linked. Ashton (1969), on the other hand, sees evidence in the lowland dipterocarp forests of selectivity that has produced marked intraspecific genetic uniformity, a seeming paradox considering the numerous species in those forests.

However much genetic differences (genotypes) explain the characters of the different forest trees, each tree is also a phenotype, a result of past events whose effects may be visible indefinitely. An early growth advantage might produce a tree that throughout its life is apparently superior to its neighbors. The end result may be that those trees that are growing more rapidly than their neighbors are doing so partly because their neighbors are not growing rapidly. This could mean that silviculturally removing the slow growers might provide products but would do little to stimulate the trees that are already growing rapidly.

Large tree crowns produce rapid growth in stem diameter. But trees with small crowns are more efficient than those with large crowns in terms of growth per unit of crown surface, crown volume, and area covered (Assman 1970). Vegetable crops behave simply: plants with tall, narrow crowns are more productive per unit of space occupied than plants with short, wide crowns (Jahnke and Lawrence 1965).

Baur (1964b) refers to another variant in tree growth, the "gap opportunists," including species in such important families as the Meliaceae *(Swietenia)* and Dipterocarpaceae. Gap opportunists start on the forest floor but may survive in what appears to be a state of near dormancy for several years, ready to grow upward if light conditions improve.

Relative tolerance explains other growth-rate differences. Schulz (1960) describes the typical canopy species of primary forests as only relatively shade tolerant. These species differ from intolerants only in that they need no light (and may even need darkness) for germination, and they grow more slowly in seedling and sapling stages than typical light demanders. However, at some later stage, more light becomes essential for most (perhaps even all) of the upper and middle story species. During these later stages, light requirements vary widely, but tree growth in all age classes and species is strongly stimulated by added illumination (Schulz 1960).

With these many causes of growth variation, it has been thought unrealistic to assume any relation between the size of trees and their age, other than the vague generality that the largest trees in the canopy are likely to be old. But there is no corollary because the small trees may not be young; they may be as old as the main occupants of the canopy. So it is easy to imagine wrongly that size reflects age.

The entire organic mass arising from the photosynthetic activity of the green leaves of a plant community, including that portion immediately respired, is termed gross primary production (Walters 1973). Gross primary production minus respiration is termed net primary production (table 3–17). Both are expressed in terms of oven-dry organic matter as grams per square meter or as kilograms per hectare (Whittaker 1970).

Poore (1964) points out that there is no evidence that the flora and fauna of primary ecosystems utilize all the habitat's resources. Greater utilization seems possible by using certain plants and animals not naturally available and by concentrating on production from young, rapidly growing individuals. This, however, may not be a sustainable practice.

Ovington (1972) describes the development of a stable forest in terms of productivity. He points out that as forests reach maturity, net primary production diminishes, presumably because of the greater respiration accompanying the buildup of nonphotosynthetic tissue and because of the raising of the forest canopy higher above the soil, the source of water and mineral nutrients for plant growth. He further points out that in mature climax forests, net primary production and loss of organic matter are in balance, the energy captured by photosynthesis being dissipated by respiration. As the climax forest develops, basal-area growth slows. Even though some favored trees may continue to grow, their increment is offset by mortality.

Considering that respiration rates approach the rates of gross primary productivity in primary forests, leaving little for net production, the "increment" in such forests is about the equivalent of mortality and litterfall.

Reproduction

In primary tropical forest ecosystems, trees are not replaced frequently or rapidly. Most of the trees can survive for decades or centuries. Notwithstanding this fact and the many adversities facing seeds and young trees, most tropical forests contain at least a sparse stand of trees well below mature size. One study in a seasonal forest in Venezuelan Guyana showed that 1 in every 10 quadrats of 1 m^2 averaged 7 trees that were less than 2 m tall (Rollet 1969).

The frequency of heavy flowering and seed years varies widely. Among the dipterocarps, good seed years occur at 1- to 9-year intervals (Cockburn 1975) but may involve only half the trees. In other years, a fourth of the trees may fruit (Medway 1972). In India, some seeds of most species are available somewhere every year, but not at every location; seed years are variable in periodicity and extent (Griffith 1941a). Overstory species fruit less frequently than understory species. In northern Suriname, most of the canopy species fruit only every second year, including all Vochysiaceae and many Burseraceae, Lecythidaceae, and Leguminosae (Schulz 1960). Long intervals between fruiting may reduce the population of insect predators to a level that permits an oversupply of fruit (and thus more escape to germinate) when fruiting takes place (Janzen 1975). Nevertheless, Harper (1977) points out that not all predators are specialists, so they may move from one species to the next.

In the Temperate Zone, heavy seed years may be accompanied by narrow growth rings, suggesting that abundant seed production slows growth (Assman 1970, Harper 1977). No corresponding observations from the Tropics have been reported.

Tropical plants may belong in any of the following flowering classes (Koriba 1958):

- Everflowering
- Nonseasonal—variation from plant to plant and even from branch to branch
- Seasonal—related to seasonally dry weather or day length (some everflowering and nonseasonal trees of the equatorial Tropics are seasonal in the outer Tropics)
- Gregarious—mass flowering irregularly (some Dipterocarpaceae).

Most of these classes have been found in forests near Manaus, Brazil (Araujo 1970). A 4-year study of 36 timber and latex tree species showed that most flowering occurred in the middle of the dry season (June to November). Flowering may take place once, twice, or several times a year. Some species flower irregularly and are not season dependent.

In the moist forests of Costa Rica, flowering of 42 species peaks in the dry season (Daubenmire 1972). Flowering of periodic overstory trees is heavy in the first 2 months of the dry season (Frankie and others 1974b). Flowering among less seasonal species peaks in May, then tapers off to November. In the drier forests where rain is normally absent from December to April, about two-thirds of the pollination coincides with the dry season (Daubenmire 1972). In other dry forests of Costa Rica, flowering was greatest in July (107 of 113 species) and decreased until November (Frankie and others 1974b).

In moist lowland forests in Costa Rica, one-fourth to one-half of all tree species have unisexual flowers, and most such species are dioecious, that is, with male and female flowers on separate trees (Bawa and Opler 1975). In a semideciduous forest of Costa Rica, 22 percent of the 130 species were found to be dioecious, 10 percent monoecious, 14 percent self-compatible, and 54 percent self-incompatible (Bawa 1974).

In Malaysia, 26 percent of 722 tree species that grow to 10 cm in d.b.h. or more are dioecious, and these are mostly in the lower strata (Ashton 1969). Among dipterocarps, self-pollination is reportedly usual, although outcrossing takes place within clumps. Primary forest conditions are believed to select against outcrossing and intraspecific variation (Ashton 1969, Fontaine 1976). Because a tree's survival in a dense forest probably depends more on the hazards of its surroundings than on genetic suitability, adaptation does not vary greatly among individuals.

Much remains to be learned about the role of insects in pollinating rain forest trees (van Steenis 1972); floral fragrance does not fully explain this role. There is much variation among species, even within genera.

Published information is generally sparse on the length of time between flowering and ripening of fruit of many potentially important tropical trees for which seed collection can be anticipated. Systematic documentation of such information has reportedly begun in Malaysia (Ng and Loh 1974).

Within the year, there are single peak periods of seeding, even in rainy climates (Medway 1972). Certain gap opportunists and understory species may bear mature fruits much of the year (Baur 1964a). But most fruiting is clearly seasonal, although the actual dates may shift from year to year (Baur 1964a, Harper 1977).

The amount of fruiting fluctuates in seasonal climates. In Colombia, fruiting was less equitably distributed throughout the year in seasonal environments than in premontane wet forests (Hilty 1980). In Costa Rica, fruiting peaks at the beginning of the wet season and then again after the July-to-August "veranillo" (dry spell) in September and October (Fournier 1976b). Nevertheless, some species may be in fruit at any time (Daubenmire 1972, Frankie and others 1974b). In Puerto Rico, seeds of introduced *Swietenia* mostly fall near the beginning of the dry season, but seeds of most other species fall during the wet season.

Seed dispersal in closed tropical forests—like pollination—does not generally depend on the wind. Minimal air movement makes wind pollination unreliable within deep forests (Baur 1964a). Near Manaus, Brazil, pollen of only 5 of 37 tree species was found to be wind disseminated (Silva 1977). Seeds with wings are the only type that can "fly" over a long distance in the still air common to many tropical forests (Harper 1977).

Wind dispersal of seeds in Suriname is limited largely to upper story trees and the pioneer species (Schulz 1960). In a study in Nigeria, 46 percent of the overstory species proved to be wind dispersed, compared with only 8 to 9 percent of the lower story trees (Jones 1956). In a seasonal wet evergreen forest of Venezuela, more than 20 percent of the trees measuring 60 or more cm in d.b.h. produced wind-disseminated seeds, compared with only 5 percent in the understory (Rollet 1969). In Panama, the April fruiting peak consisted mostly of wind-dispersed seeds; the August fruiting peak did not (Croat 1975).

Animals are the most common means of seed dissemination in tropical forests (Baur 1964a, Janzen 1975, Schulz 1960). In fact, seed dissemination is believed to be the most important contribution of tropical mammals to forest ecosystems of the region (Fleming 1975). Wherever new growth shows little species correlation with nearby seed trees, animals are considered responsible for seed dissemination (Baur 1964a). Some linkage to animal behavior is generally observed when seeds have not been wind dispersed (Harper 1977, Jones 1956). Along large rivers, seeds may be disseminated even by fruit-eating fish (Prance 1982). In Nigerian rain forests, fruits edible by animals were found on 46 percent of upper story tree species and on 70 percent of those in the middle and lower stories (Jones 1956).

Seeds of almost all understory species of the montane wet forests of Colombia are distributed by birds (Hilty 1980). Near Manaus, Brazil, seeds of 22 of the 37 tree species studied, or 60 percent, were disseminated by birds (Silva 1977). The fruiting seasons of different species of *Miconia* are so staggered that fruits of some species are available in all seasons.

Snow (1981) lists the following genera in the diets of frugivorous (fruit-eating) birds. Those designated "(s)" are fed upon by specially adapted species: *Alchornea, Allophyllus, Aniba* (s), *Ardisia, Bactris* (s), *Beilschmeidia* (s), *Bromelia, Bursera, Byrsonima* (s), *Canella, Capparis, Casearia, Cecropia, Chlorophora, Chrysophyllum* (s), *Citharexylum, Clusia, Coccoloba, Comocladia, Cordia, Cupania, Dacryodes, Dendropanax, Eugenia, Fagara, Ficus, Genipa, Guaiacum, Guarea, Guazuma, Hedyosmum, Henrietella, Heterotrichum, Hieronyma, Hirtella* (s), *Ilex, Lactea, Licaria, Manilkara, Margaritaria, Matayba, Metopium, Miconia, Myrcia, Myrica, Nectandra, Ocotea, Palicourea, Persea, Petitea, Picramnia, Piper, Pisonia, Pithecellobium, Pouteria, Prestoea, Psidium* (s), *Psychotria, Rollinia, Rourea, Roystonea, Sapium, Schefflera, Sloanea, Tetragastris, Trema, Trichilia, Trophis, Turpinia, Virola,* and *Zanthoxylum.*

Despite the prevalence of animal dispersal, extremely concentrated distribution of seedlings of most species near parent trees has been observed (Jones 1956, Schulz 1960). In Suriname, this apparently caused the patchy distribution of many of the canopy species. Contiguous distribution of trees in Malaysian dipterocarp forests also has been ascribed to inefficient seed dispersal (Ashton 1969, Burgess 1975). Natural regeneration of dipterocarps is usually within 60 m of seed trees.

Once seeds reach the forest floor, most can germinate early under favorable conditions. A test of the seeds of 99 tree species in Malaysia showed that 70 percent of the species germinated clearly within 12 weeks, 7 percent had begun clearly after the 12th week, and the rest either before or after 12 weeks (Ng 1973).

In the forests of northern Suriname, early germination is critical to success for most of the tree species of the middle and upper stories, because seedlings must be waiting when a canopy opening favors them (Schulz 1960). Moreover, evidence from both hemispheres indicates that the seeds of many tree species are perishable (Gomez-Pompa and Vazquez-Yanes 1972, Webb and others 1972). Even those that are not may be attacked by insects or microorganisms within a few days or weeks (Schulz 1960).

Light-demanding pioneer species and some gap opportunists may require light for germination and, therefore, may need to persist on the forest floor before germination (Schulz 1960). Gap opportunists capable of germinating in the shade may still have to withstand dry weather. Some need to be in direct contact with the mineral soil to germinate (Schulz 1960). The fresh seeds of *Schefflera morototoni*, a forest pioneer, sown in nurseries in Puerto Rico, did not germinate for many months, indicating physiological dormancy (Wadsworth 1945). Four sources of such apparent dormancy have been recognized (Harper 1977): (1) seed development incomplete until after dispersal; (2) need for germination to be triggered by photoperiod, light, or temperature; (3) need to overcome an inhibitor in the seedcoat, and (4) water access restricted, usually by an impermeable seedcoat.

Species with seeds that lie dormant before germination need defenses against predation. Some carry toxic compounds. Thick seedcoats and pericarps may also provide protection. Small seeds may be safer than large seeds. Seeds bearing awns or spines tend to escape predation. Brief dormancy also favors protection against predation (Hunter and others 1977). Species adapted to poor environments, where competition may be intense, tend to have larger seeds and devote more of the limited resources to survival of established individuals than to fecundity (Harper 1977).

Variations in proximity to seed trees, size and recency of seed crops, and seed durability all affect the abundance of tree seeds on the forest floor. Studies near Veracruz, Mexico, showed the presence of many dormant seeds on the forest floor (Guevara Sada and Gomez-Pompa 1976). Collections in both Mexico and Nigeria showed seeds of upperstory species to be rare and never present throughout the year (Gomez-Pompa and Vazques-Yanes 1972, Keay 1960). Seeds of secondary species, in contrast, were abundant continuously, suggesting either greater durability on the soil or more frequent seed production. In the dipterocarp forests of Sabah, only 38 percent of the seeds collected in one study were of primary species (Liew 1973a). The seeds of pioneers such as *Anthocephalus* and *Macaranga* were abundant. These relationships sound logical, but the real differences in seedling abundance are governed also by the capacity of the seeds to germinate.

Much tropical forest regeneration takes place where the canopy has been broken (fig. 3–4). The following three degrees of disturbance and their respective regenerative responses have been distinguished (Baur 1964b):

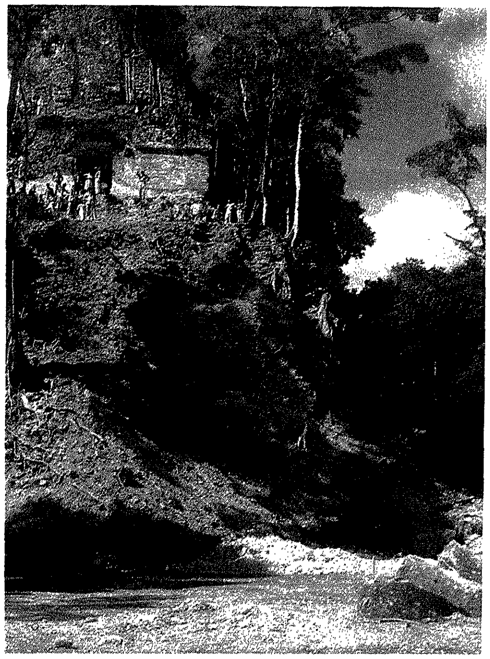


Figure 3–4.—*The regenerative power of tropical forests is seen in the trees that totally cover and hide from view the great pyramids of the Mayan city of Tikal.*

1. The death of a single, medium-sized tree may create an opening smaller in diameter than the canopy height, one that will be closed rapidly by adjacent tree crowns, prompting a surge in gap opportunist species that will soon disappear.
2. When a large tree falls, creating a canopy gap of at least 1,000 m^2, the opening stimulates regeneration of secondary species that may survive and reach maturity, enduring for many decades and contributing to a common species "patchwork." An example of such a secondary species in tropical American forests is *Cordia alliodora,* the seedlings of which may survive suppression up to 8 months, yet require a gap to develop (Tschinkel 1965).
3. Where a catastrophe "flattens" a larger area of forest, gap opportunists will leap ahead and fill the gap with light shade, beneath which longer lived species can develop at a slower pace and later succeed them.

In mixed tropical forests, the death of a tree apparently seldom favors replacement by the same species, despite a tendency for seed accumulation there. Long ago, a theory was developed in west Africa that the environment created beneath one primary forest tree species favors the progeny of others more than its own (Aubreville 1948). This theory was designated "mosaic" by Richards (1952). Although Schulz (1960) reported no evidence to support this theory in the rain forests of northern Suriname, it does seem that some mechanisms must favor a sequence of changing species. Evidence that seed predation is greatest near the parent tree supports the concept (Janzen 1970b). It has been reported that for this reason progeny of *Manilkara bidentata* do not grow up beneath their parents (Baur 1964a, 1964b).

There is also evidence to support such a theory of sequential change in species in Temperate Zone forests. There, the tendency for tree replacement by different species is due to much more than mere selectivity by insect predators (Fox 1977). Seed or seedling survival may be controlled by other predators, parasites, toxins, and direct competitors instead of insects.

Plant behavior after seed germination is critical to success in the competitive environment of primary forests. Two routes to success, as follows, have been recognized by Harper (1977):

1. Light demanders result from an evolutionary, selective force toward many descendants and precocity. Selection favors allocation of much of the assimilate to seed production. Neither competitive capability nor length of life is favored. Progeny that are produced late in life are unimportant because succession has progressed too far for them to become well established.
2. Plants that come up in an already established forest are classed as tolerant and are more aggressive than fecund or precocious. They produce larger but fewer seeds, survival during a juvenile period and longer life becoming more important than seed production. When two such species are grown together, selection favors divergence so that competitive demands on the mutually required resources are minimized.

The number of progeny per species in the forest is not proportional to the number of mature trees (Harper 1977). Apparently the reproductive capacity of a forest tree does not alone determine its abundance. Important also is the capacity of the progeny to survive hazards during the period of early growth and development. As an example, the survival of dipterocarp seedlings in a study in north Borneo decreased from about 80 percent after 1 year to 43 percent after 5 years (Nicholson 1965b). In Puerto Rico, seedlings of the opportunist *Tabebuia heterophylla* may cover the floor within moist forests from early in the rainy season until the next dry season, when they nearly all disappear.

The complex factors involved in the natural regeneration of primary tropical forests are not well understood. Past interest in exploiting these forests for timber has concentrated on a few merchantable overstory species. The adequacy of natural regeneration was assessed in terms of the sapling density of only those species. Except for dipterocarp forests on the best sites (Tang and Wadley 1976a) and a few other special circumstances, advance regeneration of these species was inadequate for a second crop composed entirely of such species. This conclusion, notwithstanding the gradual, continuous process of natural regeneration that in nature maintains primary systems, results from the limited number of species that have been acceptable on the market and unwillingness to accept the natural timespan for this process.

Where natural regeneration of a few selected timber species has been considered inadequate, it has been assumed that a thinned overstory and a prepared seedbed beneath it would engender a good crop of these species within a few years. This assumption, too, seems to have been at odds with the capability of these timber species as seedbearers or as competitors in a liberated understory. This subject is discussed more fully in the next chapter.

Environmental Influences

Responses of primary tropical forests to their environment plus the reciprocal influences of forests on the environment are considered here from the standpoint of productivity. Many of the biological variations in tropical forests are merely different points along continua rather than abrupt changes. These variations usually result from more than one cause, and these causes do not all affect the forests at the same rate or in the same way. Therefore, differences may appear gradually, and it is difficult to describe them discretely or to ascribe them to specific causes. A complicating factor is doubt as to how precisely apparently undisturbed forests represent natural conditions of the present or recent past. Sauer (1957) makes a case for questioning this point almost everywhere that drainage and relief are favorable for former human habitation. It has been said that there may not be a single climax forest in all of Africa. Findings throughout the Amazon Basin bear witness to former habitation, at least on certain soil types, and some of these sites are not even accessible. The restoration of a primary rain forest, despite rapid early filling of gaps, presumably takes more than a generation of the climax species to reach stable composition. Thus, what appear to be primary forests, however seemingly undisturbed by human intervention, may indeed have been influenced by early human activity.

Geographical isolation greatly affects forest productivity, especially on oceanic islands (MacArthur and Wilson 1967). Small islands may have fewer habitats than would an equal area on a continent because of less immigration and differentiation in dispersal mechanisms. The number of species on a given island is usually related to the island's size, as is environmental diversity, which more directly relates to species numbers.

Catastrophic weather phenomena (e.g., hurricanes) have unmistakable and lasting effects on the character and development of forests. Where hurricanes pass frequently, forests may resist winds well but lack internal stability, retaining a higher proportion of seral (successional) characteristics than elsewhere. Hurricane-lashed forests generally suffer tree-crown breakage and unidirectional uprooting. Surviving trees tend to produce buttressed roots, short stems, dense wood, and compact crowns of coriaceous leaves (King 1945). The fact that they have survived hurricanes does not mean that they do not suffer damage or take a long time to recover. The trees may resprout and replace crowns even at advanced ages, but the effects of breakage may never entirely disappear. For a recent report on the influence of hurricanes on tropical forests, see Walker and others (1991).

Environmental relationships of forest ecosystems are two-way. The forest has a general ameliorating effect on environmental extremes. Within primary forests, the microclimate varies from the top of the uppermost tree canopy, where exposure to the elements may be similar to that in deforested areas, to ground level, where external effects are moderated, producing a relatively equable environment (Baur 1964a). At the ground level, stability of litter, soil, water, and nutrients promotes sustainable forest productivity.

Moisture. Moisture is the most important environmental factor determining distribution, species composition, and growth of forests (Kozlowski 1982). Forest productivity is closely correlated with moisture availability. From wet to dry environments, forest height declines from 50 to 10 m or less. Of significance to wood production is the great difference in the amount of stemwood under different moisture conditions. Veillon and others (1977) found stemwood in Venezuelan forests to range from 35 percent where mean annual rainfall was 40 cm to 65 percent with 260 cm of rainfall.

Available moisture is also significant to other structural features. Evergreen seasonal forests and rain forests in Cambodia and Thailand with similar biomass had leaf area indexes of 7.3 and 10.7 to 12.3, respectively (Art and Marks 1971). There is less layering of vegetation in dry forests than in wet forests, and many of the special life forms are absent (Webb 1959).

Seasonal climates characteristic of the outer Tropics are very significant to forest growth. Schulz (1960) concluded that drought in Suriname is chiefly responsible for periodicity of growth. As already mentioned, stems grow mostly in the wet season.

Primary forests first encounter rainfall as it is intercepted by tree crowns. Data on the average amount of rainwater intercepted are meaningless because the degree of canopy cover and the intensity and duration of the rainfall vary widely. A study in the rain forests of Panama showed that interception percentage increased with canopy cover and was greater during light showers (Golley and others 1975). A similar relation was found in the moist forests of Puerto Rico (Clegg 1963). With a rainfall of 0.13 cm, interception was complete; with a rainfall of 2.03 cm, only about 50 percent was intercepted.

In Thailand, interception varied markedly with the forest type, being greater in the dry forests (Chunkao and others 1971). On days with rainfall between 0 and 1 cm, mean interception in evergreen forests was 24 percent, compared to 78 percent in dry dipterocarp forests. For days with from 2 to 3 cm of rainfall, the corresponding percentages were 14 and 64. Also, interception declined with increasing rainfall as the canopy reached saturation. The higher interception rates for the drier forests are not clearly explained, but may well be due to less intense rainfall in these areas even when the day's rainfall is substantial.

Intercepted water is less than a total loss to the ecosystem because it joins the system as water released through the stomata, absorbing heat in the process of evaporation and contributing to atmospheric humidity nearby (Monteith 1975). There is no significant humidity gradient at night, the atmosphere at all levels being near saturation (Davis and Richards 1933/34). Relative humidity in a terra firme forest near Belem, Brazil, measured for a year (Bastos and others 1974), showed year-round constancy of air saturation at night, even 15 m above the ground (table 3–18; Bastos and others 1974). Even at noon, no real humidity stress is evident. Evaporation and transpiration prevent the air from drying out. In Nigerian rain forests, little or no water vapor was lost from the lower to upper layers during the day (Evans 1966).

Dew at night could compensate, in part, for interception. As the temperature drops, the atmosphere is generally at or near the saturation point. Nevertheless, in some Nigerian rain forests, no dew falls to the ground (Evans 1966). Another study found that dew is retained by small leaves; only the large digitate leaves of *Musanga* accumulate sufficient dew so that some of it drops (Longman and Jenik 1974).

Of the water that passes through the foliage, the fraction that flows down the stems of the trees is insignificant except during the most intense storms, according to one study in Malaysian rain forests (Kenworthy 1971). About 1 percent of the water received evaporated from the soil surface, and only 3 percent ran off the soil surface, indicating that 96 percent percolated into the forest soil. The basal streamflow, including surface runoff, totalled about 25 percent of the rainfall. Base flow was reduced during the day because of more active transpiration, estimated at 135 cm/yr.

Temperature. As would be expected, temperature (especially minimum temperature) affects plant growth in the Tropics. For example, the minimum temperature of the outer Tropics is lower than that of the equatorial Tropics, adversely affecting the flora.

Vegetation on tropical mountains may also be affected by low temperature, but the effect is confounded by differences in rainfall, wind, and cloudiness. Nevertheless, Grubb (1977) found that as elevation increases in wet tropical forests, height drops from 42 to 2 m and species richness, leaf size, buttresses, and climbers decline. He concludes that the upper elevational limit of species occurrence is probably determined by temperature, whereas the lower extreme is probably determined by competition. He also sees nutrient deficiencies changing with elevation and transpiration reduced by cloudiness. At high elevations (and low temperatures), the trees became crooked as on poor, lowland soils. Moreover, at low temperatures, large amounts of available N and P are locked up in undecayed litter and unmineralized humus.

The effect of elevation on plant growth is not consistent, however. A study in Venezuela (Veillon 1965) indicated that the number of trees, basal area, and volume in primary forests do not decline with elevations up to 3,000 m. A similar conclusion was reached comparing tropical (>24 °C) and premontane (12 to 18 °C) vegetation in Panama (Golley and others 1969).

Plant growth rates are affected by both day and night temperatures as well as by day length (Longman and Jenik 1974). Photosynthesis is believed to be most

Table 3–18.—Mean relative humidity in a terra firme forest near Belem, Brazil, by month, time of day, and height above ground (%)

	Relative humidity			
	1.5 m above ground		15 m above ground	
Month	Noon	Midnight	Noon	Midnight
January	91	99	80	99
April	92	100	84	100
July	71	94	66	99
October	78	95	66	97

Source: Bastos and others (1974).

efficient and plant growth most rapid at about 30 °C (Thornthwaite 1948). Chang (1968, cited by Scott 1976) believes that because respiration as well as photosynthesis varies with temperature, net primary production of ecosystems is relatively unaffected by moderate changes in mean temperature.

The forest's buffering effect may reduce the daily temperature range to less than a third of that outside the forest (Baur 1964a). In a Nigerian rain forest, heat input into the lower forest strata from 10 a.m. to 7 p.m. averaged 10 kcal/m^2/h, and heat lost at night averaged 7 kcal/m^2/h (Evans 1966). No heat was lost from either upper or lower layers during the day, heat transfer occurring mainly at night.

Temperature variation within a terra firme forest along the Amazon, near Belem, was minimal during both the day and the year (table 3–19). However, the temperature at 15 m above surface level is higher than that at 1.5 m at noon and lower at midnight (Bastos and Diniz 1974).

Bastos and Diniz (1974) found greater uniformity in soil temperatures beneath the forest than in open areas; they also found that the difference in temperature between forest and open land is greater at the surface than 1 m below (table 3–20).

Brinkman and Goes Ribeiro (1971) found that at 2 cm above the ground surface under the primary forest in central Amazonia, the temperature rose above 30 °C only 3 percent of the time, and the maximum reached was 33.9 °C. In the open, they found the corresponding temperature was above 30 °C 52 percent of the time and reached a maximum of 49.9 °C.

Light. Light reduction within forests is gradual from the tree canopy to ground level. Yoda (1974) found that visible illumination received at 57 m above ground in a Malaysian rain forest drops to 30 percent at a height of 40 m, 20 percent at 30 m, 5 percent at 20 m, 2 percent at 10 m, and 0.5 percent at 1 m. In a Suriname rain forest, 1.5 percent of full sunlight prevailed in the undergrowth (Schulz 1960). The level found in a terra firme forest near Manaus, Brazil, was 1.4 percent (Conceicao and Barros 1979). Another study showed a maximum at noon of 0.1 percent, declining to 0.05 percent by 3 p.m. and to 0.02 percent at 4 p.m. (Longman and Jenik 1974). Of the 2 to 3 percent reported for Malaysian and Nigerian rain forests, from 5 to 6 percent is direct skylight, 25 to 44 percent is transmitted light, and 50 to 70 percent is sunflecks (Baur 1964a).

Because of the distance between the canopy and the soil, most gaps in the canopy are smaller than the Sun's apparent diameter, and thus a large amount of the transmitted light is in penumbra zones, resulting in relative uniformity of illumination at the forest floor (Chartier and others 1973).

The decreasing light with depth beneath a forest canopy results in tree suppression. In a Puerto Rican forest with 1,566 trees of 5 cm in d.b.h. or more per hectare, only 4 percent were dominant; 10 percent were codominant, 32 percent intermediate, and 54 percent suppressed (Anon. 1953a). The relative d.b.h. growth rates of these four classes indicate, in part, the significance of illumination. If the mean diameter growth rate of dominant trees is set at 100, the codominants may grow at a relative rate of 90 to 110, the intermediates at about 50 to 70, and the many suppressed trees at only 10 to 30. Under these

Table 3–19.—Mean temperature variation in a terra firme forest in Brazil by month, time of day, and height above ground (°C)

	Noon		Midnight	
Month	1.5 m above ground	15 m above ground	1.5 m above ground	15 m above ground
January	26.7	27.6	23.6	23.1
April	27.1	28.7	24.6	24.8
July	27.5	28.1	23.6	23.0
October	27.7	28.6	23.4	23.0

Source: Bastos and others 1974.

Table 3–20.—Soil temperatures near Belem, Brazil, by month, depth, and type of land (°C)

Month	2-cm depth		1-m depth	
	Forested	Open	Forested	Open
January	25.2	31.3	25.1	28.4
April	25.3	31.6	24.9	28.6
July	25.4	36.8	25.0	29.2
October	25.1	40.2	25.0	30.0
Average	**25.2**	**35.1**	**25.0**	**29.1**

Source: Bastos and Diniz 1974.

conditions, a tree of 30-cm d.b.h., which has spent much of its life suppressed and still may be only an intermediate, may be 180 or more years old.

Soils. Tropical forests have evolved toward maximum use of available soil nutrients. In rain forests, the limiting nature of nutrients vis-a-vis moisture and temperature highlights mechanisms of adaptation to nutrient deficiencies. On the most infertile soils (e.g., Podsols and peat swamps), rain forests include those species with a tolerance for such deficiencies, although they may be able to meet the keener competition among trees characteristic of more favorable sites.

On nutrient-poor substrates, such as Latosols near Manaus, Brazil, the nutrient content of fine roots is generally lower than elsewhere (Klinge 1976). Adaptations to these conditions include (Herrera and others 1978): (1) dense root mats with high nutrient retention capacity; (2) direct nutrient cycling through mycorrhizae; (3) accumulation of chemicals in the leaves (herbivory reduction); (4) recovery of nutrients by leaf shedding; (5) resistance to Ca deficiency, Al abundance, and acidity; (6) litter arrangement on the forest floor so as to reduce leaching; and (7) epiphytic fixation of N from the air.

Serpentine soils may be especially inhibiting to growth because of unfavorable physical factors such as high Mg, nickel (Ni), and possibly chromium (Cr) levels, or low Ca or nutrient levels (Proctor and Woodell 1975). Tree adaptations may include favoring uptake of some elements and not others or tolerance of high levels of Mn, Cr, cobalt (Co), and Fe. The effect is to exclude all but the most tolerant or adaptable species.

Poor soils reduce forest stature as well as richness of composition. The cerrados of Brazil, forests characteristic of poor soils, grow to only 12 m in height and no more than 70 cm in d.b.h. (Rizzini 1975). Schulz (1960) described an exception in the savanna forests of the white sands of Suriname. He reported that small areas of white sand may be wholly covered with tall rain forests, apparently because roots extend down 5 m to the decomposing rock.

Conversely, favorable soil conditions are reflected in the quality of primary forests. The abundance of natural regeneration of sal (*Shorea*) in India increases with the availability of N and P in the soil (Seth and Bhatnagar 1960).

Mangroves manifest the significance of adverse soils to natural forests (fig. 3–5). Flooding and the presence of salt favor the mangrove species because it is the only

Figure 3–5.—*Mangroves produce dense cover over the shores of estuaries and tidal swamps.*

species that can tolerate these conditions. Segregation of species within the mangrove may also be sharply defined. In Sabah, the occurrence of two species of *Rhizophora* is clearly related to distance from the seafront. *Rhizophora apiculata* is most abundant about 250 m from the front, whereas *R. mucronata* is at its maximum abundance 650 m from the front (Liew and others 1975). *Avicennia* is favored where salinity becomes higher than the other species can tolerate.

Experiments in Hawaii with common tropical soils—Oxisols, Ultisols, Inceptisols, and Histosols—show the influence of forests on soil porosity (Wood 1977). Infiltration rates under forests were three to five times as great as in comparable soils under pasture, sugarcane, and pineapples. Infiltration rates in the forest (measured with concentric ring tests) ranged from 15 to 39 cm/h whereas the highest rates for pasture were 5 cm/h, for sugarcane, 3 cm/h, and for pineapples, 9 cm/h. The larger soil aggregates under the forest also lower susceptibility to erosion.

Topography. Major differences in primary tropical forests as a result of elevation have already been pointed out. Less well known is the influence of local topography within different forest types. Ridgetops in wet climates are better drained than valley bottoms and may have more newly weathered material available, but they are also more erosion prone. In contrast, valley bottoms in dry climates have more available moisture and benefit from colluvial deposition.

Studies of mountain forests in Puerto Rico showed long ago that there was segregation of tree species on the basis of local topography (Wadsworth 1953). Even though hills and valleys may be very close, mature trees of some species occur chiefly on one and only occasionally on the other. *Dacryodes excelsa,* for example, is usually found near the ridgetops, whereas *Guarea guidonia* is usually on lower slopes or valley bottoms.

Stand density is also influenced by topography. In the dipterocarp forests of Malaysia, the total number of trees per hectare larger than 27 cm in d.b.h. was 58 on the ridges versus 33 in the valley bottoms (Wyatt-Smith 1960c). For the economic species, the corresponding numbers were 30 and 11. The disparity among large trees is more extreme. In the same area, Burgess (1970) later classified the lower hillsides as marginal for timber production and excluded the valley bottoms and slopes in excess of 45°.

Topography, and more specifically aspect, may be significant to forest productivity in much of the Tropics where there is a pronounced prevailing wind direction. In the tradewind zone of the outer Tropics, eastern slopes may present a surface perpendicular to the slanting fall of wind-driven raindrops, whereas western slopes may be nearly parallel. The effect may be greater rainfall and erosion on eastern slopes, leaving shallow soils that cannot absorb and retain much rainwater. Evaporation, also a result of the same prevailing wind, may then leave exposed slopes drier than protected ones.

Growth-Prediction Experience. Attempts to correlate the diameter growth of individual trees with competition and tree size have not been very successful. In Puerto Rico, no correlation was found between the diameter growth of *Dacryodes excelsa* and the basal area of neighboring trees within 8 m, although initial diameter and crown class did explain about a third of the variability (Wadsworth 1953). In northern Nigeria, girth, height, and crown size accounted for 40 percent of the variation in subsequent growth (Kemp and Lowe 1970). Density, expressed by relascope count, basal area of competitors, and summed height of competitors, accounted for 19 percent more. Site variables accounted for an additional 14 percent. In another area of Nigeria, about 70 percent of the variation in diameter growth among the trees was related to their own basal area (Lowe 1971). Height and crown diameters were strongly correlated with basal area but did not account for additional variation in growth. Competition did not account for more than 5 percent of the variation in growth, even where competition was evidently strong. Drainage and topography did not account for a significant portion of the variation in growth.

A 24-year study of 1,560 trees in subtropical wet forests in Puerto Rico showed a marked decline in percentage basal-area growth above 35 cm d.b.h., more rapid growth on valley bottoms than on ridges and on steep versus flat slopes, and 70 percent more growth on dominant trees than suppressed ones. Such studies clearly are dealing with complex multivariate relations still little understood. One hypothesis is that in stable forests the proximity of trees so reflects soil quality that individual tree growth is about the same regardless of surrounding forest density.

Other Effects. Wind speeds are sharply reduced within tropical forests. A study of wind velocities in a wet forest in Colombia during January to April showed that if wind velocity at 60 m above the ground surface is rated 100, the corresponding rate in the treetops at 42 to 45 m is 30 (Baynton 1965). At half the canopy height, the rate is 3, and at 2 m above the ground, the rate is 1, suggesting that wind and light are reduced by about the same magnitude.

A dense tree barrier may protect a downwind area 10 to 15 times the canopy height (Rosenberg 1974). Paradoxically, forests that are open near the ground allow wind through that slows the downwind descent of the turbulent air that has been forced upward by the canopy, increasing significantly the length of the downwind reduction in mean velocity at the surface.

The fact that forests reduce soil erosion is well known. The significance of this attribute increases with steepness of slope and intensity of rainfall. Mangroves in estuaries significantly trap sediment arising in tropical watersheds. The mangrove initially follows sedimentation, but once established, mangrove stilt roots slow and precipitate additional sediments (Watson 1928).

Soil degradation in humid climates is inevitable in level areas unless there is an outside nutrient source (Assman 1970). On slopes, weathering of parent rock may continuously replenish nutrients. This process is partially responsible for the lasting productivity of forests on slopes. Additional nutrients may be made available by chelation. Many forest plants appear to produce chelating agents that expedite soil formation (Longman and Jenik 1974). Even so, in ferralitic (iron-containing) soils, few undecomposed, nutrient-rich minerals are generally left within reach of plant roots. The cation-exchange capacity of these soils is very low except for the thin layer of humus at the top, a direct product of the forest itself.

Yields

The yields of primary forests may be expressed in different ways, based on their increment rate and depending on the evaluation criteria applied. Ecologists see yield in terms of net primary production, which is gross primary production minus respiration. This is equal to net growth of all organisms, above and below ground, plus the litter produced. Then, because the traditional forest products utilized are mostly made from tree stems or from stems and branchwood, the volume increments of these forest components are of special interest to the timber producer. Finally, there is the yield expressed in terms of merchantability. This excludes stemwood that is not economical to harvest, because of species, small size, crook, or defects and, generally, bark and, possibly, sapwood, slab, edgings, and sawdust, depending on the product.

Primary Productivity. Gross primary productivity of primary closed tropical forests ranges between 13 and 123 t/ha/yr (Golley and Lieth 1972). It is estimated that 60 percent of the total primary productivity of the Earth's land surface is in the Tropics, and another 20 percent is in the sub-Tropics (Rodin and others 1975). Subtracting respiration, net primary productivity ranges from 10 to 32 t/ha/yr (Murphy 1977) and is related to temperature and precipitation (table 3–21) (Lieth 1972). It also varies by forest type (Rodin and others 1975):

Forest type	Net primary productivity (t/ha/yr)
Tropical	
Humid	27–30
Seasonally humid	15–16
Flood plains	70
Mangrove	10
Semiarid	7–14
Subtropical	
Humid	16–22
Montane	18
Semiarid	5–10

Primary productivity of a tree community is related to the growth of the usable stemwood to a 7.5-cm limit (Dawkins 1961d). Annual turnover (leaves, nonpersistent twigs, inflorescences, and fruits) generally ranges between 20 and 30 percent of a tree's dry weight wood accretion. Dawkins concluded that it is highly unlikely

Table 3–21.—Relationship of climate and net primary productivity

Mean temperature (°C)	Mean annual precipitation (cm)	Net primary productivity (t/ha/yr)
10	100	14
20	200	22
30	300	26
30	400	28

Source: Lieth 1972.

that the total primary production of a tree community would exceed 1.6 times the easily measured stemwood growth.

Useful Wood. Except where fuelwood is important, stemwood productivity is the best measure of prospective useful wood yield. Stemwood makes up 70 to 80 percent of the aboveground phytomass of primary forests (Dawkins 1961d). Dawkins (1964b) studied tree diameter growth relative to relascope basal area, crown exposure, and lateral interference. He concluded that, with 90-percent crown cover and the greatest practical crown freedom, maximum wood yield is about 11 t/ha/yr. Weck (1963), cited by Bazilevich and Rodin (1966), came to a similar conclusion.

In commercial forests, the merchantable yield is not the same as net primary productivity. Not only are the roots of no direct concern, but neither are the termini of the stems, the leaves, or (usually) the smaller branches. Furthermore, maximum economic return may not relate directly to maximum volume production because, for most products, large trees are generally worth more than an equal volume in small trees.

Quantity of useful wood per unit of forest area (which may be independent of quality) is of paramount concern. As Gallant (1959) pointed out many years ago, the tropical timbers most in demand in world trade are among those most common in the forests. While any species that grows to useful dimensions and is of good form is likely to be accepted in expanding local markets, those woods that can be obtained in quantity will still be preferred.

Hughes (1968b) observes that it would be unwise to assume that changing use patterns and improved technology will eventually solve the problems of utilizing all species now considered secondary in quality. There are usually good reasons for classifying a species as secondary. It is unlikely that such problems as difficulty in sawing, excessive distortion in seasoning, resistance to nailing, and poor working properties can be overcome at a cost that will allow such wood to be used for construction and joinery (Hughes 1968b). Furthermore, the increased use of wood for pulping may not encourage management of forests of poor-quality species. To operate efficiently, paper and board industries require raw materials of uniform size and quality. Into the distant future, demand for large trees will continue because the strength and surface of their wood provide great versatility in the natural state, requiring little modification (Hughes 1968b).

Because the more valuable forest products are appraised according to dimension rather than weight, their economic productivity is more meaningfully expressed in volume growth (cubic meters per hectare per year) than in mass. However, where conversion is required, average wood specific gravity in primary moist tropical forests is about 0.6; therefore, for broad comparisons, 1 t metric equals about 1.67 m^3, or 1 m^3 equals about 0.6 t.

Only a small proportion of the wood in primary forests has generally been usable. Baur (1964b) found an average yield of usable wood of less than 3 m^3/ha/yr. Ovington (1972) found a range from 2 to 6 m^3/ha/yr, with the average below 3.5. Maudoux (1958, quoted by Catinot 1974) also gives an annual rate of growth for west African forests of 3 m^3/ha/yr. Veillon (1974) found, in Venezuela, growth of 9.3 m^3/ha/yr in a tropical moist forest, 4.0 in a tropical dry forest, and 1.0 in a tropical very dry forest. Mangroves in Madras, India, although subject to intensive demand, were once reported as producing no more than 2 m^3/ha/yr of usable wood (Venkatesan 1966).

Assuming that the growth of individual trees may be expanded to the limit of forest growth in basal area, Dawkins (1961b) theorized that potential productivity of timber from native species would reach a maximum of 24 m^3/ha/yr for lowland tropical forests. For rapidly growing, intolerant genera such as *Ochroma* and *Cecropia,* the maximum might reach 43 m^3/ha/yr. However, such levels are not attainable with our present knowledge of site values and without genotypic selection. Moreover, present standards for sawlogs and veneer logs leave at least 40 percent of the stemwood volume unused.

If Dawkins' and Weck's prediction of a maximum stemwood productivity of 11 t/ha/yr is correct, if mean wood specific gravity is 0.6 and if current stands are producing only 3 m^3/ha/yr (Baur 1964a), only about a sixth of the wood produced is considered marketable. Much more complete utilization of primary forests seems probable. Whitmore (1980) lists many of the products that could (and should) be made from the primary and secondary plants of the forests of Southeast Asia: timber, cellulose, lignin, hemicellulose, protein, insecticides, essential oils, food colorings, medicines, gums, latexes, resins, and waxes.

Variations. The variability of tropical forests, even within short distances, probably greatly affects productivity but is difficult to characterize, assess, map, or predict. One example is the extremely variable rain forest in hill country where most of the large trees are on the ridges and upper slopes, such as in Malaysia and the West Indies (Burgess 1970, Wadsworth 1953). Yet, classification of subformations or associations over extensive areas, however convenient, remains nebulous because the classes may be arbitrarily defined sections of a continuum (Baur 1964a, 1964b). Discrete grouping seldom appears (Schulz 1960). In what appears an act of desperation, even the understory has been suggested as a site indicator superior to the overstory trees.

Description of the differences among tropical forests is difficult, and the results are not very satisfactory. The mere problem of tree identification may be almost insurmountable at the outset. Ecologists and botanists have come to question some of the identifications in the large transect study of the Amazon forests made by Heinsdijk (1960), something to be expected as botanical exploration and taxonomic research intensifies. Many species are rare. Also, juvenile foliage may be unlike that of mature trees. There is little outward evidence of the environmental adaptation of tropical trees or the periodicity of their functions, many flowering and fruiting nonsynchronously.

Low maximum stand density (basal area) is a striking limitation in tropical forests. The vertical stratification of crowns in a primary forest does not necessarily increase stand growth, even though it may increase growth of individual trees (Assman 1970). For mixed broadleaf forests, the maximum stand basal area that allows for acceptable, individual tree, diameter growth is generally less than 35 m^2/ha, or about half that of Temperate Zone conifer and eucalypt forests. Crown diameter-to-d.b.h. ratios of 21 to 23 are common (Bell 1971, Paijmans 1970).

Dawkins reports that these ratios for light demanders, unlike those for tolerant species, do not decline as maturity is approached. The relatively open stand required to assure continued rapid growth of light demanders contrasts sharply with primary forests. The fact that respiration rates rise with temperature more rapidly than photosynthesis rates (by the C^3 path) may also limit the production of tropical forest ecosystems.

Primary forests contain many species that are difficult to assess, utilize, or grow. Examples are the *Calamus* spp., or rattans, which grow as a vine reaching the top canopy. Other species that are difficult to grow economically in mixed forests are those producing elastomers, resins, latexes, edible oils, medicinal products, and fruits. Many of the large trees of good form have extremely hard wood or high silica content. Some have low resistance to splitting. Others emit unpleasant odors or are a source of allergies. Many are of poor form or are so rare that not enough raw material is available for economic utilization.

The breadth of the niche utilized by each species is not obvious, leaving in doubt the causes of variation in species occurrence and performance. The presence of high buttresses and the lack of growth rings as reliable indicators of the age of woody species are major handicaps in assessing growth. Photogrammetry and other remote sensing techniques have not yet provided many details of silvicultural significance. Variations in tolerance by both species and age classes complicate growth predictions and silvicultural prescriptions. Merchantability of even apparently sound trees is highly variable because of hidden defects.

Trenching and understory weeding experiments shed light on the significance of competition for water and nutrients on individual tree growth within forest ecosystems. An experiment in a *Shorea* (deciduous) forest in India showed that weeding stimulated seedling height growth more than trenching did, the difference being highly significant (Bhatnagar 1959). In the weeded plots, trenching barely affected subsequent growth. This was unexpected because, in deciduous forests, competition from large trees was presumed to be more severe than competition from weeds. At the end of 12 months, trenching increased height growth 8 percent, compared with 39 percent for weeding. Because weeding should reduce competition for both water and nutrients, the two were probably confounded in the study. Also, the full benefits from trenching might not appear within 12 months.

Variations in growth times and rates among different species and in different places may be difficult to assess, let alone predict. Periodicity of growth in wet forests is largely independent of obvious climatic events

(Tomlinson and Gill 1973). Some species grow continuously, at least to some degree, and others exhibit periodicity of different degrees, making it necessary to measure growth in complete years. Even measuring only in the dry season is not safe for all species, because some that appear seasonal may grow even at this time (Longman 1969). Some species produce new leaves in the dry season. In Ghana, on the other hand, deciduous trees lose their leaves in November; whereas the predominantly evergreen trees tend to lose theirs in March (Longman 1969).

Not only is growth variable, but attempts to measure it can be confounded by seasonal shrinkage. Daubenmire (1972) found in Costa Rica a d.b.h. change of 0.04 cm in *Swietenia macrophylla* due solely to changes in bark moisture. Much larger differences have been recorded with *Eucalyptus robusta,* a species with spongy bark. Dry-season shrinkages in d.b.h. have been recorded up to 0.246 cm (Daubenmire 1972). Repeated growth measurements in successive dry seasons may vary significantly because of differences in dryness among seasons.

Growth rates may vary even during each day. Terminal growth of *Dendrocalamus strictus,* a bamboo, was determined for six culms averaging 137 cm in height (Dutta and Tomar 1964). New culms were produced from July to September. The maximum height growth for the six culms was 27.2 cm in a 24-hour period, but more than half the height growth occurred at night. In Suriname, measuring trees between 6:30 and 11 a.m. minimized daily variation (Schulz 1960).

The absence of clearly discernible growth rings and their unknown periodicity further complicate assessing tree growth rates in tropical forests. Most species do not produce rings sufficiently distinct and continuous to yield the same count by different observers. Even deciduous trees distinctly seasonal in stem-diameter growth may show little evidence of rings in the wood. Where growth rings are distinct, some correspond to shoot elongation, and some do not (Tomlinson and Gill 1973). *Avicennia germinans,* a mangrove, produces rings of such uniformity in separation that they correlate with stem diameter rather than age, and there apparently may be as many as six per year.

A 36-year record of the mean basal-area percentage growth of 153 trees of *Dacryodes excelsa* in an uncut, old-growth, subtropical wet forest in Puerto Rico recovering from a 1932 hurricane showed wide variation even when averaged for different periods each of several years. No readily evident explanation for the fluctuations exists, although the general tendency toward slower growth probably reflects increasing forest density with recovery. Clearly under these conditions, averages for even a few years may not represent the long term. The means are as follows:

Period	Mean annual Basal-area growth (%)
1946–82	2.04
1946–52	4.52
1952–58	2.42
1958–65	3.20
1965–76	1.42
1976–82	1.63

Assessing seed adequacy for sustaining stable tropical forest ecosystems is complicated by extreme variation among species in time of seedfall and in seed viability on the forest floor. Seeds of typical overstory species of wet forests are generally perishable and so may be present for only a brief period after they fall. Light-demanding genera such as *Cecropia,* on the other hand, may be minor components of primary forests, yet most of the viable seeds on the forest floor are theirs because of their long viability. These seeds may be dormant until some unusual event exposes them to enough light for germination, whereas germination of seeds of the tolerant species actually may be inhibited by light (Baur 1964a, 1964b).

Much has been said here about yields of harvestable products from primary forests. Such forests are still the chief source of forest products in many tropical areas. Yet, the removal of either plant or animal products from forests leaves a forest that, by definition, is no longer primary. If primary forests are to persist, their uses must be solely nonextractive, such as for preservation of plant and animal biodiversity and germplasm, soil stability, water quality, nonmanipulative scientific research, and nondestructive educational or recreational activities. Products, therefore, must ultimately come entirely from forests that are secondary and from plantations, discussed in the following chapters.

Chapter 4
Secondary Forests and Their Culture

Primary forests are forests that are undisturbed by significant human intervention. Thus, any human modification of a primary forest terminates its "primary" condition (fig. 4–1). The term "secondary" is applied to "forest growth that has come up naturally after some drastic modification (e.g., wholesale cutting, serious fire, or insect attack) of the previous forest" (Ford-Robertson 1971). Literally interpreted, secondary forests would appear to be only those forests that arise after virtual land clearing and would, thus, exclude cutover forests that retain a partial canopy. However, this chapter combines both types of forests under the term "secondary." Although the two may be different in structure and composition, with time and particularly as each may be subjected to management, their respective characteristics and treatments are bound to converge. Even now, the more advanced volunteer forests call for the same treatment as many cutover stands.

Of the forests that remained in 76 countries in the Tropics in 1980, at least half were secondary (Anon. 1982a). Of these, about 9 million km^2 were potentially productive (table 4–1), meaning those forests where terrain and current regulations did not prohibit the production of useful wood (but without regard to present accessibility).

Relative to population, the extent of potentially productive secondary forests in tropical America is intermediate between that of Africa and that of the Asia-Pacific region. In Africa, 72 percent of these forests are open (dry); only 28 percent have a closed canopy. In America, this relationship is 50:50; whereas, in the Asia-Pacific region, it is 6:94.

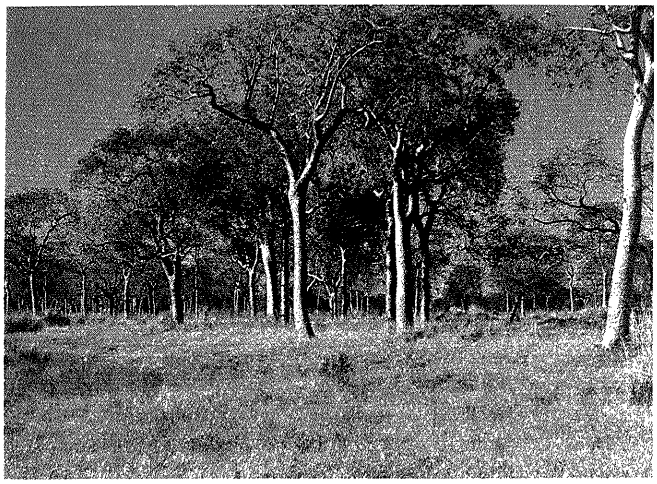


Figure 4–1.—*Residual dry forest remaining after years of overgrazing and fires; composed almost totally of* Bursera simaruba, *with no regeneration beneath.*

Existing secondary tropical forests are being lost through deforestation, but partial fellings in primary and old-growth forests are producing new cutovers classified as secondary (table 4–2; Anon. 1982e). Also, other land is reforesting naturally. The net effect has been a decrease in secondary forest area during 5 years at only about one-third the rate of primary forest decrease (Anon. 1982e).

The critical importance of current secondary forest area as a wood source in the year 2000, assuming intensified management to 6 m^3/ha/yr, is seen in figures presented by Wadsworth (1983). Because of the higher initial cost of plantations, they are much less extensive than natural forests. If, in the year 2000, plantations provide only the present proportion (12 percent) of our wood needs, we will thereafter need to exploit at least 90 percent of the remaining secondary native forests for wood. If plantations were to provide 50 percent of the timber needs, this dependence on native forests would decline to about 54 percent. However, with forest areas dwindling in the face of growing demand for the land for other purposes, the area that will be naturally regenerated and managed under sustained yield may be small in many countries.

The Nature of the Forests

There are two broad categories of secondary forest. One is residual forest that has been cut over once or more in the past 60 to 80 years, much of it within the last 30 years. Never having been completely felled, these forests retain some of their former characteristics.

The second category, termed "fallow" or "volunteer" (Anon. 1982a), is mostly volunteer growth after periodic cultivation. It lacks both the structure and the composition of the mature forest, because it is composed largely of pioneer species. About 55 percent of the secondary forests of the Tropics as a whole are cutover forests and 45 percent are fallow (volunteer). In tropical America, the corresponding relationship is 51 and 49 percent. The potentially productive secondary forest areas of the Tropics as a whole are 94 percent broadleaved and 6 percent coniferous (Anon. 1982e). In tropical America, this division is 87 and 13 percent.

Characteristics that distinguish secondary from primary tropical forests include the following (Budowski 1970, Odum 1969):

Features	Secondary Forest Characteristics Relative to Primary Forest
Nutrients and stability	
Inorganic nutrients	Extrabiotic, rather than intrabiotic
Mineral cycles	Open, rather than closed
Nutrient conservation	Less effective
Nutrient exchange with environment	More
Nutrient role of detritus	Less important
Food chain pattern	Linear, rather than weblike
Stability	Poor
Structure	
Biomass supported per unit of energy flow	Less
Size of organisms	Smaller
Upper canopy surface	More uniform
Stratification	Less organized
Lower tree stratum	Denser
Organic matter	Less
Tolerance of dominant species	Much less
Diversity	
Number of species	Fewer
Spatial heterogeneity	Less organized
Equitability of species	Lower
Niche specialization	Less
Symbioses	Less developed
Natural range of dominant species	Wider
Growth, regeneration, and productivity	
Growth selectivity	For rapidity
Regeneration of dominant species	Much less common
Seed viability	Longer
Life cycles	Shorter and simpler
Gross production	Higher
Gross production/respiration ratio	Greater than 1
Net primary production	Higher
Wood density	Less
Wood production	More

Other differences have been noted. In Trinidad, a secondary forest had a number of species that are characteristic of habitats drier than primary forests, fewer Leguminosae and Myrtaceae, and more Rubiaceae (Greig-Smith 1952). Herbivorous insects have been found to be 5 to 10 times more abundant in secondary forests than in primary forests (Janzen 1975), suggesting that the pioneers have fewer chemical defenses and dedicate more energy to growth. In Malaysia, for instance, secondary forests, lacking the predatory and parasitic insects of primary forests as controls, proved to be a major source of cocoa pests (Conway 1972). In Mexico, trees of secondary forests tend to use more energy for reproduction than for structure building, with many seeds per plant, wide dispersal, seed dormancy in the soil, and continuous seed production throughout the year (Gomez-Pompa and Vazquez-Yanes 1974). One hypothesis is that secondary forests may have deep, diffuse roots that concentrate nutrients dispersed through burning and leaching (Stark 1971).

Residual Forests. More than half the secondary forests of the Tropics have been cut, most of them selectively as opposed to clearcut (fig. 4–2). This has reduced the representation of the most valuable species and damaged some of the remaining trees, detracting from their potential productivity of useful wood.

Impacts of logging damage have been assessed in several tropical areas, chiefly in the Eastern Hemisphere. Reports commonly emphasize the number or proportion of the trees damaged; whereas future productivity depends on the opposite effect: the number and quality of the remaining trees (fig. 4–3). A study in Sabah of a dipterocarp forest (Nicholson 1958a) showed that trees 10 cm in d.b.h. or more left undamaged decreased from 76 percent to 42 percent as basal area removed increased from 2 to 10 m^2.

In Peninsular Malaysia, the harvesting of lowland dipterocarps to a diameter limit of 58 cm damaged 39 percent of the land area and 28 percent of the remaining trees between 10 and 39 cm in d.b.h. (Wyatt-Smith 1962a). Of the merchantable species, 56 percent of the saplings from 3 m tall and up to 5 cm in d.b.h. (173 trees per hectare) remained undamaged. Of the poles from 5 to 19 cm in d.b.h., 32 percent (210 trees per hectare) remained (fig. 4–4). Of the trees from 20 to 39 cm in d.b.h., 21 percent (35 trees per hectare) remained. And of those 40 to 58 cm in d.b.h., all 10 trees

Table 4–1.—Potentially productive secondary tropical forests, 1980

Region/country	Cutover forest (million ha)	Forested fallow (million ha)	Total (million ha)	Forest (%)	Land (%)	Area per capita[a] (ha)
World	494.110	402.02	896.13	37	18	1.40
Tropical Africa	213.800	165.98	379.78	46	17	2.00
Tropical Asia	108.170	73.22	181.39	44	19	.80
Tropical America[b]	172.140	162.82	334.96	31	20	1.30
Belize	.800	0.53	1.33	68	58	8.30
Bolivia	12.090	1.10	13.19	19	12	2.60
Brazil	130.650	100.62	231.27	37	27	2.00
Colombia	.900	8.50	9.40	16	8	.40
Costa Rica	.770	.12	.89	46	17	.40
Cuba	.800	.70	1.50	77	13	.10
Dominican Republic	.190	.27	.46	51	10	.09
Ecuador	.110	2.35	2.46	14	9	2.80
El Salvador	.010	.02	.03	19	1	.01
Guatemala	1.210	.30	1.57	32	14	.20
Guyana	1.350	.20	1.55	8	7	1.90
French Guyana	.150	.08	.23	3	3	3.80
Haiti	.010	.04	.03	56	2	.01
Honduras	1.190	.68	1.87	40	17	.70
Jamaica	.004	.16	.16	70	14	.08
Mexico	.300	26.00	26.30	35	13	.40
Nicaragua	.150	1.37	1.52	28	12	.60
Panama	.820	.12	.94	22	12	.50
Paraguay	2.480	3.27	5.75	16	14	2.00
Peru	6.000	5.35	11.35	15	9	.70
Suriname	.420	.27	.69	4	4	1.40
Trinidad/Tobago	.130	.06	.19	76	40	.20
Venezuela	11.610	10.65	22.26	49	24	1.70

Source: Anon.1982e.

[a] Per capita figures based on 1980 total population.

[b] Open woodland figures available for Brazil only.

per hectare remained. In all, 255 trees per hectare of 5 cm in d.b.h. or more remained undamaged.

The removal of 11 trees per hectare from dipterocarp forests in Kalimantan, Indonesia, seriously damaged 30 percent of the land area (Abdulhadi and others 1981). The number of trees was reduced from 445 to 259 per hectare and the mean basal area from 36 to 17 m^2/ha. Of the 259 trees per hectare remaining, 154 (59 percent) were undamaged. A study in Nigeria showed that removing 2.3 m^2/ha of basal area left 84 percent of the remaining trees undamaged, but removing 9.2 m^2/ha left only 44 percent undamaged (Redhead 1960a). Of the trees damaged, about 25 percent were injured only in the crown or bark. Such damage, although possibly sufficient to preclude further production of usable wood, was not considered a cause of early mortality. About 20 percent of the damage was caused by crawler tractors, a source more controllable than felling.

In the rain forests of Queensland, Australia, logging in stands with basal areas up to 80 m^2/ha has left as much as 50 m^2/ha, a third of which is made up of cabinet woods or other marketable species (Henry 1960). Such residual stands have been considered adequately

Table 4–2.—Annual change in potentially productive secondary tropical forest area, 1975–80

Tropical region	New conversion (million ha)	Reforested fallow (million ha)	Deforestation (million ha)	Net change (million ha)	Net rate of change (%)
Africa	+.64	+.95	−3.45	−1.86	−.5
America	+2.00	+1.54	−4.37	−.83	−.2
Asia-Pacific	+1.76	+.90	−1.51	+1.15	+.6
World	**+4.40**	**+3.39**	**−9.33**	**−1.54**	**−0.2**

Source: Anon. 1982a.

stocked. In fact, partial felling has only a minor impact on the rain forest environment, and its effects are quickly overcome (Anon. 1983c). Logging was reported neither to significantly extend stand recovery times nor to impair future production. Species diversity was reportedly better in logged than in virgin stands.

In Suriname, after attempts to apply the Malayan Uniform System (removing all trees down to 10 cm in d.b.h.) were unsuccessful in bringing on new regeneration, efforts to minimize logging damage to the immature trees left a residual stand that was adequate for a later second crop (Jonkers and Schmidt 1984). Despite expected further losses of up to 40 percent of the commercial trees, a crop of 19 trees per hectare, 30 to 50 cm in d.b.h., was expected to be harvestable in 20 years.

The partial cutting system developed in Suriname, designated "celos," predicts a yield of about 20 m^3/ha of quality timber every 20 years by maintaining a high level of biomass to prevent leaching of nutrients (de Graaf 1986).

In the moist foothills of Dominica, West Indies, studies of 62 0.1-ha plots showed that logging of the overwhelmingly dominant species, *Dacryodes excelsa,* left regeneration adequate for the next crop (Bell 1976). The remaining stand, ranging in basal area from 17 to 25 m^2/ha, was about 40 percent *Dacryodes* but also contained other commercially desirable species such as *Byrsonima spicata, Sterculia caribaea,* and several *Lauraceae.*

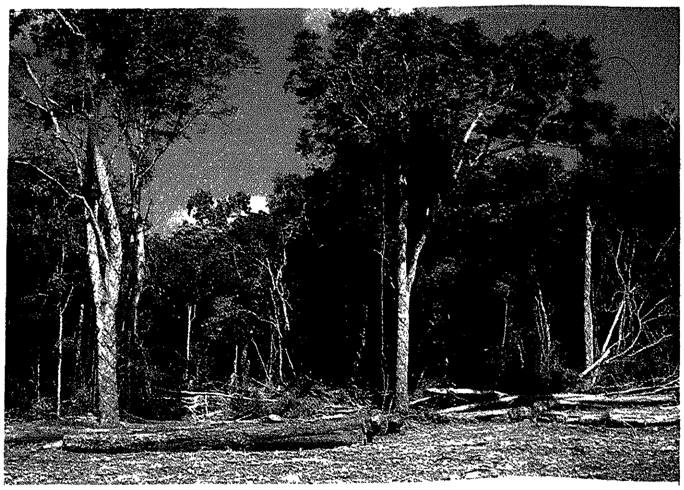


Figure 4–2.—*Residual forest in southeastern Mexico showing the density of the remaining cover.*

Figure 4–3.—*Moist forest in the Philippines immediately after logging showing remaining stand of small trees.*

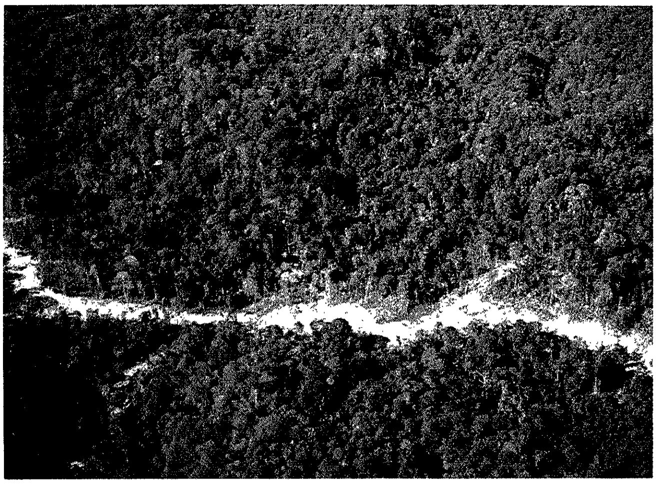


Figure 4-4.—*Residual hill dipterocarp forest in Sarawak, 18 months after removal of an average of 38 m³/ha, showing the preservation of forest cover of future potential.*

These examples suggest that logging may leave sufficient trees for a second crop, especially if logging damage is minimized through close control of field operations (Wyatt-Smith 1963). The use of high lead or cables and winches may cause less damage than tractor skidding.

However, timber harvesting may deteriorate the site even where the residual stand is adequate. Selective species removal may reduce the diversity (and conceivably the ecological stability) of the remaining forest. In one example, removing all stemwood (without bark) from moist forests eliminated 10 percent of the nitrogen (N), 39 percent of the phosphorus (P), 28 percent of the potassium (K), 20 percent of the calcium (Ca), and 57 percent of the magnesium (Mg) from the ecosystem (Ewel and Conde 1978). Even if removal is not complete, such losses, together with expected lower rates of infiltration, may threaten the quality of the site. After logging in one area in Kalimantan, Indonesia, infiltration of rainwater into the soil declined from 4.6 to 0.6 cm/min (Abdulhadi and others 1981).

However adequate the residual stand may be, its value is of little importance where abandoned logging roads invite cultivators to move in and fell what is left to convert the area to food production.

Fallow or Volunteer Forests. Where forests have been completely removed but the climate and soils still favor forest growth, the cessation of human disturbance allows gradual reestablishment if tree seeds reach the area. These forests may be deliberate agricultural fallows but, in any case, are volunteers. They resemble primary succession and usually differ significantly at the outset from the forests that preceded them.

Recovery Through Succession. Secondary forests, whether residual or volunteer, are continually changing through succession, a process whereby organisms better adapted to the redeveloping forest environment progressively replace the organisms of previous stages. Succession follows a pattern, is community controlled, reasonably directional, and therefore predictable. It culminates in a stabilized ecosystem in which maximum symbiotic function among organisms is maintained (Odum 1969). Succession increases the overall stability of the forest as an ecosystem and leads to increased resistance to disturbances. For timber production, successional forests more closely simulate rain forest behavior than do "steady state" forests (Anon. 1983c).

Four phases of forest succession in the broadleaf forests of the North Temperate Zone (Bormann and Likens 1981) appear to be relevant to the Tropics. These are as follows:

1. Reorganization, during which total organic matter declines despite an increase in living biomass
2. Aggradation, during which the system accumulates biomass and litter up to a peak
3. Transition, during which biomass and litter decline somewhat
4. Steady state, when biomass and litter fluctuate about a relatively constant mean.

During reorganization, dead organic matter from the former system is decomposing and disappearing more rapidly than biomass is being formed. Biotic regulation of water is established promptly, but rates of dissolved nutrient loss may exceed those of primary forests for a long period.

During aggradation, a modest but nearly constant excess of primary production over decomposition produces a high rate of biomass and litter accumulation. Resistance to export of nutrients is at its peak. Nitrogen accumulates from both precipitation and fixation. Also, the chemical components of drainage water and erosion are closely regulated. Streamflow is reduced, thus conserving nutrients. Interception and transpiration lower the quantity of stored water.

During transition, the rapid early rise in primary productivity that increases biomass declines with the shift to species that are slower growing but more efficient in exploiting the changing environment.

The steady state is a shifting mosaic in which patches are in different stages of development involving sequences of biomass accumulation and loss. Habitat diversity rises to a maximum. Species richness is greater than during aggradation, but in forests cleared only briefly, the richest diversity of flora may occur in the early phase, combining sprouts of the past advanced forest with seedlings of pioneers.

The composition of pioneer stands may indicate both the past and present environment (Hall and Okali 1979). Some species reflect the intensity of past land use, others, the quality of the soil. Small differences in the original environment observed in Suriname (such as concave relief) caused a remarkable divergency in succession (Boerboom 1974). Studies in wet areas of Mindanao, Philippines, on the other hand, led to the conclusion that there are also many environmental variables not correlated with vegetation (Kellman 1970).

Succession usually begins with species that, although uncommon in the stable forest, colonize major openings (fig. 4–5). Four common characteristics of such species contribute to their success during forest succession (Bormann and Likens 1981): (1) large quantities of viable seeds dormant on the forest floor, (2) germination triggered by disturbance, (3) rapid height growth, and (4) relatively rapid reproduction and reestablishment of a dormant seed pool.

Some pioneer species have such a sharply defined role that although 50 percent or more of the seeds may germinate in the light, none germinates in the shade (Vazquez-Yanes 1976). Examples are some tropical tree species of the following genera: *Cecropia, Clidemia, Myriocarpa, Solanum, Trema,* and *Urera*. Within the genus *Piper,* species common to secondary forests require light for germination, unlike those found in primary forests.

Figure 4–5.—*Gap regeneration by the opportunist* Cecropia spp., *following a hurricane in Puerto Rico, beneath which a mixed forest returns.*

The pioneer species that comprise early successional forests are especially adapted in other ways. Many depend on and immobilize a flush of nutrients such as may result from logging residuals immediately after cutting. *Trema,* a pioneer genus in cutover forests in Malaysia (also present in tropical America), grows poorly on degraded soils, apparently requiring abundant nutrients (Wyatt-Smith 1949c). Possibly for the same reason, *Musanga* in Malaysia (like *Cecropia* in America) comes up in abundance immediately after clearing but is less common following a period of farming (Baur 1964b). In Nigeria, *Musanga* still comes up after the first year of farming but is less plentiful after 2 years (Lamb 1940).

Rapid growth of pioneer species may not result purely from efficiency of energy conversion or dry-matter production. For *M. cecropioides,* such growth results from a capacity for unrestricted node elongation, leaf production, and an efficient branching pattern (Coombe and Hadfield 1962).

Pioneer stands in moist climates may be able to dominate grass but not the trees that come up beneath them. An example is seen in Malaysia where *Mallotus* and *Macaranga* quickly form a high canopy that can suppress *Imperata* grass but not woody species (Wyatt-Smith 1949c). The light canopy of most pioneers favors the regeneration and growth of the species that succeed them, although in Sabah, *Anthocephalus* reportedly may suppress dipterocarps (Meijer 1970).

Pioneer tree species generally do not live long. A species of *Trema* in Malaysia commonly lives only 2 years (Wyatt-Smith 1949c). Many pioneer trees in Brazil decline after 10 to 15 years (Weidelt 1969). *Cecropias* more than 25 years old are rare and decadent. In Sabah, only one pioneer, *Anthocephalus,* lives as long as 40 years (Meijer 1970).

Succession is progressive, with the initial conditions that favored pioneer species gradually subsiding. In the early stages, high rates of reproduction and growth are rewarded with success. Later, with increasing biomass, the ecosystem is characterized by greater internal competition (Odum 1969).

The transition that takes place during tropical forest succession is illustrated by early observations in what is now the Central African Republic (Aubreville 1948). In a primary forest with no *Musanga,* there were, nevertheless, 125 seeds per square meter of this species on the forest floor. With release, they germinated and grew rapidly for 10 years to 20 m in height. Some understory species of the primary forest then entered beneath them. Then, a second group of light-demanding trees with soft woods entered and surpassed the *Musanga*. Finally, shade-tolerant trees of the primary forest grew up through this secondary vegetation, while an understory of primary forest developed beneath.

In the early stages of succession, secondary forests apparently allocate growth first to leaves and then to stems and roots (Ewel 1971). In a Panamanian wet forest clearing, the greatest growth in leaf biomass took place during the first 2 years, whereas the greatest stem growth occurred in the 3rd and 4th years, and the greatest root growth was in the 5th and 6th years (table 4–3).

An increase in the number of tree species is characteristic of forest succession unless sprouts from the previous forest remain. During an 11-year period in a secondary forest in Costa Rica, the number of arborescent species increased from 10 to 54 (Fournier and Herrera de Fournier 1977).

The rate of succession is the rapidity with which a secondary forest approaches stability. Criteria include nutrient and organic matter levels in the soil, canopy density, basal area, and volume or biomass. A secondary forest in Suriname, arising after deforestation and debris removal or burning, attained from 40 to 70 percent of the basal area of the primary forest in 7 years (Boerboom 1974).

Table 4–3.—Biomass growth allocation in a secondary tropical forest in Panama (t/ha/yr)

Biomass unit	Age interval 0–2 yrs	 2–4 yrs	 4–6 yrs
Leaves, flowers, and fruits	1.8	1.2	0.3
Stems	4.7	11.3	2.0
Roots	1.3	1.0	4.8
Total live biomass	**7.8**	**13.5**	**7.1**
Litter	2.3	.6	.2
Total	**10.1**	**14.1**	**7.3**

Source: Ewel 1971.

Rapidly growing tree species with soft wood followed herbaceous vegetation the 2nd year after shifting cultivation in lowland Guatemala (Snedaker 1970). As these species matured, they were slowly replaced by species with denser wood. Aboveground standing crop increases after the 1st year were the result of stemwood growth. There were no discernible changes in leaf biomass during the first 10 years of succession. By the 3rd year, light transmission had declined to 5.4 percent, where it stood for the next 11 years. At age 14, the interception of precipitation was approximately as shown in table 4–4.

The recovery of soil under a secondary forest is probably as good a measure of progress toward a steady state as are the characteristics of the vegetation. One crude measure is the increased porosity of the soil as the forest

Table 4–4.—Precipitation interception in a 14-year-old secondary forest in Guatemala

Precipitation (cm)	Interception (%)
0.20	40
.40	20
.85	17

Source: Snedaker 1970.

develops. As a result of reforestation in the rain forest region of Nigeria, the bulk density of the soil rose above that of the mature forest, but the former lower level was restored in 10 years (table 4–5) (Aweto 1981b). Waterholding capacity dropped 35 percent after clearing, but one-third of that loss was restored in 10 years. In the same forest, organic matter content in the first 10 cm of soil dropped more than half with clearing, but 60 percent of the loss was regained in 10 years.

In wet forests of Colombia, above- and below-ground N losses due to deforestation, some 1,300 to 1,400 kg/ha, were restored by N fixation at rates of 100 to 150 kg/ha/yr (Salas and Folster 1976). It was predicted that losses of K, Ca, and Mg might be restored in 20 years or less.

In the humid forest region of the lowlands of eastern Guatemala, litter accumulation beneath a secondary forest was found to reach half that of a stable forest in less than 1 year (Ewel 1968). The input of organic matter by the 11th year exceeded that of the stable forest, peaked near 21 years, and returned to the level of the mature forest after 30 to 35 years. Organic matter accumulation in the soil attained the rate of a mature forest during the first 3 to 5 years of fallow (secondary forest) and then increased. Restoration of N inputs increased with age but was never higher than in the mature forest. Phosphorus input rose with litter production, reaching half the level of the mature forest in 5 weeks. Because of large quantities of accumulated Ca and Mg, inputs of these nutrients from a young secondary forest may be insignificant and not clearly related to stand age. In a later study, litterfall increased at a rate of 10 t/ha/yr up to the 14th year, at which time it equalled that of the mature forest (Ewel 1976). The apparent causes of the increase were greater deciduousness and changing species. This study also showed that the nutrient content (N, P, K, Ca, and Mg) of the litter during the first 6 years equalled that of the mature forest.

Secondary forests accumulate organic matter rapidly when used as fallow for shifting cultivation (Ewel 1968). Studies in Guatemala showed that the return of N is relatively constant and moderate amounts can accumulate in the new litter very early. Ewel surmised that this increase is the primary benefit of fallowing for the next crop. The increase of P is closely related to litter production. More than 75 percent of the P stored in the litter at the time of clearing remains 6 months later. Levels of K, Ca, and Mg are not clearly related to the age of the fallow. Potassium is rapidly cycled, with little or no accumulation, and Ca and Mg are relatively stable in accumulated storage.

The fate of the timber species in successional forests is of special interest. The natural outcome of succession is high biomass relative to productivity, whereas wood producers strive for high productivity per unit of biomass (Odum 1969). Under favorable circumstances, timber species may regenerate after cutting. In the Gambari Reserve in Nigeria, in a tract exploited for both timber and fuel, the number of seedlings of useful species increased in 4 years from 4 to 38 per hectare, and the number of saplings from 2 to 47 (Mallam 1953). Many of the seedlings were from seeds that germinated after the felling.

Timber species that are seral, adapted only for an intermediate successional role, may be forced out by natural succession before they mature. Useful (but seral) species of genera such as *Ceiba, Terminalia,* and *Triplochiton* were declining in a 14-year-old secondary rain forest in Nigeria (Keay 1963). Their growth below the canopy was slow. In contrast, the canopy species were either being maintained or increased. It was concluded that a

Table 4–5.—Restoration of soil porosity in a secondary forest in Nigeria

Forest age	Bulk density (g/cm^2)	Total porosity (%)	Waterholding capacity (%)
1 year	1.19 ± 0.01	54.4 ± 1.0	36.4 ± 0.6
10 years	0.98 ± 0.02	63.0 ± 0.8	46.5 ± 1.2
Mature	0.98 ± 0.01	63.2 ± 0.3	56.3 ± 2.1

Source: Aweto 1981b.

secondary forest without cultural treatment will produce little usable wood.

The Environment for Production

The significance of secondary forests to human society in the Tropics is traditional. Tropical farmers have for millenia depended on secondary forest fallows to restore productivity to land worn out by cultivation. A classic example is to be seen in the mangroves of Papua New Guinea (Gray 1960). The mangrove trees yield wood for shelter, fuel, and dugout canoes. Adjacent sago palms provide starch. Protein comes from marine life dependent on the mangrove. Less direct but equally significant human dependence on forests is evident in: (1) urban needs for water from forested watersheds and for industrial wood products, (2) irrigated agriculture, dependent on a continuous supply of sediment-free water, and (3) national economies, dependent on exports (or the avoidance of imports) of wood products.

General Perceptions. Making secondary forests produce usable wood in the Tropics has benefits but also costs. The employment created, entirely rural and mostly unskilled, is well adapted to social needs. However, prospective yields may be distant in time, geographically diffuse, and still largely unpredictable. Commonly seen drawbacks to tree production are its long-term nature relative to other investments and apparently limited compatibility with the practice of agricultural fallowing.

The superficial appearance of secondary tropical forests, with few large, straight trees of marketable species, suggests that they are nearly worthless economically and merit little or no managerial investment. The area of potentially productive tropical forests being managed in 1980 was insignificant (table 4–6; Anon. 1982a). A subsequent report puts the total area of moist forests in tropical America under sustainable management systems as 75,000 ha, all in Trinidad (Poore and others 1989). Nevertheless, wherever such forests are extensive and likely to persist, their social and economic potential warrants comprehensive assessment to explore their suitability for more intensive management.

Leslie (1987a), in evaluating the desirability of natural forest management, states that a clear distinction needs to be drawn between economic and financial feasibility. Economic feasibility includes all returns and all costs and may well prove more promising than the less comprehensive, direct financial feasibility. Wyatt-Smith (1987a) concludes that, although much of the future industrial wood will be produced by planted forests, the larger area suited only to natural forests is a fallback option.

C.T.S. Nair (1985) points out that the multiple values of natural tropical forests are seldom fully utilized in management. He sees a general tendency, where such values are recognized, for land-use segregation, subordinating most potential uses on any one forest area.

Despite widespread opinion that cutover and volunteer forests have little potential, there are foresters who see promise in such stands if treated early. For example, Plumptre and Earl (1986) conclude that tropical forests can produce far more without changing their essential nature or their capability to harbor forest fauna. To leave such forests without treatment after exploitation, they say, is to condemn them to inevitable, slow degradation. By developing small forest industries and applying appropriate silvicultural treatment, managers can probably make some of these forests profitable, particularly if their nontimber benefits are recognized. The understanding of secondary tropical forests is not in its infancy. More than a century of experience has yielded

Table 4–6.—Management status of closed tropical forests in 1980

Region	Potentially productive (thousand km^2)	Managed (thousand km^2)	Proportion managed (%)
Tropical America	5,217	5	0.1
Tropical Africa	1,630	17	1.1
Tropical Asia	2,010	398	19.8
Total	**8,857**	**420**	**4.7**

Source: Anon. 1982e.

much information concerning these forests and their culture. Beginning in 1880, thousands of hectares of natural forests were refined in southeastern Asia. During the first decade of this century, management of mangroves was developed in what is now Malaysia, and the "coppice with reserves" system was applied to dry forests in India for poles, fuelwood, and fodder. Tests of natural regeneration began on a large scale in Nigeria.

In the 1920s, high early mortality of natural regeneration in tropical forests was documented in what is now Sri Lanka, and problems with girth limits, in terms of unreliable regeneration, came to light in India.

In the 1930s, tropical shelterwood testing began in what is now Malaysia. Fellings in the underwood in India were found not to induce what was considered adequate regeneration of the few species then wanted. Pioneer species such as *Musanga* were found to be an asset as nurse trees in what is now Malaysia.

In the 1940s, the short lives of pioneer species became known as did the virtue of following natural succession in stand treatment.

In the 1950s, the level of stored nutrients in forest fallow was found in Ghana, with nearly complete site recovery in 14 years in Nigeria. There the rapidity with which the useful tree species return in secondary forest was documented. The Malayan Uniform System and the diagnostic-sampling technique were developed in what is now Malaysia. Significant growth rates of trees of desirable species, even in untended forests, were discovered in Australia. In Brunei it was concluded that simplifying natural forest composition does not prohibit sustained yields. The selection system was applied in the Philippines; but in Uganda it proved inadequate because of cumulative felling damage and slow growth. Nevertheless, it was found that most selected and tended crop trees survived and that only a few were needed for full stocking.

In the 1960s, it was found that logging damage in Nigeria could be significantly reduced through greater care. Dynamic sampling techniques were developed in Uganda. Potential yields were determined for many tropical areas.

Since 1970, more basic new information has been developed in both tropical hemispheres. Regeneration has been studied from the phenology of flowering through seed dispersal to storage in the forest and establishment relative to illumination and other conditions. A high proportion of the nutrients has been found to be within the vegetation. Nutrient cycling and some of the effects of interventions have been documented. Intensified study of forest fauna has shown a role critical to the well-being of forests. New knowledge of the interdependencies of animals and plants within the forests has shed light on the fragility of many species and the corresponding effects of modifications. Conservation of biodiversity has been shown critical to good forest management. Evidence is accumulating that secondary forests contain more potentially useful trees than heretofore thought. Wide variation in the growth rates of apparently similar trees suggests greater productivity potentials from enlightened liberation.

Nevertheless, in spite of the early accumulation of knowledge, natural forest management was abandoned in many tropical countries, particularly during the 1960s and 1970s, mainly because of shortages of trained staff and inadequate financial resources (Masson 1983). Even the 5 percent of closed tropical forests classified as "under management for production" for the most part is not being intensively managed.

Developments during the 1957–1982 period that have affected the management of mixed tropical forests include the following (Masson 1983):

- Increased population and sustained deforestation for shifting cultivation
- Increased importance of forests to rural communities
- Increased demand for fuelwood and industrial wood to a point where existing management cannot consistently supply needs
- Logging systems requiring large-scale operations and removal of more species and smaller trees, beyond the capacity of forestry staffs to control damage and integrate needed silviculture
- Short-term forest enterprise contracts with no long-term productivity incentives
- Public funding on an annual basis, inhibiting forest culture for the long term.

Even with careful selection cutting and extensive liberation treatments, yields have been so low that it is difficult to convince governments that combined social and economic benefits, including employment and foreign exchange, justify protection or even preservation of mixed tropical forests.

The sequence of events in Nigeria illustrates the results of this perception (Lowe 1984). Forest reserves originated in 1899, and by the mid-1920s, systematic silvicultural research was in progress. By 1950, some 2,000 km^2 had been treated by tropical shelterwood methods. By 1970, hardwood exports were prohibited in an effort to favor the local market. By 1980, even though it had been shown that natural high forests could produce 1 m^3/ha/yr on a 40-year rotation, the remaining forests were considered insufficient to meet local needs and some 110,000 ha were planted. Lowe concluded that after 50 years of efforts, sustainable yields are achievable but natural regeneration is still insufficiently understood.

Experience with the management of natural forests indicates that there will be a continuing place for such forests where land resources are adequate and rational treatments are applied (Mergen and Vincent 1987). The importance of forest plantations to future timber supplies is recognized, however, as are the remaining uncertainties about silvicultural practices under many forest conditions. An impression remains, nevertheless, among those who have worked with the forest, that cutover stands can be made to yield far more than has been evidenced to date.

Heartening conclusions for productive rain forest management came from experience in Queensland, Australia (Anon. 1983c). Selective logging was found compatible with multiple-use management of such forests. Strong growth response followed logging. Logging cycles of 40 to 50 years could be sustained. Logging at normal intensities did not increase species loss. Visual impacts of logging were short lived. An immense regeneration potential existed.

Past silvicultural treatments have been mostly trial and error, bringing to light the complexities of such forests and the need for more technical information. Silvicultural practices formerly widespread have been abandoned. Initially, hesitation to depart from nature led to treatments so conservative that little growth acceleration ensued. The large openings found necessary to stimulate crop trees in Suriname, for instance, also stimulated competitors (Anon. 1959j). Bold treatments were found necessary in Uganda, but sometimes even they failed, suggesting that unresponsive trees were stagnated by long suppression (Dawkins 1963b). The discovery that response to liberation is greatest in small trees suggested that a growth rate "pecking order" for each tree may be set at an early age and that it lasts for life (Lowe 1966). This may partly explain the difficulty in selecting prospectively fast growing trees on the basis of outward appearances.

Past silvicultural treatment of secondary forests has accelerated growth, but single treatments do not ensure sustained yield. Early treatments, widely termed "improvement fellings," were recognized as only provisional, because the main objective was merely to utilize the available stock (Troup 1921). Although a sequence of treatments would be expected to increase the proportion of seedbearers of desirable species and periodically open the forest enough to induce regeneration, there is as yet no evidence that such a process is generally a reliable source of future crops. As a result, efforts are likely to be concentrated instead on breeding superior plantation trees, further increasing the productivity of plantations.

In refining secondary tropical forests, foresters select crop trees according to their prospective marketability, present size relative to maturity, form, freedom from injuries, and apparent health. Even where many tree species may be acceptable for future products, management tends to reduce the number of species, always favoring species thought to be the best. An extreme result could be to reduce forest diversity to near species purity in local areas. This might eventually eliminate all species adapted to certain microsites to which other, more desired, species might later prove unadapted. More diversity than required for maximum timber productivity may be necessary to preserve the site and ensure the well-being of the forest. Where such information is not available, silviculture can only be provisional and should modify stands only cautiously and gradually.

Support for managing secondary tropical forests for timber is seen in the conclusions of Wyatt-Smith (1987b). He states that plantations should not be seen as an alternative to tropical moist forests because products yielded are different. Few high-quality woods, with the notable exception of teak, grow well in plantations, and conversely, mixed industrial grade woods from tropical moist forests are greatly inferior to the uniform products of plantations. Thus, managing for sustained yield as large an area of tropical moist forests as possible is recommended.

Wyatt-Smith further concluded that the increasing use of veneers and reconstituted wood rather than solid wood, the use of stains and other devices to produce decorative faces, the use of many more species (including formerly "weed" species), and the technical developments that have greatly reduced waste all influence policy decisions. However, he stated that there will always be a market for prime, solid timber and that the price for such timber of preferred species will increase greatly in excess of inflation in the face of reduced supplies. As a consequence, Wyatt-Smith saw it unlikely that there will be any economic risk in favoring tree species that regenerate easily, grow reasonably fast in relatively pure stands, are relatively free of disease and insect attack, do not cause site deterioration, and produce good-quality timber.

Leslie (1987a) concluded that it is not necessary to defend natural forest management because the economic case against it could be wrong or simply because of its inherent theoretical and practical weaknesses. He saw it to be wrong because, at the interest rates suggested for use in forest economics studies, natural management of tropical mixed forests is likely to be better financially than alternative land uses or management systems. Natural management, he concluded, wherever it is ecologically feasible, is also economically preferable on its own merits.

Public concern over the feasibility of producing timber crops economically is in part a result of management failures for other than technical reasons (Schmidt 1987). Other causes of failure include a lack of protection of the property from trespass; abandonment due to availability of already mature timber elsewhere; the promise, often unfulfilled, of higher yields from plantations; inadequate or inconsistent financing; and political instability.

Stand Complexities. Without silvicultural intervention, natural succession in cutover forests very slowly approaches the characteristics of primary forests. Left to nature, secondary forests on all but the poorest sites will usually eventually produce some trees of marketable species, size, and form. The rapidity of this process depends on climate, soil, and the severity and duration of past modifications of the forest, as well as on proximity to seed sources and fauna responsible for seed dispersal.

Whitmore (1983), in a review of secondary succession from seeds in tropical rain forests, pointed to the complexity of the process and gaps in our knowledge. The presence of seeds of pioneer species beneath forests is now generally recognized. Whitmore rejected the separation of species into two groups: pioneers and climax. He saw a continuum from one extreme to the other. Differences in the size of forest gaps, the time that they persist, their causes, and their proximity to seed sources all influence the course of succession. Disturbances due to logging may vary widely from place to place, leaving a mosaic of conditions for subsequent succession.

Although the diversity of secondary forests may be less than that of primary forests, it nevertheless complicates utilization, except where fuelwood is so scarce that all woody material is accepted. Elsewhere, the number of trees that are suitable for a specific use and that will reach harvestable size at one time may be too small to cover harvesting costs. If so, silvicultural costs can only be amortized over a longer period. This prospect operates against diversity, favoring instead simplification of stand composition and greater uniformity of stand structure, conceivably at some risk to ecological values.

An aspect of stand diversity often disregarded in silviculture is the vital role of the "consumers" within the ecosystem, particularly the higher forms of animal life. Many game species are eliminated by hunting before silviculture is even considered. However, their potential contribution to pollination, seed dispersal, and control of other forms of animal life could eventually prove crucial to forest productivity. The significance of different components of forest diversity needs study and, meanwhile, managerial deference.

Silvicultural treatment with only present knowledge may do as much harm as good to diversity because the results may not be immediately obvious. Treatment will favor trees thought to best meet future markets or most likely to grow rapidly at the expense of others. Liberation that stimulates growth of selected trees may open stands sufficiently to change composition toward intolerant species. Also, reduced representation of what appear to be potentially useless species, however gradual, may later be found to be ecologically or even economically undesirable.

Heterogeneous secondary forests complicate silviculture for other reasons. Past treatment of these forests generally varies from place to place, from a light cut to remove mature trees of only one species, to clearing, cultivation, overgrazing, and repeated burning. Drastic changes affect the soil quality and may accentuate site variation not apparent in primary forests. The following complications to sustained utilization of tropical moist forests have been suggested (Davidson 1985): species richness; long-lived character of trees; interdependence of plants, animals, and forest dwellers; patchiness of species occurrence; susceptibility to nutrient depletion; and uncertain regeneration.

Cutover forests are generally impoverished in quality as well as quantity because harvesting concentrates on the best species. In certain Philippine forests, the more valuable dipterocarps, which made up more than half the original stands, represented less than 20 percent after harvesting (Caneda 1963, Nastor 1961).

Cutover stands generally contain more timber species than volunteer stands, but they tend to be less uniform as to tree size and canopy continuity. They also may carry a nonproductive overstory. An added variable in such stands is the secondary impact of logging damage, the effects of tree injury being long term as well as immediate. Another uncertainty in cutover forests is the unknown age of the trees that look best for the next crop and its possible significance to their potential. Trees long constrained by suppression, unlike young trees, may be slow to accelerate growth if liberated.

The presence of well-formed trees of marketable species in cutover forests depends heavily on the intensity of prior timber removal and control of logging damage. Concern for the residual stand during logging of tropical forests has been rare, so heavy damage is commonplace. Such losses of future crops can be avoided because many primary moist forests have a large component of trees below harvestable size. Control of logging damage in the Philippines has in large areas saved future crops that are adequate to justify their care for the future (Fox 1967c). If such controls were applied throughout the Tropics, the adequately stocked areas would be extensive. The potential of immature crops within secondary forests is commonly underestimated, because saplings or small poles so widely spaced they are inconspicuous may result in full stocking at maturity.

Trees that remain after cutting, if left untended, may not survive. In one moist forest studied in Sabah, nearly all saplings were smothered by undergrowth 8 years after logging (Anon. 1957a). In a forest in Nigeria, saplings of *Khaya grandifoliola* were reduced from 217 to 22 per hectare during the same period (Anon. 1965c). Even those trees that survive may be of little use because of small size of the species at maturity, poor form, or inferior wood. This is to be expected where logging has removed all of the good trees or has seriously deteriorated or exposed the site.

Volunteer secondary forests commonly are stratified vertically; distinct pioneers are on top and successionally more advanced species beneath. The species of the later stages (beneath) are generally better prospects for traditional timber products. They tend to be straighter and larger at maturity and produce denser and more versatile woods. During the early stages of development, the number of these trees with crop potential may be too small to justify silvicultural treatment, even if some species now considered mediocre are accepted as prospects for the future crop. Yet, the intermediate and subordinate trees down to sapling size may make up a potentially well-stocked forest. Obtaining this forest may warrant immediate or gradual elimination of most of the unwanted overstory, leaving a stand of trees that is relatively uniform in diameter and expected time to maturity.

Silviculture

Silviculture is defined as the theory and practice of controlling the establishment, composition, constitution, and growth of forests (Ford-Robertson 1971). Its practice rests on the natural laws of forest ecology. Although silviculture has a human purpose, management should be the servant of silviculture rather than its master (Schlich 1925). Silvicultural intervention in natural forests may modify the microenvironment, hydrologic cycle, soil properties, and the structure and genetic composition of the forests as well as their growth. With skillful culture, stands that are judiciously modified, even if they differ widely from natural forests, may be more vigorous and productive, as well as free from injury (Smith 1962).

The apparent biological balance of primary forests has long intrigued foresters as a key to sustained yields of usable wood. The attributes of natural forests treated silviculturally to produce timber lie somewhere between those of primary forests and those of intensively managed plantations. Therefore, the culture of secondary forests may not achieve the ideal of ecologists, economists, or even many foresters. Ecologists may see such forests as being of questionable sustainability and as poor substitutes for primary forests as reservoirs of germplasm. Economists may see them as less than competitive with other land uses. Many foresters view natural forests as less productive, at least in the short run, than plantations, despite silvicultural treatment. Results so far tend to support these views.

A fundamental problem faced by silviculturists dealing with natural forests is to determine how "natural" they must be kept to sustain needed environmental values and site productivity given the need to favor the most promising trees at the expense of the others. Much more must be known about natural forests before the consequences of silviculture can be fully understood and predicted in terms of sustainable timber productivity.

Productivity of secondary forests depends ultimately on the effectiveness with which the silviculturist can maintain the site, soil quality, and ecosystem integrity; stock unproductive areas; control competition and growth rates; avoid damage; and harvest products (Poore 1968). Restoration of primary forests would not achieve all these ends. Nevertheless, a cautious approach would be to proceed in the direction of natural succession. Retention of a multistoried, closed canopy should reduce risks (Barnard 1954). Stands could contain more of the preferred timber species, yet also contain a variety of other species in the lower stories to preserve diversity. The result would be a compromise between ecological and economic requirements.

Abandoning the natural stand structure with trees of all sizes growing together in favor of monocyclic practice (one harvest period per rotation) is a departure from nature that has long concerned foresters. The Eighth All-India Silvicultural Conference in 1951 warned that any radical departure from selection fellings (with multiple, light harvests per rotation) gravely risks disturbing delicate ecological balances to the detriment of long-term interests (Rosayro 1952). Whether the structure of unmodified forests must be restored and perpetuated if yields are to be sustainable is still debated (Leslie 1977). Experience in Sarawak suggests that the highly complex and differentiated structure and composition of primary forests are not essential to maintaining sites and healthy stands (Brunig 1967). Secondary stands with a simpler structure and a higher timber volume did not necessarily imperil ecosystem stability and well-being and, in some cases, were clearly an improvement. Such concerns have never worried the farmer, who grows his crops in the most unnatural way imaginable (Laurie 1941g).

Concern has also long been expressed by foresters for the consequences of treatments that reduce forest diversity. However, the more complex the mixture and the more uneven the canopy, the more difficult is economical timber production (Wilkinson 1960). Blind preference for native species has been questioned, because many do poorly in parts of their natural ranges. Nor is it rational to outlaw exotic species that have been prevented from extending their range solely by barriers other than those of biological adaptability (Peace 1961).

Retention of some natural mixture may be desirable, even at some expense to yield because loss of diversity may affect stability (Odum 1969). Retention of good diversity may also be favored by the potential for markets for more of the existing growing stock. Management may benefit more by intensified processing and marketing of products than by eliminating trees presently unmarketable (Synnott 1979). Experience in the Amazon led to acceptance of common, second-class species that are easy to regenerate (such as *Goupia glabra*) over first-class desirables (such as *Cedrela odorata*) that are difficult to regenerate. The principle is to follow nature, perhaps to guide, but not to dictate (Pitt 1961a).

Silvicultural refinement of forests favors the most promising trees at the expense of others, gradually reducing the representation of other species. Because the ecological consequences are generally unpredictable, a cautious policy would be to retain, at least until their role is more fully understood, little-used species that "look good," and understory trees and opportunists that apparently interfere little with crop production.

Even with these precautions, sustained yield may not result. The favored species may not fully utilize the soil. They may constitute an inadequate nutrient trap. They alone may not support an animal population vital for pollination, seed dispersal, or pest control. Only continuous monitoring can determine sustainability with such departures from nature. Ultimately, even retrenchment could be required.

Agricultural fallows account for large, accessible, and presumably manageable areas that become covered by trees. Cropping/fallow systems will persist where continuous cultivation is not feasible. An untended secondary forest, as a fallow, can restore the soil for recultivation before any trees (except those of extremely rapid growth) become large enough to utilize other than for posts or fuel. Studies in Guatemala and Nigeria have shown that, through fallowing, the organic matter of the soil can be restored to the level of the mature forest in 3 to 10 years (Aweto 1981a, 1981b; Ewel 1981; Machado 1977). Under such circumstances, short-term wood crops of value to rural communities may mature within the fallow cycle.

Application of fertilizers should increase food-crop production, thus reducing pressure on fallow forests and consequent adverse effects on soil and water resources. Under some conditions, fertilizers increase tropical crop yields fivefold at a benefit-to-cost ratio of 3 (Gutschick 1978). Increases in yields due to fertilizers could lengthen fallow periods by reducing the cultivated area, by lengthening the period of food cropping, or both. On favorable sites, fertilizing can even eliminate fallowing, leaving marginal land for continuous food crops. However, because fertilizer must generally be imported, its use is commonly considered politically or economically impractical to the detriment even of experimentation. Despite these disadvantages, crude fertilizer imports into tropical America increased in value between 1987 and 1992 at an annual compounded rate of 16.6 percent (Anon. 1993b). Importing food must cost more than importing the fertilizer to produce it. Food imports into tropical America increased in value at a compounded rate of 12.7 percent from 1987 to 1992 (Anon. 1993b).

Structural Goals. Forest structure is the representation of trees by age, size, crown, or other classes. It is a basic consideration for management for quantity, quality, and continuity of yields. Optimum structure for wood production from secondary forests undoubtedly varies with location and crop. Cutting is generally controlled by stipulating what may be removed rather than what must be left. Commonly, cutting is prescribed in terms of a minimum diameter for trees to be removed, presuming that the next crop will develop from the trees that are left. Residual stand structure is further modified by harvesting damage. The optimum structure the residual forest should have for future productivity is seldom considered when cutting is being planned. Nor are forest managers generally so well financed that they can make a commitment to postlogging treatments that would favor the next crop.

Goals selected for forest structure dictate the degree of uniformity of eventual stands and the severity of cuttings and are thus of ecological as well as silvicultural significance.

Secondary tropical moist forests are irregular in structure. But primary moist forests are so uniform in structure that a single, pan-tropical stand table represents many of them (table 4–7; Dawkins 1959, Leak 1963). Table 4–7 illustrates the "positive" structure of common stands, as shown by the de Liocourt quotient (Sammi 1961) in the final column. If the logarithmic rate of increase in tree numbers constantly increases downward through the d.b.h. range, it would appear that replacement of mortality losses from beneath is uniformly adequate in all tree size classes below a cutting diameter limit of 60 cm. The positive structure illustrated has a larger quotient among the small trees (0.39) than among the large trees (0.17), indicating an apparent abundance of trees in the smaller sizes relative to replacement needs.

The "all-sized" structure suggests that undisturbed tropical forests are also "all-aged," assuming that tree size and age are directly related. However, this assumption is not necessarily true. The fact that most large trees are old does not mean that most small trees are young.

It was recognized early that secondary forests preserve some of the diversity thought critical to the preservation of site productivity (Barnard 1954). A minimum number of tree species was assumed to be all that was necessary to maintain environmental values. More recently, it was recognized that sustained forest productivity requires a balanced nutrient cycle, arising in natural forests from a diversity of forest physiognomies, trophic levels, life forms, and compositions (Brunig and others 1975).

The significance of irregular (all-sized) stocking to forest management has been outlined by Meyer (1956). To manage such forests for sustained yields, a balanced distribution of trees by d.b.h. is necessary. This balance can presumably be expressed by the de Liocourt curve, with a constant quotient of increasing tree numbers in

Table 4–7.—Pantropical stand table for primary moist forests

D.b.h. (cm)	No. of trees per hectare		Logarithm of trees per class	Difference in logarithms
	Per class	Cumulative upward		
10	242.0	431.1	2.38	0.39
20	97.0	189.1	1.99	.39
30	40.0	92.1	1.60	.32
40	19.0	52.1	1.28	.24
50	11.0	33.1	1.04	.21
60	6.8	22.1	.83	.17
70	4.6	15.3	.66	.14
80	3.3	10.7	.52	.16
90	2.3	7.4	.36	.18
100	1.5	5.1	.18	
>100	3.6	3.6		

Source: Dawkins 1959, Leak 1963.

successively smaller d.b.h. classes. Successively harvesting or eliminating trees above a parallel but lower curve and leaving adequate space for growth between cuttings were expected to produce mature timber, liberate immature trees, and foster regeneration while maintaining or attaining the balance needed to sustain yields in the future. This technique was found applicable to *Shorea robusta* forests of India, but a different quotient between adjacent d.b.h. classes was required under different conditions (Mathauda 1960).

A debate between proponents of irregular stocking and converts to uniformity was active in India through the 1930s and 1940s and has not entirely subsided. Irregular stocking has been considered more efficient in that better site use was possible with vertical stratification, leading to more large trees (Bourne 1935). Champion (1936c) agreed with the theoretically greater efficiency but saw no advantage in converting regular forests to irregular ones. He pointed out that teak *(Tectona grandis),* under irregular stocking, becomes poorly formed. He also foresaw reproduction problems. Sagreiya (1941) disagreed with Bourne that in irregular forests more of the basal area can be in large, maturing trees, although he accepted irregularity for dry teak and other understocked areas. He postulated that wood of more even grain is produced in irregular forests.

Laurie (1941b) called for conserving irregular stocking until research could do it justice. He saw advantages such as saving space and harvesting at the right size. He recommended that instead of converting a forest to uniformity, it should be managed as an irregular forest wherever feasible. Davis (1941) summed up the debate at that time by indicating that the best course is flexibility, with uniformity a consideration only where stocking is adequate to provide a choice.

Managing large areas of natural forests with irregular stocking continued over a long period. The system in vogue in what is now Sri Lanka in 1955 used a diameter limit of 50 cm with a felling cycle of 10 years (Rosayro

1955). Tending (weeding of saplings and liberation of poles) was done to rebuild the growing stock. In Ghana, 12 years of tests with uniform systems showed that they were not universally applicable (Foggie 1957). The conclusion was that irregular forest management was best. Ten years later, irregular stocking was still considered suited where highly desirable species are present. The technique operated on a 20- to 30-year felling cycle, with a midcycle of thinning (Osafo 1970). Irregular management schemes have been used extensively in parts of Malaysia, Nigeria, and Queensland, Australia, and on a small scale in Trinidad and Puerto Rico (Baur 1964a).

Foresters in India in 1959 were practicing a form of selection management. Generally, they used diameter-limit control on 20- to 30-year cycles, but intensities of tending varied widely (Stracey 1959). By avoiding heavy fellings, they thought they would preserve the character of the forest. This, Stracey said, was a widespread misconception. He concluded that using "selection" for harvest cuttings followed by felling and girdling to establish regeneration—the common procedure—tended to produce an even-aged forest. Stracey recommended carefully controlled tendings, conservation of some less valuable species, concentration on shade-bearers (tolerant species), and a longer transition period of conversion.

Preserving natural stand structure presents practical problems as difficult as those of maintaining the natural composition. A major argument for saving secondary forests is that they contain immature trees with economic potential. These trees may range in size from seedlings to trees nearly mature. Efforts to produce economical crops of large trees from such stands have not yet been generally successful; therefore, conversion to forests of uniform tree sizes, regardless of the sacrifice of larger and smaller trees, became the general practice.

Management systems retaining irregular forest structure by several partial cuttings during a rotation, termed "polycyclic," resulted in cumulative logging damage that was considered unavoidable and intolerable in Uganda and Nigeria (Dawkins 1961b). Also, the continuous overstory was said to so suppress potential crop trees during their early years that they were incapable of growth acceleration later. An added drawback was the high unit cost of harvesting the small volumes yielded per unit of forest area from partial cuttings (Philip 1962).

Repeated partial fellings have been criticized on another count. In all forests, the large trees, whether or not they are older than the others, are obviously successful, and thus may be genotypically superior to others. The removal of these large trees with each cut may leave trees genetically inferior for future crops and seed sources (Ranganathan 1951). This dysgenic trend, if it exists, was seen as progressive (Palmer 1975). In volunteer secondary forests composed of trees that may have all become established at about the same time, harvesting only the largest may accentuate this effect.

Vanniere (1975) recommended converting to monocyclic management in stands where the immature trees make up a small fraction of the volume before harvesting. Palmer (1975) questioned the degree to which logging damage can or will be reduced. His view is supported by observations in Malaysia where even after tree markers indicated the felling direction for each tree, little effective control was exercised (Tang and Wadley 1976a, 1976b).

Dawkins (1958b, 1958e, 1961b), on the basis of personal study in Uganda and widespread observations elsewhere, questioned polycyclic management of irregularly stocked tropical forests as a continuing source of export-size timber. He concluded that a number of constraints limit the potential of irregularly structured forests. These are as follows:

- Cuttings must be repeated at intervals shorter than the difference between the rotation for the oldest trees to be produced and that of the youngest merchantable trees. This constraint limits yield per cutting.
- The cycle must be less than 30 (and preferably less than 20) years to avoid premature removal of still-growing stems.
- The cycle must be long enough to produce an economically extractable volume. When the previous constraint is also taken into consideration, this constraint calls for fast growth. Very few natural high forests grow desirable species faster than 0.4 m^3/ha/yr.
- The crop tree species must be shadebearers and able to expand an initially stunted crown after decades of suppression. (Fast-growing trees of Uganda are capable of neither.)
- To produce 3.5 m^3/ha/yr, at least 10 trees must be removed per hectare every 10 years. Such a harvest will destroy or damage 20 to 25 percent of the

adolescent and pole stock. Saplings may have to survive five such cuts to reach maturity, an unlikely prospect.

- Longer cycles mean heavier cuts and even fewer trees for replacements. With shorter cycles, there is less prospect that the damaged areas will overlap.
- The stand table must be strongly positive, with an abundance of saplings entering from below.

Dawkins (1959) further concluded that the large crown-diameter-to-d.b.h. ratio required for rapid growth of tropical trees (>20) calls for early crown growth and, therefore, a lack of suppression. His records indicated that a d.b.h. of 60 cm may be attained in 30 to 90 years and 80 cm in 40 to 120 years, the faster growth occurring in stands of 18 m^2/ha of basal area or less, and the slower with 25 m^2/ha or more. However, growing beneath or alongside trees of an older generation, no African tree is capable of reaching 80 cm in less than 80 years. Thus, unless rotations can be reduced to 40 to 50 years or logging damage to much less than 0.01 ha per tree felled, Dawkins (1958b) foresaw no prospect for sustainable yields of export-size timbers of more than 1.4 m^3/ha/yr. Yields might, nevertheless, be more than doubled where there is a market for intermediate-size trees, he concluded.

These constraints led Dawkins to encourage monocyclic systems where neither the problems of felling damage nor of early suppression impinges on productivity. A positive stand curve is still required. Yields as high as 4.3 m^3/ha/yr were seen as possible under good management and favorable markets.

Nicholson (1965b) questioned Dawkins' conclusion that long-suppressed trees are moribund. He presented data from Sabah showing that growth accelerated 1 year after logging (table 4–8) and added that growth was still increasing at the time of measurement.

Polycyclic (Selection) Practice. As fundamental as Dawkins' reasoning may seem, it has not settled the stocking issue. Some continue to favor irregular stocking as ecologically conservative. Others question the general applicability of the Ugandan findings. But no evidence has come to light that challenges the modest yields Dawkins predicted, except better markets for smaller trees, something that he foresaw.

Table 4–8.—Growth acceleration after logging in Sabah (cm)

D.b.h. class	Mean annual diameter growth	
	Before logging	1 yr after logging
5–15	0.28	0.87
15–25	0.46	1.26
25–35	0.49	1.46
35–45	0.53	0.70
45–55	0.52	1.20

Source: Nicholson 1965b.

The experience in Uganda of conversion from irregular to uniform stocking brought to light a number of concerns (Philip 1962), including the following:

- Diagnostic sampling, revealing not only the number of future crop trees but their silvicultural needs, is required for designing treatments of cutover stands. To avoid the impediment of logging slash, such sampling should precede felling.
- Prediction of the effects of different logging intensities on the residual forest is difficult.
- Ordering of the "coupes" (annual compartments) must be related to the dates at which their stands mature. The cutting rate must be adjusted during conversion to avoid breaks in harvesting yet ensure an orderly second rotation.
- Because regeneration is extremely variable from place to place, tending operations must be sensitive to differences from one coupe to another.

Stracey and Saikia (1960) favored selection in Assam, India, to avoid sacrificing good immature trees in converting to uniform stands. They advocated that a third of the currently noncommercial tree species should be saved because they may become useful. Schulz (1967) hesitated to convert to a monocyclic system in Suriname, apparently for the same reason. On the other hand, Sabharwal (1941) had earlier pointed out that, in converting from irregular to uniform structure, all the advanced growth need not be sacrificed if some irregularity is acceptable.

Selection management of the mora *(Mora excelsa)* forest of Trinidad has been recommended after removal of overmature, unsound, and defective trees (Bell 1971). Removal of five to eight trees per hectare was proposed on 10- to 15-year cycles after the initial treatment. Felling all trees down to 58 cm in d.b.h. left 107 undamaged or slightly damaged trees per hectare of 10 cm in d.b.h. or more (a residual basal area of 3.4 m^2/ha). Felling of 12 evenly spaced, large trees per hectare left 159 undamaged or slightly damaged trees per hectare (a residual basal area of 12.4 m^2/ha).

Under some conditions, the amount of logging damage does not itself preclude a polycyclic system (Redhead 1960a). For example, crawler tractors may do almost twice as much damage as felling, but the damage can be reduced by avoiding groups of advanced growth so that enough trees of 20 cm in d.b.h. or more remain to make a second crop as good as the first. Observations in Ghana (Mooney 1963) also suggested that felling damage need not be as great as Dawkins concluded.

In Philippine dipterocarp forests, marking of needed immature trees before the harvest kept tractor damage within tolerable limits even though far more trees were removed than in Uganda (Fox 1967a, Tagudar and Quintana 1957). Marking selected crop trees before logging has also been prescribed in Indonesia (Soerianegara 1970). Developments in yarding partial cuttings in the Temperate Zone suggest that logging damage in the Tropics might be significantly reduced with overhead removal systems such as skylines (Wendel and Kochenderfer 1978).

Baur (1964b) generally accepted Dawkins' conclusions concerning selection forests, referring to the repeated logging damage, high yields required by mechanized logging, and their unsuitability for light demanders. He also pointed out some disadvantages of converting to uniform stand structure: the loss of small healthy stems and possibly also species as well as greater soil exposure after complete harvests.

Dawkins convinced forestry officials in Uganda to convert to uniformity but with the understanding that it would not soon produce crops that are either even sized or even aged (Dawkins 1958g). Thus, reverting to selection could still take place if needed. However, only under uniform structure did Dawkins expect to bring a sufficient crop of unscathed juveniles to maturity. Conversion to uniform structure as visualized by Dawkins could begin with a salvage cut in which the minimum profitable harvest is less than the total stand.

Palmer (1975), like Dawkins, concluded that the prospects for low final yields and small growth increases as a result of silvicultural treatment make investments in silviculture in irregular forests unattractive. He held out one hope that Dawkins also recognized: Over time, keeping the basal area below two-thirds of the maximum might substantially increase growth. This would require repeated thinnings, but where markets for the products exist, they might be profitable.

In the Temperate Zone, Bormann and Likens (1981) concluded that a number of environmental constraints should be applied to any production system (such as uniformity) calling for clearcutting: (1) utilize only sites with strong regenerative capacity, avoiding steep slopes and shallow soils; (2) leave uncut strips on both banks of stream channels; (3) limit the size of cuttings to several hectares to ensure peripheral seed sources and minimize losses of dissolved nutrients and eroded material;
(4) select a rotation long enough to permit the system to regain nutrients and organic matter lost by extraction and site exposure from clearcutting; and (5) respect postcutting recovery species, even if they are not ultimately marketable.

Heavy monocyclic cuts will periodically interrupt nutrient conservation because large volumes of logging slash will be decomposing at a time when the remaining network of live roots is incomplete. With survival of an adequate natural understory or prompt natural regeneration, this period of imbalance may be short. However, more needs to be known about the magnitude and duration of nutrient losses as affected by different harvesting intensities and treatments of slash.

What does all this mean in terms of structural goals for secondary forests? Many of the experiences reported begin with primary forests having a wide range of tree sizes and dense overstories with high tree crowns. In favored circumstances, enough adolescents 20 cm in d.b.h. or more may be left for a second crop long before newly regenerated trees could mature. Young stands that contain potential crop trees of uniform size suggest maintenance of uniformity. Late secondary forests with a wider range of diameters may offer either option, uniformity or irregular stand structure. In typical secondary forests, some of the problems that concerned Dawkins (1961c) may be less serious. Felling damage should be much less, because there are few or no large trees. The lighter cuts implicit in polycyclic systems may prove more practical in view of the rapid growth of local demand for wood and the greater accessibility of secondary forests. Additional species may enter this local market, increasing the proportion of marketable trees and raising yields correspondingly.

Obviously, silvicultural treatment must consider both the composition and the structure of the forest. But the decision on structure may be postponed. With typical unmanaged secondary forests, the first step may be to improve composition rather than to select potential crop trees. As time passes and as the potential of natural regeneration, the marketability of more tree species, and the economics of intermediate cuttings become more predictable, the basis for a decision on forest structure for crop production should become clearer.

Diameter Limits. Given the natural structure of mixed tropical forests and the assumption, albeit generally unproven, that mature trees cover a younger understory waiting to be released, foresters have presumed that the selection system should be appropriate. Under such luxuriant growth, this system presumably would call only for harvesting the mature trees, liberating those suppressed, and fostering regeneration where needed. Because selection felling preserves a wide array of diameters, this method has been considered unobjectionable. It certainly seems more judicious than alternatives calling for drastic modification or sacrifice of forests before their dynamics and potentials are fully understood.

Past study of the structure of natural tropical forests has led to the supposition that repeated removal of mature trees should stimulate adequate replenishment from beneath. An almost universal practice has been the application of minimum diameter limits in timber exploitation to preserve the immature trees so that they can be available for later harvests. An additional assumption was that repeated cuttings of this kind would preserve the natural forest structure and, therefore, would perpetuate production. In the absence of knowledge of, or financial resources for, more intensive systems, this practice leaves open the options for more refined silviculture in the future. Therefore, diameter limits may be a defensible, interim, harvesting guide. Even if the residual stand is later replaced, the site and trees are as well protected as possible with current supervision.

It became apparent long ago that diameter-limit cuttings in tropical moist forests did not ensure high productivity of future timber crops. Alone, they do not protect immature trees from damage that results from harvesting. They fail to balance the growing stock or thin the smaller trees (Trevor 1923). Nor do they offer any promise of sustained yields. Nevertheless, diameter limits and subsequent selection cutting of teak forests in India were recommended because financial resources were insufficient to fell and replant these forests. The residual forests, even if less productive than plantations, provided a buffer against human trespass.

Shelterwood. Forests composed of trees of about the same stem diameters have been referred to here as "uniform." Silvicultural systems leading to uniformity include shelterwood, in which an overstory is removed during a brief period, and clearcutting, which subjects the future crop to full sunlight from the outset. Cutting takes place only during one part of the rotation, so such systems are termed "monocyclic." All trees mature and are harvested at about the same time.

Simplicity is the great advantage of these systems. Compartments are treated in sequence, producing a series of age classes, preferably as many as there are years in the rotation. Regulation of the rate of harvest may be either by forest area or by timber volume.

A disadvantage in converting secondary forests to this structure is that trees in the crop to be harvested must mature at about the same time, a condition that many secondary forests do not meet. Trees too large or too small to mature in synchrony with the harvest may have to be sacrificed. Application of this conversion in Uganda required removal at the outset of all "weed" trees down to 10 cm in d.b.h. (Earl 1968).

By 1932, a modification of the European shelterwood silvicultural system, termed "tropical shelterwood," was in use in what is now Malaysia (Hodgson 1932). Its main objectives were to remove all mature timber in one or more fellings within a short period (usually less than 10 percent of the rotation) and to apply ancillary silvicultural treatments to stimulate regeneration of a new crop of relatively uniform age or tree size.

Tropical shelterwood resulted from a number of widespread conditions. The naturally low merchantable volumes of marketable trees made it financially necessary to remove nearly all of them at once. Consequently, only small trees of the better species were left. These, to prosper, needed more light than is available beneath typical residual overstory (Baur 1964b).

Shelterwood cutting has been superior to systems that maximize present harvest and leave future crops to chance. Indeed, shelterwood has favored the next crop in felling practice, canopy manipulation, seedbed preparation, and control of vines and weeds. It has also tended to protect the soil and existing saplings of desirable species.

Shelterwood does have its restrictions: (1) regeneration of a new crop of the desired species must be either advanced or obtainable promptly after cutting; where unmerchantable species make up much of the forest, such regeneration may be rare; (2) regeneration of the fast-growing species may require almost full sunlight rather than overhead shelter; and (3) any second or final harvesting of the overwood must be done through the new crop, with inevitable damage.

Regeneration of select species following shelterwood cuttings has required a host of silvicultural treatments, including climber (vine) cutting, canopy openings, understory removal, burning, soil scarification, liberation, thinning of advance regeneration, and even supplementary artificial regeneration (Baur 1964a).

Tropical shelterwood, at best, has proved acceptable. Because as few as 75 stems per hectare may be sufficient to produce a fully stocked crop of export timber, adequate regeneration already may be present or quick to appear. The presence of early shade is believed to increase the diversity of regeneration. With canopy manipulation, growth of the next crop may be accelerated. Yields from secondary forests receiving no cultural treatment may average no more than 2 m^3/ha/yr; yet, shelterwood yields on the best sites might reach 7 m^3/ha/yr and increase still further if uses are found for thinnings (Baur 1964a). These yields are clearly below the maximums for plantations, but the latter may not repay establishment costs on sites that would otherwise regenerate naturally.

Tropical shelterwood has seen limited success. In Nigeria (where markets have long been favorable), the practice began in primary forests with a pole felling (Hodgson 1932). This was followed by a seed felling that opened the overstory but left seed bearers believed capable of inducing regeneration. After 2 or 3 years, a low-level cleaning was done, followed by a second seed felling in the 4th year. In the 6th or 7th year a second cleaning was made, followed by the final felling if regeneration was then adequate. Cleanings followed thereafter as necessary.

Tropical shelterwood in what is now Malaysia, despite repeated tests, proved unreliable. The irregularity of seed years played havoc with scheduling. Fellings had to be scheduled around seed years, because the intolerants could survive only 2 to 3 years without release (Durant 1936). For tolerant species, cleanings had to be scheduled to stimulate growth before fellings. A uniform system was substituted in Malaysian lowland forests to exploit the capacity of some of the light-demanding dipterocarps to escape climber growth under full sunlight.

Despite the problems with tropical shelterwood in what is now Malaysia and growing disenchantment generally with natural regeneration techniques in India (Ranganathan 1951), a Malayan forester reintroduced the system into Nigeria in 1943, proposing to concentrate on regenerating *Triplochiton* (Mutch 1949). An earlier uniform system, attempted in 1927, failed for what was believed to be a lack of adequate light control (Lancaster 1961b). The objective of the new system was to convert mature natural forests into a series of relatively even-aged coupes in one rotation (Onyeagocha 1962). Climber cutting, done well before exploitation, was followed by poisoning of unwanted trees of intermediate size, leaving the overstory untouched. Cleanings followed harvesting of the mature timber by 1, 3, 8, and 13 years.

Although the initial treatments were not successful, reportedly because of inadequate seed bearers and ineffectual poisoning, more than 25,000 ha were under treatment by 1948 (Anon. 1949d). Seedling counts of 150 to 200 per hectare, well over the accepted minimum of 100 per hectare, were encouraging, and suggested that the number of seedlings had doubled. Some well-illuminated seedlings also doubled their height in 1 year (Anon. 1949d). Providing enough light to encourage regeneration but not weeds was a problem. Light insufficient for *Terminalia* and *Triplochiton* but adequate for shade-tolerant Meliaceae had become the goal (Mutch 1949). After the final felling in Dahomey, now

Benin, 53 of 55 ha contained more than 500 saplings per hectare 3 m tall or more, and 27 ha had 1,000 or more saplings.

In Nigeria, leaving understory trees was considered necessary to control vine growth (Anon. 1957d). Yet, poison-girdling was needed to keep the canopy open enough to encourage sapling growth. A study of a shelterwood forest at Sapoba, Nigeria, showed that the cost of poisoning must be considered in selecting liberation practices (Henry 1957). The elimination of all trees of no economic value 58 cm in d.b.h. or more took 10 trees per hectare. Removal of trees overtopping economically valuable saplings and poles took 114 per hectare. Removal of all trees 10 cm or more took 273 per hectare.

A Nigerian technique, as revised in 1954, may represent the maximum development of a tropical shelterwood system. It consisted of the following operations (Anon. 1955a):

- Year 1—Demarcate grid lines.
- Year 1—Cut within 15 cm of soil climbers, herbs, shrubs, and trees of no economic value and deformed trees of desirable species.
- Year 2—Conduct prepoisoning cleaning. Cut back new creepers and maintain condition of previous operation.
- Year 2 (and possibly year 4)—Count regeneration and enumerate pole crop.
- Year 2—Perform seedling poisoning. Work up canopy from below by eliminating lower trees to encourage existing reproduction and to strengthen new regeneration if fewer than 100 trees per hectare.
- Year 2 or 4—Perform clearance poisoning. If regeneration yields fewer than 100 trees per hectare in year 2, poison all shade-casting, noncommercial trees of lower and middle stories, leaving only those that are straight and have small crowns.
- Year 3 to 5—Perform postpoisoning cleaning to about knee height.
- Year 3 to 5—Free established seedlings and saplings.
- Year 6—Exploit (harvest) and repair damage.
- Year 7—Remove shelterwood, including all noncommercial trees interfering in any way with the new crop.
- After year 7—Dibble in trees if fewer than 100 trees per hectare.
- After year 7—Line plant if needed.

Climber cutting was continued as long after shelterwood removal as necessary, in rainy seasons of the 9th, 14th, and 17th years (Okon 1962). The provision for dibbling and line planting suggests that natural regeneration may be only partially successful. One postexploitation stand of reproduction averaged 210 trees per hectare, then considered inadequate (Lancaster 1961a). Much doubt arose concerning the technique. Nevertheless, under favorable circumstances, seedling, sapling, and pole counts in Dahomey, now Benin, seem to have been adequate (table 4–9; Onyeagocha 1962).

By 1970, the Nigerian experience had led to disenchantment with tropical shelterwood (Baur 1964a, Oseni and Abayomi 1970). It began with failures in postlogging gaps, followed by difficulties of synchrony with seedfall, and finally, necessity for continued release. The main effect has been to release regrowth already present rather than to induce new regeneration. The stands produced were not of even-sized trees (such

Table 4–9.—Shelterwood crop production in Dahomey (Benin) and Nigeria

Tree size		No. of trees per hectare	
Height (m)	D.b.h. (cm)	Before pretreatment (1952)	After exploitation (1957)
0–1	—[a]	6	74
1–3	—[a]	19	62
3–10		44	71
—[a]	10–50	48	48
Total		**117**	**255**

Source: Onyeagocha 1962.

[a] Not measured.

as in a plantation) because of different growth rates within and among species. The fastest growing trees were maturing in half the time required for the slowest! Even where tropical shelterwood succeeded in bringing on a new crop, noncommercial trees comprised more than half the stands, requiring continued freeing in order to make the site produce to capacity. The composition of the forest shifted from upperstory to middle-story species, and the light demanders generally failed (Lawton 1976).

Lowe (1984) pointed out in his "obituary" to tropical shelterwood in Nigeria that the practice was intended to supply mainly the export markets from stands where only natural regeneration was considered possible because of limited funds. The system failed to reconcile the need to open the canopy and at the same time control growth of climbers and herbaceous weeds. It was complex to apply and difficult to assess. Yet, canopy opening appeared to double the amount of regeneration, and climber cutting doubled the number of potential final crop trees. Nevertheless, tropical shelterwood was abandoned in Nigeria, not because of technical deficiencies but because shelterwood forests, however successful technically, did not compete with cocoa or other alternative crops for which the land was considered better suited. Also, pressures for wood forced a reduction in the rotation from 100 to 50 years. Lowe concluded that, at the then-current rate of conversion to timber plantations, it was unlikely that there was sufficient time for a naturally established seedling to reach merchantable size before the forest would have to be converted to a timber plantation or some agricultural use.

Extensive experience in what is now Ghana, with tropical shelterwood, beginning in 1947, showed that shelterwood required two conditions: a normal forest and a reasonable number of seed bearers (Taylor 1954). These conditions were not common to large areas. The system proved difficult in overmature forests, pole stands, or old secondary forests with poor seed sources. Even the presence of mother trees did not ensure success (Foggie 1957), although an early test in the Bobiri Forest yielded 490 trees of 4 cm in d.b.h. per hectare of 13 valuable species (Lane 1961).

The complexity of treatment in Ghana is illustrated by practices in the Bobiri Forest (Osafo 1968a). One compartment went through 19 years of shelterwood treatments. These included three canopy reductions, 6, 5, and 4 years before felling; regeneration assessments carried out 3, 2, and 1 year before felling and every third year thereafter; cleanings 2 years before and after felling; climber cuttings 1, 9, 11, and 12 years after felling; and poisoning of residuals 4, 5, 6, 8, and 11 years after felling. Damage from the removal of the overwood was generally excessive. Under any shade density chosen, the trees of commercial species were outgrown by weeds.

Mooney (1962, 1963) concluded that, if quality timber was the goal, the results to 1962 in Ghana ranged from excellent to hopeless. He foresaw difficulties in bringing quality species through fast-growers after the stand is opened. When the overstory is removed, light-demanders invade, requiring repeated thinnings to preserve the export species. As an alternative, he recommended abandoning the export species for the light demanders. Many of these have since become readily marketable.

An allied technique in the Congo, termed "uniformization par le haut," began with enumeration and treatments to increase uniformity before harvesting (Baur 1964a). Useless overstory trees were eliminated, and the range of size classes was reduced by selective poisoning. Light intensity at the ground level was increased to 30 to 40 percent of full daylight. Under favorable conditions, climbers were not a serious problem.

In the Western Hemisphere, the outstanding example of a tropical shelterwood system is that which apparently is extant in the Arena and McNair Ravine Sable Forest Reserves in Trinidad, where the work began about 1935 (Baur 1964a). Early observations had concluded that plantations of species such as *Calophyllum brasiliense, Carapa guianensis,* and *Vitex divaricata* did poorly on sandy soils (Ayliffe 1952, Brooks 1941b). In contrast, natural regeneration under shelterwood on sandy soils had proved adequate. Nine species in Arena and 18 in McNair, including species of *Byrsonima, Hieronyma, Nectandra, Schefflera, Tabebuia,* and *Terminalia,* were accepted as potentially marketable. Tendings (including climber cutting and cleaning of undergrowth) were followed by gradual removal of shelterwood for the next 3 or more years. The best overstory trees were left, but the understory trees were removed, after which the remaining overstory was thinned to provide adequate light (Moore 1957). Charcoal-burner labor has been used for much of the work. At Arena, a 50-year rotation to 50 cm in d.b.h. has been contemplated for the rapid growers, and 60 years for others, to be left as standards (Raets 1963). A yield of about 5 m^3/ha/yr was expected (Ayliffe 1952).

In summary, it is clear that a strong effort was made to apply tropical shelterwood in many countries. The record suggests that it was generally a failure. Most discouraging were the impressions at many locations that where it "produced" a new crop, the crop was already on the ground and, elsewhere, that it failed to induce new regeneration of the export timber species of the day. Less has been said about the labor costs, which became prohibitive as wages rose. The concept, however, may again be worthy of trial, now that many former weed species are marketable. The advantages of monocyclic management with preservation of a continuous canopy and much of the natural diversity are now assessed more highly than in the past.

Clearcutting. Clearcutting of tropical forests to harvest industrial timber (as opposed to fuelwood) is almost unknown because most trees of mixed forests have not been marketable. Nor is clearcutting of such stands a priori a logical option for the silviculturist. Immature trees of valuable native species come up naturally through at least partial shade. Successful regeneration of desirable species after clearcutting is a rarity.

The most notable and possibly a unique example of successful heavy cutting for regenerating moist tropical forests for the production of large trees is in Peninsular Malaysia where, after the Second World War, logging became mechanized (Baur 1964a). Early improvement cuttings had shown that regeneration was usually already present. A single heavy felling, leaving no seed trees, was then proposed, counting on advanced regeneration. This proposal marked the beginning of the Malayan Uniform System (Baur 1964a), which depended on: (1) adequate stocking of seedlings of useful species at the time of exploitation, (2) complete removal of the canopy, (3) no tending until access was clear beneath the regrowth, and (4) prevention of redevelopment of climbers.

Regeneration averaging one seedling up to 2 m tall in 40 percent of the 2.5-m^2 plots was considered adequate. If this level was not met, a seed year was awaited. Felling was done within 2 years thereafter and was followed by poisoning all useless stems down to 5 cm in d.b.h. From 3 to 5 years later, sampling indicated the need for climber cutting or followup poisoning. Experience and improved markets later led to less stringent requirements: 30 percent stocking became accepted as adequate, and up to 20 percent of the selected seedlings could be in the light wood classes (Baur 1964a). A later shift in land use, relegating forest production to the uplands where natural regeneration was less plentiful, led to the conclusion that future wood supplies in the area must ultimately rely chiefly on artificial regeneration.

In Nigeria, four methods of converting cutover forests to new crops were tried, beginning in 1927. The first, cutting all but 10 seed trees per hectare and burning, apparently failed, because it produced a climber tangle (Baur 1964a). A second system, leaving overstory groups to bear seeds and cutting and burning the lower stories and climbers, proved more successful but called for more supervision than was available. A third system, calling for planting openings (enrichment), proved too dispersed to administer. A fourth, a uniform system, involved a gradual opening by climber cuttings and girdling undesirables about 3 years before logging. It was successful in that the increased light stimulated existing natural regeneration (Baur 1964a). Nevertheless, gap planting was sometimes required.

Preharvesting Treatments. Failures in natural regeneration have generally been ascribed to an absence of advance seedlings, a lack of seeds due to harvesting of seed bearers of the desired species, logging damage, and the smothering effect of subsequent vines and weeds. These conclusions have led to efforts to promote natural regeneration in mature forests before harvesting.

Experience in India has produced varied results. Fellings in the understory do not induce regeneration but may help an existing crop (Champion 1936b). Indian dipterocarps reportedly need bare soil for germination and gradual liberation thereafter (Sen Gupta 1939). Removing undergrowth and working soil just after seedfall encouraged natural regeneration but mostly of noncommercial species (Iyppu 1960). Until the sapling stage, weedings were required three times per year.

In what is now Malaysia, it was concluded early that overstory fellings do not induce new crops of dipterocarps. Instead, openings in the canopy in advance of regeneration produced a dense understory, jeopardizing any desirable seedlings that might have appeared (Watson 1936). In the dipterocarp forests of the Andaman Islands, reducing the density of the canopy at different heights and burning the debris before seedfall reportedly brought in good regeneration but also weeds (Pooraiah 1957).

African experience with preharvest inducement has been more encouraging. Intensive treatment of small areas has produced some spectacular results. In Nigerian studies, manipulating seedfall and light conditions and cleaning around seed trees led to local successes with many species (Kennedy 1935, Paul 1953). The standard regeneration treatment from 1932 to 1935 included understory clearing around one seed bearer of economically valuable species for each 2 ha (Paul 1953). Clearings were as large as 0.8 ha, and debris was burned before seedfall. Regeneration, where copious, was thinned to a 1- by 1-m spacing. Secondary species were allowed to remain where needed for shade. But the labor cost was about 200 days per hectare (d/ha).

Cultivation beneath seed bearers of *Maesopsis eminii* produced abundant regeneration in Uganda (Swabey 1954), as it did for *Callitris calcareta, C. robusta,* and *Cupressus lusitanica,* in Nyasaland, now Malawi (Anon. 1952f), and for *Flindersia brayleyana* and *Toona ciliata* in tropical Australia (Anon. 1958g).

Larger scale treatments in Africa, however, have been less convincing. Between 1944 and 1948, light poisonings and cleanings were done in Nigeria during each of the 5 years in advance of harvest (Jones 1950). As many as 200 seedlings per hectare were found in some areas, double the minimum standard. An opinion persisted, however, that much of this regeneration was present before silvicultural treatment (Onyeagocha 1962). This belief seemed supported by the fact that gaps in the regeneration, when cleared, did not regenerate but instead came up in weeds. The 5-year advance period before felling exposed larger saplings to logging damage. In one study, the larger saplings were found more vulnerable to felling damage than smaller ones (Jones 1950), but in another study they were considered better able to withstand logging than seedlings (Ellis 1951). The lack of widespread success of these treatments has been laid to irregular fruiting, a lack of seed bearers (as few as one per hectare), and differences in shade requirements for each species (Catinot 1974).

In America, few observations of the results of preharvesting treatments have been recorded. *Cedrela odorata* regeneration was found to be abundant on a farmed area adjacent to a forest in what is now Belize (Anon. 1949a). In the Amazon, an experiment in a secondary forest compared three intensities of opening: (1) cutting back noncommercial saplings of less than 5 cm in d.b.h., (2) the same as (1) plus poisoning some understory trees, and (3) the same as (2) plus killing some of the larger trees (Pitt 1961b). Fifteen native species were considered marketable. By the end of the first year, regeneration in the light treatment rose from 18 to 60 percent of full stocking. In the second treatment, regeneration rose from 37 to 89 percent, and in the third treatment, from 20 to 100 percent. It was concluded that basal area must be reduced to 15 m^2/ha for trees of 10 cm in d.b.h. or more (10 m^2/ha for trees 25 cm or more) to induce regeneration.

Elimination of Relics. Relics are large trees that remain singly or in groups well above cutover forests. Some may have been left for seeds, but most lacked a market. Their survival is uncertain, their growth is of little moment, and they may create unwanted shade or fall onto the future crop.

Experience in handling these relics is mostly from countries in the Eastern Hemisphere. In what is now Malaysia, Watson (1936) disproved any need for heavy initial shade for dipterocarp saplings, showing that rapid growers can come through in large openings. He recommended early felling of seed bearers to avoid greater damage later. His observation that the meranti group of Dipterocarps (desirable light woods) respond vigorously to full light convinced him that, where regeneration is adequate, the canopy should be removed as rapidly as considered safe. He saw removing the canopy in one operation as both economical and effective. He considered removing the upper canopy alone to be of benefit only to the lower canopy, not to regeneration. Watson's conclusions were confirmed 10 years later by the Malayan Uniform System. By 1950, the standard practice in lowland dipterocarps with advance regeneration was complete harvesting in one operation and poisoning of useless stems as felling progressed (Barnard 1950a).

Early reports from Sabah led to the same conclusion: If adequate seedlings are on the ground before logging, all noncommercial trees should be poisoned soon thereafter (fig. 4–6; Nicholson 1958b). At that time, it was unclear whether some commercial overstory should be left for an interim harvest before the seedlings matured.

Later studies in Malaysia supported leaving large seed trees that were healthy and had good crowns (Wyatt-Smith 1963). It was expected that they would be fast

Figure 4–6.—*Elimination of a relic in Sarawak, using frill-girdling and an arboricide.*

growing and would continue to grow well if retained. Later removal of such trees was seen as a potentially profitable, intermediate cutting. Measurements in one such felling indicated that harvesting these trees would not unduly harm the future crop if logging were carefully controlled (Wyatt-Smith 1963). However, if such a felling is imminent, tending of the young growth should be postponed until logging has been completed (Wyatt-Smith and Vincent 1962b).

Other studies in lowland dipterocarp forests indicated that relics did not contribute to future production (Wong 1966b). In one forest, 15 of 74 relics died within 7 years, and in another, from 6 to 28 percent of the *merantis* died within 10 years. By 1970, the standard Malayan Uniform System practice with dipterocarps was harvesting down to 40 to 50 cm in d.b.h., in one or two stages 7 years apart, and girdling down to 30 (or even 10) cm in d.b.h. (Burgess 1970).

Treating relic stands has been considered the most important silvicultural operation in the Malayan Uniform System (Tang and Wadley 1976b). Reduction of the overstory to 25 m^2 of basal area per hectare is important to the development of regeneration. Further reduction is much less so. With a relatively tolerant new crop, elimination of the relic stand may be delayed up to 4-1/2 years. If relics must eventually be girdled, however, it is advantageous to do so immediately.

Removing relics as well as other unwanted trees in secondary forests requires the use of safe, effective, and inexpensive techniques. Felling was discontinued years ago because of the cost and the damage to residual trees done by live crowns (after which, climbers were a problem). Girdling is much less costly than felling, but the death of the tree may be neither prompt nor certain. Moreover, girdling is difficult on trees with fluted boles, and if incomplete, the tree may persist indefinitely. Girdled trees generally do not die immediately anyway, so the benefits are slow to appear. This is a sound argument for the use of arboricides. Whether girdled or poisoned, trees normally lose their crowns and otherwise deteriorate before falling, reducing the impact on trees below.

Natural Regeneration. The term "natural regeneration" means renewal by self-sown seeds or vegetative means (Ford-Robertson 1971). There has been much confusion in the past between inducement of new seedlings and stimulation of seedlings already present. The distinction is important because inducement has generally proved much more difficult than stimulation. The two have commonly been confused where the abundance of a seedling crop was not reliably determined before treatment was begun. Many of the greatest successes reported in natural regeneration are where the new trees appeared before any treatments (Paul 1953).

Tropical moist forest sites have remarkable recuperative powers and rapidly revegetate disturbed areas or openings (figs. 4–7, 4–8). In strictly quantitative terms, natural regeneration in the region is seldom much of a problem

Figure 4–7.—*Complete regeneration of* Pinus occidentalis *after heavy logging in the uplands of Haiti.*

Figure 4–8.—*Abundant regeneration released by liberation of a crop tree (center) 10 years earlier.*

Figure 4–9.—*Twenty-four-year-old volunteer secondary forest development in the Philippines.*

except where deforestation is so extensive or lasting that root systems and nearby seed sources are destroyed (fig. 4–9). However, an adequate crop of naturally regenerated seedlings of desirable species is not awaiting the forester in most volunteer tropical forests. Regenerating only those tree species that are potentially marketable for export calls for something distinct from ordinary natural forest succession. Several difficulties have confounded efforts to naturally regenerate these selected species (Banerji 1958, Wadsworth 1962): (1) commercial harvesting deteriorates the forest's potential to produce seeds of marketable species; (2) harvesting leaves both openings and untouched areas, neither of which may be ideal for regenerating desired species; (3) good seed years may be irregular and infrequent; and (4) the degree of canopy opening that favors desirable regeneration, usually light demanders, and at the same time controls climbers and weeds (if indeed, such exist) has proved elusive.

The patchy occurrence of desirable natural regeneration in the moist forests of tropical Africa and America was recognized early (Champion 1934). A study in Nigeria found that most of the seedlings on hand were of middle-story species, not the outstanding dominants termed emergents (Jones 1950). Local variations in the abundance of regeneration not apparent in broad survey statistics were found in the moist evergreen forests of Venezuela (Rollet 1969).

Even where natural regeneration has been adequate, it has sometimes been disregarded as a source of a new crop. Teak *(Tectona grandis)* in India and Pakistan, for example, may adequately regenerate by seedlings, coppices, or root sprouts, yet stands have been regenerated by planting (Imam 1969).

Success with natural regeneration calls for more than the appearance of a new crop, as illustrated by early experience in what is now Sri Lanka (Holmes 1945). It was noted in 1921 that a carpet of seedlings appeared in openings in moist forests. Two years later it became apparent that cleaning these seedlings would be crucial to their survival. Treatment revealed that the regeneration occurred in patches concentrated near seed bearers. After 4 years, the remaining stand was even more spotty, a result of variations in light and animal damage. In the 5th year, a marked dry season caused further losses. By the 8th year, it was concluded that regenerating a stand was not a problem, but its survival through the first years was. Even in the 12th year, the saplings were still being choked out by weeds. Apparently, commercial timber production could not depend on untended natural regeneration.

Natural regeneration was attempted in the forests of Nigeria from 1906 to 1944, at which time a general failure was recognized (Oseni and Abayomi 1970). By 1957, Uganda was the only African country in which forests were managed on the basis of planned, natural regeneration (Anon. 1957e). By 1966, most African countries were promoting planting within existing forests (Galinato 1966). A proposal was made in what was formerly Zaire to convert land abandoned by shifting cultivators to naturally regenerated secondary forests by first establishing sparse plantations of eucalypts (Pierlot 1952).

In Uganda, authorities shifted to natural regeneration after 1952 because of costly plantation failures, including underplantings (Baur 1964a). Since then, the forests have been sampled to assess treatment needs, then refined before exploitation. Natural regeneration was found more plentiful than expected. Where regeneration was adequate, the overstory was removed in a single operation.

Similarly, in Queensland, Australia, generally adequate natural regeneration has occurred. Up to 2,200 trees per hectare 10 cm in d.b.h. or more remained after logging, of which nearly 200 were of cabinetwood species (Baur 1964a). Girdling of the undesirables and cutting climbers doubled the diameter growth of the selected trees.

In tropical America, attempts to induce natural regeneration have been extremely local and insignificant compared with plantation projects. A study of the causes of natural regeneration losses in *Swietenia macrophylla* in what is now Belize is of some interest (Wolffsohn 1961). Strips 6 by 36 m were cleared to the leeward of 10 seedbearing trees and subdivided into 6- by 6-m plots. Half the plots were treated with the persistent insecticide aldrin. The seedling crop that year ranged from 1 to 6 per plot in the untreated plots and 40 to 255 when the plots were treated. Seedlings were also abundant on abandoned logging roads, suggesting that many also escaped insects there.

Natural regeneration under extremely wet conditions (750 cm of rainfall annually) at low elevations in western Colombia was found adequate in quantity 2 years after logging (Ladrach and Mazuera 1985). Before cutting in the mature forest, there were about 1,400 trees per hectare 4 cm in d.b.h. or larger; 2 years after cutting, there were 6,800 trees. Only about 1 percent of these were sprouts. It was apparent that in order for new seedlings to enter the cutover stand before the vegetation again closes, germination would have to take place immediately after cutting, or certainly within 2 years. On this site, the volume in trees 13 cm in d.b.h. and more 15 years after cutting was half that of the mature forest, suggesting that by the 30th year, it would be equal to that of the mature forest (Anon. 1979e).

Experience in Peru offers further evidence that in moist forests, natural regeneration need not be a serious problem (Hartshorn and others 1986). Clearcutting strips 20 to 50 m wide, separated by 200 m or more, with full utilization of the wood yielded, led to regeneration at 15 months of 1,500 saplings of 50 cm or more in height, with 132 species represented. Although a local market for fuelwood apparently exists at the site, it remains to be seen how valuable for other purposes these species will prove.

The general inadequacy of high-quality, natural regeneration has led to three options: substitution, inducement, and planting, in that order (Dawkins 1958c). Substitution is appropriate where other potentially commercial species that reproduce well naturally are available. Elsewhere, research into induced regeneration of native desirables should be undertaken before natural regeneration is entirely abandoned. Studies should center on seeding, the ground environment, and canopy manipulation.

Even where natural regeneration appears to have failed, a shift to planting should be made cautiously. Plantations can produce higher yields, but their greater costs require land that is of better quality and more accessible than the kind of land that can produce naturally regenerated forests. The relative costs of the two practices, however, vary widely from place to place. Total costs are seldom included in such comparisons. In some areas, natural regeneration may prove less costly than expected (Kio 1976). Moreover, more of the cost for natural regeneration goes toward employment of unskilled workers. However, progress in genetic improvement of selected plantation species should, in time, make natural regeneration a less competitive option.

The process of natural regeneration is not fully understood. Local studies of phenology, seed dispersal, and relations to light, moisture, and forest gaps are needed. Guidance can be found in a collection of studies published in Mexico (Gomez Pompa and del Amo 1985).

In summary, the inducement of new regeneration of export-quality species by silvicultural techniques in moist forests has been successful only locally. However, in forests where seedlings and saplings are naturally plentiful, such as in Queensland, the Philippines, and parts of Malaysia, Sri Lanka, and Africa, their protection, stimulation by prefelling treatments, and liberation have been successful (Baur 1964a, Dawkins 1961d). The key questions are how much tending is required and how the benefit/cost relations compare with those of plantations and alternative agricultural land uses.

Refinement Treatments. Refining is the elimination of undesirable trees, climbers, and shrubs to foster complete site utilization by the desirable crop (Dawkins 1955b, 1958a, 1958g; Ford-Robertson 1971). It requires the allocation of growing space to promising immature trees at the expense of others (fig. 4–10). It is a varied practice that may include the elimination of giant relics left after logging, felling or killing unsound trees and those of inferior species, cutting back damaged stems, liberating desirables, thinning juveniles, and freeing seedlings. The practice is also commonly termed "improvement felling." In the Tropics, the term "selection felling" has in English been applied about as broadly as improvement felling for refinement.

A major argument for refining secondary forests rather than replacing them with plantations is the presence of an immature crop that replacement would sacrifice. Such stands may have a wide range of tree diameters, of which the largest may appear to be the most worthy of being brought to maturity. This situation, plus the common assumption that tree diameter and age are strongly related, has led to attempts to apply the selection silvicultural system in tropical forests, preserving an array of tree sizes and proposing periodic (polycyclic) partial fellings that both harvest the mature trees and liberate the immature ones. Nicholson (1979) concluded that the fact that a high proportion of cutover forest areas is composed of immature trees not released by logging indicates that silvicultural treatment is needed.

Figure 4–10.—*Thinned white mangrove* Laguncularia racemosa *after removal of about half the basal area in poles and fuelwood.*

The place of refinement in silviculture is illustrated in figure 4–11 (Wadsworth 1966). Clearly, after a harvest that leaves an immature crop or where such a crop has volunteered, the remaining stand component of primary interest is the canopy trees. If the immature trees in the canopy are not adequate for the next crop, attention shifts to the understory. If this is adequate in species quality and density, it will generally need to be liberated by removing part or all of the overstory, removing unwanted trees or climbers, or thinning the crop trees themselves. In typical forests, more than one of these treatments are needed. For example, in Ghana, selection felling reconditioned the stands following logging, including releasing the crowns. However, this does not by itself lead toward (much less ensure) the development of a selection or all-aged forest (Osafo 1970).

Refining of irregular forests has been successful under favorable conditions in the dipterocarp forests of the Far East where logging was carefully controlled and cutting cycles were long (Liew 1973b). Almost everywhere else, however, the preservation of irregularity has been in disrepute, as described earlier in this chapter.

Refinement became widespread in the vast and increasing areas of cutover forests on lands not needed for agriculture or forest planting. The practice has been favored as a silvicultural option because it is less expensive than other practices, such as planting, making it under some circumstances the most profitable management course (Earl 1975). In modifying the forest gradually and conserving natural components, even when the goal is uniformity, refinement is a conservative departure from nature. It had an early origin throughout the Tropics, as indicated in appendix E.

Refinement has varied widely over time, beginning in 1880 and covering hundreds of thousands of hectares. From 1910 to 1947 in what is now Malaysia, refining included climber cutting, thinning, and cutting back second growth (Baur 1964a). By 1927, it was evident that a lack of followup had resulted in much wasted effort. Immature trees of good species were not adequate everywhere. Girdling was not always effective.

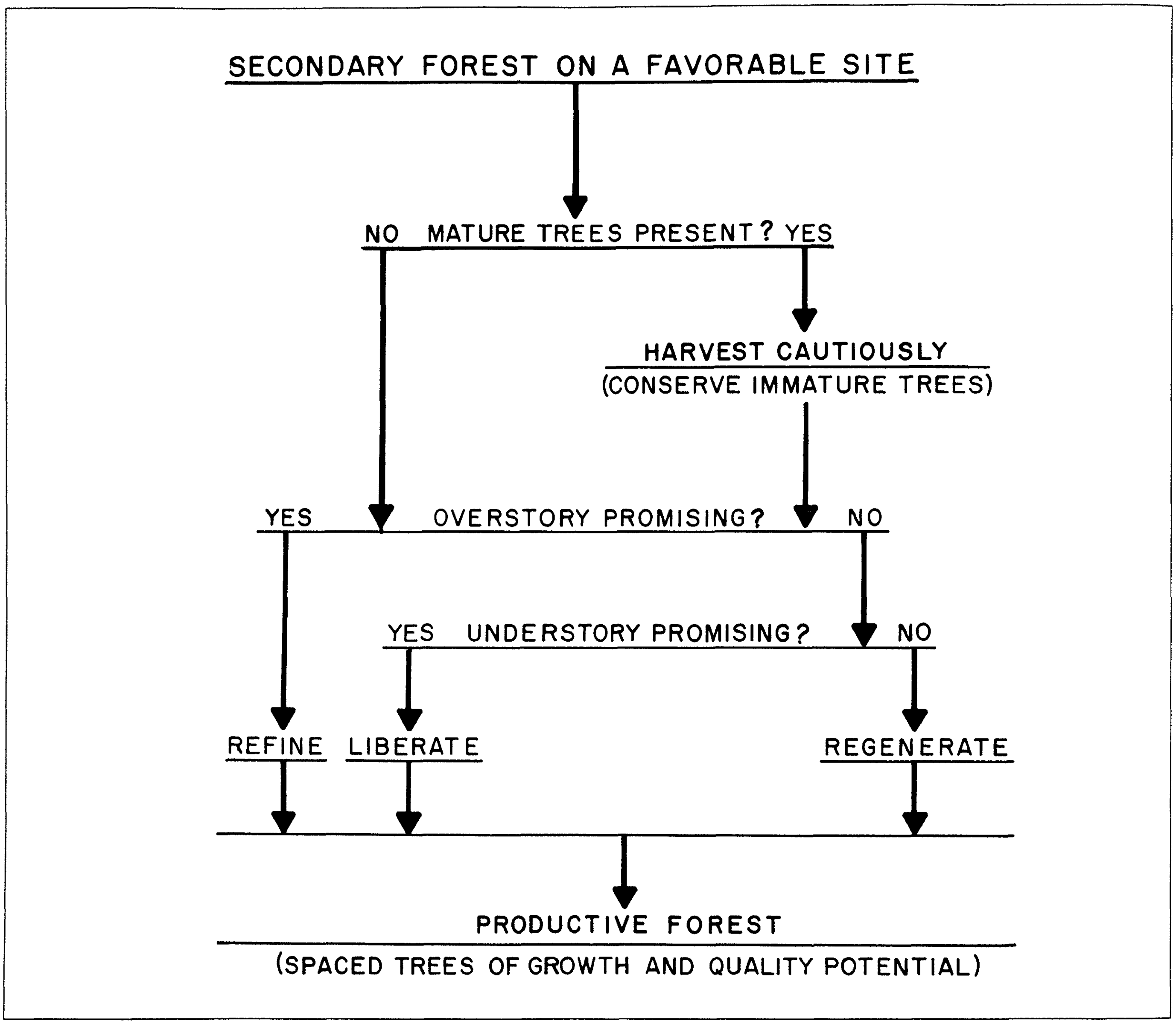


Figure 4–11.—*The place of refinement in secondary forest silviculture (Wadsworth 1966).*

Improved markets were making the girdling of poles unwise. The shift was to "regeneration improvement fellings," directed toward regeneration as well as improving the existing stand, a reversion to shelterwood. In 1930, the practice was to fell poles where there was a market, followed 2 years later with a light seed felling, a cleaning 3 or 4 years after that, a second seed felling in the 7th year, a cleaning in the 9th, and a final felling in the 10th, followed by more cleanings (Paul 1953).

By 1939, some 80,000 ha had undergone regeneration and improvement fellings in what is now Malaysia, and postwar studies showed that the proportion of rapidly growing species of *Shorea* had increased. The prospective productivity of about 5 m^3/ha/yr on a rotation of 70 years, although not as high as in plantations, was expected to produce forests much more valuable than their predecessors (Baur 1964a). After the Second World War, when it was seen that seedlings and saplings of some dipterocarps could cope with weed growth, there was a dramatic shift to clearcutting.

In what was formerly Zaire, irregular structure was retained. About 80 to 90 percent of the forests were allowed to develop naturally, and widely spaced strips were planted to selected species (Paul 1953). In francophone Africa, variable abundance of desirables after logging generally led to abandonment of natural regeneration and a shift to underplanting. In Nigeria, it was recognized in 1927 that regeneration was generally spotty, so gap plantings supplemented improvement fellings. Heavy fellings produced an impenetrable tangle and led to longer and longer periods of weeding and climber cutting until, by 1952, they had continued for up to 21 years. Experience in Ghana was similar. In both countries, it became apparent that success of refinement treatments depended on adequate regeneration at the outset.

Refining was applied in Suriname (Jonkers and Hendrison 1986). Initially it included cutting lianas and poisoning undesirable trees down to 5 to 10 cm in d.b.h. Seedlings and saplings of commercial timber species proved to grow too slowly to compete. Larger trees grew at rates of 1 cm or more in stem diameter, but tending costs were considered too high, so the shift was to plantations.

Soon planting was also abandoned because of the rising costs of clearing, planting, and tending (Jonkers and Hendrison 1986). What followed has been a testing of reduced-intensity, polycyclic management of natural cutover forests. Refinement is scheduled at 1, 8, and 16 years after logging. Only trees larger than 20 cm in d.b.h. are poisoned. Scheduled reductions in basal area for the first treatment were from 28 to 12 m^2/ha; for the second treatment, 7 years later, from 20 to 10 m^2/ha; and for the third, 15 years after logging, from 18 to 15 m^2/ha.

Reducing the basal area to 15 m^2/ha may require the poisoning of 100 trees per hectare (Jonkers and Schmidt 1984). Increased diameter growth on the trees that are left will continue for 8 to 10 years, then followup treatments will be needed. The mean annual diameter growth ranges from 9 to 10 mm. Three treatments several years apart each cost about 7 worker-days per hectare. The harvest, after 20 years, is expected to come from 13.5 trees per hectare, compared to only 2.7 harvestable trees after 25 years with no treatment.

Coupled with the revised refining technique under study is intensified logging, termed the "celos system" (named for the source institution, Centrum voor Landbouwkundig Onderzoek in Suriname), with a focus on reducing damage to the immature trees (Jonkers and Hendrison 1986). Preliminary inventories, mapping, trail layout, and direct supervision of felling direction and skidding practice significantly reduced logging damage. Where 3.4 commercial trees were removed per hectare, 82 percent of the remaining trees were undamaged. Where 16.2 trees were removed, 65 percent remained undamaged.

A recent study of the growth response of high forests to refinement (Synnott 1979) has shown that, within certain limits, reductions in stocking and basal area by felling and/or poisoning may sufficiently accelerate growth of the remaining trees, more than compensating for reduced basal area. Net basal-area growth per unit area under these circumstances increased with basal-area reductions.

It bears repeating that improvement fellings were recognized early only as a provisional treatment, mainly to utilize the available stock (Troup 1921). Refinement is not a silvicultural system in itself in that it does not ensure successive crops. Although repeated refinement of secondary forests should gradually increase the number of useful tree species and their seeds, there is no assurance that a new crop will develop and survive harvesting of the overstory.

Refinement invariably leaves the forest more open by eliminating unwanted trees to stimulate growth of the trees that remain. The elimination of relics may produce large canopy openings. Such openings may also stimulate (or possibly smother) existing seedlings of trees that might comprise the next crop. They may also make the forest floor warmer and drier.

Where refinement is directed toward monocyclic management, the ultimate harvest is intended to be total, producing exposure and logging effects similar to those in plantations. However, if advanced regeneration develops and logging is carefully controlled, an adequate new crop of young trees may survive and protect the site after the harvest.

Favored tropical species must be not only highly productive and potentially marketable but also fully site compatible rather than merely site tolerant. The ecological and technical knowledge about species and sites necessary to make refinements fully effective is not yet available. Until it is, all species that look good should be preserved so that they may be treated more judiciously in the future as more information about them comes to light.

Refinement to maximize production of useful wood ultimately reduces the representation of more than half the tree species and, therefore, probably also reduces forest diversity. Such simplification could eventually endanger the ecosystem. A reasonable compromise might be to leave (until the effects are better understood) the trees of understory species and some unmarketable overstory species, such as species of Palmaceae and opportunists, removing only those that clearly overtop the crop trees, possibly at little or no sacrifice to yields of useful wood.

The yields from refinement may be lower than those of more intensive technologies, but the required investments are also low and often more in tune with available financial resources (Palmer 1975).

A supplement to refinement in coniferous tropical forests is prescribed burning to reduce the understory or the accumulation of slash that might fuel an uncontrollable fire during dry, windy weather. Burning has a place when cautiously done under favorable weather conditions. However, on steep slopes prescribed burning can increase surface runoff and sediment loss. Even a low-intensity burn in a natural *Pinus oocarpa* stand in Honduras on slopes ranging from 10 to 40° raised the surface runoff from 1.7 to 5.0 percent and sediment loss from 80 to 1,732 kg/ha/yr (Hudson and others 1983).

Yield data from refined forests are not yet adequate to predict ultimate limits of timber productivity. However, higher yields will be required in the future. One way to raise average returns is to concentrate on only the best available sites. Another approach to higher returns is to increase the marketability of little used, rapidly growing species. This could also immediately increase the eligibility of stands for refinement.

Crop Adequacy. Experience in refinement, like that of silviculture in secondary tropical forests, has taught more what not do than what to do. As with silviculture, however, it is not clear that plantations are a better alternative everywhere. With improved markets raising values on more forest products and tree species, much of what was done in the past would now be done differently. Increasing public understanding of the noncommodity values of tropical forests brings about a recognition that preservation and management of tropical forest ecosystems are imperative to human welfare. Because it is improbable that a need for forest production will decline, subsequent sections of this text extract from past experiences those policies and practices for forest refining that deserve further study and testing in the search for optimum sustainable management of the forests for all their values.

The number of timber crop trees in a fully stocked, immature stand depends on their final spacing requirements and their expected mortality during the rotation. The number of trees of export size constituting full stocking at maturity is small. For 1,469 trees of 15, large, wet-forest, tree species in Puerto Rico, the mean crown-diameter-to-d.b.h. ratio is near 20 for trees 20 to 40 cm in d.b.h. with extremes of 5 and 39 (Wadsworth 1987; fig. 4–12). At a basal area of 25 m^2/ha and a crown-diameter-to-d.b.h. ratio of 20, no more than 90 well-illuminated trees of 60 cm in d.b.h. can be accommodated in a hectare. In tended forests, crop-tree mortality is remarkably low (Dawkins 1961c, Wilkinson 1960), and therefore, the number of saplings and poles need not be more than two or three times that of the final crop to ensure full stocking. Dawkins (1958c) has arrived at the number of trees that he feels are needed for full stocking to 80 cm in d.b.h. in Uganda (table 4–10).

In mixed stands, tending can concentrate on removing trees of little potential value because of species or form (Dawkins 1961c). This method, plus evidence that tended crop trees survive well, suggests that as few as 100 saplings and poles per hectare can result in full stocking at 60 cm in d.b.h. Danso (1966) considered 22 to 25 stems per hectare of commercial tree species 10 to 70 cm in d.b.h. worthy of silvicultural treatment in Ghana. However, he noted that because these trees may occur in dense groups, they may have to be thinned before reaching maturity.

In the Philippines, where there has been generally an excess of trees of 20 to 70 cm in d.b.h. before the first harvest, a goal has been to save 60 percent of them (Tagudar 1967). In Indonesia, the number of trees left for the next crop has ranged from 25 per hectare for those 35 cm in d.b.h and larger to 40 per hectare for those 20 cm in d.b.h. and larger (Soerianegara 1970). In Suriname, 200 to 500 "juveniles" (probably 10 to 20 cm

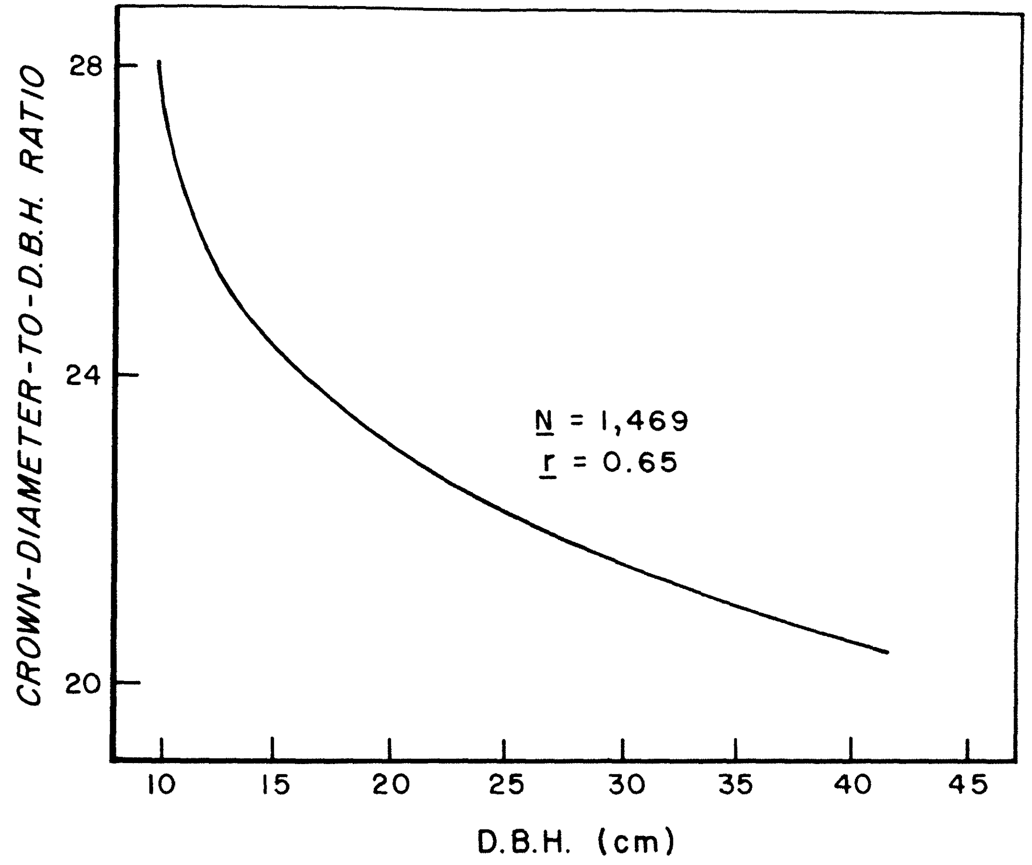


Figure 4–12.—*The uniformity of crown diameter-to-d.b.h. ratio for trees above 20 cm in d.b.h. (Wadsworth 1987).*

in d.b.h.) per hectare have been accepted as adequate. These have been tended in strips running east and west, 2 m wide and 10 to 20 m apart (Boerboom 1966). Should smaller trees at maturity be the objective, a larger number would make up the final crop (125 trees of 50 cm in d.b.h. per hectare), but because of lower mortality, the same number of well-spaced starters may prove adequate.

Something less than full stocking in secondary forests might still be preferable to the cost of artificially regenerating a full crop. Therefore, fewer crop trees may be worth tending, as they may well make a higher return on the investment than starting anew with planted trees. Wyatt-Smith (1960d) reported that in Malaysia, 40 percent seedling stocking at the time of felling corresponded to 55 percent stocking of saplings 5 years later, amounts he considered minimum.

In secondary volunteer forests that arose on cleared areas, the overstory ordinarily appears to have little crop potential. It is commonly a mixture of poorly formed pioneer trees, many of which mature at a small size.

Table 4–10.—Number of trees corresponding to full stocking in Ugandan forests

D.b.h. (cm)	No. of trees per hectare
0–10	2,000–25,000
10–20	200–400
20–50	100–150
50–80	50–75
>80	35–50

Source: Dawkins 1958c.

Attention there should be focused on the understory, where saplings of tree species of more advanced successional stages may be appearing from seeds recently introduced by animals. Some of these may produce marketable wood. If liberated early, they may also be capable of rapid growth.

The proportion of the secondary forests of the humid Tropics that contains adequate stocking may be larger than generally supposed. A systematic survey of 97,000 ha of secondary forests and abandoned coffee plantations 10 years old and older in Puerto Rico showed that about 52,000 ha were adequately stocked with trees of 21 species that were potentially marketable locally (although not for export) (Wadsworth and Birdsey 1985). Of this area, 24,000 ha were stocked with 100 poles per hectare or more (averaging 176) 12.5 to 27.5 cm in d.b.h. and 28,000 ha with 250 saplings per hectare or more (averaging 725) 2.5 to 12.5 cm in d.b.h.

Identification of Timber Crops. Early improvement felling emphasized eliminating trees rather than stimulating them. This reflected more confidence in identifying trees of little value than in selecting those that might prove most valuable at some future date. Because the trees in natural stands are generally crowded, eliminating what seemed worthless was considered an infallible step toward higher productivity of what was left. No doubt such treatment enhanced future timber productivity. However, this strategy generally ignored the possibility that the gaps thus produced would leave vacant microenvironments unsuited to the timber species or the habitat needed for animal life that contributed to the forest's well-being. Also, it was seldom known whether this kind of enhancement was cost-effective.

More recently, treatment has focused only on stimulating those trees expected to form the next crop. Concentrating on stimulating timber crop trees presupposes that they can be identified with certainty. For identification, a set of minimum qualifications for crop trees is needed. Such trees must be potentially superior to their neighbors and free from interference from other crop trees. The basic criterion for selection is that species of trees should be likely to be uniform in size at maturity, form, tolerance of competition, growth rate, freedom from insect and disease problems, and wood properties. The following considerations should guide species selection:

1. Include species with diverse characteristics and even doubtful future utility to preserve ecosystem stability and anticipate value changes
2. Include tree species whose products supplement rather than compete with plantation species
3. Include tree species that in nature grow to a larger diameter than the desired size for harvest, so maturity will be reached during youthful vigor
4. Include species with straight stems, an advantage even for fuelwood.

Freezaillah (1984) points out that 93 percent of the tropical forest volume is of little-known species. Most of this volume is wasted, suggesting potential gains from market development. Perishable woods can be treated with preservatives. Small trees and woods considered mediocre are becoming marketable.

Export markets for new species will develop only gradually as long as select timber supplies remain. For local markets, processing capacity must exist, preferably for products more valuable than chips.

The prospect that many tree species not now used *could be* used by the time present crops mature is supported not only by what has happened in the past but also by studies of existing stands. The closed forests of South America are contributing to the local economy far below their potential (Ramos de Freitas and others 1987). Research on wood properties and processing promises to increase productivity 10 to 30 percent without large investments.

Among the hundreds of tree species available, some will no doubt continue to be much more useful than others regardless of how great the demand for wood may become. This suggests that simplifying the natural composition of tropical secondary forests should increase their productivity. Such simplification, if cognizant of any adverse ecological consequences, should make subsequent silvicultural treatments more practical and comprehensible. An approach undertaken by the author to classify timber tree species of Paraguay by their apparent potential utility illustrates the process. The total number of timber species listed for the moist forests of eastern Paraguay was 230. These were then classified on the basis of existing (incomplete) information as follows:

- Tree species that in nature do not grow larger than 50 cm in d.b.h. or generally do not have a straight bole of at least 6 m—152 (class VII) (leaving 78)

- Of those left, species that produce woods having no apparent promise for any usable product—8 (class VI) (leaving 70)
- Of those left, species with woods clearly unsuited for industrial uses, such as furniture, plywood, or construction—10 (class V) (leaving 60)
- Of those left, species with woods of unknown suitability for such industrial uses—17 (class IV) (leaving 43)
- Of those left, species with woods adequate for construction but not for furniture or veneer—9 (Class III) (leaving 34)
- Of those left, species with woods considered acceptable for furniture or veneer but heavy or difficult to work, specific gravity 0.71 to 0.90—12 (Class II) (leaving 22)
- Of those left, species with woods considered superior for furniture and veneer, specific gravity 0.40 to 0.70—22 (Class I).

Under such a classification system, nearly 10 percent of the woods of the forest are in Class I. In all, 19 percent are in the three classes known to be of industrial utility. An additional 7 percent are of potential industrial utility, and 4 percent are of nonindustrial utility. The rest seem unlikely to produce more than fiber or fuel, both low-value forest products in moist regions. The total number of prospectively useful tree species then comes to 70, or 30 percent of the total. Others may be of some value only for roundwood, pulpwood, or fuel, but the first 70 may be equally suitable for these purposes. Such a classification system guides tentative assessments of the quality of secondary forests. To such a classification system should be added values for other products, such as palm hearts, fruits, or species critical as wildlife habitat.

Rejecting species with heavy wood is more justifiable than rejecting light-wooded species because expanding fiber uses and shorter rotations may favor light-wooded species of rapid growth. Balsa *(Ochroma lagopus)* is one of the world's lightest woods and yet is in demand for this very reason. In fact, much of the balsa found in secondary forests is less marketable because of its higher wood density. Light, pithy woods, however, will probably always be difficult to market. Dense woods may be in more demand in the future because of their potential energy content, but only if they grow fast enough to give high-energy yields per unit of time.

Many of the species considered potentially useful may be little used because their rarity in forests precludes the marketing of significant volumes. Such species should not be ignored in management, because rare species of value presumably can be made abundant.

Characteristics appropriate for further ranking of species within the groups mentioned include ubiquity, abundance on available sites, mature size, form, growth potential under full stocking, windfirmness, facility of regeneration, freedom from pest and disease problems, and responsiveness to silvicultural treatments. Most species may already have one or more of these characteristics; none may get high marks in all of them. For many species, some of this information is sketchy. Although initial classification may be provisional, it should improve as silvical characteristics and uses become better understood. In the meantime, however, misclassification within the select list is likely to occur only among species of similar potentials. Moreover, questionable species are seldom eliminated completely by treatment, so there remains time for adjustment.

Even the most liberal of species classification schemes recognizes only a fraction of the tree species as suitable for industrial timber. In Paraguay, it was 19 percent; in Puerto Rico, 16 percent. Thus, by discriminating against the other species, repeated refinement might ultimately reduce the number of tree species in productive forests to one-fifth or one-sixth of the original. Further refinement, favoring only the most preferred crop-tree species, might lead to nearly pure forests before the end of a rotation.

Favorable as such simplification may seem, it may not prove sustainable. In extreme cases, it may ultimately approach a monoculture with the corresponding risk of instability. Therefore, as studies indicate microsite preferences or tolerances for each crop-tree species, refinement should preserve a mix of adapted species.

The productivity of secondary forests is affected by stand structure as well as composition. For polycyclic management, the goal may be crop-tree-size groups similar in size and equal in number to the cutting cycles in the rotation, with the number of trees in each group producing a positive de Liocourt trend. For monocyclic management, the goal is a single harvest period, so crop trees might best be selected in part for the synchrony of their prospective maturity with the predicted time of harvest.

Long, straight stems are critical to industrial wood yield and of value for all other products, even fuel. Many broadleaf species of tropical America stop merchantable height growth while the trees are still small, because forking, rather than diameter, is the determinant of merchantability. The tendency for merchantable height to remain constant after a d.b.h. of 20 cm has been reached is evident in data for 1,600 trees of 15 species from moist forests in Puerto Rico (table 4–11; Wadsworth 1987). A tree with an unusually long, usable bole may simply reflect heavy shade during its youth, but it may also be genetically superior, a characteristic worth favoring in crop trees and their progeny.

Critical to the productivity of crop trees are their prospective growth rates. However, the prediction of growth rates as a basis for selection is not yet reliable. Growth rings in the wood of most species are not distinctive enough to gauge the growth rate. Comparisons of predicted and actual growth rates based on repeated tree measurements are rare. Units to express tree growth must be selected to avoid bias. Palmer (1975) notes the lack of comparability in growth between small and large trees when measured by d.b.h. in the absolute or as a percentage. He sees basal-area growth as a better measure than diameter, one that is also closely related to volume and commonly linear with time. He concludes that basal-area growth as a percentage may be a better measure still, because stem basal area apparently is linearly related to both nutrient and energy resources (root and crown area). Basal-area growth as a percentage would appear to reflect net wood productivity per unit of forest area occupied and, thus, the relative efficiency with which each tree utilizes its space. In a 24-year study of 1,600 trees of 14 timber species from moist forests of Puerto Rico, mean basal-area growth as a percentage was fairly constant for trees between 10 and 40 cm in d.b.h.

Table 4–11.—Merchantable height by d.b.h. of 1,600 trees of 15 species from moist forests in Puerto Rico

D.b.h. (cm)	Merchantable height (m) Mean	Extreme[a]
20	5.0	9.8
30	6.3	11.1
40	7.0	11.8

Source: Wadsworth 1987.

[a] Upper 95-percent productivity limit.

Free growth over long periods or for groups may vary little among species (Palmer 1975). Nevertheless, the wide variation that is commonly observed from tree to tree suggests a large, untapped growth potential that might be released by the silviculturist. However, the rapid growth of some trees may partly be made possible by the slow growth of others. To the degree that this proves true, the growth of crop trees may not benefit much by the removal of the less promising, slow growers.

A circumstance widely overlooked in assessing diameter growth is that means are underestimates because it is only trees growing faster than the mean that make up eventual crops. Conceivably the top quartile is more indicative.

The study of 1,600 trees in mixed moist forests of Puerto Rico showed the maximum basal-area growth (as a percentage) for trees 10 cm in d.b.h. to be far above the mean (fig. 4–13; Wadsworth 1987). The 24-year, basal-area growth of 43 trees of the same species, all in an intermediate canopy position and all between 10 and 20 cm in d.b.h., ranged from 0.7 to 6.9 percent per year, almost a tenfold spread. In this same forest, an attempt to relate 24-year, basal-area growth of individual trees, as a percentage, to the basal area of the trees around them, as determined by a three-diopter prism, explained only 0.1 percent of the variation, suggesting that tree growth rate and surrounding stand density are unrelated. Studies of 16 tree species in 22 forests in Uganda revealed some trees growing 25 times as rapidly in diameter as others (Dawkins 1964a). It was concluded that the fastest growing trees are the most efficient genotypes standing on the most favorable microsites.

In a study of 512 trees in mixed subtropical wet forests and rain forests in Puerto Rico, it was found that basal-area growth of individual trees was about the same for one 12-year period as it was for the subsequent 12-year period (both between hurricanes). This suggested that each tree, when released after an indeterminate, early period of suppression, fills an available canopy and soil

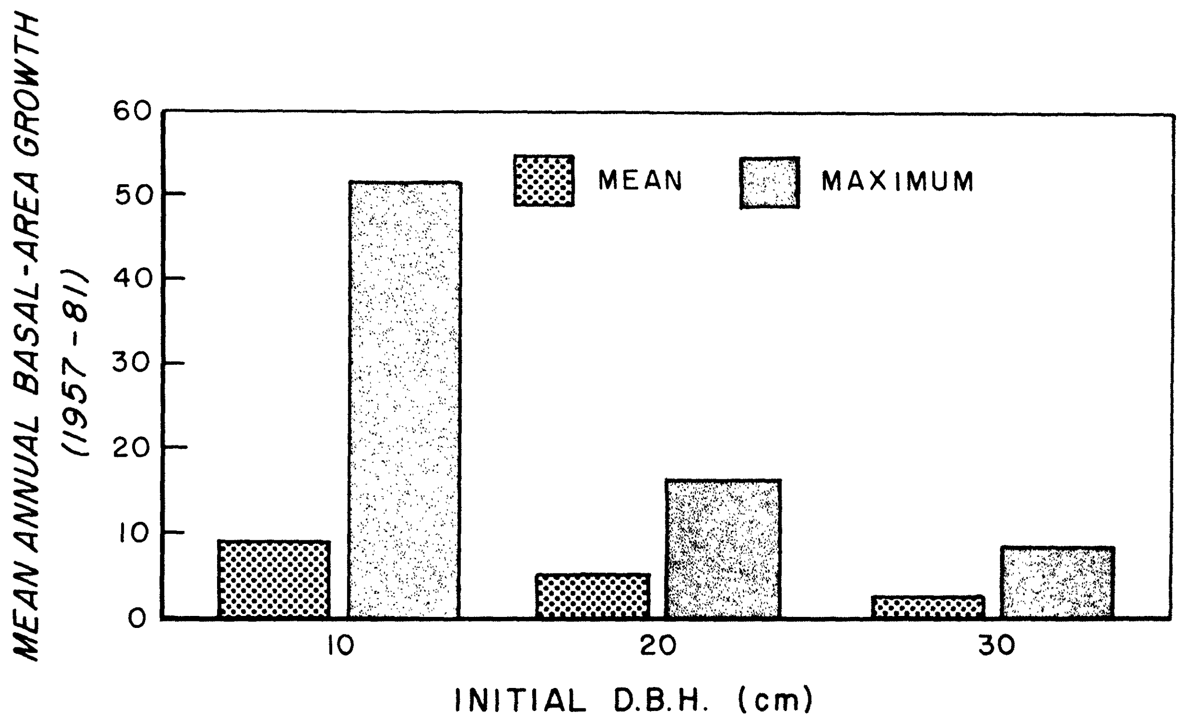


Figure 4–13.—*Comparative mean and maximum tree growth of 1,600 trees in a mixed moist forest of Puerto Rico (Wadsworth 1987).*

niche and then increases stem basal area at a relatively constant rate. From this assumption, a hypothetical growth period was derived for each of these trees by dividing its current stem basal area by its recorded mean annual basal-area growth for the previous 24 years and subtracting the resulting number of years to indicate when, had it always grown at about that rate, it might have started growing. When the numbers of trees were arrayed by these hypothetical, growth-starting dates, unusually large numbers of trees appear to have started at the time of past hurricanes: 1899, 1916, 1928, and 1932. This suggests that the hypothesis may have merit. If so, current tree growth in stable forests may reflect the size of a relatively constant niche, in terms of root and crown space, available to the tree since it was released.

A lack of correlation between tree growth and surrounding stand density has already been described. Wide variation in apparent productivity between individual trees found in Uganda and Puerto Rico is evidently virtually independent of stand density (Dawkins 1964a). In Nigeria, the basal areas of trees surrounding selected trees accounted for no more than 11 percent of the variation in growth, usually for much less (Lowe 1966). In thinned stands, "competition" so measured proved to be even less of a contributor to growth variation. Eliminating the variation due to species and basing the study on species of *Khaya* alone still failed to distinguish any significant influence of the basal area or numbers of relascope-counted surrounding trees on crop-tree growth (Kemp and Lowe 1973). One possible explanation of this apparent paradox is that competitive stress tends to equalize, stand density being greater on good microsites. This could offset any tendency for an inverse relation between surrounding stand density and crop-tree growth in closed ecosystems.

More profound investigations in Nigeria, using pattern analyses, showed that basal-area growth of surrounding trees was a better indicator of competition than either their summed diameters or basal areas (Lowe 1971). Low density appeared to benefit intermediate and codominant trees more than either the dominants or suppressed trees.

The position of tree crowns in the forest canopy has also been suggested as a predictor of growth rates. A strong relation between canopy position and mean d.b.h. growth was reported early by Wadsworth (1947b). In wet forests in Puerto Rico, the codominant trees grew 92 percent as fast as the dominants, the intermediates 65 percent, and the suppressed 35 percent.

An inverted 90° cone with the apex at the base of the crown was conceived in Uganda as a means for mathematically expressing the degree of crown exposure (Anon. 1956d). But again, a wide range of growth was found to be independent of this measurement (Dawkins 1964a). The only rapidly growing trees were those clearly dominant or with very large crowns (Dawkins 1958c). Beneath the top canopy, crown position appeared to be of little significance to growth rates.

Position in the canopy as a basis for predicting tree growth is confounded by tree size, because the dominants or exposed trees tend to be large and the suppressed ones small. A study with *Khaya* in Nigeria showed that canopy position significantly affected the regression between initial tree basal area and subsequent basal-area growth (Lowe and Walker 1977). Other studies in Nigeria gave no evidence that the vigor of dominant trees is inherent. Their growth superiority was much less among clones lacking genetic variation (Lowe 1971).

When tree growth is related to the space required (i.e., expressed in annual basal-area growth as a percentage of the mean basal area), the relative efficiency of codominant and intermediate trees is brought out. The study of 14 timber species in moist forests in Puerto Rico covering the period from 1958 to 1982 showed that trees that were initially dominant had a mean annual increase in basal area of 3.6 percent; codominants grew 3.6 percent, intermediates 2.9 percent, and those suppressed 2.1 percent.

Crown dimensions as an expression of leaf area per tree have also been studied as tree-growth predictors. The suitability of overall crown area for this purpose was studied in detail in Uganda (Anon. 1956d, Dawkins 1958c). Crowns were classified by grading their apparent capabilities for growth or need for release. Wide, circular, deep crowns were considered perfect. However, there has generally been little success in correlating individual tree growth with crown factors (Dawkins 1963a). In Nigeria, a strong correlation between crown and stem diameter appeared to confound the relation between crown diameter and growth (Kemp and Lowe 1973, Lowe 1966). No significant amount of individual tree growth variation could be ascribed solely to crown diameter or crown height (Lowe 1967a).

Initial tree diameter or basal area is the strongest single known predictor of tree growth; and in this, trees in natural forests do not appear to differ greatly from those in pure, even-aged stands (Lowe 1966). A study of natural forests and teak coppices showed that variation in basal-area growth of individual trees was about 70 percent resolved by their own initial basal areas; i.e., growth was apparently largely a function of initial size. A later study of *Khaya* in Nigeria showed that initial basal area accounted for 54 to 60 percent of the variation in basal-area growth over 6- and 14-year periods, respectively (Lowe and Walker 1977). Another study determined that the rapid growth attributed to large trees applied to all trees, not just to crop trees alone (Palmer 1975).

Other variables have been considered as indicators, causes, or results of differing growth rates of trees in secondary forests. Mervart (1969) points out that the response of individual trees may change with time or age. Ruehle (1972) suggests that the importance of healthy roots has been underestimated. He points to plant-parasitic nematodes as possible suppressants of fungal symbionts, such as mycorrhizae, which are known to be present on the roots of most tree species. In Nigeria, climber infestation was found related to growth rate (Lowe and Walker 1977). Studies of 234 dipterocarp trees showed that variation in specific gravity of wood was an indicator of past growth (Virtucio 1976). It was found that specific gravity reflected 51 percent of the variation in basal-area growth and 48 percent of volume growth. The lighter the wood, the faster the growth.

Frustration with seemingly logical predictors of individual tree growth has led some observers to morphological tree features. In the wet forests of Puerto Rico, it was observed that the fast-growing trees may have exceptionally straight boles free of blemishes and epiphytes (Wadsworth 1953). In west Nigeria, it was also found that factoring in stem form improved growth predictions over those based on initial basal area alone (Lowe and Walker 1977). Better stem form meant faster growth.

These diverse studies have so far failed to reveal any single, universally reliable criterion for predicting relative growth rates of tree "A" versus tree "B." To the contrary, they clearly show that individual trees may grow at very different rates regardless of perceived causes, such as visible site factors, species, tree size, and density of neighboring trees. Some interesting conclusions and hypotheses resulting from these many studies are as follows:

- Tree growth may be sufficiently random to frustrate any attempt to interpret it systematically (Mervart 1969, cited by Palmer 1975).
- The individual-tree approach to growth prediction may have little practical potential in tropical stands containing diverse species and age classes (Gerrard 1968).
- Stand projections based only on mean growth (average time of passage from one size class to the next) are erroneous for individual trees. Passing through broad diameter classes does not affect individual tree performance within the previous diameter class. Only the worst and best tend to remain in rank (Lowe 1977, Mervart 1972).
- Reducing the total error of growth estimates via regression analyses of the diameter-growth relations has limited possibilities (Mervart 1972).
- The "smoothing" effect of long periods of measurement on growth should not be overrated. The ever-changing trends in individual tree growth tend to maintain the variation of the aggregate growth almost the same as over shorter periods (Mervart 1972).
- Trees within a stand apparently establish early a growth rate "pecking order" that varies with shade tolerance, a situation that may be difficult or almost impossible to alter by silvicultural treatment.
- Silviculture may only be following a pattern already formed by the crop itself. Departures from this pattern may impair overall stand growth (Lowe 1966).
- Only very early release can have much influence on growth rate (Lowe 1966).
- Even drastic canopy manipulation may fail to significantly affect the growth of some trees (Dawkins 1963a).
- If the prospective influence of silvicultural treatments on the growth of secondary forest trees proves limited, then treatments should be based on the local profitability of management alternatives rather than on the benefits of silvicultural treatment (Lowe 1966).

Obviously, the search for criteria that precisely predict growth of individual trees has not been successful. As a result, the process of selecting and treating crop trees has not yet attained its potential as a means of increasing productivity in secondary tropical forests. Until this can be done, the productivity of secondary forests will suffer when compared with that of plantations. Nevertheless, even where plantations are a feasible alternative, secondary forests remain complementary, a source of different woods and other necessary benefits. Moreover, it appears that early and repeated liberation of crop trees, however imperfect may be their selection, has not been fully tested and might yet greatly increase yields.

Until greater success is attained in selecting crop trees on the basis of prospective growth, other more obvious criteria may still be beneficial in stands as yet untreated. In such secondary tropical forests, the first steps generally involve improving composition, structure, and spacing. Tree selections made this way should have no inherent bias against those of rapid-growth potential, so the process at least should not be dysgenic. Better prediction is still urgently needed and warrants further study. Absolute crown size or its relation to d.b.h. merits priority.

Regeneration Assessment. Because most efforts to regenerate natural tropical forests have been concentrated in the Eastern Hemisphere, assessment techniques for timber management have not been widely applied in tropical America. For this reason, this section describes in some detail practices used elsewhere that would appear applicable to this region. The emphasis of Eastern Hemisphere systems on seedlings and saplings as well as on poles and larger trees appears equally appropriate for tropical America. Also, the success of the more recent diagnostic techniques in the East suggest that they may be universally adaptable.

The adequacy of stocking and horizontal distribution of crop trees and the need for tending have been assessed by various sampling techniques. By 1944, assessment of natural reproduction in India had developed an "establishment stocking factor" (Prasad 1944a). The basic sample was a 2-m square within which seedlings, established saplings (those <3 m tall), and established trees (>3 m tall) of crop species were counted. The mean height of the established saplings divided by 3 m and multiplied by the percentage of the squares with established trees produced the establishment stocking factor.

Techniques termed "diagnostic sampling" appeared in what is now Malaysia about 1950 as improvements in enumeration practices that had begun as early as 1930 (Barnard 1950a). Regeneration sampling was in use in what is now Cameroon in 1952 to distinguish areas for natural regeneration or for planting (Morellet 1952).

In what is now Malaysia, systematic sampling was done as a preliminary to enrichment of cutover forests. Natural regeneration neglected during the Second World War was found capable of coming through (Wyatt-Smith 1958b). Three sampling levels were commonly used (Barnard 1954, Majid and Wyatt-Smith 1958). Linear sampling, millacre (LSM) plots (4 m^2 or 0.0004 ha) were taken before felling to inventory commercial tree species seedling regeneration to a height of 1.5 m. One crop tree was chosen per plot. Adequate stocking required a selected tree in at least 40 percent of the LSM plots, indicating about 1,000 selected trees per hectare.

After harvesting, linear sampling, quarter-chain plots (LS 1/4), about 5 m square, or 0.0025 ha, were established to ascertain the stocking, composition, development, and competitive status of commercial saplings and small poles from 1.5 m tall to 10 cm in d.b.h. Adequate stocking required that 60 percent or more of these plots have a selected tree, corresponding to 240 per hectare (Wyatt-Smith 1960a).

Five to 10 years after harvesting, a third set of plots was measured. These linear sampling, half-chain plots (LS 1/2), about 10 m square, or 0.01 ha, were designed to ascertain the status of commercial large poles and trees 30 cm in d.b.h. or more. Seventy-five percent or more stocking was considered acceptable, corresponding to 75 trees per hectare. The LS 1/2 samples have provided: (1) density and composition of the overall stand; (2) stocking, composition, size, and distribution of the crop trees; and (3) urgency and degree of treatment required for crop trees (Wyatt-Smith and Vincent 1963). The LS 1/2 plots sampled 10 percent of the forest and were located on lines spaced 200 m apart. They were set up permanently in the field to permit resampling at intervals of 10 to 20 years. Each chosen tree was scored as follows:

5 = Tree suppressed by larger, sound trees of equal quality outside sample area.

4 = Crown good and would improve with treatment, but this is not urgent and may not be necessary.

3 = Crown good but not full and would improve with immediate light increase, but delay up to 5 years is possible.

2 = Crown deficient, requires immediate moderate treatment.

1 = Crown poor, requires immediate, drastic treatment.

0 = Crown very poor, probably incapable of responding.

Diagnostic sampling was introduced from what is now Malaysia into Uganda and Queensland, Australia (Dawkins 1961c). In Uganda, it was intended primarily to: (1) evaluate stand condition, (2) assess whether regeneration is adequate to replace the crop to be harvested, (3) determine what treatment may be required, or (4) determine what tending is appropriate to establish and develop the stand (Hughes 1961). The system was designed to provide a set of permanent plots to facilitate remeasurement if necessary and to set up a bookkeeping system to ensure accurate records and speedy analyses.

The standard sampling plot was 10 by 10 m, or 0.01 ha; plots straddle lines paced 400 m apart (Dawkins 1958f, 1958e). Halves of the plot on both sides of the line were further divided into two 5- by 5-m plots (0.0025 ha). Subsampling was so planned that approximately a 0.001-ha sample is taken of seedlings to 1.5 m tall, a 0.00625-ha sample of saplings 1.5 m tall to 20 cm in d.b.h., a 0.0125-ha sample of poles 30 to 50 cm in d.b.h., and a 0.025-ha sample of trees larger than 50 cm in d.b.h. (Walker 1962). Within each 10- by 10-m plot, a "leading desirable" was selected, and the stems in the plot that equal or exceed the d.b.h. of the leading desirable were counted. For each leading desirable, the diameter class, crown position, and degree of independence were recorded.

It was also in what is now Malaysia that linear sampling was developed as a means of assessing immature trees, already described in some detail (Barnard 1950b). It was assumed that fully stocked stands contain 2,500 seedlings (less than 1.5 m tall) per hectare, 400 saplings (over 1.5 m tall and up to 10 cm in d.b.h.) per hectare, or 100 poles (10 to 50 cm in d.b.h.) per hectare. The size of square plots along adjacent transects for each of these three classes was set at the corresponding proportion of a hectare per tree, or 1/2,500, 1/400, and 1/100 ha. For intensive sampling, plots along transects were spaced 100 m apart, corresponding to a 2-, 5-, and 10-percent sampling, respectively, for the three plot sizes. For extensive sampling, the distance between seedling plots along the transects was set at 400 m, or a 0.5-percent sample. For saplings and poles, the distance was 200 m, or 2.5- and 5.0-percent sampling, respectively. Within the sapling plots, the desirable saplings were recorded by size, as 1.5 to 3.0 m tall, 3.0 m tall to 5 cm in d.b.h., or 5 to 10 cm in d.b.h. For the poles, the size classes recorded were 10 to 20 cm in d.b.h., 20 to 30 cm, 30 to 40 cm, and 40 to 50 cm. Because one select tree per plot was considered full stocking, the degree of stocking of the area corresponded to the number of stocked plots as a percentage of the total. A secondary tree was selected and recorded if present (Barnard 1950b).

Hutchinson (1991) defined diagnostic sampling as an operation intended to estimate the potential productivity of a stand. He used diagnostic sampling in the American Tropics for the following purposes:

- To establish priorities for beginning silvicultural operations in order to optimize productivity and plan where to apply each operation
- To outline a suitable initial sequence of silvicultural operations
- To estimate an overall cutting cycle in relation to the ingrowing classes of desirable trees.

Hutchinson prescribed five steps in diagnostic sampling as follows:

1. Establish representative 10- by 10-m quadrats, at least 100 and preferably more.
2. Register the best of any trees larger than the maximum cutting diameter; note species, health, and stem quality.
3. Classify the leading desirable in each quadrat as a tree, sapling, or seedling. Select a tree before a sapling. If none, record as unstocked and distinguish potentially productive from permanently unproductive quadrats.
4. Record the d.b.h. of the leading desirable.
5. Record the crown-illumination class (vertical and lateral, vertical, partial vertical, oblique, and no direct) of the leading desirable.

Summarizing these data yields information as to the trees ready for harvest, large trees that could possibly yield a commercial harvest in the future, stocking of large noncommercial and defective trees hindering development of seedlings, and the adequacy of the illumination of the leading desirables.

The assessment technique in the rain forests of northern Queensland used plots 5 by 5 m square laid out contiguously on lines (Nicholson 1972). All trees 20 cm in d.b.h. or more are recorded.

Linked to diagnostic sampling is dynamic sampling, measuring large-scale changes in the forests over time. Developed first in Queensland, it is a form of continuous forest inventory based on permanent plots sited systematically throughout all productive forests and measured by permanent inventory teams at regular intervals (Dawkins 1961c). Plot sizes have been generally 0.08 ha in Queensland, 0.4 ha in what is now Peninsular Malaysia, and 1 ha in Uganda and Sabah (Dawkins 1961c). With emphasis on the crop trees, such sampling can provide a wealth of management information at minimum expense.

Composition Improvement. Initial silvicultural efforts in mixed tropical forests commonly have been directed at increasing the representation of the few most desirable species at the expense of the many inferior ones (Wyatt-Smith 1958a). The potential of this practice is seen in moist forests of Suriname, where only a third of the growing stock larger than 35 cm in d.b.h. was composed of commercial species (Schulz 1967).

Early concern with the consequences of eliminating species was expressed at the Eighth All-India Silvicultural Conference of 1951, already cited (Rosayro 1952). The conference warned that any radical departure from selection fellings in evergreen forests should be made with full realization of the grave risk of disturbing the delicate ecological balance that exists and of causing irreversible changes in the floristic composition of the forests to the possible detriment of their long-term productivity. An earlier warning had been sounded in what is now Malaysia that species generally wiped out in tending should be left in mixture with *merantis* (Mead 1937). Leaving an understory of poles of noncommercial species was also suggested to reduce the risk of epidemics.

The selection system appeared to critics in India to be but a screen covering drastic forest modifications (Stracey 1959). When selection cuttings were followed by fellings and girdlings to favor the next crop, the tendency was to produce uniform-sized crops of a few species. Stracey opposed the radical elimination of all but a few valuable species. A longer transition period, he thought, would permit a multispecies crop with a more desirable, broken, and irregular profile. Wyatt-Smith (1958a) recognized these risks but countered that it was not possible at the outset to base silvicultural prescriptions on ecological studies that had so far yielded only tentative results.

Early refinement of rain forests in what is now Malaysia, including climber cutting and poisoning of overmature, defective, inferior, and weed trees, significantly affected the composition of the dominant and subdominant stand (Wyatt-Smith 1958c). In the 5 years following treatment, the desirables in one forest increased from 58 to 64 percent, whereas in an untreated forest, they declined from 57 to 38 percent.

Trees of little or no foreseeable commercial value may be so dominant in secondary tropical forests that eliminating them in one treatment may create undesirably large breaks in the canopy, and subsequent regrowth of similar species or vines could smother remaining crop trees. Killing trees by girdling or poisoning is preferable to felling, because openings appear gradually and are smaller. Where heavy harvest cuttings are made, openings may be so large and advanced growth so damaged that special measures, such as underplanting, may be needed to ensure that a new crop quickly dominates.

Experience in the secondary forests of Puerto Rico further confirms the degree to which representation of the desirable species may result from first refinement treatments. In a thicket of saplings and small poles where a good fuelwood market was at hand, treatment increased the representation of desired timber species by 33 percent, and 6 years later, the volume growth of the treated stand exceeded the untreated stand by 9 percent (Marrero and Wadsworth 1951). The first improvement felling in more advanced stands in a moist secondary forest in Puerto Rico removed 75 percent of the trees of undesirable species and an even higher percentage of basal area (table 4–12; Anon. 1958i). The desirables were thinned by about 28 percent. Although the residual basal area is low, there are enough desirable trees to take over the entire stand (assuming they are well spaced) if further treatments are applied. The average d.b.h. of the desirables declined from 16.3 cm to 15.7 cm, indicating that some of the desirable trees removed were of above average size but of poor form. The increase in the volume-to-basal-area ratio (m^3/m^2) shows increased average usable stemwood height in the remaining desirables.

Liberation. To liberate means to release or set free. Silviculturally, "liberation" is defined as a cutting that relieves young growth from overhead competition (Ford-Robertson 1971). If regularly practiced, liberation can maximize growth rates in natural forests (Baur 1964a).

Liberation is a major objective in a broad range of refinement treatments. It is the primary reason for eliminating relics and may be the main motive for tending immature crops. Liberation is founded on the common belief that tree diameter growth is directly related to crown position and probably inversely related to crowding or stand basal area (Dawkins 1957). Pronounced anomalies do exist, however, e.g., stagnant emergents standing adjacent to growing subordinate trees of the same species with apparently the same crown quality (Dawkins 1961c).

Liberation is seldom the sole objective of silvicultural treatment however. In tending secondary tropical forests,

Table 4–12.—Stand composition improvement from forest refining in a moist secondary forest in Puerto Rico

Index	Before treatment	After treatment
No. of trees per hectare ≥10 cm in d.b.h.		
Desirables	430.0	311.0
Other	368.0	91.0
Percentage desirable	54.0	77.0
Basal area (m^2/ha)		
Desirables	9.0	6.0
Other	6.0	1.0
Percentage desirable	60.0	86.0
Mean d.b.h. of desirables (cm)	16.3	15.7
Ratio of volume to basal area of desirables (m^3/m^2)	2.6	3.0

Source: Anon. 1958i.

it is not enough to concentrate only on freeing individual trees from competition (Dawkins 1958c). The crop as a whole must be kept in mind. This concept may mean retaining more trees, some apparently less productive than others, as insurance or to favor some balance of tree sizes or species diversity.

Liberation of young trees has been tested most widely in the Eastern Hemisphere. In India, "tending" (which includes liberation) was applied in the 1940s wherever natural regeneration was present and was continued through the sapling to the pole stage (Griffith 1947). In what is now Malaysia, selection fellings in 1937 were done in advance of a partial commercial removal of the overwood to assist regeneration (Wyatt-Smith 1961a). In dipterocarp cutovers in Sabah (Nicholson 1965b), the best treatment sequence has been climber cutting and tree marking 1 to 2 years before felling, poison-girdling 3 to 6 years after felling, and liberation and other refinement of the rising crop 10 to 15 years after felling (Fox 1972, Hepburn 1973). The impact of release is seen in a stand logged in 1958 with relics poisoned thereafter (Fox 1972). The basal area averaged 19 m^2/ha in 1966, before 395 crop trees per hectare were released. Elimination of all trees competing with these called for the removal of 8 m^2/ha of basal area, or about 45 percent of the stand, leaving 9 m^2/ha of basal area in crop trees.

The rain forests of Queensland generally have enough regeneration to make liberation preferable to replacement (Henry 1960). Cutover stands may retain a basal area of about 50 m^2/ha with about one-third of the species marketable. Useless stems are then removed, and additional liberation may be done. In Uganda, liberation of existing advance regeneration has been adopted on a large scale (Earl 1968) because of difficulties with line and group planting. Well-formed desirables are marked with paint and charcoal burners remove any unmarked trees, thus precluding later damage.

Liberation treatment in tropical America began early in Guyana, Puerto Rico, Suriname, and Trinidad. In Trinidad, improvement of degraded forests on sandy soils by refinement began in 1932 (Beard 1944b). Natural regeneration at first had to be freed from grass and vine competition. Later, excess shoots were removed, competition between saplings was reduced, and palms were eradicated. After four treatments over a 10-year period, the number of saplings of economically valuable species 5 m or more in height averaged more than 70 per hectare. More recently, clearcutting of Trinidad's mora forests has been abandoned in favor of irregular stocking. Crop trees for future harvests were left and liberated, beginning 10 to 15 years after the initial harvest (Bell 1972).

Crown-diameter-to-d.b.h. ratios for the desirables have been used in Trinidad to determine spacing and maximum basal area consistent with crown exposure (Bell 1971). Under a system of triangular spacing that allows circular crowns to touch (utilizing 91 percent of the total land area), a crown ratio of 17 for *Sterculia* corresponds to a maximum desirable basal area of 32 m^3/ha. For *Dacryodes*, with a crown to d.b.h. ratio of 19, the maximum desirable basal area would be 25 m^2/ha. For the Lauraceae, with a crown-to-d.b.h. ratio of 20, it would be 23 m^2/ha.

On the South American continent, information regarding liberation cuttings is available chiefly from Suriname. A 1958 study (Anon. 1959j, 1961e) showed that only slight release induced the germination and vigorous growth of opportunists such as species of *Goupia, Qualea, Schefflera,* and *Simarouba*. The seedlings and saplings of preferred species required a second liberation. The cost of complete tending was considered excessive, so the treatment was applied only in east-west strips 1 to 3 m wide separated by distances inversely related to the abundance of desirable regeneration, generally 10 to 20 m. Within the strips, all weeds were cut and all undesirables from 10 to 20 cm in d.b.h. were removed, but no large openings were made (Boerboom 1964). Crop trees were sometimes pruned. The strips were tended twice in the first 2 to 3 years following the first liberation cutting. Three or 4 years later, after most of the poisoned trees were gone, the small, unwanted desirables were eliminated. There is no evidence that this practice pays, but it stimulates regeneration of light demanders that should mature in 30 to 40 years.

Before 1960, liberation tests were begun along the Amazon (Pitt 1961b). Results were promising with *Virola,* a species with regeneration already present in patches, and *Goupia,* a species that is not preferred in Suriname but that is a promising light demander in gaps in lower Amazon forests.

In Puerto Rico, liberation practice evolved from highly subjective judgment as to what was adequate (Wadsworth 1947a, 1958). From the 1930s to the 1950s, emphasis was on reducing stand density by eliminating apparently unproductive trees, including mature and overmature trees and trees of poor form and inferior species. Not all unproductive trees could be eliminated in a single treatment without serious weed invasion. By 1958, the guidelines were as follows:

- Treat only forests where tree crowns touch.
- Limit canopy openings to 8 m in diameter, except where required by the removal of a single large tree. Eliminate no trees adjacent to such openings.
- Harvest or eliminate trees larger than 50 cm in d.b.h. but only selectively within dense groups of merchantable species.
- Maximize representation of the desired sawtimber species in the next crop.
- Retain a mixture of desirable species in the crop.
- Strive for balanced structure with approximately equal basal areas of crop trees in each d.b.h. class between 10 and 50 cm.
- Eliminate trees that overtop crop trees.
- Give canopy desirables crown freedom averaging 2 m.
- Eliminate useless species and those usable only for fuel.

Only those forests containing at least 100 trees per hectare 10 cm in d.b.h. or larger of desirable species have been silviculturally treated in Puerto Rico. Test compartments have been demarked temporarily in 0.04-ha squares on lines 20 m apart. Within each square, up to 10 crop trees were selected. Each must be of a species on a selected list of 25, be between 10 and 50 cm in d.b.h., have at least 5 m of straight bole, and be at least 2 m from other crop trees. Among the selected trees, priority was given to their position on the species list; however, to preserve diversity, no more than 4 of any species were selected unless the total were less than 10. Next, the trees were ranked according to merchantable height, d.b.h., and regularity of spacing, in that order. Then, each crop tree was liberated by eliminating all "competitors," defined as noncrop trees as tall as or taller than the crop trees and closer than the spacing indicated in table 4–13.

Table 4–13 was derived empirically from local observations and other information on maximum basal area, allowing for rapid individual tree growth. Maximum tolerable basal area is less for small trees than for those nearing maturity. At the time this table was developed, the influence of the crown-diameter-to-d.b.h. ratio on growth was not recognized, but the spacings selected (triangular) were later found to correspond closely to those ratios for local timber trees. This density corresponds to the maximum desirable basal area for the principal species, *Dacryodes excelsa,* based on its crown-to-d.b.h ratio of 19. The ratios for a group of species are 26 for trees of 10 cm in d.b.h. and 20 for those at maturity (60 cm in d.b.h.). The minimum separations shown are rounded to facilitate use in the field.

Table 4–13.—Spacing guide for liberation of crop trees in Puerto Rico

Summed diameters (cm) $(D + d^a)$	Minimum separation (m)
20–39	3
40–59	5
60–79	7
80–99	8
>100	9

Source: Wadsworth 1958.

[a] *D* = d.b.h. of a crop tree and *d* = d.b.h. of each of its noncrop neighbors.

A forest liberated by this technique may not "look" as good as one where all apparently unproductive trees have been eliminated, because trees not interfering with the crop trees remain. However, because these trees, all shorter than the crop trees, are not believed to be detrimental to crop productivity, their immediate elimination is unnecessary. Left alone, they constitute diversity and may help stabilize the ecosystem or possibly even increase in marketability.

The intent in Puerto Rico has been to repeat liberation at 10-year intervals. As the remaining trees grow, more of the noncrop trees impinge on the increasing space required by the crop trees and become due for elimination. Sooner or later, a choice must also be made as to which of the excess crop trees are to be eliminated (and harvested if marketable). Those apparently least in synchrony with the prospective eventual harvest date for the crop are least worth keeping in the stand.

This silvicultural technique may appear complex and impractical. Field crews can soon estimate the d.b.h. and spacing of most trees well enough by eye, measuring only those near the limits. In Sarawak, where the system has been applied to thousands of hectares, crews have abandoned the layout of plots and judge crop-tree spacing on the basis of their initial experience with the plots.

The results of the treatment in terms of yields and financial returns are as yet unknown. The initial treatment may require 5 d/ha with a crew of three. Later treatments, with the painted crop trees still identifiable and fewer trees to be removed, require less time.

In Sarawak, the similar technique is termed "liberation thinning." Crop trees are selected in cutover stands of hill dipterocarps. Each is then liberated by reducing the basal area surrounding it to stimulate rapid growth, somewhat as in Puerto Rico (Hutchinson 1980). This treatment has almost immediately stimulated the growth of the trees that were left with overhead light (table 4–14; Bryan 1981). The mean growth increase was 29 percent; trees that had been overtopped increased 125 to 160 percent.

Improvement fellings have not always lived up to expectations. The assumption that such treatments would accelerate the growth of good trees in the residual stand and stimulate regeneration of select species as needed has not everywhere proved valid. More proof is needed that manipulating the canopy to improve the crown position of a large tree will increase growth, or even that reducing the surrounding basal area will have a similar effect.

In Philippine dipterocarp forests, results of improvement fellings reportedly have been more favorable. Treatment of residuals by cutting climbers, girdling defectives, and liberation increased growth of selected trees threefold and promised a shortened cycle (Utleg and Reyes 1967). But in Sabah, during the first 5 years after release of an existing crop, growth acceleration of large trees proved disappointing (Fox 1972). Nevertheless, saplings of 10 cm in d.b.h. or less did respond to release.

Application of Hutchinson's (1993a) liberation thinning to mixed secondary forests in Costa Rica has produced further evidence of early growth acceleration as a result

Table 4–14.—Response of dipterocarps to liberation in Sarawak (cm)

D.b.h. class	4-year mean annual d.b.h. growth	
	Unliberated	Liberated
10–14	0.57	0.79
20–24	0.52	0.72
30–34	0.54	0.72
40–44	0.61	0.79
50–54	0.71	0.88
60–64	0.81	0.98

Source: Bryan 1981.

of treatment. Basal-area increment as a percentage doubled in 17 months.

The jury is still out on the magnitude and duration of the effects of liberation, but recent studies continue to indicate that liberated crops mature faster than those not liberated. Uebelhor and others (1989) report that liberating Philippine dipterocarps from crown competitors reduces rotations at 60 cm in d.b.h. by 10 to 15 years, the benefits being greatest among small trees. The International Tropical Timber Council (Anon. 1990b) reports that 8-year results of liberating hill dipterocarps in Sarawak suggest cutting cycle reductions of 5 to 10 years.

In Nigeria, postlogging climber cutting and poisoning in the middle of the upper canopy liberated 16 economically valuable species (table 4–15; Henry 1956). The number of large trees renders the decrease in regeneration unimportant.

A study of two liberated 0.1-ha plots in a subtropical, wet forest in Puerto Rico shows rapid acceleration (Anon. 1953b). Immediately after liberation, there were 1,961 trees per hectare more than 5 cm in d.b.h., with a mean d.b.h. of 12.2 cm and a basal area of 23 m^2/ha. Five years later, there were 2,601 trees per hectare (ingrowth of 640) and a basal area of 30 m^2/ha. Mean annual d.b.h. growth was 0.34 cm/yr for all trees and 0.58 cm/yr for dominants and codominants alone. Volume rose from 101 m^3/ha to 140 m^3/ha, or 7.8 m^3/ha/yr.

Another early test, in Guyana (John 1961), determined the mean growth of three canopy classes of *Virola surinamensis* during 18 months following liberation (table 4–16). In this study, contrary to the one in Nigeria, the subordinate trees accelerated their growth faster than the dominants.

In Suriname, poisoning of undesirables down to 10 cm in d.b.h. stimulated growth of all trees up to 50 cm (Schulz 1960). Some of the rapidly growing trees, such as *Goupia glabra* that are 5 m or more in height, may be released adequately with one treatment. For smaller trees, the treatment must be repeated, especially for strong light demanders, such as *Schefflera morototoni* and *Simarouba amara* (Schulz 1967). Eliminating the overstory can increase the height growth of saplings and poles of the desirables tenfold.

Synnott (1979), reviewing general results but especially those of Africa, concluded that felling or poisoning normally results in faster mean growth on all the remaining trees, including leading desirables and individual species groups. In one case, the faster growth of remaining trees more than offset the effects of reduced basal area, so that net basal-area growth increased as original basal area was reduced.

Liberation, and in fact all refinement treatments, are costly and conducive to only distant future returns. An analysis in Sarawak, however, adds an important dimension to those benefits. Laursen (1977) concluded that the increased growth from liberation in cutover residuals in Sarawak could ultimately generate 10 days of employment per year in primary processing for every day of work dedicated to treatment.

Thinnings. Thinnings are fellings made in immature stands, primarily to increase diameter growth but also to

Table 4–15.—Postlogging changes in a Nigerian stand of 16 economically valuable species liberated by climber cutting and poisoning in the middle of the upper canopy

Table 4–16.—*Virola surinamensis* response during 18 months following liberation in Guyana (cm/yr)

Canopy position	Mean annual d.b.h. growth	
	Untreated	Treated
Below canopy	0.37	0.54
Canopy	.61	.88
Emergent	.87	.99

Source: John 1961.

improve the form of the remaining trees (Ford-Robertson 1971). Despite this broad definition, the term "thinning" is generally applied to stands where the trees are all about the same size, typically even-aged plantations. Thinnings are thus concerned with lateral competition among trees of about the same height in contrast to liberation, which reduces competition chiefly from above. In secondary forests, only young volunteer stands or local groups of trees are of uniform size, so thinning is only one of several purposes of improvement fellings in such forests. Nevertheless, the results of thinning in secondary forests are usually reported with those of liberation, because in irregular stands, the two are inextricably mixed.

Thinned forests, at least those of the Temperate Zone, reportedly respire less relative to assimilation than unthinned forests and thus may grow faster, in part, for that reason (Assman 1970). In the Tropics, where rapid respiration significantly decreases net primary productivity, this benefit of thinning might be accentuated. Thinning also shifts growth to the lower part of the stem, increasing taper.

Recognition that thinning should be an integral part of refinement developed early. In Malaysia, removal of relics over a new crop proved inadequate to stimulate growth, thus thinnings were needed in addition (Wyatt-Smith 1963). In Sabah, girdling noncommercial and defective commercial trees down to 5 cm in d.b.h. was prescribed in 1965 to open dense clumps (Nicholson 1965b). Early selection fellings in Nigeria included thinning of desirables (Osafo 1970).

One limitation of thinning is the effect of opening the canopy. Extremely heavy thinning can encourage unwanted opportunists and climbers. In evergreen hill forests in Thailand, opening the canopy more than 30 percent on 20 to 25 percent slopes also led to serious soil erosion (Ruangpanit 1975).

A guide to the degree of thinning that should stimulate growth increases was offered by Palmer (1975), who suggested maintaining the basal area at less than two-thirds of the maximum. Where there is a market for thinnings, such treatment could be profitable. A basal area of about 25 m^2/ha has been recognized as a maximum for rapid tree growth in mixed broadleaf forests of the lowland Tropics (Dawkins 1961b). As was indicated in the prescriptions for Puerto Rico, even lower limits may apply to small trees. There is no evidence that these limits can be increased by technology, although virtually no attempts have been made.

In Ghana, high stand density retards growth, whereas medium density favors export-market shade bearers and low density favors rapidly growing light demanders (Danso 1966). Well-regulated, frequent thinnings are needed. Eliminating only the noncommercial species does not necessarily result in early crown building on the commercial ones.

Arboricides. The use of chemical herbicides to kill trees in the Tropics apparently was introduced from the Temperate Zone. Sodium arsenite, despite its extreme toxicity and the occasional loss of human lives associated with its use in forestry, was applied throughout much of the Tropics in the past. Its use continued even long after the advent of other herbicides that were safer to use and less persistent as environmental pollutants. There were several reasons for this continued use. In Ghana and Sierra Leone, sodium arsenite was more effective and less expensive (Anon. 1958f, Pickles 1958). King (1965) favored it because of balance-of-payment advantages in not having to import the solvent. As a soluble powder, it was easy to transport and mix with locally available water.

In forests in what is now Malaysia, sodium arsenite killed 70 to 80 percent of the treated trees within 12 months (Strugnell 1937, Wyatt-Smith 1960b). In one test of trees 30 to 90 cm in d.b.h., other chemicals killed only 25 percent of the trees after 21 months and were particularly ineffective on large, thick-barked, buttressed trees.

Sodium arsenite was also more reliable in wet weather than some other arboricides (Dawkins 1961b). Sodium arsenite has disadvantages other than its toxicity.

Whereas King (1965) favored its rapid kill, Durant (1936) and Dawkins (1958a) considered it too effective in this regard, producing a sudden brief opening of the canopy rather than a gradual, more durable one. Also, arsenite does not usually kill unless complete frills are cut, a step that is difficult with some trees and not necessary with some other arboricides.

Organic arboricides have been available for decades. Many chemicals, including sodium arsenite, have been withdrawn because of environmental hazards and others are suspect. Only broad observations are cited here. Local trials must precede widespread application.

In Uganda, many trees were killed in 5-1/2 months simply by applying diesel oil to frills (Dawkins 1958a). Applications from December to February seemed to work faster than those from March to August.

In what is now Malaysia, 3 percent solutions of 2,4-D mixed with 2,4,5-T and 5-percent solutions of 2,4,5-T alone, both in diesel oil applied on unbroken bark did not kill large buttressed trees (Wyatt-Smith 1960b). On frill-girdled bark, a 2-percent solution of 2,4,5-T was also ineffective on large trees. Of the trees 30 to 90 cm in d.b.h., only 25 percent were dead 21 months after treatment. Spray treatments on unbroken bark were also found ineffective in francophone Africa (Catinot and Leroy-Deval 1960). (2,4,5-T has since been withdrawn from the U.S. market.)

In Puerto Rico, the effectiveness of organic arboricides has varied among tree species. Particularly resistant are members of certain genera such as *Mangifera* and *Eugenia* (Myrtaceae).

Killing bamboo is desirable under some circumstances. One species *(Bambusa gigantochloa)* has been killed by basal application of sodium chlorate (20 percent solution), TCA (10 percent sodium trichloroacetate), dalapon (5 percent), and amatrole (5 percent); amatrole was the most effective (Burgess 1975).

Recent concern over secondary environmental damage from chemical treatments has questioned the silvicultural use of arboricides. Possible side effects on soil and aquatic organisms and higher animal life have been cited. Even accelerated loss of nutrients has been suggested (Barclay-Estrup 1972). The fact that manual methods of removing unwanted vegetation provide more manual employment than chemical methods is also cited as a drawback of arboricides. Some of the concern is with silviculture per se, including complaints that removing understory vegetation removes cover and food for wildlife. Removing "inferior" species is also questioned on the basis that they may make some contribution to the ecosystem and might become marketable.

Use of chemical arboricides in silviculture must not be impetuous; it must be rationally defensible. Any potential hazards should be well understood and demonstrably tolerable. The primary objective of silviculture is to maintain or improve the site; this requires a concern for the whole ecosystem that transcends the need for commodities. When serious doubt as to the superiority of arboricides exists, the most prudent course may be to use girdling without the use of chemicals.

Any silvicultural program using arboricides must incorporate two features: safety and research. Safety measures must reflect a thorough knowledge of the chemical properties of the products and prescriptions for their use to avoid serious hazards to human society. Research should address both the effects, direct and indirect, of any herbicide and ways to make applications safer and more cost-effective.

Yields

Silvicultural treatment of secondary forests was initially intended to eventually yield a profit (Barnard 1954). However, comparing secondary-forest production with that of other crops led to the conclusion that in Malaysia, maintaining forests purely for their productivity is questionable (Wycherley 1969).

Yield data from treated stands are not yet adequate to define the upper limits of timber productivity in secondary forests. Meanwhile, opinions differ widely. Some have assumed that yields from managed natural forests will ultimately equal those from plantations of the same species on similar sites (Poore 1968). Others (Leslie 1977) have expressed doubt that even the most optimistic silvicultural projection can improve the economic performance of natural forests enough (relative to other forms of land use) to justify their management solely for wood production.

Refined moist secondary forests containing the most productive species seem capable of yields of 4 to 10 t/ha/yr of stemwood, 50 percent more if branchwood is included (Dawkins 1964b)—the difference from untreated forests being more in quality than in quantity. Results vary widely with stand history. Wyatt-Smith (1987a) concluded that a tropical moist forest, on the average, yields up to 2 m^3/ha/yr; silvicultural treatment can increase this to about 6 m^3/ha/yr. Lowe (1984) concluded that a natural high forest in Nigeria could produce only 40 m^3/ha in 40 years. Productivity of a dipterocarp stand in the Philippines after removal of 9 to 15 percent of the timber trees, ranged between 5 and 6 m^3/ha/yr (Miller 1981). Yet, removing 23 percent of the timber trees caused such damage to the residual stand that postlogging mortality offset growth for 7 years. In the wet lowland forests of Colombia, natural regeneration 15 years after cutting was yielding 54 m^3/ha of pulpwood from trees 10 cm in d.b.h. or more, an average of 3.6 m^3/ha/yr (Ladrach 1983).

Although timber yields from secondary tropical forests may be lower than those of the best plantations, investments required may also be lower and are often more in tune with available financial resources (Palmer 1975). With dipterocarps in Sarawak, liberation thinnings were said to promise a second harvest in about 30 years compared with a wait of 60 years or more without treatment (Hutchinson 1980).

The difficulty in quantifying potential productivity of secondary forests, particularly when compared with pure plantations in terms of volume yield, complicates justifying silvicultural treatment. In the absence of annual rings, reliable growth data are rare, and those that are available can seldom be applied with certainty to many sites and species or attributed largely to treatment. Data for unmanaged stands generally compare unfavorably to those for well-managed plantations, but the intensive care that plantations normally receive makes such comparisons invalid. Such comparisons on the basis of volume may also be invalid because the products of secondary forests may have a higher intrinsic value per unit of volume than those of plantations.

Trees in untreated secondary forests indeed grow slowly. A basic limitation of most tropical angiosperms is the requirement of low stocking for rapid growth (Dawkins 1961b). Rapid growth requires direct illumination of tree crowns, a condition that for most tropical trees in untreated forests either never exists or endures only briefly after a natural catastrophe. Thus, as secondary forests increase in basal area toward a maximum, tree-diameter growth declines. The disappointingly slow growth rates are apparently universal, having been reported from India (Khan 1946, Page 1948), Fiji (Cottle 1957a, 1957b), east Africa (Pudden 1957a), the Sudan (Jackson 1960), Guyana (John 1961, Prince 1973), and Puerto Rico (Crow and Weaver 1977).

In cutover forests in Nigeria, *Khaya grandifoliola,* a tree known for its growth potential, would require 80 years to attain 50 cm in d.b.h. (Dawkins 1961c). Diameter-growth rates of marketable species in a rain forest in northeastern Australia averaged less than 0.2 cm/yr (Haley 1954). Early tests in Kenya with a variety of indigenous tree species showed their growth too slow to be considered economical (Anon. 1952h).

In the Western Hemisphere, *Virola surinamensis* in Guyana grew for 20 years after logging at average rates of 1.3 cm/yr for emergents, 0.9 cm/yr for canopy trees, and 0.6 cm/yr for those of the understory (John 1961). Similarly, *Ocotea rodiaei* in Guyana averaged 0.4 cm/yr (Prince 1973). In Puerto Rico, 18-year records of 20 species in cutover forests showed that annual d.b.h. growth of dominants and codominants averaged less than 0.8 cm/yr (Crow and Weaver 1977).

It is readily apparent that higher yields will be required from natural forests in the Tropics. One approach is to concentrate management on the most productive sites. Another is to increase marketability of little-used, fast-growing species. Whatever the approach, it must be supplemented by liberation treatments that stimulate trees to meet their growth potential.

Freshwater Swamp Forests

Swamp forests, those inundated part of the year or with water tables constantly near the soil surface, generally have not received due attention from silviculturists. Their extent, some 160,000 km^2 in South America alone (Lanly 1982), is much less than that of upland forests, but their potential importance as a wood source may be much greater than this would indicate. Many of them are more accessible than remaining upland forests, and they are less likely to be converted to other land uses. But managing these forests for wood production has scarcely been undertaken in the Tropics of this hemisphere.

Particularly neglected are the forests of freshwater swamps. Those fed by river sediments annually enjoy unusual nutrient deposits that should sustain productivity. Ecological studies of some of the *varzea* and *igapó* forests along the Amazon have been made recently, but only a few timber species have been utilized.

Peatswamp forests are extensive in Malaysia, particularly in Sarawak, where they are forested with *Shorea albida,* a dipterocarp that produces useful timber, although many old trees are hollow. Cutting of swamp forests in some places is controlled by area and girth limits, but no formal silvicultural studies have been conducted. Slow growth has been reported from such forests in what is now Peninsular Malaysia (Wyatt-Smith 1961b).

Mangroves

The systematic management of mangroves apparently began in what is now Malaysia in 1904 (Kader 1979). Seventeen principal mangrove tree species and 23 secondary species were described there nearly 70 years ago (Watson 1928). The products extracted have been fuelwood, charcoal, poles, piling, chips, and tannin. Large volumes of chips have been exported from both Sabah and Sarawak (Kader 1979). The mangrove species of greatest commercial importance worldwide are those of the genus *Rhizophora* (Huberman 1959), although in Indonesia, the preferred timber species have been those of the genera *Avicennia* and *Sonneratia,* followed by those of *Bruguiera, Rhizophora mucronata,* and *R. spiculata,* (Versteegh 1952).

From afar, mangroves may appear uniform, but in fact, they vary widely within short distances in response to soil types, levels and quality of floodwater, tides, salinity, and the degree of protection from marine currents and wave action. These differences have been classified for tropical America (Lugo and Cintron 1975). However, most discussions of mangrove management pay little attention to these fundamentals. An exception is the description by Noakes (1952) of *Rhizophora* forests in what is now Malaysia. He stated that *Rhizophora* thrives there in areas inundated by ordinary high tides but with dry periods of 4 to 8 days at each neap tide. It does well in soil aerated and enriched by pioneer species but will not thrive on stiff clay, requiring at least some sand and streams nearby.

The culture of mangrove forests has been chiefly concerned with how to extract wood economically without jeopardizing future productivity. Cutting practices include minimum girths, clearcutting with or without seed trees, shelterwood, and coppices. The selection system was dismissed in what is now Malaysia because transport difficulties dictated light harvests of low value (Finlayson 1951, Watson 1928).

A shelterwood-coppice system was proposed for mangroves in India (Hall 1937). From 220 to 250 standard trees 20 cm in d.b.h., or 100 to 125 standards 30 cm in d.b.h. were to be selected and all other trees felled. The standards were to be removed a few years later after the coppice had developed. The results apparently were not reported.

Two-story mangroves, with cutting every 20 years, a system favored for what is now Malaysia by Watson (1928), resulted in serious felling damage to the understory (Anon. 1948c). On a 4-ha plot, removing 247 trees per hectare more than 20 cm in d.b.h. left only 140 undamaged, or 38 percent of the 370 trees per hectare between 10 and 20 cm in d.b.h. Of these, about 90 were in dense clumps where little cutting was done, leaving only about 50 trees per hectare scattered elsewhere. Experiences such as this sparked interest in clearcutting after the presence of a heavy seedling crop was confirmed (Hodgson 1932).

The development of cultural practices reached an advanced stage in the mangroves of Perak, in what is now Malaysia (Noakes 1951, 1952, 1957, 1958). Minimum girth fellings, tried at the outset to 10 to 12 cm in d.b.h., yielded a harvest of trees averaging 14 to 24 cm in d.b.h. This system resulted in good regeneration of *Rhizophora* except for blank areas that were costly to plant. Leaving a lighter canopy of 10 seed trees or fewer per hectare was then tested. The resulting larger canopy openings favored the less desirable *Bruguiera parviflora.* Both of these methods were later abandoned because of excessive felling damage. The leaving of standard trees, then tried, led to heavy mortality and windthrow. A return to clearcutting continued to favor *Bruguiera* and gave fair regeneration. Where markets are good, thinnings have been guided by the use of a "stick," calling for removal of the poorer of any two trees closer to each other than the stick's length. In stands 10 to 15 years old, a stick 1.2 to 1.5 m long was used. At 20 years, the stick was 1.8 m long, and at 25 years, 2.1 m. This ingenious technique requires minimum supervision.

In Thailand, removal of all mature trees left areas nearly open; therefore, a type of shelterwood, retaining overstory shade, has been applied (Banijbatana 1958). *Avicennia alba,* which was found to be a light demander and poor coppicer, has been regenerated in Adhra Pradesh, India, by clearcutting (Khan 1960).

In the Western Hemisphere, mangrove harvesting has rarely been concerned with future productivity. However, experimental clearcutting of *Laguncularia racemosa* in Puerto Rico in strips 20 m wide and perpendicular to the prevailing wind produced a new, fully stocked generation in 2 years (Wadsworth 1959). There was no perceptible damage from windthrow along the edges of the strips. A young stand of trees averaging 4.3 cm in d.b.h., thinned from 34 to 14 m^2/ha basal area, doubled its mean d.b.h. growth in 3 years. Growth acceleration was general, even on trees whose canopy position had not changed.

A management program was developed for the Tamavenca mangrove in Venezuela (Luna 1976). The average number of trees 8 cm in d.b.h. or more was 428 per hectare, with basal area ranging from 10 to 40 m^2/ha, and average volume about 200 m^3/ha. Clearcutting was prescribed for alternate strips 50 by 300 m; the remaining strips were to be cut after 15 years. The trees were to be used for utility poles, sawtimber, parquet, particleboard, charcoal, and tannin.

The wetness of swamps, generally, and the salinity of mangroves preclude a sharp change in the composition of successive forests after human intervention. The main concern in regeneration is usually numbers rather than composition.

Mangroves are generally prolific seeders, and *Avicennia* (except *A. alba* in India [Khan 1960]) and *Laguncularia* coppice freely. *Rhizophora* may also do so when young (Noakes 1958). The seeds of *Rhizophora* are viviporous; i.e., they germinate on the parent and are released ready to take root. Others, such as *Avicennia* and *Laguncularia,* produce seeds that are so readily waterborne that, where flooding is frequent, clearings need not be close to seed trees. Fruiting of *Rhizophora* in what is now Malaysia begins in the 4th year (Noakes 1952). In Perak, in what is now Malaysia, *Rhizophora* natural regeneration was common beneath the trees but irregular elsewhere. Some of the gaps left after felling did not regenerate for 10 years. Failures of the *Rhizophora* regeneration may be due in part to drifting slash and the difficulty new hypocotyls have in penetrating through it to the soil. Seedling regeneration of *Laguncularia racemosa* in Puerto Rico surpassed the height of coppice shoots by the 9th year following clearing (Wadsworth 1959).

Planting *Rhizophora* in unregenerated areas has been a standard practice in Indonesia (Versteegh 1952). Bare spots are planted up to 2 years after felling. *Rhizophora* seeds are commonly collected on the ground. Wildlings 60 cm tall have also been used successfully in Puerto Rico (Holdridge 1938). Damage to planted seedlings by crabs was reported in what is now Malaysia (Noakes 1952). In Thailand, trees were protected from crabs by wrapping the hypocotyls in plastic sheeting (Anon. 1976i).

The giant fern *Acrostichum aureum* is a problem because it tends to spread into open areas within mangroves and may interfere with regeneration. The fern develops two forms, one large and one small (Noakes 1952) and responds rapidly to full light. If no tree seedlings are present when it invades, none can get in later unless there are seed bearers standing directly over the area. This threat was one of the early arguments for retaining a shelterwood because the fern reportedly was easily controlled by light shade (Finlayson 1951; Noakes 1951, 1952). Removing it is impractical because it is intimately mixed with established seedlings (Noakes 1958). Periodically, in what is now Malaysia, the fern acts as a "nurse" to seedlings already established within it (Noakes 1951).

A handbook for mangrove area management is available, summarizing policies, planning, timber management, rehabilitation, regeneration, and economic considerations (Hamilton and Snedaker 1985). Research methods are outlined in a second recent publication (Cintron and Schaeffer-Novelli n.d.).

Despite the apparent rapidity with which mangroves recolonize a cleared site, individual tree diameter growth within unthinned stands is slow. In what is now Malaysia, diameter growth of trees less than 10 cm in d.b.h. was found to be less than 1 cm/yr; for larger trees, it was less than 0.5 cm/yr (Noakes 1958). Mean annual volume growth culminates at about 25 years; the maximum on the best areas is about 10 m^3/ha/yr; the average is much less. Trees 12 to 25 cm in d.b.h. have a rotation of 30 years (Noakes 1957). Rotations formerly 30 to 50 years have been reduced to 20 to 30 years to meet growing fuelwood demands. Yields in the Matang mangroves of Peninsular Malaysia at 30 years ranged from 3.5 to 7.8 m^3/ha/yr of firewood plus thinnings (Christensen 1983).

Mangroves in Fiji have been compartmented and worked on a 40-year rotation for poles (Anon. 1950c). Stick thinnings have been made at ages 15, 25, and 35, using stick-lengths of 0.9, 1.5, and 2.4 m, respectively.

In tropical America, the growth of mangroves has been found no more rapid than in the Eastern Hemisphere. In Puerto Rico, a pole-size stand of *L. racemosa* had, over a period 3 years, an average d.b.h. growth of 0.46 cm/yr for dominants, 0.40 cm/yr for codominants, 0.24 cm/yr for intermediates, and 0.17 cm/yr for suppressed trees (Wadsworth 1959). A 14-year record in the same stand gave a mean of 0.37 cm/yr for *L. racemosa* and 0.29 for *Avicennia germinans* (Weaver 1979b).

Dry Forests

Dry forests, those classified by the Food and Agriculture Organization (FAO) (Anon. 1993b) as dry deciduous, very dry, and desert forests, make up some 14 percent of the world's tropical forests and 5 percent of those in tropical America but have generally been neglected. They are concentrated mostly in Africa and Asia but are also common on the Pacific slope of Central America, in eastern Brazil, and in other parts of tropical America, such as the Gran Chaco of Paraguay. Foresters tending dry forests in Africa and Asia have had some success with coppicing and fire protection.

Probably the longest record of study of dry forests has been in India. In Madhya Pradesh, dry deciduous forests have been satisfactorily managed since the 1830s by the coppice-with-reserves system, in which quality trees are left to grow for two coppice rotations (Sagreiya and Nath 1968). Where the trees were protected and tended, their value increased rapidly. Site quality improved and the principal species regenerated. In contrast, where pole crops were overcut or fires or grazing were not controlled, the crops regressed.

The coppice-with-reserves system arose out of imperfections in the former coppice-with-standards system, applied in India since 1905 (Chaturvedi 1963). The main difference is a lessening of the distinction between the two stories; under the newer system, the upperstory can include good trees of almost any size. The system was designed to meet demand for small- and medium-sized timber, poles, fuel, and fodder. The rotation is commonly 30 to 40 years, with thinnings at 15 to 20 years. Most of the regeneration for both stories is in coppices, although seedlings, where available, fit into the system.

The coppice-with-reserves system was used (Tiwari 1968) where: (1) the valuable species are scarce but are vigorous coppicers and light demanders, and (2) there is a clear reason for coppicing, such as badly malformed stands.

Coppices are not applicable where: (1) the valuable species are shade bearing; (2) there is a danger of invasion by rapidly growing, obnoxious trees, weeds, or grasses; (3) species composition will not be improved; (4) there is little demand for the felled trees; and (5) protection from fire and grazing is impossible.

In Pakistan, riverine dry forests of *Dalbergia sissoo* were stimulated to regenerate by suckering along trenches dug 25 cm deep within 12 m of each *D. sissoo* stump (Paul 1953).

In the upper Nile, leaving seed bearers when cutting the forests and then burning after the rainy season produced a dense crop of coppice and seedlings of *Acacia* and *Zizyphus;* even so, a heavy grass cover may follow (Anon. 1954a). Elsewhere, in the savannas of Sudan-Guinea, protection from fire for 10 years alone was enough to produce crops of poles and firewood adequate to supply the local population (Tilton 1961). The germination of *A. senegal* in such areas was stimulated by increased dry-season rainfall; frequent light showers are as important as the total amount of precipitation (Obeid and Seif el Din 1971).

In the dry regions of Uganda and northern Nigeria, total exclusion of fire appears to be the only way to encourage reinvasion of forests (Anon. 1952m). In Nigeria's *Isoberlinia* woodlands, protection from fire has also improved canopy development and diversity. In the adjacent savanna zone, fire protection led to a thicket in 10 years (Anon. 1951b). The soils are too poor for forest plantations and must remain in native forests to protect the soil and water (Kemp 1963). Cutover areas may be cultivated at the end of the wet season, but must thereafter be protected from fire for 10 years in order to produce a new stand. Even then, fall burning will ultimately wipe them out. Spring burning, on the other hand, is tolerable. Natural regeneration is by coppice and sucker shoots (Paul 1953).

The extensive miombo (dry forest) woodlands of the east African uplands are physiognomically similar to the forests of twisted trees in the Brazilian cerrados, although the former reflect primarily climatic influences and the latter, soil effects. In the Copperbelt of Zambia, formerly Northern Rhodesia, these forests are believed to have been stable for the past 500 years (Fanshawe 1956a, 1956b). Some 90 percent of the area has been cultivated for food crops in the past. Fires sweep through almost the entire area every year. When the forest is cut for mine timbers, poles, posts, or fuelwood, seedlings are generally waiting and may survive, but they grow more slowly than the sprouts. Root suckers are successful if the fires have not been too hot; they may produce two or three crops on a 40-year rotation. A 5-year study in the miombo of Tanzania showed seedling regeneration to be best with no burning and next best with alternate years of late burning and no burning (Kimber 1963).

An experiment in the Copperbelt of what is now Zambia compared three treatments: (1) conventional exploitation for mine timbers; (2) removal of all firewood, leaving only crop trees; and (3) conversion to a selection forest. Treatment (2) resulted in the greatest increase in growth after 20 years (Storrs 1956). However, growth rates began to decline after 10 to 15 years, suggesting a need for further treatment. When 12 to 50 standards were left per hectare and the rest of the forest was felled, the standards respond well with more rapid growth (Fanshawe 1956a).

As silviculture of the miombo forests developed, both site and market distinctions were made. On especially good sites, the forests have been converted to plantations of pines, eucalyptus, and other rapidly growing, broadleaf species (Fanshawe 1960). Elsewhere, depending on site quality, the native forests have been managed for firewood, smelter poles, sawtimber, or all three. Early burning was done to protect areas from more destructive late fires. Coppice shoots may not appear for up to 5 years after a serious burn. About 40 percent of the stand coppices successfully. The canopy closes after 25 to 30 years.

Firewood crops in the miombo forests have been harvested at 40 years. Smelter poles and sawtimber have been produced as standards on rotations of 60 to 100 years, with coppices beneath but only on fairly good sites. Growth rates average 0.05 to 0.20 cm in d.b.h. per year for dominant species but may range up to 0.5 cm/yr during the first 30 years. Final crops contain 125 trees per hectare, of which 12 to 60 may be standards. Average and maximum rotation yields per hectare are 4 to 24 m^3 of sawtimber, 12 to 25 smelter poles, 100 to 250 small poles, and 140 to 200 m^3 of fuelwood.

Management of native dry forests in tropical America has rarely been attempted. There is ample evidence that indiscriminate felling, burning, and grazing deteriorate or destroy these forests. More than 35 years ago, Petrak (1959) noted the deterioration of quebracho *(Schinopsis balansae)* forests of the Argentine Chaco due to cutting and grazing. He saw no physiological obstacles to maintaining the forests if heavily shaded areas were opened up. On some of the better sites in Minas Gerais, Brazil, it appears that forest plantations can be much more productive than the native forests, at least for one rotation. Brazil's campos and cerrados have long survived in the face of heavy fuelwood drain because of their coppicing power. Nearly all of the more useful tree species regenerate by sprouts (Barros 1965–66).

An interesting proposal for the use of dry forests for energy production was made in the Dominican Republic (Trehan and others 1980). A 50-megawatt power plant would be supported by wood fuel from 78,000 ha of land considered unsuitable for agriculture. The source would be dry forests composed largely of *Acacia, Leucaena,* and *Prosopis.* A yield of 5 m^3/ha/yr was assumed, and post-establishment employment was predicted to be approximately 1,000 persons.

Conclusion

This chapter has dealt with a subject having many diverse facets. Secondary tropical forests are little appreciated, yet there have been decades of efforts to assess their present and potential productivity. There persists a perception that unless their volume yield compares favorably with the yields of managed plantations, they are a submarginal investment. Such a perception clearly underestimates the potential benefit-to-cost ratio of the management of, at least some, secondary tropical forests. It ascribes no value to the diversity of such forests not found in plantations. It assesses the returns of management on the basis of timber alone. It makes a judgment on the basis of past efforts, some producing conflicting results, to produce a small fraction of the forest products that have since become marketable. It sees labor intensity as a cost rather than a social asset. The experience reported here is extremely diverse and much of it far from tropical America, but it suggests new approaches that might be more appropriate under present local conditions for providing the variety of forest products that tropical peoples will need and that cannot come entirely from the much less extensive area of plantations. Predictions of yield limits and their value under past conditions are undoubtedly low. The reader is encouraged to further the studies and testing that could lead to a complete reversal of the present conservative assessment of the potential productivity of these forests.

Chapter 5
Forest Plantations: Policies and Progress

Logging in the Tropics is commonly followed by deforestation and agriculture that degrade the soil, precluding subsequent continuous cultivation or pasturing. Agriculture persists on the best sites, leaving the poorer ones to return to forests. Of these, the best may be suitable for forest plantations.

The growing need for plantations was recognized decades ago by Champion (1949). He pointed out that there are many millions of hectares of land that should be afforested as soon as possible for society's benefit. He further stated that although the technology to restore forests may be based on incomplete understanding of the underlying principles, the work must proceed in the light of existing experience. His plea is still valid.

The ultimate extent of forest plantations in the Tropics will be determined by the degree to which they can compete with other land uses, meet growing demands for wood, outproduce alternative wood sources, and protect the environment for future generations. In spite of the uncertainty of long-range predictions regarding these stipulations, forest plantations have recently attracted far more interest and investment than the management of natural forests, primarily because of their reported high productivity potential. These and other matters pertinent to the decisions as to whether, how much, and what to plant are reviewed in this chapter.

Earl (1972) described how emphasis on commercial gain has led to shorter tree rotations and even-aged, pure stands (plantations). He foresaw that wood for fuel will be increasingly in demand for at least 50 years, even if an infinite source of pollution-free energy can be found.

The Food and Agriculture Organization (FAO) (Anon. 1981g) summarized the need for forest planting as follows:

- The current deficit in fuelwood in the Tropics is estimated to equal the production of nearly 48 million ha of fuelwood plantations.
- About 30 million ha of intensively managed, tropical hardwood plantations would be needed to meet the expected demand for sawlogs currently being harvested from primary tropical forests.

Ladrach (Anon. 1985f) further pointed out the greater labor requirements of forest plantations as compared with traditional grazing. Taking pine pulpwood on a 15-year rotation as an example, he concluded that employment is nearly 5 times greater in forest plantations than in pasture production, and yet the forest may be grown on poorer soils.

Two valuable references on forest plantations in the Tropics are available. Evans (1992) emphasizes the planning of plantations, taking into account social and economic factors and describing practices from establishment to harvest. Zobel and others (1987) clarify misunderstandings concerning exotic species and document the high yields attainable through plantation tree improvement.

The Case for Planting

The case for planting rests partly on land availability and foreseen timber shortages. One analysis concluded that plantations are needed where: (1) natural forest area is inadequate, (2) natural forests grow too slowly to meet bulk forest-product demands on a sustained-yield basis, (3) natural forests are too scattered to permit economical harvesting, and (4) natural forest timber is too remotely located to be transported economically (Marsh 1962). All of these problems were said to be avoidable by establishing plantations of fast-growing species near communities and processing industries.

Evans (1992) supported plantations by contrasting negative and positive factors. Negative factors include past and continuing destruction of the native forests, decreasing access to remaining forests, and unsatisfactory natural regeneration. Positive factors are increasing land availability, high productivity, the potential of current plantations, and environmental benefits.

A review of the situation in Nigeria showed the close relation between land availability and reforestation needs (Lowe 1984). There, even though only about 10 percent of the country was reserved for forests and most of this is poorly stocked savannas, encroachment by farmers could be prevented only by planting exotic tree species on threatened areas. The best reserved forests, some 2,000 km^2 of which were formerly under a shelterwood system, have been converted to plantations to increase productivity. A national plan described in 1985 was to plant over a 20-year period half the high forest reserves and one-tenth of the savanna reserves, even though doubts remain as to successful techniques.

Wadsworth (1983) analyzed the potential environmental benefits of expanding timber plantations. For the Tropics as a whole, he calculated the prospect for reducing the demand for timber from natural forests by increasing the timber supply from plantations (table 5–1).

Public concern over planting proposals, even where reforestation is itself favored, must be addressed. A prime example is the opposition to the planting of eucalypts. This opposition is most evident in the Eastern Hemisphere but has existed throughout the long history of planting these species in Brazil. The complexity of this matter is to be seen in the scope of arguments used against eucalypts, summarized by Spears (1987) as follows:

- Eucalypts, as nonleguminous species, deplete nutrients.
- Eucalypts jeopardize the hydrological water balance.
- Eucalypts have allelopathic effects on some farm crops.
- Eucalypts usurp good farm land.
- Eucalypts require less rural employment than other crops.

In part, these concerns reflect problems with eucalypts planted in the wrong place. But to a larger degree, they are generalizations without much factual basis. Clearly, there is a need to inform the public about any possible deleterious effects of eucalypts (or any other plantation species) together with the prospective benefits in terms of rapid growth, timber and fuel supplies, forage values, protective values, employment, and economic returns. This subject was treated in depth by Poore and Fries (1985).

Productivity Advantages of Plantations

The superiority of plantations over natural forests as a source of timber rests primarily on their higher productivity of marketable wood. The advantages of plantations are most evident where natural regeneration is deficient, where native trees are of limited utility, and where differences in growth rates are pronounced.

Other reasons for planting include the need to rehabilitate deforested land (Baur 1964b). Further, there is growing pressure to replace natural forests, perceived by the public as jungles, which contrast unfavorably with nearby agriculture that is increasingly in demand and producing greater economic returns.

The failure of prompt, natural regeneration of desired timber species is common on land farmed and abandoned. Moreover, under some circumstances, useful, natural, tree regeneration has proved almost impossible to achieve. One instance is that of *Araucaria angustifolia,* the "pino" of southern Brazil. Because it does not regenerate well naturally, plantations of this and other species of pines are preferred to the natural forests (Krug 1968).

Natural regeneration, even where adequate, may promise only fuelwood rather than industrial wood. Except where fuel is extremely scarce, this prospect dooms naturally regenerated forests to low economic yields. Successful plantations on the other hand, offer greater certainty as to composition, quality, yield, and timing of the next crop.

Table 5–1.—Plantation timber as a substitute for natural forest timber in the Tropics

Requirements currently met by plantations (%)	Timber source needed to meet demand in the year 2000[a] (million km²)		Reduction in natural forest cutting[a] (million km²)
	Available from plantations	Natural forests required	
12	0.2	6.0	0.6
20	0.4	5.5	0.9
30	0.5	4.8	1.5
50	0.9	3.4	2.5
100	1.7	0.0	5.1

Source: Wadsworth 1983.

[a] Estimated.

That natural forests grow slower than plantations throughout the Tropics is of concern. Most comparisons are somewhat biased, however; often they are made between leftover trees of unknown ages and histories in cutover forests and young, well-spaced, well-cared-for trees in plantations. Other inequalities may prevail, such as site quality, market value per unit of volume, and completeness of utilization. Despite all these, trees in plantations generally produce more usable wood than do trees in natural forests.

Growth of trees in native forests in Brazil showed them to be no match for planted eucalypts (Navarro de Andrade 1941). In Mauritius, the indigenous trees of mountain forests were found to be slow growing (King 1945), and in Kenya, the growth rate was so slow that the regeneration of native species by either natural or artificial methods was considered uneconomical (Dyson 1965).

The implications of growth-rate differences between naturally regenerated and planted forests are spectacular in terms of crop rotation. A review of silviculture in Nigeria (Wyatt-Smith 1968) led to the conclusion that replacing natural forests with plantations of species of the genera *Khaya, Lovoa, Tectona, Terminalia,* and *Triplochiton* (native to the region) might reduce the rotation to 60 cm in diameter at breast height from 100 to 50 years.

In Malaysia, plantations of budded rubber 81 months old have produced a phytomass of 20 tonnes per hectare per year, converting 2.5 to 2.8 percent of visible radiation (Wycherley 1969). Productivity (above and below ground) of oil palms in plantations ranges from 30 to 37 t/ha/yr. At high altitudes, planted conifers and eucalyptus, indigenous or introduced, attain 13 to 40 t/ha/yr, a level of production that could not possibly be attained by the natural forest communities that such crops replaced (Dawkins 1967). Retaining natural forests on the grounds of productivity is seen as questionable, although a much stronger case can be made where other values, such as soil or water conservation, are important (Wycherley 1969).

Added arguments for tropical plantings are based on their superiority as a source of wood supply over plantings in the Temperate Zone (Machado 1977). Average conifer yields are 5.3 t/ha/yr in the Temperate Zone versus 12.6 t/ha/yr in the Tropics. For broadleaf species, the corresponding averages are 5.1 t/ha/yr and 13.1 t/ha/yr.

An early report from Uganda (Laurie 1962) cited natural forest production of 0.7 m^3/ha/yr, yet nearby *Eucalyptus* produced more than 40 m^3/ha/yr. Dawkins (1964b), after a regionwide review, concluded that managed, moist tropical forests might attain 4 to 10 t/ha/yr of stemwood versus 14 to 24 t/ha/yr for conifer or eucalypts plantations. Natural coniferous forests in the Tropics are rare, but under favorable circumstances, such forests can produce stemwood volumes of 35 m^3/ha/yr (Wood 1974). In the miombo forests of Nigeria, Jackson (1973) reported a yield of 1.4 m^3/ha/yr for a native *Isoberlinia* forest versus yields to 24 m^3/ha/yr for six plantation species.

Fuelwood produced in plantations can be a viable alternative to petroleum. Petroleum equivalents for 7-year-old *Eucalyptus* in Africa from the Centre Technique Forestier Tropical relative to rainfall are presented in table 5–2 (Catinot 1984).

Studies of the U.S. National Research Council (Anon. 1984c) indicate that agroforestry and improved charcoal production and use are among the most promising prospects for increasing energy production. With the development of practical systems to convert lignocellulose in wood to alcohol, charcoal plantations may compete with farming for arable land.

The average productivity of plantations of various tropical tree species is summarized in table 5–3 (Evans 1992). An analysis in 1980 (Brown and others 1986) showed that plantations constitute less than 2 percent of the organic matter in tropical vegetation, but their biomass per unit of land area (123 t/ha) averages more than that of natural tropical forests (106 t/ha).

Table 5–2.—Petroleum equivalent of 7-year *Eucalyptus* yields in Africa

Mean annual precipitation (cm)	Wood yield (m^3/ha/yr)	Petroleum equivalent (t/yr)
30–60	3–4	0.7–0.8
60–80	4–8	0.8–1.6
80–100	15–25	3–5
>100	25–80	5–10

Source: Catinot 1984.

Table 5–3.—Productivity of tropical plantations

Species	Rotation (yr)	Yield (m^3/ha/yr)
Paraserianthes falcataria (Philippines)	10	28
Eucalyptus		
Subtropical	8–25	5–30
Tropical	7–20	≤60
Gmelina arborea (Brazil)	10	35
Pinus caribaea (Fiji and Brazil)	8–16	21–40
P. patula (Africa)	15–16	18–19
Swietenia macrophylla (Fiji)	30	14
Tectona grandis	40–80	4–18

Source: Evans 1992.

There is a serious need for more precise descriptions of plantation performance. Qureshi (1968a) noted the lack of clear specifications as to the size and quality of the material yielded and the precise period in which it is obtained. These deficiencies are exemplified by the studies reviewed, some of which present data in cubic meters, others in tonnes, often with no rotations or size limits specified. In a study of 502 timber plantations in tropical America (Lugo and others 1988), the data were adequate and comparative for only 8 tree species. Some data were for too short a growth period, and thinnings were not accounted for. In addition, the status of bark was not specified nor were the utilization limits.

Malcolm (1979) concluded that the structure of plantations resulted in a higher percentage of usable wood in plantation trees than in natural forest trees. In comparing a natural forest and a 35-year-old plantation of *Shorea robusta* in India, Raman (1975) found that 92 percent of the aboveground phytomass in the plantation was in usable stemwood compared with only 71 percent in the natural forest.

Land Considerations. With land increasingly in demand for other uses, the shift from the lower productivity of natural forests to plantations has become commonplace. In Kenya, a major motive for shifting to plantations has been to concentrate production on a smaller area, because forest area was being lost to other uses (Dyson 1965). In Nigeria, transition has taken place from natural methods through *taungya* to intensive plantations in the face of growing competition from other land uses (Lowe 1977).

In Puerto Rico, it became evident early that unless timber yields per unit of land area could increase as rapidly as adjacent agricultural productivity, land use would increasingly favor agriculture (Wadsworth 1961). Baur (1964a) concurred, concluding that forestry will ultimately be confined to smaller areas and that intensified management is inevitable. He noted that export timbers yield less profit than cocoa or rubber and emphasized the growing need for more forest plantations.

Economic arguments for plantations have been presented for many years. Beresford-Pierse (1962) saw a need to change the prevailing view that more natural forests should be managed. The difficulty of utilizing inaccessible or complex forests can make the wood extracted from them so expensive that it becomes uneconomical, he argued. Vast areas of land would thus be unsuitable for management because of this high cost. He favored depending more on genetics, fertilization, cultivation, and integration with farming.

Ovington (1972) emphasized the need to consider plantation location, product requirements of industry, and the economics of management. A complicating factor is the large plantation area necessary to support processing industries. Evans (1992) estimated the minimum size of plantations needed to support various wood-using industries and the employment each would generate (table 5–4).

The selection of land for planting should also be sensitive to site quality because it affects potential tree growth. Contrasts between good and mediocre sites are shown in table 5–5.

The choice between natural regeneration and planting is not always easy. Where there is doubt, Synnott and Kemp (1976) favored the "greater robustness" and long-term security of maintaining natural forests. Nevertheless, they agreed that, where land is limited and greater production is essential, plantations are indicated. They further saw that planting should be concentrated on nonforested, degraded lands (provided of course, that the sites are not submarginal for practical forest production).

Wood (1974) saw three land-use choices in countries with extensive primary forests: (1) conserving naturally

Table 5–4.—Minimum tropical plantation size to support wood-using industries

Operation	Annual wood requirement (m³)	Plantations needed (ha)	Human resources (no. of jobs)
Sawmilling	15,000	1,000	30
Integrated sawmilling and plywood	100,000	7,000	200
Integrated pulping	500,000	25,000	2,000

Source: Evans 1992.

regenerated forests and management on long rotations, (2) increasing naturally regenerated forest yields and shortening the rotation by silvicultural treatment, or (3) replacing naturally regenerated forests with "compensatory plantations." For countries without extensive forests, plantations were considered inevitable. In Ghana, it was concluded that 1 percent of the original forest area converted to timber plantations could equal the former yield of the native forests (Foggie 1957).

Leslie (1967) points out that a cost-benefit analysis of the decision between plantations and natural regeneration could favor natural forests when watershed, recreation, wildlife, and floral values are factored in. These values are seldom assessed in such decisions.

Limitations of land capability present a convincing argument for reforesting cleared land within much of the Tropics, whether for timber or other tree crops. Goodland (1986) sees the most sustainable development for Brazil's Amazonia to be forest based. He proposes a mixture of perennial crops and subsistence cultivation of annual crops. Extracting the most valuable timber with concomitant silviculture could provide the capital for development. Other tree crops recommended by Goodland were rubber, oil palms, cocoa, Brazil nuts, coconuts, coffee, and babassu.

Throughout the Tropics, most plantations have been established on former grasslands and savannas (table 5–6; Evans 1992). Scrub woodland is the second most common type of land used for plantations in tropical America, but in Africa and Asia, it is the rain forest type.

Timber Supply

Even where land for forests is plentiful, intensification of management may still be called for because of increasing inaccessibility or deficient quality of the remaining native timber supplies. Concern for the wood supply led to the first efforts to plant teak in Malabar in 1830 (Laurie 1937). In Thailand, fuelwood plantations followed a twentyfold rise in fuelwood prices (Thirawat 1952). In Uganda, doubts concerning the adequacy of naturally regenerated forests led to timber plantations on the grasslands (Anon. 1957e).

By 1959, the only hope seen for a substitute for dung as fuel in India lay in the production of 3.4 million m³ of fuelwood each year (Ishaq 1959). By 1975, demand for both wood and land left no alternative but to increase production in existing forest areas (Singh and Randev

Table 5–5.—Mean annual increment superiority of good over mediocre tropical planting sites for various species

Species	Age (yr.)	Superiority of good over mediocre site (%)
Araucaria angustifolia	30	105
Azadirachta indica	9	234
Cryptomeria japonica	30	117
Cupressus lusitanica	20	47
Eucalyptus camaldulensis	12	72
E. deglupta	12	20
E. globulus	12	118
E. grandis	12	139
E. saligna	12	122
Gmelina arborea	12	40
Pinus caribaea	20	28
P. patula	16	68
Swietenia macrophylla	40	120
Tectona grandis	65	123

Source: Evans 1992.

Table 5–6.—Land converted to tropical timber plantations

Previous status	Converted to plantations (%)			
	America	Africa	Asia-Pacific	World
Grasslands and savannas	52	67	40	52
Scrub woodlands	25	6	11	16
Rain forests	4	18	34	15
Idle, deforested areas	18	3	8	12
Timber plantations	1	5	6	3
Other	0	1	1	2
Total	**100**	**100**	**100**	**100**

Source: Evans 1992.

1975). The demand for fuelwood called for rapid growth, and the need for construction timbers required plantations because of the excessive density and seasoning problems of the woods from native forests (Sahni 1965).

By 1973, it was seen in Nigeria that 12,000 ha needed to be planted annually to supply foreseeable national requirements (Oseni 1973). Fuelwood scarcity was most severe in the savannas where the productivity of native woodlands was low (Jackson 1973).

Timber scarcity has also spurred planting in tropical America. Trinidad, with no outstanding local species, converted to plantations. So did countries with land on high Andean slopes (Laurie 1962). Despite extensive remaining native forests in Suriname, plantations were being established on a large scale by 1966 because natural regeneration was deficient (Schulz and Rodriguez 1966). The need to plant was evident in the deficit of accessible timber anticipated for 1985. Reducing waste and using more species of the native forests were not expected to forestall this need (Dickinson 1967). In Brazil, where most timber is sold to processors, incentives were used to get plantations started (Dickinson 1967). In Peru, where wood consumption is largely rural and local, planting was undertaken without incentives, even though the crop took a decade to mature.

Planting has in some areas succeeded in solving problems. In Fiji, by 1984 the 38,000 ha of successful plantations were more profitable than tourism, sugarcane, or copra (Rennie 1974). In Brazil, one-third of the industrial wood raw material comes from plantations. By 1965, existing tropical plantations had the potential to supplant half the current annual drain of industrial roundwood from natural forests; at the then current rate of planting it was felt they could meet prospective cellulose demand by the year 2000 (Anon. 1965e).

Teak in Trinidad, introduced in 1913, now covers more than 5,000 ha. These plantations fostered the creation in 1978 of the Trinidad and Tobago Forest Products Company Ltd. and are expected to produce a sustainable annual yield of 18,000 to 24,000 m^3 of teak poles and 34,000 to 57,000 m^3 of teak sawtimber (Anon. 1982c).

Lanly (1982), in his worldwide inventory of tropical forests, distinguishes the following two types of forest plantations based on their objectives:

- Industrial plantations, established totally or partly to produce wood used mainly for pitprops but also for sawlogs, veneer logs, and pulpwood
- Other plantations, established to produce fuelwood or charcoal wood (possibly for industrial use), wood for domestic (in particular rural) consumption, fruits, palm hearts, gum arabic, cinnamon, etc.; and to protect the soil

About half the forest plantations of the Tropics are devoted to the production of industrial wood (table 5–7; Evans 1992). Fuelwood is the next most common product, accounting for 18 percent of the tropical plantations worldwide and 29 percent in America.

Wood (1976) pointed out that the apparent capability of stable high forests to supply human needs in perpetuity is not commercially feasible, even using labor paid at the lowest rates. The high cost of wood harvesting, whether

Table 5–7.—End products of tropical forest plantations and percentage of forest land area devoted to production of each

	Forest land area (%)	
Primary end use	World	America
Industrial wood	54	50
Fuelwood	18	29
Protection	17	10
Minor products, agroforestry, other	11	11
Total	**100**	**100**

Source: Evans 1992.

by hand or machine, demands that as many trees as possible be felled at each harvest. This operation disturbs the ecosystem so much that the resulting regeneration rate cannot sustain the forest, particularly after selective removal of the best trees. It is only by planting that the genetic quality of the original trees can be maintained or improved. Where forest land is in short supply, the production of wood is not by itself a strong enough argument for keeping natural, tropical forests (Wood 1976). There must also be benefits for soil, water, scientific study, genetic conservation, or secondary forest products.

In Malaysia, retaining mixed forests results chiefly in the production of cellulose; rapidly growing plantations could supply this product much more economically (Tang and Wadley 1976a, 1976b).

Some precautions are noteworthy in a shift to plantations. Such a shift calls for high performance and a quality crop from tree species usually grown far from their native sites. Zobel (1978) warns that it is a mistake to think that because the wood of a native species is good, it will be equally good when grown in a different habitat. He notes that any silvicultural treatment undertaken to increase growth rates will affect the wood. Rapid early growth means juvenile wood at maturity. Crookedness in pines in the Tropics is not only common in plantations but may lead to "compression wood" (wood compressed beyond its elastic limit).

Hughes (1968a) reports that wood from *Pinus caribaea* plantations often has poorly developed latewood and thus may be much lower in density than naturally grown wood. This reduces its value for heavy construction but increases its value for joinery. Infiltration of the heartwood zone by resin and the common occurrence of compression wood are serious defects of rapidly grown trees. Spiral grain (twisted fiber) may also appear. The major differences between plantation wood and naturally grown wood appear to be related largely to climatic and site conditions (Hughes 1968a).

Studies of teakwood from plantations and from naturally grown trees have shown no significant difference in resistance to subterranean termites (Da Costa and others 1958). Resistance increased with tree age and wood extractive content. Tests of 51-year-old, rapidly grown plantation teak from India (1 to 3 rings per centimeter) showed it to be 15 percent weaker and 15 to 25 percent softer, but 12 percent stronger in tensile strength than more slowly grown Burmese teak (Wood 1968).

Legitimate concerns notwithstanding, plantations of high-value tropical woods (such as *Cedrela, Maesopsis, Tectona, Terminalia,* and *Triplochiton*) promise returns greater than most other investments in the countries where they grow (Spears 1980). Furthermore, the prospective wood requirements of a long and lengthening list of tropical countries can no longer be met by domestic sources other than plantations.

The widely used term "compensatory" plantations refers to plantings undertaken to produce at least as much timber as the natural forests they replace (Dawkins 1958g). Compensation usually requires planting a much smaller area than the forests being replaced.

Even where plantations are justified, it does not necessarily follow that all remaining naturally regenerated forests are best left unproductive. If they are, they become vulnerable to destruction; whereas they might still produce forest crops to supplement those of the plantations and continue to provide other values.

In a study of biomass energy needs in developing countries, the U.S. National Research Council (Anon. 1984c) concluded that when the price of petroleum fuels rises above the cost of biomass-based energy, the production of energy in tropical forests will attract those who have depended on petroleum for energy. These conditions already exist in many developing countries where increased biomass production is essential both to meet energy needs and to counter deforestation. Agroforestry and charcoal production were seen as promising energy technologies. Competition for arable land currently prevents adoption of large-scale fuel production in many areas. This was seen to be less of a problem as soon as practical systems to convert lignocellulose in wood to alcohol become available. Reforestation for fuelwood and charcoal, when properly managed, is expected to generate an attractive rate of return without a perpetual subsidy.

Site Considerations

Most plantations are more beneficial ecologically than nonforested areas. The ecological effects of plantations on the sites are similar to those of natural forests. A comparison of mineral cycling in Ivory Coast between a natural forest and a 38-year-old plantation of *Terminalia ivorensis* showed that leaffall and soil percolation were similar (Bernhard-Reversat 1976). The accumulation of organic matter and nitrogen (N) in the topsoil was actually greater in the plantation, but the exchangeable cation reserves of the soil were lower, particularly on sandy soils. The influence of plantations on the disposal of rainfall can be beneficial. For example, in a 93-week test in Brazil, a 13-year-old plantation of *Pinus caribaea* and *P. oocarpa* intercepted only 12 percent of the rainfall versus 28 percent in nearby cerrado vegetation (Lima and Nicolielo 1983).

Concern over the effects of plantations on sites has prompted many studies throughout the tropical world. In Trinidad, in *P. caribaea* plantations, total reserves of N decreased for 5 years but recovered by the 12th year (Cornforth 1970b). Phosphorus (P) reserves decreased slightly after the preparatory burning and although the availability of P in the soil increased through the 7th year, it had not regained its original level by the 12th year. Reserves of potassium (K), calcium (Ca), and magnesium (Mg) released by burning were rapidly lost by erosion and leaching.

The characteristics of the top 7.5 cm of soil in a 25-year-old plantation of neem *(Azadirachta indica)* in northwestern Nigeria compared with nonforested land are summarized in table 5–8 (Radwanski 1969).

In *P. radiata* plantations in subtropical Australia, soil N increased 50 kg/ha even where nodulated species were not present in the understory (Richards 1964). Rainfall contributed 10 kg/ha/yr, and free-living, N-fixing bacteria, about the same amount. Soil N was rapidly absorbed by the pines.

Table 5–8.—Soil characteristics of neem *(Azadirachta indica)* plantations compared with nonforested land in northwest Nigeria

Soil parameter	Nonforested	Plantation
pH	5.4	6.8
Carbon (%)	.120	.57
Total nitrogen (%)	.013	.047
Carbon-to-nitrogen ratio	9.4	12
Total phosphorus (ppm)	201	131
Potassium+ (meq/100g)	.08	.23
Calcium+ magnesium+ (meq/100g)	.29	2.15
Total cations (meq/100 mg)	.39	2.4
Base saturation (%)	20	98
Cation exchange capacity	1.7	2.4

Source: Radwanski 1969.

Note: Listed characteristics are means for values found at a depth of 0–7.5 cm depth.

In the Temperate Zone, the shift from broadleaf forests to conifer forests has increased N availability on the site over and above the intake of the pines (Stone and Fisher 1969). This effect, which extends beyond the area covered by the tree crowns, has been attributed to mineralization, not fixation. Accretion in N fixation has also been associated with the growth of pines (Wollum and Davey 1975).

An intensive study of plantation effects on the soil, including those in Belize, Brazil, and Suriname, as well as in west Africa, was made by Chijioke (1980). He concluded that in plantations of rapidly growing tree species in the lowland humid Tropics, harvesting of the stemwood plus bark removed 70 to 80 percent of the nutrients immobilized in the tree. *Gmelina* exports significantly more nutrients with rotations of 5 to 6 years than with rotations of 13 to 15 years. Leaving slash, as opposed to whole-tree harvesting, could reduce nutrient losses 25 percent. Leaving the bark could conserve an additional 5 to 10 percent. Chijioke found total N to be more than adequate despite the large quantities immobilized by *Gmelina* and pines.

Plantations may markedly benefit the water regime. Their influence on the disposition of rainfall is indicated by tests made in India with plantations of *P. roxburghii* and *Tectona grandis* (table 5–9; Dabral and Subba Rao 1968). The large amount of interception of light rains is impressive. Nevertheless, in subtropical Jodhpur, India, soil depletion at a depth of 10 cm 39 days after a rain was 76 percent under 3-year-old *Eucalyptus* and 92 percent under 11-year-old *Acacia,* compared to 86 percent under grass. At a soil depth of 60 to 90 cm, corresponding percentages were 36, 7, and 7 (Gupta and others 1975).

The apparently high productivity of *Eucalyptus* and *Pinus* plantations suggests that they draw heavily on soil water. But a study in Brazil indicates that they consume no more than herbaceous vegetation (Lima-Freire 1976). May-to-September evapotranspiration was 20.6 cm for a 5-year-old plantation of *E. citriodora,* 21.2 cm for a 5-year-old plantation of *P. caribaea caribaea,* and 19.6 cm for herbaceous vegetation. Conclusions to the contrary were reached by Poore and Fries (1985) to the effect that eucalypts decrease water yields more than grasses, herbaceous vegetation, and broadleaf tree species but less than pines. Eucalypts reduce runoff if thinned enough to conserve ground vegetation and if fires are excluded.

In Kenya, plantation softwoods managed on rotations of 20 or fewer years and subject to annual fellings consumed less water over a 10-year period than did a natural forest on a comparable site (Pereira 1967). However, the plantations did use about 10 percent more water than perennial pasture grasses.

Despite the fact that plantations are much less ecologically diverse than natural forests, in New South Wales, Australia (latitude 34° S.), mature *P. radiata* plantations 40 years old had as many or more birds as two indigenous forest types, but only about two-thirds as many species. The species of birds under the two conditions were different.

A mature plantation of *Araucaria cunninghamii* in Australia was similar to a rain forest in annual, mineral-element accessions to the soil (Brassell and others l980). This held true on fertile and infertile soils and on wet and dry sites, suggesting that if there were any site deterioration in the plantation, it would not be due to a reduction in mineral cycling during the later stages of the rotation.

The prospect of lowered yields as a result of site deterioration under intensive management of short-rotation, planted tree crops has been a concern of foresters for decades (Lamb 1969a). The use of light demanders on sandy soils was seen to be particularly risky. There is obviously a need to monitor continuing performance and to learn of any input needed to maintain levels of productivity during succeeding rotations (Evans 1976).

Much controversy has arisen in Australia over the different effects on sites of plantations versus native forests. Evidence does not yet strongly support appeals for natural forests (Anon. 1971–72). Evidence of decline in the second and third rotations in *P. radiata* plantations in South Australia is not yet convincing (Boardman 1978). In fact, there is overwhelming evidence that the productivity achieved by the time the canopy closes tends to be maintained. Silvicultural practices and weather appear to have great influence.

Studies of the oldest teak plantations in Nilambur, India, reportedly have shown no decline in height growth in the second rotation (Venkataramany 1960b).

A thorough study of second rotations of *P. patula* in Swaziland suggested no significant decline in site quality (Evans 1972). Second-rotation height growth was 90 to

Table 5–9.—Rainfall disposition by plantations of *Pinus roxburghii* and *Tectona grandis* in India

	Rainfall amount per storm (%)			
	1.35–2.5 cm		>5 cm	
Rainfall disposition	*T. grandis*	*P. roxburghii*	*T. grandis*	*P. roxburghii*
Interception	37	29	4	4
Stemflow	7	3	9	5
Throughfall	56	68	87	91
Total	**100**	**100**	**100**	**100**

Source: Dabral and Subba Rao 1968.

95 percent as rapid as that of the first rotation in 64 pairs of plots. Evans concluded, however, that there is no basis for assuming that growth of successive forest crops gradually declines. In the test area, rainfall was slightly lower during the early years of the second rotation. A 10-percent loss in fiber through less dense corewood was indicated, but this was conjectural. Of many site factors studied, however, none clearly caused the growth changes observed.

Soil N declined in second-generation *P. radiata* plantations in New Zealand (Stone and Will 1965). One theory is that the pine roots may be able to break down some fraction of the soil organic matter that is inaccessible or resistant to the previous flora. This capability would be an advantage to the first crop over the preceding vegetation (without pines), an advantage that would not be equally available to succeeding generations of pines.

In regions subject to hurricanes, plantations may suffer more general damage than natural forests (Brouard 1960). The plantations of *P. caribaea* in Jamaica suffered severely during the hurricanes of 1980 and 1988, whereas nearby natural montane forests were much less affected (Tanner and Kapos 1991). The ecological and economic consequences of storms may differ widely. A plantation of pines, even if severely affected, may represent fewer years of management and a higher productivity prior to the storm, much of which could promptly be harvested for posts and cellulose products. Storm effects on a mixed forest, even if superficially less severe, may result in breakage of trees on a longer rotation and of higher ultimate value per unit of volume than the pines. At intermediate size, with little heartwood and scattered in the stand, those species valued only for sawtimber are generally impractical to harvest.

Natural forests, according to Peace (1957), do not necessarily have fewer pathogens than plantations. He points out that every departure from nature is not bound to encourage diseases. Site and pathogens play differing roles in the occurrence of diseases. Foresters must not think that "unnatural" is the same as "unhealthy." Peace concluded that the greatest single factor in successful plant cultivation is the removal of competitors, something that seldom takes place in the natural environment.

In summary, although there is much evidence to show that tropical forest sites deteriorate after deforestation, there is little to suggest further decline from successive timber crops. Research indicates that such a decline has not yet occurred to any significant degree (Bednall 1968; Evans 1972; Laurie 1934, 1941b). However, the nutrient drain implicit in repetitive cropping, particularly on short rotations, may be sufficient to bring on such a decline, presumably toward a lower nutrient-level plateau corresponding to the natural rate of replenishment.

Plantation Planning
Ladrach (Anon. 1985f) used experience in Colombia to formulate guidelines for establishing industrial-forest plantations and suggests that the following items be considered in preliminary planning:

Community relations
Land tenure and acquisition
Mapping
Protection of existing natural forests
Boundary maintenance
Road and firebreak layout
Species selection
Rotation length
Yield estimation
Seed supply
Nursery establishment
Site preparation
Fertilization
Spacing and stand density
Planting procedures
Fire control
Pest control
Recordkeeping
Personnel training
Development of contractors

He lists the major industrial-plantation risks as wildlife, pests, wrong species selection, inadequate seed supply, nursery and planting problems, poor wood quality, and inadequately trained personnel. He concludes that most of these risks can be reduced by proper planning, organization, and research.

Lewis (1968) predicted that although natural regeneration might continue where planting is most difficult, such as on mountains, large areas of timber plantations will be established in the Tropics because of increasing concern for the time, cost, and control of natural regeneration. Genetically improved stock will not be wasted on poor sites, and replacement of slow-growing species with rapid growers will continue, even if the new species are not as well adapted and need fertilizer. Research will have to show how far this process can be permitted to proceed without risk. A remaining question is how to stabilize production after the first crop.

Interplanting. Forest planting usually means establishing tree crops on deforested land. But in the Tropics, planting is also commonly done within existing forests. Such plantings are believed to re-create an environment similar to that experienced in nature by young trees entering the forest ecosystem. The forest left after partial cuttings has been thought to protect recently planted trees. Planting within an existing forest may also be less costly because part of the residual stand may be suited for the next crop.

Trees are planted in existing forests either for "enrichment" or "gap planting," which is the filling in of natural gaps in forest regeneration, or as "underplanting," the planting of young trees or the sowing of tree seeds, usually spaced systematically under most or all of an existing forest (Ford-Robertson 1971).

In Nigeria, enrichment began in 1927 (Wholey 1955) to maintain a stable forest environment and to avoid the cost of land clearing. Brasnett (1949) concluded that the practice is appropriate where natural regeneration of desired species is deficient and cannot be adequately induced by known silvicultural methods. It is also appropriate where so few trees can be sold per unit of land area that gradual freeing of scattered regeneration requires more skilled supervision than is justified. He suggested that planting should be done systematically, in lines, to facilitate tree relocation. Because adequate overhead light can be provided at the time of planting, the species planted may be light demanders. He also recommended the use of planting stock 2 to 3 years old, seedlings that have survived the difficult, early developmental stages in the nursery.

In Papua New Guinea, different intensities of enrichment have developed (White 1976b). The least intensive practice, termed "opportunity enrichment," involved planting only the logged openings where no further clearing is needed. Where practice was more intensive, all gaps are planted, and between them a stand of overstory trees of good species 45 to 60 cm in d.b.h. was thinned to preserve a spacing of approximately 60 by 60 m as a crop and for future seeds.

Gap Planting. Gap planting has been the most common form of enrichment. Gaps occur in cutover forests where several trees close together have been felled, at landing sites, or where charcoal burning has destroyed all natural regeneration (fig. 5–1). Gap plantings were tested as an inexpensive way to supplement the next crop. One of the arguments for the practice is that "nothing else will come up and that there is a need to husband a forest or lose the land to other uses" (Laurie 1934). Gaps are generally larger than 300 m^2. The undergrowth may be burned. Teak may be planted at 1.8 by 1.8 m near the center of the gap.

Figure 5–1.—*Gap planting, or forest enrichment, using pines on the slopes of Jamaica.*

In Uganda (Earl 1968), charcoal kiln sites were planted at a spacing of 100 trees per hectare, with trees set at 20 m or more from the edge of the nearest adolescent crown. Planting was done as soon as the charcoalers leave in order to minimize the need for weeding. Two trees were planted per spot; one of the pair was removed after 1 or 2 years. Species used have included *Burtdavyia nyassica, Cedrela odorata, Maesopsis eminii, Nauclea diderrichii, Terminalia ivorensis,* and *T. superba.*

Experience in India and west Africa with gap planting led to its early demise. In India, gap planting was tested in various provinces as early as 1934 (Laurie 1941b), but gaps proved difficult to tend because of the scattered distribution of the trees (Griffith 1941b). Even when they no longer need tending (after 2 years), gap plantings are wasteful in that the overall crop may be poor. By 1941, gap planting had been abandoned in India (Laurie 1941b).

In west Africa, gap planting was tried after close planting beneath the canopy (2 by 2 m) failed because of inadequate light (Wholey 1955). The planting of gaps, however, was found to leave poorly regenerated areas between the gaps. The relocation of all but the largest gaps was difficult, and repeated clearings proved costly (Catinot 1969b, Foggie 1957, Laurie 1934a). At best, gap plantings have been considered wasteful in that they produce less than concentrated plantations might on better soils.

Gap plantings have been practiced in the dipterocarp forests of the Philippines, where they prevent postlogging entry by shifting cultivators. Landings, cableways, skyline routes, and other poorly stocked areas left after logging have been filled successfully with *Paraserianthes falcataria* and *E. deglupta* (Tagudar 1979). These have been seen as a temporary pulpwood crop to be replaced naturally by dipterocarps. After 4-1/2 years, one planted area had an understory of 2,900 dipterocarp seedlings per hectare. Use of dipterocarp wildings to plant landings has been recommended as a practical technique in Sabah (Fox 1971).

Enrichment planting has proved of limited usefulness in tropical forests and generally has been abandoned (Stern and Roche 1974). Only in the dipterocarp forests of Peninsular Malaysia have the natural seedlings and saplings grown fast enough to supplement the prospective crop of the species planted. Tests with slower growing species and with slow removal of overhead shade led to repeated searching to relocate seedlings and interminable ground slashing, costing up to 10 days of work per hectare per treatment (Dawkins 1956, Mooney 1963).

An international questionnaire led to the conclusion that the failure of enrichment planting was also due to late or inadequate opening or the wrong choice of species (Fontaine 1976). Enrichment was no longer being practiced in west Africa by 1970 (Wood 1970).

Underplanting. Underplanting is distinguished from enrichment because it is not limited to the stocking of canopy gaps but rather is aimed at replacing the entire forest by planting a new crop beneath it. The term "line planting" is sometimes applied but is confusing because it is equally applicable to reforestation planting. Underplanting is intended to ensure full stocking, species control, crop uniformity, short rotations, and yields competitive with those of other land uses (Britwum 1976). Underplanting sets out trees in narrow, parallel corridors cut through the forest at a spacing that leads to full stocking as the planted trees approach maturity. It is intermediate in intensiveness between natural regeneration and reforestation planting and is most appropriate for countries with large areas of secondary forests (Wood 1976). It requires few trees, may save any natural regeneration present, and is usually less costly than complete plantations. Underplanting may also greatly increase prospective yields of secondary forests that would otherwise produce no more than 1 or 2 m^3/ha/yr (Earl 1975).

Underplanting apparently began in India and francophone Africa in the early 1930s (Catinot 1969a, 1969b; Laurie 1934a). By 1965, some 30,000 ha had been underplanted in Gabon and Ivory Coast. Extensive underplantings have also been made in what was formerly Zaire; smaller scale and experimental underplantings have been done in Brazil, Costa Rica, Ghana, Malaysia, Mexico, Nigeria, Puerto Rico, Suriname, Uganda, and Venezuela.

Underplanting with *T. superba* in French Equatorial Africa in 1938 was described as successful (Aubreville 1953). A small number of trees was planted per unit of area (12- by 12-m spacing), and a large percentage developed well. The need for similar tests in Cameroon and Ivory Coast was pointed out, with the suggestion that 23 tree species were worth trying (Aubreville 1947). Good results were predicted for *Swietenia macrophylla* in francophone Africa (Aubreville 1953).

Terminalia superba has also been underplanted in what was formerly Zaire (Wagemans 1958b). Tree spacing was 4 by 12 m or 8 by 12 m, and the stock planted was 2 to 3 m tall and stripped of leaves. At 8 years, the mean d.b.h. was 17 cm.

By 1961, underplanting of *Aucoumea* was being tested in Gabon (Biraud and Catinot 1961), and 130 ha of underplantings with *Aucoumea, Azfelia, Cedrela, Swietenia macrophylla,* and *Terminalia spp.* were established in what is now Malagasy (Bertrand 1961). By 1962, underplanting was the chief planting technique in Ivory Coast (Mensbruge 1962). Some 3.6 million trees had been planted, chiefly *Tarrietia utilis* and several Meliaceae. An area of 4,300 ha had been underplanted with *Senna siamea, G. arborea,* and other species (Mensbruge 1961).

By 1965, a wide variety of planting spacings and techniques were being used in the moist forests of francophone Africa (Catinot 1965). Spacings ranged from 4 to 6 m within strips and strip spacings ranged from 4 to 25 m. Typically, the strips were 3 m wide and 10 to 30 m apart (Catinot 1969a). The technique was described as easy, inexpensive, and protective of most of the ecosystem (Catinot 1974).

In west Africa, opening regularly spaced corridors destined to provide a full crop of planted trees required about 75 days of labor per hectare (Wholey 1955). Then, when light demanders such as *Aucoumea, Terminalia,* and *Triplochiton* were found to need nearly full light from the outset, less and less attention was given to retaining the natural forest. Retaining side shade had also been largely discontinued.

In Nigeria, tests with light demanders such as *Terminalia superba* failed. A common error was making the corridors too narrow. (They should be about 4 m wide.) It also proved necessary to release the corridors on both sides from the lower canopy and overhanging overstory. Some early failures were due to the use of undersized stock. (Plants should be at least 1.5 m tall.) Acceptable genera included *Chlorophora, Khaya, Lovoa, Swietenia, Terminalia, Terrietia,* and *Triplochiton.*

In Nigeria, Meliaceae striplings 1 m tall survived better than stumps and grew faster in height because they received more light. Running lines east and west to provide both early and late direct sunlight helped. Mortality and slow growth resulted from cutting only narrow lines through the undergrowth and not felling all overstory trees. Poisoning of overhead trees for at least 5 m on each side of the lines was needed.

Most underplanting in Nigeria was done from 1930 to 1962 (Oseni and Abayomi 1970). A shift to complete plantations followed because underplanted trees required more protection from animals and weeds than was considered justifiable.

After shelterwood proved unreliable in Ghana, underplanting became favored, even though it required protection from grazing animals, thorough ground preparation, and rapidly growing tree species (Danso 1966). By 1968, underplanting had become standardized; trees were planted 5 m apart in lines spaced 20 m (Osafo 1968b). The first year's work included demarcation, line cutting, canopy opening, cleaning, and planting. Line cleaning, "beating up" (replanting), and further canopy opening were done in the second year. Cleaning and opening continued for the next 3 years. Underplantings entailed rotations of up to 100 years. The best species were the African Meliaceae and *Tarrietia utilis,* the latter requiring full light from the outset. However, as logging roads were not maintained, the plantings became inaccessible and difficult to treat, so many failed.

In Papua New Guinea, clear felling and planting led to serious invasions of *Imperata* grass; therefore, felling intensity was reduced and *Araucaria hunsteinii* was underplanted, controlling the *Imperata* with the natural forest undergrowth (Godlee and White 1976).

Underplanting has been successful in the hill dipterocarp forests of Malaysia (Gill 1970). Spacing is 3 by 10 m, and both wildings and direct seeding have been used.

Observations of the regeneration of *Cedrela odorata* in Cuba led early to suggestions for underplanting (Roig 1946). The species apparently can withstand partial shade during its first years. As early as 1942, Holdridge (1942a) proposed that *Cedrela* be established in Puerto Rico at a density of about 12 trees per hectare among compatible neighbors.

In Suriname, underplanting has been tested (Vega 1977), with lines spaced 10 m apart. All undesirable trees 20 cm in d.b.h. or more were poisoned; repoisoning was done at 6 months if it was necessary. Promising species include *Aucoumea klaineana, C. angustifolia,* and *Cordia alliodora.*

Underplanted *Cedrelinga* trees at Tingo Maria, Peru, attained a height of 14 to 16 m at 6 years (Burgos 1955). Tests at Belterra, Brazil, along the Tapajos River also gave promising results after 4 years with *Bagassa guianensis, Carapa guianensis, Cordia goeldiana, Schefflera morototoni,* and *Swietenia macrophylla* (Yared and Carpanezzi 1981). *Enterolobium maximum* proved branchy, *Aspidosperma desmanthum* and *Genipa americana* grew slowly, and *Hymenaea courbaril* tended to lean. In Misiones, Argentina, underplanted *C. trichotoma* grew to 10 cm in d.b.h. and 8 m in height in 7 years (Cozzo 1969). Large openings (10 to 15 m) were necessary for this species.

An unusual technique was successfully applied in southern Queensland, Australia (Bevege and Richards 1970; Richards, B.N., 1961). On sites where *Araucaria cunninghamii* did not prosper because of poor soils, the species grew well when planted beneath 6-year-old plantations of *P. taeda.* This success was attributed to: (1) the role of N fixation, (2) the increased availability of N because of changes in the N cycle, and (3) reduced light intensity, improving the carbon (C)-to-N balance in the *Araucaria* where little soil N was available.

The French invested heavily in underplanting because they considered even close planting under shade superior to clear felling followed by reforestation (Lamb, A.F.A. 1966). This made it possible to retain the forest environment and to save pole-sized trees that otherwise would have been sacrificed. By 1970, two types of underplanting were being used in west Africa (Wood 1970). In one, all trees 30 cm or more in d.b.h. and the understory were removed, followed by planting light demanders, such as *Cedrela*. The other method recognized a need for initial shade for such species as *Entandrophragma utile;* therefore, the canopy was gradually removed after planting.

Reviews of underplanting experience have led to the following general recommendations for its use (Dawkins 1958c, 1961c; Foury 1956; White 1976a):

- Apply only where there is no prospective market for thinnings.
- Keep out fire and browsing animals.
- Leave no upper canopy.
- Plant as soon as possible after logging.
- Run lines east and west.
- Space lines 20 percent greater than final crown diameter to foster stand diversity between rows.
- Space trees within lines less than one-fifth of tree spacing between lines.
- Use only vigorous light demanders (such as gap species) that also tolerate intense root competition.
- Choose species that will grow 1.5 m/yr in height and self-prune from the outset.
- Plant stock 1 to 2 m tall.
- Reduce competition from overhead shade promptly and completely.
- Thin within lines for form and height, not for d.b.h. (except to favor trees much larger than the rest).

Few marketable tree species meet the growth-rate requirement specified here. In Africa, *Cedrela, Maesopsis,* and *Triplochiton* qualify. Many woods in prospective demand cannot be produced efficiently by this technique.

Underplanting has evolved to require large early openings and drastic cleanings for intolerant crops, removing nearly all of the former forest (Catinot 1969b). The canopy may be completely poisoned down to 30 cm in d.b.h., and the understory cut back as well (Wood 1970). In the Western Hemisphere, some of the canopy is left until trees such as *Cordia* and *Swietenia* develop before full release (fig. 5–2). In all cases, however, the former forest is greatly reduced.

Where accessible secondary forests abound, underplanting may be superior to either natural regeneration or field planting. It promises an immediate start on production with a small investment, even on some sites too poor for more intensive planting. Should pressures for shifting cultivation become overwhelming in the face of the long wait for a final harvest, intermediate products such as poles, pulpwood, or fuelwood might be harvestable from trees that survive or arise in association with the main agricultural crop.

Figure 5–2.—*Trees planted beneath openings in a forest canopy tend to develop straight boles.*

Figure 5–4.—*Eucalypts have been selected widely in tropical America because of their rapid growth and adaptability to degraded soils.*

Group Planting. Group planting is a variant of underplanting. Groups of 9 to 25 seedlings are spaced 10 to 20 m apart. The trees are spaced about 1 m apart, usually in triangular arrangements (Ironside 1954). Group planting has not been used widely but shows promise in some places in west Africa (Catinot 1969b). The system has been used successfully in what was formerly Zaire (Dawkins 1955a). In Uganda, *Aucoumea, C. alliodora,* and *M. eminii* developed better in groups than in lines (Kriek 1968a). Dawkins (1958e) recommended groups of 13, 19, or 21 trees with the groups planted 30 to 60 cm apart, 75 to 125 groups per hectare. The central trees in a triangle tend to grow straight and free of weeds and climbers. In Suriname, groups containing only three trees, generally *A. klaineana, Cedrela angustifolia,* or *Cordia alliodora,* have been spaced 5 to 10 m apart. Tests in Brazil with *S. macrophylla* under high shade show some success in thwarting the shootborer problem. Generally, however, underplantings in lines provide more potential crop trees for selection than group plantings and may require less planting stock.

Forestation. Forestation relies solely on planted trees to develop a forest cover or a timber crop, either where no cover has existed before (afforestation) or where it has been removed (reforestation). Even where land clearing or other site preparation is not needed or is comparatively inexpensive, the initial investment required is sufficiently high to demand favorable terrain, soil quality, and accessibility—characteristics that may also eventually lead to great pressure for conflicting, marginal, agricultural uses. For sawtimber, the number of trees planted may be many times that of the final crop, the excess being thinned out and either sacrificed or harvested as intermediate products.

The potential for both productivity and risks is high in forestation. Usually, yields of good-quality, harvestable trees greatly exceed yields of alternative production systems. But failures have been common and often extensive because site limitations and the limits of adaptability of tree species (few of which are truly "native" to deforested and, particularly, degraded sites) were not recognized.

Plantation Composition

The species composition of a plantation is the primary key to its success or failure in terms of productivity, yield, and return on the investment.

Evaluating Tree Species. Forest planting has been done in every tropical country, and every country has searched for tree species as insuperable as teak seemed in India. Many failures convinced most foresters not to be coerced into undertaking large plantings in the Tropics without prior species testing (Lamb 1968a). The need for early testing is evident in Hawaii, a group of islands with few native tree species. Between 1921 and 1947 as many as 700 tree species were introduced, leading to the planting of nearly 10 million trees (Bryan 1947). Of these species, only 72 adapted well. Nevertheless, species selection continues to be somewhat arbitrary in spite of (or possibly because of) long experience and tradition. And the problem is exacerbated by a failure to communicate existing pertinent information to those who select the species. Much good information is now available in such excellent compendia as those of Streets (1962), Fenton and others (1977), Jacobs (1981), Francis (1984–Present), and Webb and others (1984).

Faulty species selection continues to cause many plantation failures in the Tropics because those making the selections do not take into account the intricate climate and soil patterns in mountainous regions and any site degradation caused by past cultivation practices, grazing, or fire. Careful species selection is important, however, because even among adapted species, selecting the best strains can double yields (Krishnaswamy 1957b).

Quoted yields of conifers and eucalypts generally include thinnings. Annual yields of 28 m^3/ha/yr (43 m^3/ha/yr on first-class sites) are commonplace. Even higher yields are reported from clones in Brazil. These contrast with a range of 14 to 21 m^2/ha/yr for other species, for which thinnings generally have little value.

Dawkins (1964a) points out that tropical yields exceeding 30 m^3/ha/yr generally occur at high altitudes or latitudes in areas with cool nights or a cool season. He speculates that respiration may be so rapid and continuous in the equatorial lowlands that the resultant photosynthate losses significantly reduce net productivity.

Whatever the causes of high productivity, it has been the chief criterion for selecting species for plantations, and selection is often made on the basis of early performance of trees planted at uncrowded spacings. A more comprehensive assessment is warranted. Odum (1969) points out that the more foresters select for succulence and growth, the more they must invest in chemical pest control, increasing the possibility of poisoning useful organisms, not to mention people and the environment. He asks: Why not practice the reverse strategy, selecting plants that are essentially unpalatable or that produce their own systemic insecticides while growing?

Bunting (1976) suggests that selection be made not on the basis of competitiveness but rather on commensalism (one organism benefits, the other is unharmed), mutualism (both organisms benefit), or compatability (the organisms "get along" with each other with little or no cost to either).

In the long run, the sustainability of different species in plantations will become a primary consideration. The importance of this is to be seen in the effects of different species on the nutrient reserves in the soil over a period of 18 years (table 5–10; Jorgensen and Wells 1986).

Schulz and Rodriguez (1966) conclude that the final decision on timber-species selection always rests on economic considerations. The acceptance of the product by industry and commerce is fundamental. Thus, tree species unknown to the trade, even if they have excellent silvical characteristics, may not merit selection for plantations.

Barnes and Mullin (1976) suggest that the productivity of plantations may be increased more by increasing the adaptability of accepted species through breeding and management than by seeking new species. Burley (1980b) described a logical sequence of selection: (1) matching species to the site through elimination trials; (2) selecting among possibles, a species-proving phase; and (3) genetically improving selected species.

Pure Versus Mixed Plantations. Simplicity has led to pure plantings of timber trees, and the pros and cons of monocultures versus polycultures, or mixtures, have been debated ever since. The advantages of mixed plantings were outlined by Laurie (1941c) and Wakeley (1954): (1) maintenance or improvement of site quality, (2) insurance against plantation destruction by a single agent (such as insects or fungi), (3) possible improvement of timber form (nurse crops), (4) comparison of species performance, (5) insurance against stagnation if thinning must be postponed, (6) insurance for a future seed source of the best of more than one species, and (7) possible higher value output by two or more compatible species. However, some of the support for mixtures is more emotional than intellectual. A mixture looks to be more in harmony with the natural vegetation of the moist Tropics; thus, there is a tendency to trust mixtures and question monocultures. Viewpoints presented abstractly and without support (Dickenson 1972) do little to clarify the issue. Nevertheless, the term monoculture has come to have almost an unsavory connotation. The reasons offered for this include: (1) the threat of excessive demand for certain soil nutrients, (2) the massing of food material and breeding environment for insects and fungi, (3) unbalanced return of nutrients to the soil, (4) questionable soil protection, and (5) little or no variety of food sources for bird life (Boyce 1954).

Table 5–10.—Effects of different tropical tree plantations on soil nutrient reserves over a period of 18 years

Site and species	Rotation (yr)	Nitrogen change (%)	Potassium change (%)
High-fertility soil			
Eucalyptus	3.0	-0.9	—[a]
Leucaena	4.5	+24.7	—[a]
Pinus	1.0	—[a]	-0.2
Low-fertility soil			
Eucalyptus	3.0	+9.5	—[a]
Leucaena	4.5	+213.0	—[a]
Pinus	1.0	—[a]	-7.5

Source: Jorgensen and Wells 1986.

[a] Not measured.

Florence (1967) predicted that a productivity decline is more probable in pure than in mixed forests because certain nutrients are more likely to become scarce where cycled according to the needs of but a single species. However, this effect may be buffered by the composition of leaf litter, which tends to reflect the nutrient content of the crowns.

Notwithstanding these concerns, in New Zealand, with its vast expanse of pure plantations of *P. radiata,* there are no reports of early prospects for planting any other species. Yet, responsible opinion favors developing alternative species to be available if ever needed (Anon. 1979a).

Based on experience in Ghana, Foggie (1957) concluded that pure timber plantations should be avoided except where such plantations are necessary for economic or other reasons and that a natural understory should be allowed to develop as soon as the main crop dominates the site. Nevertheless, Foggie does describe management complications using mixtures with different growth rates. *Terminalia* and *Triplochiton* grow four times as fast in height as African Meliaceae and form crowns much earlier; therefore, mixtures with the slower species prolong the tending period.

Experience in England suggests that the use of three or four species may be most productive, but it is a complicated practice (Darrah and Dodds 1967). Conifer/broadleaf mixtures are successful if the conifer outgrows the broadleaf and is salable early. Special planting patterns are suggested to accommodate differences in crown form.

An observation in Britain seems applicable to the degraded sites usually planted in the Tropics. Poor sites tend to restrict the choice of species and lead toward monocultures (Malcolm 1979).

Laurie (1941c) described a number of attempts at mixtures in India that apparently failed. Mixtures with teak led to poorer tree form than that obtained in pure stands. Even species that are complementary are not equal in value, so the better species would presumably be worth more alone. Mixing teak with *Pterocarpus marsupium* suppressed the teak. Mixing teak with *S. macrophylla* led to teak dominance on teak soils and *S. macrophylla* dominance on Latosols. Mixing *Gmelina arborea* and *Dipterocarpus turbinatus* resulted in *G. arborea* being so dominant that it had to be overthinned to bring through the *D. turbinatus.* Teak with a bamboo *(Melacanna)* understory was considered a possible crop combination.

An early statement regarding teak (Champion 1932) is still of interest:

> From the purely economic point of view, the value of teak timber is so much greater than that of any other species likely to be grown with it that relatively poor teak is almost always a sounder financial proposition than any other possible alternative. Expenditure is therefore justifiable to overcome the silvicultural difficulties if such really exist.

In support of mixtures, it has been noted that even though a species may grow pure in nature, this is no indicator that it should be grown that way commercially (Peace 1957). The lack of competitors on its natural site may be due to causes independent of species preference.

An almost universal problem with species mixtures is their maintenance. Differences in growth rates lead to dominance by one species, with the others falling progressively further behind (Anon. 1952g, White 1976a).

An example involving two rapidly growing trees in the Philippines illustrates some of the difficulties in managing mixtures (Zabala 1975). The two species used, *Paraserianthes falcataria* and *Anthocephalus chinensis,* were planted at 2 by 2 m. After 5-1/2 years, the *Paraserianthes* was larger in d.b.h. and volume than in a monoculture, whereas the *Anthocephalus* was smaller. The *Paraserianthes* suppressed the *Anthocephalus* and apparently took its space.

Experience in Puerto Rico further exemplifies the difficulties of managing species mixtures. Two or more species initially thought compatible seldom prove to be. If one outgrows the other, the slower must either be preserved at a sacrifice in productivity or sacrificed at the expense of the mixture. Mixing a rapidly growing intolerant and a more slowly growing intolerant may solve the problem of compatibility, but it leads to two rotations, with the later crop subject to felling damage from the first and probably lower growth rates for both.

What has been said here appears mostly to be in defense of pure plantations, but there should be no objection to an understory of species different from the main crop, except where it might create a serious fire hazard. Such an understory might be (and generally is) of mixed native species.

Pure plantations, even of teak, have been criticized from the very outset, notwithstanding an early conclusion that called the "problem" of the pure teak plantation a false alarm if good sites and good strains of the species are used (Laurie and Griffith 1937). A favorite rejoinder to those favoring monocultures is "Saxon spruce sickness," referring to a progression of worsening crops beneath successive pure spruce plantations in Germany on a site formerly covered by a mixed broadleaf forest (Smith 1962). However, exhaustive study has shown the phenomenon resulted from planting the wrong tree species on the site rather than from the purity of the plantation *per se*.

Encouraging diversity for its own sake, on the other hand, may not improve ecosystem stability (Murdoch, cited by Clarke 1976). The crucial variable is not simply the number of species but rather the species themselves and the interactions among them.

Early observations in pure teak plantations in India did not support the serious concern then expressed (Kadambi 1945). No growth decline took place. The undergrowth beneath well-managed stands appeared to control erosion. Fluting of teak boles was no worse than in natural forests, nor was damage from insects. And the timber sold at the same price as old-growth teak.

A study of the nutrient content of litter in Brazil provided no evidence that monocultures per se lead to more rapid depletion of soil-nutrient reserves than do mixtures, other things being equal (Chijioke 1980). Rapid nutrient depletion is clearly associated with rapid growth, short rotations, and whole crop harvesting; but further study is needed to show whether a single crop immobilizes nutrients faster than does a mixed crop.

Yields. Widespread pure planting would not have taken place or continued unless there were also arguments in its favor. A classic statement by Champion (1933) describes the position that led to large areas of pure teak plantations in southern and southeastern Asia:

> Even more than in Europe single species tend so greatly to outdistance all their associates from an economic point of view that a crop quality inferiority of even two quality classes as compared with potentialities with the associates is insufficient to equalize returns from the first rotation if financial prospects alone are considered. Since no drop in soil quality has ever been demonstrated it is unlikely that the formation of mixtures will improve soil conditions by more than a fraction of a quality class, much less two. Such little improvement as can be expected from a mixture is likely to be almost as well provided by maintenance of a good natural mixed undergrowth. More investigations are required on this point, but it appears that the formation of mixtures for the maintenance or improvement of site quality is unlikely to be worth while.

The famed Changa Manga plantations in Pakistan are mixtures of various tree species destined primarily for fuelwood. When an Australian visitor saw the possibility to double the yields by planting *Eucalyptus* (Pryor 1968a), he specifically recommended against mixing the *Eucalyptus* with *Dalbergia* and *Mora,* the species planted hitherto. Instead, he recommended testing three species of *Eucalyptus* and then presumably choosing the species that was best suited for each site.

The prospect of mixed-crop production "overyielding" (that is, exceeding the yield of any crop alone) is one of the attractions of species mixtures. Financially, such a result must be extremely rare. In physical terms, mixed yields of 572 grasses and grains usually fell somewhere between the monoculture yield of the best and poorest components (Trenbath 1974). Relative yields approached unity; that is, what one species gained, the other lost. In the few cases where mixed yield surpassed that of each component in monoculture, it was not clear whether the results were repeatable.

An interesting example of overyielding among forest trees was found in Hawaii (DeBell and others 1985). *Eucalyptus* was grown with leguminous trees in alternate rows at a spacing of 2 by 2 m. Not only were the eucalypts in the mixtures larger than those in pure stands at 65 months, but the mixed stands also produced 1.4 to 2.5 times as much dry wood fiber as the eucalypts alone (table 5–11). Nutrient levels in the *Eucalyptus* in the mixed plantations suggested a contribution from the leguminous trees. Similar findings were reported in the northwestern United States for a 27-year-old stand of *Pseudotsuga* grown with and without an understory of Alnus, an N fixer (Tarrant 1961). The N content of the

Table 5–11.—Overyielding of *Eucalyptus* planted with leguminous trees in Hawaii

	Results at 65 months		
Plantation type	D.b.h. (cm)	Height (m)	Dry weight (t/ha/yr)
Pure *Eucalyptus saligna*	9.5	11.6	6.9
Mixed			
Eucalyptus	12.1	14.9	6.5
Acacia melanoxylon	9.3	11.3	3.0
Total			**9.5**
Mixed			
Eucalyptus	15.3	19.0	10.7
Paraserianthes falcataria	14.6	18.1	6.8
Total			**17.5**

Source: DeBelle and others 1985.

Note: Overyielding is defined as exceeding the yield of *Eucalyptus* planted without leguminous trees.

Pseudotsuga foliage and of the soil was significantly higher with the *Alnus*. After age 20, the *Pseudotsuga* in mixed stands was also growing more rapidly.

Laurie (1941c) hailed mixtures as a protection against insect attacks, arguing that separating the tree species would slow the spread of the pests. However, in close plantings of few species, such protection may be negligible. Moreover, he cited no evidence where dilution of the crop by mixture significantly affected the incidence of insect attacks or diseases. Nevertheless, mixed undergrowth is a good habitat for the parasites and predators of insect pests.

Shootborer attacks by *Hypsipyla* spp. have led to abandonment of *Cedrela* as a pure crop in much of tropical America. Mixed plantings were proposed long ago (Andrade 1957) and in some areas have reduced (but not eliminated) shootborer attacks. The discovery that the insects have a limited flight radius tends to explain the reduction (Grijpma 1976).

A summary of experience with forest monocultures concluded that the system has led directly to an increase in the number and severity of pests and diseases of forest crops (Gibson and Jones 1977). Effects of diseases have been greatest in the nursery and early plantation stages. But much of this increase is attributed to the uniform and crowded conditions in plantations and to the cultural operations that have often exacerbated other problems.

The most pessimistic forecasts of the dangers arising from forest monocultures are thought by some to be fully vindicated (Gibson and Jones 1977). However, few of the most disastrous outbreaks of forest pests and diseases in the Tropics can be attributed to monoculture systems. Foresters have avoided pest problems by strategic choice of species. The economy of intensive plantations allows for expenditures for protection. Moreover, the compact nature of intensively managed plantations benefits pest control (Gibson and Jones 1977).

Peace (1957) cites the example of the fungus *Armillaria mellea*. If it attacks a pure stand, the damage is serious. In a mixed stand, the attack is less devastating only if one or more of the components is resistant. Of course, if all the trees were of the resistant species (leading toward purity), the attack would have least impact. Stated in another way, if there are two or even five species in a mixture, trees of each would still be close enough so that all of any species might suffer just as heavily from an insect attack or disease as it would grown as a pure stand. If only one species of the mixture is susceptible, an epidemic would be only one-half or one-fifth as damaging as if all the trees of a pure plantation were the susceptible species. By the same token, however, the probability of an epidemic occurring to a single species in a pure plantation should be only one-half to one-fifth as great as where two to five species are exposed. Theoretically, at least, the risks may be about the same. The warnings of theorists about monoculture susceptibility to pest and disease risks have been supported by only a few examples in the Tropics, Rosayro (1954) noted, and his statement apparently is still valid.

Recent planting of *Leucaena leucocephala* in pure stands in the Asia-Pacific region encountered an insect defoliator termed the leucaena psyllid *(Heteropsylla cubana)* (van den Beldt and Napompeth 1992). First reports described a sudden and dramatic dieback of the leucaena. By the second year the pest population had peaked. By the third year the pest was largely absent. Even highly susceptible varieties of leucaena survived in infested areas. Resistance may have resulted in part because of the existence of resistant varieties in the vicinity.

Native Versus Exotic Species. Of the thousands of tree species that grow in natural tropical forests, many are sufficiently valuable to justify harvesting for human use. So what better source of trees for future crops might be expected than that of the native forests? Is there not also a danger that exotics might wipe out natives? Such reasoning has produced strong support for the use of native species wherever possible (Parker 1940).

The term "exotic" is not generally used in any ecological sense, because it commonly refers to political rather than natural boundaries. For example, some species from what is now Myanmar became "exotic" to India when the two countries were separated in 1937. Are not coastal species equally "exotic" to the uplands of the same country? Likewise, the term "native" may not be very meaningful. Although a species native to an area may be better adapted to it than a nonnative, the site being planted is seldom the same as where the "native" species grew in nature. The important question is whether the species is "native" or "exotic" to a site that may long have been cleared and repeatedly burned, cultivated, or grazed. These changes may be so drastic that species not found in the former native forest may now prove best adapted there. Broad capability of adaptation to such conditions characterizes eucalypts and pines and explains their popularity in the Tropics. Prospective performance is more important than origin in selecting species to plant. Arbitrarily rejecting exotics excludes many species that merely never had an opportunity to migrate to the site and do not lack adaptability thereto.

To be successful, an exotic timber tree must be: (1) able to better serve a particular purpose than available local species; (2) suited to the local climate and soil; (3) easy to grow and regenerate; and (4) resistant to local hazards, such as fire, insects, diseases, and grazing (Laurie 1941f). These seem to be stiff requirements, and it is reasonable to question how any exotic tree could outperform natives in such respects. Nevertheless, some promising exotics have extraordinary vigor and growth rates. Rejecting the theory that aliens are inherently more aggressive because they are alien, Egler (1942) pointed out that in Hawaii exotics seem to succeed because the local environment has been altered by humans. He concluded that if human influences were removed, the advantages to outsiders would diminish.

The introduction of exotics may be doomed to failure if they do not come from a similar environment or may, at the other extreme, lead to unwanted escape and "naturalization." Even the most carefully selected exotic species need testing for site adaptability and performance while planting is kept to a small scale.

Early species introductions usually were based on imprecise information as to the requirements and usefulness of the species and sometimes even their identity. By 1960, 837 tree species were introduced into Hawaii (Nelson 1965). More than 10,000 trees of each of 80 different species were planted. Of 16 species from tropical America, 1,290,000 trees were planted; few proved promising.

Early plantation testing in tropical America led to more use of native species. Gonggryp (1948), after establishing a remarkable set of early planting tests in Suriname, recommended further study with *Bertholletia, Carapa, Caryocar, Eperua, Goupia, Hymenaea, Manilkara, Mora, Schefflera, Triplaris, Virola,* and several native Lauraceae.

From Brazil also came early proposals to make the most of the native forest flora (Klein 1966, Pitt 1966, Wasjutin 1951). It was concluded that substituting foreign species for the local flora would result in disharmony among the soil, flora, and fauna of the region. Lists of pioneer species suggested for trial plantings, by genera, included *Andira, Araucaria, Aspidospermum, Balfouradendron, Buchenavia, Calophyllum, Cedrela, Chlorophora, Colubrina, Copaifera, Cordia, Hieronyma, Jacaranda, Lonchocarpus, Manilkara, Myriocarpus, Ormosia, Piptadenia, Tabebuia,* and *Xylopia.*

In India, numerous native species outgrow exotics (Qureshi 1968a). Genera with species reportedly capable of exceeding 10 m^3/ha/yr include *Anthocephalus, Artocarpus, Gmelina, Lophopetalum, Michelia, Terminalia,* and *Toona* (fig. 5–3).

In addition to the timber species known to produce useful woods, there are many more tree species that are sparingly used, even within their natural ranges. Such species include *Acacia albida* (for feed and protein), *Brosimum alicastrum* (for feed and protein), *Caryocar brasiliensis* (for oil), *Gulielma utilis* (for oil), *Orbignya martiana* (for oil), *Prosopis tamarugo* (for feed and protein), and *Simmondsia chinensis* (for wax and oil) (McKell 1981). These species thrive under adverse conditions and apparently do so because they are native.

Early planting tests in the wet Pacific region of Colombia (300 to 440 cm of rainfall annually) indicate that some

Figure 5–3.—*Avoidance of costly weed control has led to the selection for planting of tree species of very rapid early growth, as illustrated by this first year development of* Anthocephalus chinensis.

native species may do better than exotics there (Peck 1976a). *Anthocephalus chinensis* was rejected because of poor form. *Cedrela* spp., *Cordia alliodora, J. copaia, Ochroma lagopus,* and *Zanthoxylum tachudo* showed promise.

Exotics were not introduced into what is now Malaysia, especially well endowed with native species, until later than most other countries. As late as 1953, Barnard (1953) wrote that the timber quality, stem form, and growth rate of many indigenous tree species left little to be desired. He concluded that exotics would need to be outstanding in timber quality, growth rate, and ease of establishment to be introduced in place of indigenous species for which natural regeneration could successfully and economically be established.

With the growing population of the Tropics and resultant increased local demand for utility woods, markets for an increasing number of native tree species have developed. Nevertheless, local shortages promise to worsen. This prospect has shifted attention from quality to quantity timber production. Despite the presumed advantages of native species, the need for increased yields has forced their reassessment. Indeed, in spite of the current promotion of native species, experience in timber production throughout the Tropics has led to an almost universal preference for exotics. For example, although some 450 native tree species had been test-planted in India by 1937 (Sen Gupta 1937), exotics have been much more widely used. Exotics are particularly popular for pulpwood production on the worst sites, such as coastal sands, dunes, swamps, and degraded soils where the native forests were a low-grade mixture of little commercial value (Chaudhuri 1952).

It was apparent early that India's needs for construction timber required more rapid production than was possible with many indigenous tree species (Sahni 1965). In the dry regions especially, the native species grow too slowly (Kaul and Nambiar 1966). In addition, most native timbers are heavy, hard, and difficult to season. Therefore, from 1958 to 1966, a total of 277 species of trees and shrubs was introduced in Jodhpur for fuel and livestock feed. About 15 were found promising, including 8 species of *Eucalyptus.*

In India, a 15-year-old exotic plantation of *E. camaldulensis* accumulated more organic matter than a 55-year-old, mixed, native *Shorea robusta* forest (Jha and Pande 1984). The physical soil properties were also better under the *Eucalyptus* than the *Shorea*. The *Eucalyptus* raised the soil pH and the *Shorea* lowered it.

The greater fire resistance of some exotic species led to their introduction into African savannas (Adekunle 1965). On the northern grasslands of southern Cameroon and on the Nigerian savannas, eucalypts and pines were found to resist fires and produce much more fuel than native trees.

In Nigeria, the need for pitprops at Enugu led to plantations of the native *Nauclea*. But as these failed, the exotic *Gmelina* was substituted and proved successful (Foote 1953). In South Africa, 15 indigenous species were tested from 1912 to 1927; none produced adequate yields (Pudden 1957a). *Juniperus procera* (East African pencil cedar) was planted on a large scale, whereas *Ocotea usambarensis* (camphorwood) was found adapted only to high elevations. Meanwhile, plantations of *Eucalyptus* had, since 1910, proved productive of fuelwood for railroad use. Tests of 48 conifers showed three species of *Cupressus* and two of *Pinus (P. patula* and *P. radiata)* to be promising. Tests of 150 broadleaf trees, including 70 eucalypts, showed *E. saligna* and *E. globulus* to be especially well adapted (fig. 5–4).

On the savannas in Nigeria, indigenous species planted for fuelwood compared unfavorably with those from India, such as *Azadirachta indica, Senna siamea,* and *Dalbergia sissoo* (Page 1948). No Nigerian savanna

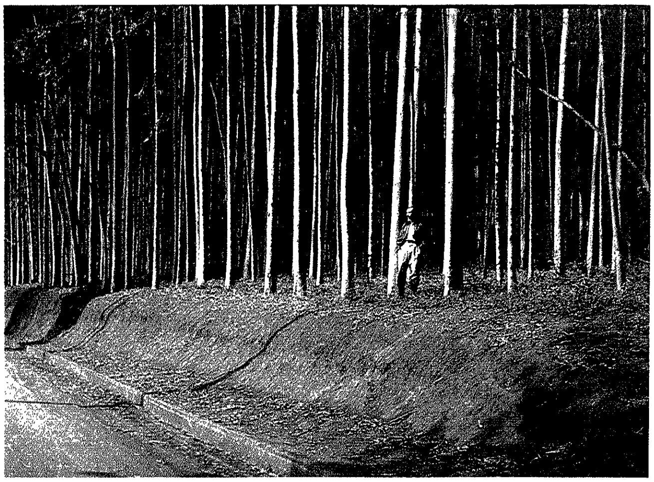


Figure 5–4.—*Eucalypts have been selected widely in tropical America because of their rapid growth and adaptability to degraded soils.*

species grows more than about 2 m in height per year, and most grow much more slowly. However, native African species such as *Daniellia oliveri, Khaya senegalensis,* and *Prosopis africana* struggle through grass and scrub growth in their young stages and withstand some fire damage, which the Asian species could not.

In the dry areas of the Sudan, the only indigenous genera that have produced merchantable timber are *Juniperus* and *Podocarpus,* and both require 150 years to reach maturity (Jackson 1960). On the other hand, exotics such as neem *(Azadirachta)* and *S. siamea* were considered very promising for fuelwood. Similarly, in Ivory Coast, the native species were found to be slow growing, leading to the introduction of exotics (Mensbruge 1968).

By 1957, 110 exotic timber tree species were being tested in what is now Malawi (Willan and McQueen 1959). In 1960, the main trees being used in Uganda were American species, *Cupressus benthami, C. lindleyii, Pinus caribaea,* and *P. patula* (Leuchars 1960). Also being tested were other pines and *Abies religiosa,* also from America. At about the same time, 18 American species were being tested at the Maguga Arboretum, Kenya, including (in addition to those just mentioned) *Araucaria angustifolia, Cedrela odorata, Fraxinus berlanderiana, P. ayacahuite, P. engelmannii, P. leiophylla, P. montezumae, P. occidentalis, P. oocarpa,* and *Prunus salasii* (Howland and Griffith 1962).

In Fiji, indigenous timber species, including the most widespread native conifer, *Agathis vitiensis,* were also found to grow slowly (Cottle 1957, Loweth 1953). Among native species, only *Endospermum macrophyllum* shows promise for plantations; its soft wood is usable chiefly for construction and boxes. Meanwhile, 74 species of greater promise were introduced.

In Suriname, 30 native species were tried, including large plantations of *Carapa* and *Hura;* the conclusion was that generally they do not warrant extensive planting (Schulz and Rodriguez 1966). Growth of these species was slow and tree form was poor. Two exceptions were *Simaruba amara* and *V. surinamensis.* Puerto Rico has had a similar experience, even though more than 100 potential native timber candidates were tested (Wadsworth and Schubert 1977).

Wright (1976) suggests the following reasons natives tend to fare worse than exotics:

- Selection in nature favors survival more than economic traits.
- Evolutionary response lags behind environmental changes.
- Human-caused changes do not produce evolutionary responses.
- Evolutionary possibilities in native flora are limited.
- Native species may be decimated by introduced pests.
- Native species tend to be sensitive to planting shock.
- Natural species distribution may be limited by factors unrelated to performance.

A 1966 survey of trials of rapidly growing trees in tropical countries in the British Commonwealth showed that of 19 "probable species," 3 were from America, *C. odorata, Cordia alliodora,* and *Swietenia macrophylla* (Pitt 1966). Of 28 "possibles," *Araucaria angustifolia, Enterolobium cyclocarpum,* and *Simarouba amara* were from America. Low-density species from America included the following genera: *Bombax, Cecropia, Ceiba, Jacaranda, Ochroma,* and *Trema.*

Wood (1974) pointed out that the area of high forests economically "renewable" under sustained yield in tropical countries is small because the extensive tending and long rotations that were practical in the past are now of questionable feasibility. He concluded that except for a few species, such as those of *Terminalia* in west Africa, *Maesopsis* in Uganda, *Cordia* and *Hibiscus* in the Caribbean, and *Tectona grandis* in southern and southeastern Asia, indigenous trees grow too slowly, a drawback that only forest-rich countries can afford. Thus, long-term planning must not exclude exotic species from planting proposals.

The high productivity of eucalypts grown as exotics has been ascribed in part to higher nutrient levels (particularly N and P) abroad than in their native Australia (Pryor 1968a). Escape from the insects of the native environment has also been considered partly responsible. Jacobs (1956) explained that savanna species of eucalypts grow much faster in suitable localities outside Australia than within the country, provided the leaf-eating insects that have evolved with the genus in Australia are not also introduced. Jacobs advised foresters abroad to pay as much attention to the strain of the species introduced from Australia as to the species itself. Expenditures for strain selection and collection from elite trees (verified by testing as being of superior genotypes) within the strain are likely to prove rewarding. He further pointed out that the more rapid growth of the trees overseas may be accompanied by poorer wood quality than is obtained in Australia because growth stresses have not had time to subside. Longer rotations should reduce growth stress.

Baker (1970a) also asserted that the best reason for growing commercial plants outside their native habitat is separation from diseases and pests that have evolved along with them. An analysis of the diseases of *Pinus caribaea* in its native range between 300 and 900 m in elevation in what is now Belize indicated that geographic factors limiting the distribution of these diseases minimize any threat to this tree as an exotic (Etheridge 1968). Among the diseases mentioned are dwarf mistletoe, true mistletoe, needletop necrosis, and progressive dieback.

Species Selection

Champion and Brasnett (1957) pointed out that foresters choosing species to plant on a given site or selecting sites and species for the production of a particular kind of timber need to know about local climates and plant associations so they can explore other similar sites for additional species. If it appears appropriate to test exotic species, foresters will obviously first consider making introductions from homoclimes.

The planting of *P. caribaea* in Misiones, Argentina, showed how taking a species well beyond its natural range can affect productivity (Larguia 1967). At age 6, only 4 percent of the trees had good enough form for future timber. Many were too crooked even for pulpwood. Other defects included excessive foxtail (resulting in storm breakage) and spiral grain.

Where climatic matching has been successful and the source is distant, the time lag for pests and diseases to follow introduced species may be long. As an example, *P. radiata* from California was planted in Australia in about 1877 (Thomas 1957). A dieback was observed 5 years later but caused no concern for more than 30 years, after which planting was suspended for 3 to 4 years. Thereafter, planting continued until 1957, when 38,000 ha were planted. A zinc (Zn) deficiency diagnosed in 1940 was correctable. Browntop was also discovered but could be reduced by adding N and superphosphate. Similarly, the eucalypts brought to Brazil from Australia early in this century, although not entirely disease free, are not yet plagued by the leaf-eating insects common to their native environment. Even if this were to happen, as well it might, few foresters would regret the years of high-performance plantations, and the investment involved should support the research necessary to either solve the problems or develop alternatives.

The ecology of exotics itself seems to arouse interest in their testing. Factors limiting natural distribution are not purely a reflection of species adaptability to climate and soil. Factors responsible for the natural range of a species (Good 1953) usually include: (1) place and time of origin, (2) distribution of climatic limits, (3) distribution of edaphic limits, (4) potential for dispersal, (5) configuration of land and sea, and (6) influences exerted by other plants (direct competition and indirect effects). If the influence of any one of these factors is sufficiently adverse, a species could be excluded from an area where it might otherwise be successfully introduced.

In the exotic plantations of New Zealand, maximum yield is not necessarily obtained only under conditions identical to the species' natural habitat (Jackson 1965). A clear distinction must be made between the ecological and physiological limits of productivity. The importance of this distinction will increase as management intensifies.

When the disease susceptibility of natives and exotics is compared, both must be planted at similar spacings (Harper 1977). It is not valid to compare disease incidence in pure plantings of exotic species with that in widely spaced, uneven-sized, natural stands of native species. Native species, when planted at the same time and spacing, may develop some of the same problems as exotics.

Characteristics To Consider. Two compilations of significant factors in species selection (Fenton and others 1977, Webb and others 1984), taken together, include the following:

- Nomenclature—Preferred scientific name; botanical family; variety, race, or provenance; local and trade names; other scientific names in use
- Natural occurrence—Geographic units, latitude range, altitude range
- Where in use—Managed natural forests versus plantations
  - — Site tolerances—Annual rainfall, rainy period, length of dry season, mean temperature, mean temperature of hottest month, mean temperature of coldest month, light requirement, soil texture, reaction, drainage, salinity
  - — The tree—Size, description, form, utility of wood, utility of other products, utility for nonwood purposes, protective value, ornamental value
  - — The wood—Density, natural durability, preservation, facility of sawing, seasoning, other features
  - — Regeneration—Natural regeneration, seed sources, reproductive phenology, seed weight, seed storage, seed pretreatment, germination rate, germination percentage, direct seeding, coppicing capacity, tree improvement in progress, planting stock, spacing, light requirements, water requirements, shade tolerance, need for root pruning, lifting size, production time, containers, other nursery needs
- Plantation management—Weeding, pruning, thinning
- Yields—Mean annual increment by age.

Information in these categories is presented for many promising tree species in appendix F.

In their classic treatise on the choice of tree species, Champion and Brasnett (1958) focused on the following factors: water requirements, temperature requirements, topographical requirements, light requirements, susceptibility to damage from physical agents and biotic factors, and known extension outside natural range. Other studies (Barnes and Mullin 1976, Jacobs 1981, Moni 1965) have emphasized some additional characteristics: freedom from need for presowing seed treatment, natural regeneration propensity, capacity to colonize bare ground, vigorous root system, resistance to drought and wind damage, capacity for rapid growth, performance as a plantation tree, short rotation length, durability of timber, and versatility of wood. For underplanting, Wood (1974) emphasized the need for species that not only undergo rapid initial growth but also close a canopy quickly, such as those in the genera *Cedrela, Gmelina,* and *Terminalia* do in Africa. Evans (1992) lists characteristics that are helpful in classifying tree species for different end uses (table 5–12).

A wide natural range indicates broad adaptability in tree species (Sahni 1965). *Eucalyptus camaldulensis* is a good example, because it is found in nearly every state in Australia. A notable exception to this rule is *P. radiata,* which is restricted to a small natural range in western North America yet has adapted to a much larger area in the Southern Hemisphere.

The outstanding success of planted eucalypts is attributable to a number of exceptional characteristics of this genus and its nearly 700 species and varieties (Cromer 1956). They are adapted to a wide variety of climates and soils, ranging in latitude from 10° to 43° and in altitude from sea level to 2,100 m. Most withstand fire, regenerate easily from seeds or coppices, and self-prune readily. A wide range of wood properties is also found within the genus; eucalypts make excellent firewood, they are capable of exceptionally high yields, they thrive where there is periodic drought (Pryor 1968), they grow well outside their area of origin, they are highly productive on short rotations and close spacing does not hinder growth, they respond to fertilizer better than conifers, and the large number of species and provenances promises great genetic gains through selection and hybridization. One significant drawback is the high density of

Table 5–12.—Timber production and property requirements by end use

End use	Production requirements	Property requirements
Fuel	Rapid growth, early culmination, easy to grow, economical, coppicing desirable	Quick drying, low ash content, readily burnable with no odor
Pulp	Same as above, but with straight stems	Fiber length, light color, low extractives, papermaking quality
Solid products	Large size, moderate to rapid growth, good form, ease of pruning, freedom from buttrot	Strength, stability, uniformity, good seasoning, working and finishing
Sheet products	Very large size, good natural pruning, rapid occlusion	Figure, peeling or slicing quality, good bonding

Source: Evans 1992.

most species, making sawing and seasoning the wood difficult.

The attributes of *P. caribaea* (Lamb 1973) that make it favorable for planting include ease of seed collection, duration of seeds in storage, ease of germination, rapid early growth, adaptation to degraded sites, adaptation to shallow soils, fine branches, wind resistance, relative freedom from diseases, wide natural variation permitting genetic selection, ease of form improvement in one generation, ease of hybridization, pulpwood quality, and quality of resin. Drawbacks include poor seed crops where winters are moist, lack of frost tolerance, need for container planting, lack of competitiveness with climbers, presence of compression wood in young crooked trees, and weakness of the central wood core of rapidly growing trees.

The foxtailing (terminal hypertrophy) of pines may be an indicator of both adaptability and productivity (Kozlowski and Greathouse 1970, Lanner 1966). Foxtails are pines that do not stop growing, make no rings, and produce no lateral buds until eventually, after a long stem has formed, moisture stress slows growth and terminates the phenomenon (fig. 5–5). Some 12 species are reported to produce foxtails, including *P. caribaea, P. kesiya, P. merkusii, P. oocarpa,* and *P. tropicalis.* Within Belize, the home range of *P. caribaea,* foxtailing occurs on 1 to 2 percent of the trees, with a tendency to increase with elevation and fertility (Abell 1969). Foxtailing is said to be strongly inherited (Kozlowski and Greathouse 1970), but there is also marked climatic influence. In the uniformly moist climate of Misiones, Argentina, 80 percent of the pines are foxtails (Lanner 1972). Foxtailing has been reduced in Australia by strategic selection of phenotypes and progeny.

Other potential coniferous genera for the Tropics are listed in appendix G (Weck 1963).

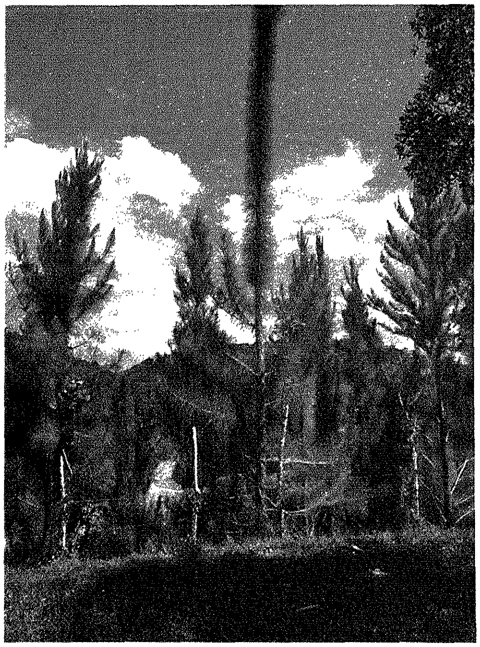


Figure 5–5.—*Pine foxtails, although characteristic of vigorous, fast-growing trees, are generally perceived as abnormal and eliminated in early thinning.*

Nitrogen-fixing species might appear to be superior on poor soils. For example, a 13-year-old plantation of *Casuarina equisetifolia* on a sand dune in the Cape Verde Islands (Dommergues 1963) produced 58 kg/ha of N per year. However, about the same accretion of N, 50 kg/ha/yr, has been found in plantations of *P. radiata* in Australia; this is two to three times what might be expected of a species not considered an N-fixer (Richards 1964). For this amount of N to be produced, other known fixation agents would have to be greatly stimulated. Whatever the process, this characteristic makes pines even more desirable than other species in tropical areas.

Golfari (1961, 1968a, 1981) has found details of climate to be highly significant in determining the adaptability of coniferous species in South America. In addition to the mean temperature, the forester should consider monthly temperature means, temperature extremes, the distribution of precipitation, relative humidity, and illumination. Likewise, the soil texture, pH, porosity, and depth to water table will affect species suitability. Golfari classifies species by their adaptation to winter or summer rainfall, moisture deficit, and temperature difference between winter and summer, and their thermal efficiency (*P. patula,* cool; *P. caribaea,* warm) and minimum limiting temperature (degree of frost resistance). He uses survival and the rate of height growth as measures of adaptability.

Golfari (1963) concluded that all conifers fall into one of three major groups regarding adaptation to rainfall distribution, those requiring: (1) moisture mostly in the winter and capable of withstanding summer drought, (2) moisture uniformly distributed throughout the year, and (3) moisture in the summer and capable of withstanding dry winters. These three rainfall patterns were recognized as significant to vegetation some 30 years earlier (Troup 1932).

Golfari (1978a) and Golfari and others (1978) derived further guidance in tree selection from the performance of different species already established on a variety of sites. Their conclusions, which follow, should apply universally:

- Early height growth is a good indicator of adaptation of species to a site.
- Uniform growth of individual trees denotes favorable conditions.
- Self-pruning is a sign of a favorable site.
- Susceptibility to insects and diseases is minimal on sites to which trees are well adapted.
- Water deficit (derived after Thornthwaite and Hare 1955) is of great importance in identifying homoclimes.

The significance of winter/summer rainfall to species adaptability is reported to be similar for *Eucalyptus* (Pryor 1972b). Trials of *Eucalyptus* offsite show that species from winter rainfall zones fail in summer rainfall zones, although the reverse is not true. Species in the monocalyptus (a taxonomic subgroup including the stringybarks, ashes, and peppermints) group, including the major timber-producing *Eucalyptus* species of Australia, are less apt to adapt elsewhere than others. Species known to be naturally limited by fire can, if protected from fire, be extended into sites adjoining where they occur naturally.

Tree productivity per unit of area is related to crown shape (Ashton 1978a). Many-layered crowns with single, central stems produce more per unit of area than broadly hemispherical, multistemmed, single-layered crowns. This finding confirms Dawkins' (1964a) recognition of the advantage of trees that grow well with a small crown-diameter-to-d.b.h. ratio. This advantage (seen by both Ashton and Dawkins to be affected by tree age) also differs among species. Dawkins (1964a) notes that all high-yielding conifers and eucalypts are small crowned, with crown-diameter-to-d.b.h. ratios less than 15, and less than 10 in *E. saligna*.

Characteristics of no silvicultural significance may dictate species preference. In the Brazilian states from Sao Paulo to Rio Grande do Sul, most recent plantations are coniferous, whereas in Minas Gerais and Espiritu Santo, eucalypts have chiefly been used (Golfari 1970b). The state of Sao Paulo has been the most heavily planted with eucalypts in the past, but they have been found to be inferior to pines for paper because their wood is dark and requires more bleaching. Also, the sawmills in Brazil are not yet accepting much *Eucalyptus* wood. A change in this trend is foreseen, as happened in Australia (Golfari 1975b).

Currently, eucalypts and pines are the species most commonly used in tropical timber plantations (Evans 1992); together, they account for 72 percent of all plantation area (table 5–13).

Table 5–13.—Species composition of tropical timber plantations

Species group	Percentage of plantation area
Eucalyptus spp.	38
Pinus spp.	34
Tectona grandis	14
Other nonconiferous spp.	11
Other coniferous spp.	3
Total	**100**

Source: Evans 1992.

Preplanting Site Analysis. The numerous spectacular examples of highly productive plantations of either native or exotic timber tree species have resulted either from "luck" (sometimes a euphemism for expensive trial-and-error) or, less commonly, from carefully analyzed matching of species tolerances to site conditions. Usually, an extensive, time-consuming period of trials involving not only many species but also their varieties and provenances (seed sources) is required (Baur 1964a).

Even within the limits of individual planting areas, sites may vary enough to call for a variety of tree species. And even within large genera such as *Eucalyptus,* judicious selection of species and provenances may be critical. Selections are usually based on natural ranges and corresponding climatic limits or on proved adaptability to altered environments (Cromer 1956).

The results of broadscale species trials are highlighted by experience in Puerto Rico (Wadsworth and Schubert 1977). Of more than 400 tree species introduced there since 1922, only 25 are currently in use or show promise for timber production. Between 1924 and 1946, 9,000 ha of public forest lands were planted with 131 tree species, but these plantations were only 60 percent stocked by the end of that period, even including acceptable natural regeneration. Of the promising species, 17 were introduced (Marrero 1948, 1950). These results indicate an urgent need to recognize the degraded nature of many planting sites, a factor that may transcend climatic matching in selecting species (Marrero 1950a).

Holdridge's life zones (Holdridge 1967) can be used for first approximations of homoclimes and the species native to each. A study covering central and northern South America (Falla 1968) grouped species by their gross climatic tolerances (table 5–14). It is apparent, however, that some species that are grouped together are not natural associates. This discrepancy may result only from the annual total, not from the season of rainfall, being considered.

The sites on which trees grow fastest may or may not be the most productive in terms of quality. An analysis of *P. caribaea* productivity in Queensland, Australia, (Smith, W.J., 1973) indicated that rapid growth was accompanied by a reduction in density (table 5–15), a property that could be significant for solid wood or sheet products. For cellulose production, the only disadvantage would be slightly larger bulk. Futhermore, the greater gross dry weight on the good sites may more than compensate for this disadvantage where fiber is the end product.

Seasonality of rainfall is an essential criterion in selecting trees for planting in South America. In Venezuela, Veillon (1960), after determining elevation homoclimates for pines, used monthly rainfall patterns for final matching of species to site. Golfari has used this guide extensively in selecting species and sites for Misiones Province in Argentina, for Brazil, and for tropical America as a whole (Golfari 1961, 1963, 1965, 1967, 1975c; Golfari and Barrett 1967).

Golfari's studies probably have been of greatest value in local species selection in tropical America. With Thornthwaite's water balance calculations (Thornthwaite and Mather 1957), pines could be selected for subtropical Puerto Piray, Argentina (Golfari and Barrett 1967). Similar predictions using species site maps were completed for many states of Brazil (Golfari 1967). For *P. elliottii,* Golfari (1968–69) measured 186 plantations to make site-index curves based on mean stand height at age 25, which ranged from 11 to 27 m. His water-balance technique was extended to eucalypts as well as conifers and used eventually in the States of Bahia, Espiritu Santo, Goias, Matto Grosso, Minas Gerais, Parana, Rio Grande do Sul, and Santa Catarina (Golfari 1975c, 1978a, 1978b).

Matching species to sites has improved markedly in recent years, thanks to expanding literature. However, visiting source areas to observe the species in their native environments and to obtain unpublished details about them is still generally justifiable. Navarro de Andrade's (1939) visit to Australia led to the subsequent spectacular

Table 5–14.—Tropical tree species adaptation by life zones in central and northern South America

	Lower montane			Montane		
Species	Dry	Moist	Wet	Moist	Wet	Rain
Acacia decurrens		x	x			
Cupressus lusitanica		x	x	x	x	
Eucalyptus globulus	x					
Pinus caribaea		x				
P. elliottii		x				
P. patula	x	x	x			x
P. radiata	x			x	x	
P. taeda		x	x	x	x	

Source: Falla 1968.

tree-planting program in Brazil. Loock's (1950) studies of Mexican and Central American pines and seed collections for South Africa underlie much of the early success with these species in Africa. Golfari's (1961) trips to the southern pinery of the United States (searching for homoclime provenances of *P. elliottii* and *P. taeda* for Celulosa, Argentina) and to Australia and Timor (for Aracruz, Brazil) are additional examples of the value of firsthand observations.

Experience in Puerto Rico has shown that species selection involves more than matching broad classes of climates, soils, and products. Performance of tree species that appear to qualify on all of those counts varies greatly with local topography and particularly with the degree of soil degradation (Marrero 1950a). Certain species grow best on convex topography (well drained), and others on concave topography (humidity retaining). As planting progresses, these differences are certain to influence the selection of species or provenances.

Present vegetation may be a clue to species choice. Lamb (1968c), after wide travels in America, concluded that pines are a safe bet for trials on extensive grasslands in the Amazon, Guyana, Suriname, Central America, Cuba, and the Bahamas. Subsequent experience seems to bear him out. Baur (1964a) also recognized that on the periphery of what may have been a rain forest, the effects of fire may leave the site productive only for *Eucalyptus* or *Pinus*.

Wherever many plantations of the same species have attained advanced age, site-index curves should be developed to classify sites in terms of tree growth. From the curves derived by exponential regressions of height over age, the index of any site can be determined from the age and height of sample trees.

Variation Within Species. Genetic variation within a species may affect productivity as much as variation among species.

Table 5–15.—Site effects on *Pinus caribaea* productivity in Queensland, Australia

Site index[a] (m)	Merchantable volume (m^3/ha)	Dry weight (t/ha)	Basic wood density (g/cm^3)
21–25	200	95	.473
26–30	258	121	.470
31–35	290	132	.454

Source: Smith, W.J. 1973.

[a] Height at 18.5 years.

Ideally, the species-selection process should compare all the variants of each species. Because all variants are not usually known at the outset of species testing, first selections are tentative. Genetic manipulation may improve the variants of any species. This potential should not be overlooked during the initial selection of species and should be continually pursued thereafter. The use of seeds from selected and improved sources may increase growth rates as much as or more than silvicultural techniques (Donald 1979).

Types of morphological variation among eight sources of teak detected early in Java (Coster and Eidmann 1934) included differences at 1 year ranging from early height growth and branching to almost none.

In classifying the pines of Mexico, Martinez (1948) concluded that in addition to 37 species, there were 21 varieties and 8 forms that were morphologically distinct from the typical species. Loock (1950) also recognized 18 varieties and 9 forms. Critchfield and Little (1966) mapped 36 species in Mexico and referred to additional varieties and subspecies that were not adequately reported for mapping.

Within the natural range of *P. caribaea hondurensis* in Belize, variation within species is evident (McWilliams and Richards 1955). Not only are there two geographically distinct populations, one coastal and one montane, but in the mountains, the trees range in form from good on granitic areas to small and misshapen on exposed quartz and shale ridges. A comparison of three nearby provenances of *P. caribaea hondurensis* showed a wide variation in windfirmness and foxtailing and illustrated the importance of careful selection and testing (Evans 1992).

Tests with different provenances of *P. caribaea* at Monte Dourado, Brazil, disclosed significant differences at age 6 in height, diameter, straightness, forking, branch number, branch angle, wood density, volume growth, and cone production (Woessner 1981a). Of 16 provenances, the 4 best outproduced the worst in biomass by 26 percent. Selecting a seed source from Guanaja Istaul, Honduras, instead of Poptun, Guatemala, promised to increase yield 42 t/ha (Woessner 1981a). Foxtailing can also be reduced. Although accentuated by uniform rainfall, it is strongly inherent and may be largely eliminated through selection (Kozlowski and Greathouse 1970). With *Gmelina,* improved straightness and higher wood density appear attainable through selection of provenances.

A need for obtaining seeds from known sources is generally recognized. Tests of *P. kesiya, P. merkusii,* and *P. oocarpa* in South Africa showed highly variable (and generally poor) form from unselected seeds (Marsh 1972).

Selecting the larger seedlings from a single source of *P. elliottii* in a Brazilian nursery had a significant effect on later productivity (Shimizu and others 1977b). Selecting 1 seedling out of 3,500 in the nursery at age 9 months yielded a group of seedlings that maintained height superiority in absolute terms for 3 years.

Variation in *P. oocarpa* led to the recognition of the variety *ochoterenai,* which has been tested separately and, on some sites, found superior in early growth in Argentina (Molfino and Vairetti 1972) and in Ivory Coast (Goudet 1975).

Significant within-species variations have been found in *P. kesiya* and *P. merkusii* in Papua New Guinea (Howcraft and Davidson 1973a, 1973b). *Pinus merkusii* from Cambodian seeds had a grass stage, an early period of apparent dormancy. Trees from two Sumatran sources varied sufficiently in height at 3 years to indicate a need to discriminate among provenances. By 4.2 years, *P. kesiya* from what is now Malagasy had grown to a mean height of 7.6 m versus 5.2 m for trees from a Thai source and 6.3 m for trees from Philippine seeds. The difference in growth between the Malagasy and Thai provenances was highly significant.

Eight regional races of *Araucaria cunninghamii* have been identified within the natural range of the species (Reilly 1974). They differ significantly in growth rate, stem straightness, and tendency to develop multiple leaders and in branch, bark, and needle characteristics.

Pryor (1978) points out some qualities of the eucalypts that offer opportunities for genetic improvement. There are some 450 distinct species and numerous variants. They comprise the arborescent vegetation of more than half of Australia and, to a limited extent, appear in Celebes, the Lesser Sunda Islands, Mindanao, Papua New Guinea, and Timor. The genus reproduces primarily by random outbreeding, depending heavily on insect pollination.

Different provenances of *E. camaldulensis,* one of the most widespread species of Australia, were found highly variable in six locations in Nigeria (Jackson 1973). Provenances from regions with pronounced summer rains grew best for the first 5 years. The highest tree volume averages were triple the lowest.

Golfari's studies (1977) of *Eucalyptus* in Brazil have shown that different introduced provenances may appear and perform like different species. He cites studies of 35 provenances of *E. camaldulensis,* indicating that for the cerrado regions of Goias, Matto Grosso, and Minas Gerais, seeds from certain areas in northern Australia produce trees superior to those from other provenances. In the caatinga region of Rio Grande del Norte, on the other hand, provenances from other parts of Australia with extreme droughts are required. Only one provenance—from Atherton, Queensland—produced trees resistant to the stem canker, *Diaporthe cubensis.* Progeny from Brazil's earliest plantations, which came from provenances south of Sydney (lat. 34° S.), have been found unsuited to the more tropical latitudes of Brazil. Unfortunately, early plantations of different species of *Eucalyptus* in Brazil were located side by side, so that hybridization and unpredictable progeny resulted.

At Aracruz, Brazil, local sources of *E. "alba"* and *E. saligna* proved susceptible to the canker, *D. cubensis* (Evans 1992). *Eucalyptus grandis,* from latitude 26° to 31° S. in Australia, was also susceptible to this pathogen. The problem was solved by using *E. grandis* seeds collected at latitude 17° S. in Queensland, a provenance that so far has proven to be canker resistant.

At Monte Dourado, Para, Brazil, on the Amazon, early results of provenance tests with *E. deglupta* suggested a genetic gain in height growth of at least 30 percent (Woessner 1980a). Success has been achieved in reducing the susceptibility of *Eucalyptus* to canker farther south at Aracruz by using seeds only from sites environmentally similar to the sites being planted (Campinhas and Ikemori 1977).

In 1973, Golfari's findings led to an exemplary program of provenance testing in which plots of 36 species and 406 geographical provenances of *Eucalyptus* and 4 species and 36 geographical provenances of *Pinus* were established on 46 sites in 5 states of central Brazil (Golfari 1978b). Similar trials in Colombia with 44 provenances of *E. grandis,* 11 provenances of *E. viminalis,* 25 provenances of *E. saligna,* and 43 provenances of *E. globulus* are under way; each plot is sufficiently isolated to permit collection of the best seeds to use as improved seed sources (Ladrach 1980).

A notable example of intraspecific variation is that of *Leucaena leucocephala* (Brewbaker 1975, Brewbaker and others 1972, Hutton and Bonner 1960). Yields in Hawaii from four 2-month harvests of four strains showed the following variation by source: Hawaii, 1.5 kg/ha; Guatemala, 5.5; El Salvador, 6.6; and Peru, 12.6. Another test in Hawaii of 90 strains of this species showed marked variation with day length, growth habit, leaf characteristics, pod length, pubescence, number of seeds, ultimate tree size, and mimosine content. What has become Hawaiian Giant K8 *Leucaena* was an arboreal, summer-flowering variant received from Zacatecas, Mexico. It proved to have exceptional vegetative vigor and aggressive arboreal growth with larger leaves, leaflets, flowers, pods, and seeds than common strains. At a spacing of 1.3 m, this variety produced trees averaging 24 cm in d.b.h. and 17 m in height at 6 years of age.

An intermediate form of *Swietenia,* apparently a cross of *S. macrophylla* and *S. mahagoni,* has appeared in many tropical countries where these two species have been grown in close proximity. Tree form is intermediate, growth on dry sites is apparently more rapid than that of *S. mahagoni,* and drought tolerance is superior to that of *S. macrophylla* (Geary and others 1972).

Tree Improvement. Until 1910, silviculture was chiefly concerned with cultural techniques and the favoring of what were thought to be the best phenotypes (Melchior 1969). Since then, the application of genetics—through provenance selection, hybridization, mutation, and polyploidy—has been directed toward increasing timber yields above what is possible purely by silvicultural treatment. In the Tropics, however, the development of different genotypes of tree species suited for planting has hardly begun, despite prospects for gains in yields well beyond the yields of present forests (Namkoong and others 1980). For example, mass selection of *Eucalyptus* in Brazil has shown it possible to nearly double yields (Venkatesh 1976), with yields of more than 100 m^3/ha/yr foreseen. Genetic betterment of pines is to be expected in terms of straightness, fork reduction, and volume and value growth. Increased tolerance of poor sites and resistance to pests and diseases may also be produced through tree breeding.

Burley (1969), Jones (1966), Melchior (1969), and Wright (1976) list steps to be followed in the tree-improvement process once the species has been selected:

1. Conduct provenance trials.
   a. Short-term, results before first thinning, rangewide comparisons
   b. Medium-term (to one-third or one-half of the rotation), early growth performance, form, and wood quality
   c. Long-term, few provenances, one-half or more of the rotation, fruiting, yield comparisons

2. Establish plantations.

3. Rigorously select superior phenotypes from plantations in a uniform environment so that nongenetic effects are minimal.

4. Identify areas for seed production from the best stands.

5. Establish initial seed orchards from grafted, superior stock.

6. Test progeny of trees for performance and wood-quality characteristics also possessed by the parents.

7. Establish progressive seed orchards, selected from step 6.

8. Begin second and later cycles of selection and control.

Provenance trials are conducted to identify as quickly and economically as possible those provenances yielding well-adapted and productive forests (Burley 1969). Productivity may not always mean rapid growth, however. It might mean survival, resistance to adverse environmental factors or pests, wood quality, or seed productivity.

A second objective of provenance trials is to establish local seed-production stands. Seed-production areas are a relatively cheap means of obtaining seeds of known origin almost immediately (Squillace 1970). Good stands of trees are selected and thinned to favor the best ones. Other cultural practices to stimulate seed production may be used. For example, annual applications of NPK fertilizer to *P. elliottii* have significantly increased cone crops in the southeastern United States (Shoulders 1968). Tree selection for seeds should be done by weighting numerically coded traits. The extent of possible genetic gain depends strongly on the degree of genetic variation in the population, the uniformity of the environmental conditions, and the intensity of selection.

Zobel (1972) emphasized the need for concern about the breadth of the genetic base during genetic selection. He pointed out that it is not possible to preserve all natural genotypes; there will be some loss of genetic potential for certain characteristics following selection and breeding. Even 300 distinct clones may not be enough to prevent long-term deterioration of seed production. Nevertheless, Zobel found that careful selection of the traits to be retained need not seriously narrow the genetic base. In fact, a well-planned operation can do the opposite, bringing together distant provenances to establish new combinations. Zobel concluded that the search is not for highly specific clones for each condition, but rather for broad groups of superior combinations that are widely adaptable. He foresaw the development of rapidly growing clones with low nutrient requirements.

Seed orchards are fundamental to progress in genetic tree improvement and should be located on good sites and isolated from pollen contamination (Zobel and others 1958). For pines, isolation of at least 150 m is desirable. The selection of scions for use in seed orchards should consider the following factors (Zobel and others 1958):

- Especially suitable wood characteristics
- Silviculturally desirable morphological and physiological characteristics
- Growth rates
- Genetically (rather than environmentally) controlled desirable characteristics
- Proved genetic worth (or at least with progeny tests in progress).

Heybroek (1978) noted some difficulties experienced with seed orchards. Many tree families fail to produce enough male or female flowers. Thus, the yield of saw may come from a few individuals, defeating the plan for a broad genetic base. Heybroek saw an inherent antagonism between seed production and vegetative growth. He believed production of the bulk of the seeds in orchards by a few clones should be minimized in the selection of the climate, soil, and cultural practices for the orchards. Another danger lies in the gradual selection of the best clones at the expense of diversity. This he saw as leading toward the planting of large areas with trees of minimum genetic variations. Haybroek reported few firm data indicating a greater difference in production from genetic variation than from genetic uniformity. But he speculated that a mixture might produce more because of varied resistance to the vicissitudes of climate and other factors.

Eighteen provenances of *Swietenia* were collected from Mexico to Panama by the Institute of Tropical Forestry in Puerto Rico from 1966 to 1967. A gene bank has been established and adaptability tests conducted in Puerto Rico and the U.S. Virgin Islands.

The spectacular growth of *Eucalyptus* at Aracruz, Brazil, resulted from the careful testing of more than 1,000 provenances of 37 species (Kalish 1979a). Based on 12 criteria, including an underbark volume of at least 1 m^3 solid at 7 years, foresters selected 1,500 superior trees from among 20 million of the oldest trees.

By 1972, provenance trials of many pines were under way in different tropical countries (Wood 1972). So far it has been found that, generally, the best provenance of *P. oocarpa* is the *ochoterenai* variety from Honduras, that the best *P. merkusii* is from the islands, not the mainland *(P. merkusiana),* and the best *P. kesiya* is generally from Vietnam provenances, not the Philippines. Teak trials promise better provenances for high altitudes and dry zones.

By 1974, provenance trials of 10 major tree species were being internationally coordinated (Wood 1974). Included were 30 provenances of *P. caribaea,* 25 of *P. oocarpa,* 21 of *P. kesiya,* 11 of *P. merkusii,* and 10 of *Cedrela odorata.* Other species included *E. deglupta, E. grandis,* and *Tectona grandis.* The *P. caribaea* provenances, collected and coordinated by the United Kingdom in cooperation with the Food and Agriculture Organization, included 22 provenances in Central America from Belize to Nicaragua, 7 from Cuba, and 1 from Andros Island in the Bahamas (Kemp 1973a). Shortly thereafter, under the same auspices, 25 provenances of *P. oocarpa* were collected from Belize to Nicaragua. Thirty tropical countries participated in the resulting provenance studies (Kemp 1973b).

The urgency of collecting germplasm before deforestation wipes it out is paramount in tropical countries (Kemp 1978, Wood 1976). Some valuable species have already become scarce. For example, few seed sources of *Taiwania* remain (Hung 1969). Kemp saw a particularly serious prospect in rain forests where so many species are affected. Forest reserves are not an entirely satisfactory solution either because they cannot possibly contain all variants. Also, as Kemp pointed out, if reserves are used for multiple purposes, even with stable protection, not all species are favored.

Assessments of the international *P. caribaea* and *P. oocarpa* provenance trials are beginning to show some constant relations (Greaves 1980, 1981b). The *P. caribaea* results come from 205 assessments of 113 trials in 26 countries, and the *P. oocarpa* results are from 166 assessments of 77 trials in 24 countries. A year after planting, evident in *P. oocarpa* were provenance variations that affect choice of seed source and plantation management. For *P. caribaea,* the appearance of such variations took 3 to 4 years. Trials show that the most vigorous variety of *P. caribaea* is *hondurensis* and that the least is *bahamensis.* But *bahamensis* is best and *hondurensis* worst in stem and crown form and resistance to frost damage. Among the *hondurensis* provenances, those from the lowlands offer best stem and crown form, growth, and windfirmness. Provenances from higher and drier inland localities flower earlier (in 3.5 years) and have fewer foxtails but produce needleless shoots and dieback on lowland equatorial sites. At age 5, the most vigorous and windfirm trees are from the southern coastal regions of Honduras and Nicaragua, but some have extensive foxtailing. For *P. oocarpa,* foxtails were produced only by the provenances from Mountain Pine Ridge, Belize.

Numerous independent provenance tests are under way in different tropical countries. In 1968, a test of 12 provenances of *A. angustifolia* was undertaken in Brazil (Baldanzi and Araujo 1971). By the third year, differences in height growth were becoming apparent. From 1972 to 1976 in Nicaragua, a test of 134 forest species and provenances was undertaken (Evans 1977). Early results suggested that several species may be adapted to different regions for various purposes.

The process of hybridizing selected genotypes holds great promise. The exceptionally high yields of *Eucalyptus* at Aracruz, Brazil, come in part from hybridizing *E. grandis* and *E. urophylla* (Kalish 1979a), a hybrid now used at Jari as well.

Genetically improved trees make intensive management attractive. But trees of great growth potential may tax a site more than less productive, native stands (Wollum and Davey 1975). Thus, these advances in yields may increase the drain on the nutrient resources of the site and possibly affect succeeding crops.

A well-planned tree-improvement program for Amazonia was proposed by Pitcher (1976). It called initially for elimination trials to screen out all but the best species, followed by performance trials of the best species, and then, a third elimination of the poorer species and provenances. Finally tree-improvement efforts, based on the results of these trials, would be directed toward: (1) increasing growth rates, (2) improving form and quality, and (3) determining heritability of characteristics of economic value or for future genetic improvement.

Pitcher favored "plus-tree" (phenotype judged superior in some quality) selection for the few species that have been planted in Amazonia in areas larger than 50 ha but convincingly argued against attempting to make such selections in native forests. One of his most telling points was the variability of growing conditions in natural forests that would confound any attempt to attribute tree superiority to genetic characteristics. He foresaw the greatest genetic gains in nurseries, from mass selection with intensities of 1/1,000 to 1/10,000. He further recommended that tree improvement be concentrated on only a few species, including: *Carapa guianensis, Eucalyptus* spp., *G. arborea, P. caribaea, Platonia insignis, Schefflera morototoni, Schizolobium amazonicum, Terminalia ivorensis,* and *V. surinamensis.*

Tests with open-pollinated *P. taeda* families showed the superiority in volume of selected trees at 20 years, based on selection at 5, 10, and 15 years (Lambeth and others 1983). When the selection was made on height, the best one-third of the trees had a volume superiority of 15 to 18 percent. Selection of only the top three individuals gave a volume superiority of 58 to 64 percent. When the selections were made on the basis of volume instead of height, the superiority for the best one-third of the trees was 16 to 19 percent and for the best three, 54 to 102 percent. Selections made at age 5 were generally as effective as at age 15.

A recent definitive work on tree improvement by Zobel and Talbert (1984) is worldwide in scope but treats the Tropics in detail. It is an extremely useful reference for species or provenance selection and the development of improved races. The concepts developed include advantages and limitations of tree improvement, where and when to attempt tree improvement, and essentials of an improvement program. Chapters deal with provenances, seed sources, and exotics; selection in natural stands and unimproved plantations; selection and breeding for resistance to diseases, insects, and adverse environments; vegetative propagation; wood quality; and the economics of tree improvement.

Planting Progress

Information from reports from around the tropical world and covering the early and recent history of forest planting is presented in appendix H. This account is far from complete but presents significant developments, first from the Eastern Hemisphere, where efforts began, and ending with tropical America.

General reports give some evidence of the relative rates of tree planting in different tropical areas (Anon. 1965c, 1968c, 1993b). What were classified in 1964 as rapidly growing plantations covered 700,000 ha in Brazil and 750,000 ha in Argentina, Chile, and Uruguay combined. In Africa, there were 710,000 ha, and in the Asia-Pacific region, 1,650,000 ha. Of the tropical total, 25 percent were coniferous, chiefly *A. angustifolia, P. patula,* and *P. radiata.* Among the broadleafs, *Eucalyptus* covered 1.3 million ha, and *Tectona grandis,* 1 million ha. Establishment rates for fast-growing plantations in 1965 were estimated to be 150,000 ha/yr in Latin America, 120,000 ha/yr in the Asia-Pacific region, and 50,000 ha/yr in Africa (Anon. 1965f).

Incentives provided for planting in the Tropics in 1968 included credit, tax exemption, tax reduction, technical assistance, cheap planting stock, and the formation of cooperatives. Difficulties included inadequate public support, weak forest departments, lack of planning, insufficient seed supply, and inadequate knowledge of species and provenances.

By 1990, 8.6 million ha in tropical America were devoted to plantations (table 5–16; Anon. 1993b), only about 0.5 percent of the total land area. About 373,000 ha are planted annually in tropical America, only 4 percent of the area already planted. Because replanting is included, probably less than half of this amount constitutes a net increase in the plantation area.

The plantation area is about equally divided between industrial and nonindustrial (the farmer producing

Table 5–16.—Forest plantations in the Tropics, 1990 (thousand ha)

Country	National land area	Existing plantations	Annual planting rate[a] 1980–90
Belize	2,280	3	0.1
Bolivia	108,438	40	1.4
Brazil	845,651	7,000	279.2
Colombia	103,870	180	12.7
Costa Rica	5,106	40	3.7
Cuba	10,982	350	19.3
Dominican Republic	4,838	10	0.4
Ecuador	27,684	64	2.1
El Salvador	2,085	6	0.5
Guatemala	10,843	40	2.5
Guyana	19,685	12	1.1
French Guiana	8,815	0	0.0
Haiti	2,756	12	1.1
Honduras	11,189	4	0.4
Jamaica	1,083	21	0.8
Mexico	190,869	155	7.5
Nicaragua	11,875	20	1.8
Panama	7,599	9	0.5
Paraguay	39,730	13	1.0
Peru	128,000	263	12.6
Suriname	15,600	12	0.4
Trinidad/Tobago	513	18	0.2
Venezuela	88,205	362	23.8
Total America	**1,650,147**	**8,636**	**373.0**
Africa	2,236,063	3,000	129.5
Asia-Pacific	892,137	32,153	2,104.1
Grand Total	**4,778,347**	**43,789**	**2,606.5**

Source: Anon. 1993a.

[a] Plantations planted per year.

timber, fuelwood, rural poles and posts, nonwood products such as palm hearts and forest tree fruits, and soil protection) (Lanly 1981; table 5–17). Rubber, palm oil, coconut, and agricultural shade plantings and fruit orchards are excluded.

Most of the industrial plantations are coniferous, whereas nonindustrial plantations are mostly fast-growing, broadleaf species. The planting rate, overall, is about one-eighth of the area deforested each year (Anon. 1993b).

Known and estimated planted areas in tropical America for the major species, up to 1980, are shown in table 5–18 (Panday 1983). Evans (1986) summarized the progress of forest planting between 1978 and 1985 as follows:

- Probably more than 1 million ha are planted per year.
- Most new plantations are for social and environmental rather than industrial purposes.

Table 5–17.—Plantation establishment in tropical America, 1985 (thousand ha)

Purpose and species	Planted area, 1985
Industrial	
Broadleaf	3,979
Fast-growing species[a]	1,393
Other[b]	183
Nonindustrial	
Broadleaf	3,314
Fast-growing species[a]	2,619
Other[b]	613
Conifers	82
Total	**7,293**

Source: Lanly 1981.

[a] Mean annual increment more than 12 m^3/ha/yr.

[b] Mean annual increment less than 12 m^3/ha/yr.

Table 5–18.—Planted areas in tropical America by species, 1980 (thousand ha)

	Planted Areas	
Species	Known	Estimated
Eucalyptus saligna	674	702
Pinus elliottii	281	281
P. patula	199	199
E. grandis	189	192
P. caribaea	137	337
E. globulus	118	131
Gmelina arborea	76	86
Cupressus lusitanica	26	48
Casuarina equisetifolia	20	20
Others	93	775
Total	**1,813**	**2,771**

Source: Panday 1983.

- Arid-zone planting for fodder, firewood, and fencing has greatly increased.

- New planting must continue to increase, with emphasis on social objectives if increasing hardships among the rural poor are to be avoided.

The recent rate of reforestation will clearly not offset deforestation (table 5–19; Anon. 1985f). An overall planting rate one-tenth the rate of deforestation might be adequate to sustain timber yields because of the much higher production rates for successful plantations. However, the planting rate is far below 10 percent of the deforestation rate in nearly all countries, and the plantations, generally monocultures of exotics, whatever their industrial potential, are, in the ecological sense, no tradeoff for the loss of primary ecosystems (table 5–19).

Tropical forest planting has nevertheless increased rapidly since the 1940s, with more than 60 percent of the plantations established during the 1970s (Brown and others 1986). The total biomass of the plantations at that time was estimated to be between 650 million and 2.22 billion t and constituted an atmospheric C sink of between 30 and 110 million t/yr, possibly adequate to balance the C released from harvesting forests and other land uses in the Temperate Zone (Brown and others 1986).

Table 5–19.—Planting rate relative to major deforestation in tropical America, 1980–90 (thousand ha)

Country	Annual deforestation	Annual forest planting
Bolivia	625	1.4
Brazil	3,680	279.2
Colombia	367	12.7
Costa Rica	50	3.7
Ecuador	238	2.1
Guatemala	81	2.5
Honduras	112	0.4
Mexico	678	7.5
Nicaragua	124	1.8
Paraguay	402	1.0
Peru	271	12.6
Venezuela	599	23.8

Source: Anon. 1993c

Chapter 6
Tree Propagation and Planting

Much has been written about seed handling, propagation, and nursery practices for tropical trees. Significant contributions are included in appendix F and the bibliography. These processes are dynamic, changing with new species, materials, and ideas. Practices among projects or nurseries vary greatly because of different levels of ingenuity among nursery workers and, more particularly, because of lack of communication. Early planting efforts emphasized the use of bareroot stock. Excessive field mortality then led to the use of containers for eucalypts and pines. And now, because of the high cost of container use, there is an attempt to revert to bareroot planting, with more care given to the selection of weather conditions and to the planting technique.

This chapter is not intended to be a comprehensive guide to the propagation of the many potential timber species of the Tropics. Instead, the reader is referred to numerous excellent sources of information. Then, under each phase of the operation, typical or unusual findings are described as indicators of what to expect under local conditions (fig. 6–1).


Figure 6–1.—*Large-scale reforestation with industrial plantations, a long-term objective in southern Brazil.*

Plantation Planning

Most countries in tropical America have already expressed interest in forests through preambles to legislation or national policy statements. These statements recognize the benefits natural forests and plantations offer: soil conservation, watershed protection, wildlife preservation, and wood production. The first step toward creating these forests, the assessment of resource potentials, and the decisions as to where, when, and how to achieve these potentials are the function of national resource planning.

The Resource Planning Process. National planning rests heavily on the following kinds of information about the region's physical environment:

1. Planimetric maps of entire countries, accurate and up-to-date, and on a scale that is large enough to display major natural features in some detail
2. Topographic maps of countries on a scale and at contour interval adequate to locate watersheds and slope classes that indicate desirable limits of land-use intensity
3. Soil maps with adequate details and descriptions to distinguish, on the basis of soil stability, depth, and productivity potential, those areas most appropriate for food, forage, productive forest, and protective forest for soil, water, and biodiversity
4. Prospective water requirements and the location and extent of principal surface and subsurface water resources and reservoir sites
5. The location of present and potential flood hazard areas and the extent of foreseeable damage to irrigation works, prime croplands, and urban, commercial, and industrial infrastructures
6. Rainfall data, including long-term records and storm intensities
7. Recent aerial photographs with stereo overlap adequate for mapping forest cover and, if possible, major forest types, both commercial and noncommercial
8. Current and prospective national rates of timber drain, deforestation, and reforestation; imports and exports of forest products; and internal consumption trends
9. Productivity of existing forest plantations of different tree species on a variety of sites within the country or under similar conditions elsewhere.

In most areas of the region, enough of these resource data are available so that planning can proceed reliably.

In some areas, the information is stored in computerized geographic information systems (GIS). The following steps should lead to the selection of the land most in need of forest planting:

- A single map scale should be chosen to display and synthesize relevant aspects of site assessment and selection.
- Slope classes should be identified so as to tentatively delineate those areas that (1) are suited for mechanized agriculture, (2) may be clean-tilled continuously or periodically, (3) require permanent vegetative cover, (4) may be pastured continuously, (5) should be kept tree-covered, (6) may be logged feasibly, or (7) should be left unmodified to protect soil, water, or genetic resources.
- Information on soil groups or types may be added as more precise criteria become available for defining safe limits for land-use intensity within slope classes. Potential productivity of various agriculture and forestry activities is particularly important.
- Areas that provide critical water resources and their tributary watersheds can be located as a supplementary constraint on intensity of land use.
- These data can be synthesized to generate a provisional map of forest lands of the nation, showing all the areas that should be forested for any of the several resource values forest cover could contribute. Priorities for the maintenance of forest cover should be governed by slope, soil type, water resources, or unusual ecosystems.
- National (and possibly export) wood requirement target dates should be established far enough in the future to permit a realistic local production goal one tree rotation hence, predicted from current trends.
- Experience with forest and plantation productivity can be used to locate land areas able to meet production goals.
- Priority should be set for proposed forest plantations on the basis of the land's potential productivity and present land use (its availability, adequacy of vegetative cover, potential for adequate alternative natural regeneration, and ease of planting).

An analysis such as this commonly identifies more deforested, operable land than is needed to meet wood-production goals. The most productive sites should be selected for intensive management as either natural forests or timber plantations. The remainder can be allowed to reforest naturally, except where severe erosion or watershed problems may require rapid development of a protective cover.

Wood production may be less economically competitive than even intermittent food and forage production, partly because of the cost of transporting large volumes of bulky material. This problem, however, may be mitigated by concentrating wood production in areas where processing facilities either exist or can be established advantageously. Studies in Mexico led to the conclusion that no commercial timber plantation should be located more than 75 km from a processing plant (Gonzalez Navarro 1978a). Under these circumstances, a continuous source of wood, taken together with the value added in primary and secondary processing, may outstrip land values for agriculture, particularly those that are marginal.

The best sites for timber production may already be covered with natural forests. If inventories show these to be adequate for future crops, planting should be unnecessary. Otherwise, underplanting may be indicated, beginning with the best sites (or sites with the poorest stands, under the assumption that, in the meantime, stocking may become adequate naturally on sites where it is already better than the poorest stands).

A common problem is the lack of a clear distinction between good forest land and land that is considered marginal for agriculture, particularly pasturing. Where possible, clear distinctions should be made, and forest crops should be assigned to the best land that is clearly not suited for agriculture. On marginal land not designated as such, forest crops might at any time be destroyed by even ephemeral farming; therefore, their contribution to national wood requirements is doubtful. In these areas, a mixed practice—the production of food, forage, and fiber crops in some harmonious combination, either concurrently or sequentially—may seem most appropriate. How much wood such practices might supply beyond strictly local requirements will depend upon the number and the quality of the trees in the mixture. Based on these general principles, Lupatelli (1978) derived eight land-capability classes for Brazil (table 6–1).

Table 6–1.—Land capability classes for Brazil

Sustainable use	Appropriate land-capability class I	II	III	IV	V	VI	VII	VIII
Cultivation unrestricted	X							
Cultivation with conservation practices								
Simple	X	X						
Complex	X	X	X					
Cultivation infrequent	X	X	X	X				
Forage unrestricted	X	X	X	X	X			
Forage with conservation practices								
Moderate	X	X	X	X	X	X		
Complex	X	X	X	X	X	X	X	
Production forests	X	X	X	X	X	X	X	
Natural vegetation, wildlife	X	X	X	X	X	X	X	X

Source: Lupatelli 1978.

Note: Roman numerals correspond to use classes; these classes are defined differently by different counties, with I being the most versatile class and VIII being the least.

For tropical Brazil (excluding Parana, Rio Grande do Sul, and Santa Catarina), occasional cultivation of crops is the maximum land-use intensity acceptable on 65 percent of the land area (table 6–2). Tree production is permissible on 98 percent of the land.

In combining classes V through VII, the summary does not distinguish between land for forage and land for fiber, suggesting a possible conflict. However, it should not be serious because Brazil's current wood requirements apparently could be met by well-managed plantations on less than 15 percent of the land in these three classes. The fact that most of Brazil, including much of the Amazon Basin, is classified for "occasional cultivated crops" indicates the prospective extent of shifting cultivation or possibly some form of agroforestry, yielding tree crops in combination with other crops.

This planning process may seem irrelevant to a forester instructed to plant some deforested mountainside. However, such instructions often lack a basis in sound planning and, therefore, may be wrong. Sites selected may be too poor for growing usable wood or too inaccessible to harvest it, or they may be capable of adequate natural

Table 6–2.—Land-use areas in tropical Brazil

Sustainable use limit	Capability class	Land area Extent (thousand km^2)	Proportion (%)
Continuous cultivated crops	I–III	640	8
Occasional cultivated crops	IV	4,500	57
Forage or tree production	VII	2,650	33
Native vegetative cover	VIII	130	2

Source: Lupatelli 1978.

Note: Roman numerals correspond to use classes; these classes are defined differently by different counties, with I being the most versatile class and VIII being the least.

reforestation within an acceptable period. Planting instructions may also specify trees that are either not adapted to the site or are unsuitable for prospective markets. Even a superficial review of the planning considerations described may suggest important improvements. Planning is essential to successful planting.

Forest Plantings. Once a planting area has been selected, the rate of planting must be decided. If the purpose is solely to protect soil and water resources, the sooner the project is finished the better. If, on the other hand, sustained timber yields are desired or if techniques must be tested, planting may begin with small experiments and slowly approach the rate of 1/*n*th of the area per year (*"n"* being the number of years for the trees to mature). The result should be a sequence of age classes supporting a sustainable annual harvest at some later date.

The project area should be divided into compartments or "coupes," generally no larger than 1/*n*th of the total area, a single year's planting. To facilitate identification on the ground, compartments should be bounded by stable features, such as streams, ridges, site changes, and permanent roads. These boundaries will be irregular and produce compartments of various areas, but this inconvenience is minor compared to the advantages of boundary identification without the need for monuments or cleared lines.

A system of permanent access roads will be needed to bring crews and equipment to each compartment. This system can serve not only for planting but for later tending and harvesting. In parts of Mexico, such road systems are also the backbone of fire control (Gonzalez Navarro 1978a). Up to 1 km of road may be needed for each 20 ha of forest (Mathus Morales 1978b). Accessibility may be as significant as site quality in planning the different compartments.

Formal training of all planting personnel should benefit operations. All workers should be aware of the local, national, and future significance of the plantings and their products. They should understand how success depends on their personal performance, and they should know the reasons for each operation and the right and wrong ways of carrying it out. Safety measures and safety equipment should be accepted and used. Workers at all levels should participate in planning and setting standards for their work and be offered incentives for performance, including safety. These preliminaries are not frills, and they are as critical in small, remote projects as in any others.

Plantation programs in the Tropics commonly proceed without adequate advance pooling of outside expertise. As a result, practices may vary widely from place to place, even within a single country, for no apparent reason other than lack of communication. Some flexibility and variations are undoubtedly healthy, but the variations are commonly to the detriment of the least informed.

Planting Materials

Wilding Stock. The use of wildings—seedlings already present in existing forests—obviates the cost of both seed procurement and nursery propagation and permits precise coordination between planting-stock acquisition and the planting schedule. Nevertheless, it is not a common practice because wildings of most species are not sufficiently abundant or accessible for their acquisition to be easy. As tropical plantation areas expand, these problems may diminish, but using wildings greatly limits the possibilities of tree improvement through genetic selection, so their use may only be suitable for special conditions.

The lifting of wildings for use as planting material has proved possible with many species. In eastern Nigeria, for example, *Gmelina arborea* wildings were found to be as well suited for planting as for nursery stock, so the nurseries there were closed with a large saving in investment (Anon. 1958c). Wildings of *Tabebuia heterophylla,* an aggressive pioneer species, and of *Swietenia macrophylla* have been used extensively in Puerto Rico. Wildings of dipterocarps have also been used successfully for enrichment planting of hill forests in Malaysia (Gill 1970, Tang and Wadley 1976a).

Terminalia myriocarpa has been successfully regenerated by encouraging wilding production (Das 1937). Felling the forest around mother trees and plowing lines to receive the seeds resulted in a good crop of seedlings. When seedlings reached acceptable size, they were transplanted into gaps in the forest. This practice was considered less expensive than conventional artificial regeneration. Profuse seedling regeneration has also been produced by clearing beneath relic trees of *Cedrelinga catenaeformis* in Peru (Anon. 1985h).

The use of 1-month-old wildings of *Avicennia officinalis* on tidal sites in coastal Pakistan can be successful if lifting is done without root injury (Howlader 1971).

Seed Acquisition. Problems of seed procurement in the Tropics are international. Those described for Asia (Kamra 1973) also seem typical of tropical America. There is a need for large quantities of seeds, for an information system to channel requisitions to the best available sources, and for reliable testing and storage practices. Dependable seed-certification services and trained seed technicians are also needed.

The occurrence of "seed years" for tropical trees has long been recognized but, in most cases, has been neither well explained nor found predictable. As has already been pointed out, flowering and fruiting do not correlate well with weather in many species. Infrequent fruiting has been hypothesized as a response to seed predation by animals. The significance, however, is that for some species, seeds for more than one crop of seedlings may have to be accumulated when abundant seed crops occur.

The season of fruiting is more regular than the occurrence of seed years. The season is critical to collection, because few fruits or seeds are easily collectible after they fall or are viable for long periods thereafter. Mexican conifers illustrate this point (Hinds and Larsen 1961). Pines there are distributed through 12° of latitude, yet the seed collection season lasts only about 2 months.

The "Mysore hybrid" of *Eucalyptus tereticornis* in India flowers twice each year, in May and June and in October and November (Lohani 1978). Studies of *E. grandis* in Uganda (Kingston 1974) showed that flowering and fruiting were not confined to one period of the year. Some trees flowered and fruited far ahead of others.

Casuarina equisetifolia in Orissa and Bombay, India, flowers from February to April and from September to October; fruits ripen in May and June and in November and December (Kesarcodi 1951b, Sharma 1951). In Puerto Rico, this species fruits from January through April and from July through November. The best cone harvest of *Araucaria hunsteinii* in Papua New Guinea occurs during a short period from late September to early October (Havel 1965). In Yangambe, in what was formerly Zaire, some seeds of *Musanga smithii,* a species much like *Cecropia peltata,* are always available, but there the main seedfall occurs from July to September (Kesler 1950).

These are but a few illustrations of seasonal seed-production variability from place to place and by species. Because variation also occurs from year to year, cropping times for one locality are not reliable indicators for another. Therefore, phenological records must be compiled for each species and locality.

The need to select appropriate areas for seed collection was recognized early (Kesarcodi 1951b). Choosing an area with abundant seeds is, of course, one prerequisite. Mexican pine seeds, for example, were found to be more abundant in open, cutover forests than in virgin stands (Hinds and Larsen 1961). However, an equally important consideration is the variation in tree quality from place to place. Even those variations that may merely reflect better sites are of interest because they imply potentialities not ensured elsewhere. Good sites should be nearly free of unhealthy stock. On the other hand, if planting sites are especially adverse, it may be best to collect seeds from similarly adverse sites, because tolerance of such conditions may vary within species.

Selection of superior mother trees (female tree parents) has long been recommended because of the numerous inherited traits affecting the quality and yields of progeny (Kesarcodi 1951b, Tang and Wadley 1976a). For example, seedlings of *S. macrophylla* from plus-tree seeds were found to be superior to those from other parents in diameter, height, and dry weight at 10 months (Zabala 1978).

"Plus" stands have been selected for teak *(Tectona grandis)* seed collection in Papua New Guinea until adequate seed orchards become available (White and Cameron 1965). For a teak stand to be acceptable as plus, it has to be at least 8 years old and have a high percentage of well-formed, vigorous trees with log lengths exceeding 12 m. Where plus stands are not available, better-than-average stands have been thinned to 200 trees per hectare, or as a last resort, average stands are thinned to about 400 trees per hectare.

In Ghana, seeds from some *Cedrela odorata* trees germinated well before the peak of general seedlots (Jones, N., 1968). Therefore, identifying and selecting such mother trees could lead to earlier germination and more uniform seedling crops.

Selection of mother trees that are especially heavy seed bearers offers multiple advantages. Not only do they themselves constitute a good collection source, but if they are also of good quality, their progeny may likewise be both high in quality and prolific seed bearers.

Selection of mother trees for genetic tree improvement must be delayed for the time required for trees to reach the minimum age at which fertile seeds are produced. With the faster growing species, this period may be as short as 2 to 3 years for *Anthocephalus chinensis, Leucaena leucocephala,* and *E. deglupta,*3 to 4 years for *Ochroma lagopus* (Nair 1953), 5 years for *E. tereticornis* (Lohani 1978), and longer for *S. macrophylla.*

Determining the earliest time of seed maturity is critical to both plantation costs and seed quality. The earlier that seeds can be collected, the more likely the possibility of capitalizing on the economics of mass collection directly from the mother trees, establishing the certainty of parentage, and preventing losses to herbivores.

The earliest time for seed collection depends on individual characteristics of each species and thus must be determined locally. With *Cedrela odorata* in Ghana, seeds collected up to a month before the capsules opened had the best germination rate, up to 78 percent (Jones, N., 1968). *Cordia alliodora* seeds in Costa Rica showed good germination when collected 3 weeks before falling (Tschinkel 1967). In India, *O. lagopus* seed capsules have been gathered when they begin to open (Nair 1953).

Collecting seeds of selected quality has become a complex practice in tropical regions, requiring special climbing equipment, segregation of seeds from different mother trees, observance of safety measures, and trained personnel. Care must be taken to avoid damaging mother trees or removing too many branchlets to the detriment of future seed crops.

Seed Processing. The seed-cleaning process varies for each species or species group. The first step is usually separating the seeds from the fruits, followed by air-drying. With *Cedrela, Pinus,* and *Swietenia,* air-drying the cones or fruits releases the seeds without deterioration, provided insects and rodents are excluded. With *Casuarina equisetifolia,* one important problem may be loss of seeds to ants.

Bamboo seeds, because of immediate destruction by birds, rodents, insects, or fungi on the ground, should be shaken onto sheets and treated with pesticides before being dried (Hadfield 1958).

Cleaning very small seeds presents special problems. Seeds of *Eucalyptus* normally are removed from the dried capsules and left impure with fragments of the carpel walls. Small lots of the silky seeds of *O. lagopus* may be placed on a coarse screen over water and ignited to free the seeds (Holdridge 1940b). This practice also may increase germination. *Anthocephalus chinensis* seeds, with 17,000 per gram (Pollard 1969), are usually collected in Sabah as the fruits fall. The fruits are then allowed to soften and are macerated. To extract the seeds, the macerated fruits are rubbed through a coarse screen, pounded in a mortar, and then separated with a fine screen before being air-dried.

Grading of tree seeds in tropical America is in its infancy. Standards of purity and viability are obviously needed. However, there also may be other important criteria such as size. Although tests in India (Venkataramany 1960a) indicated no superiority for large teak seeds, tests in Mexico with *P. pseudostrobus* var. *oaxacana* have shown that seed size affected seedling height, hypocotyl diameter, and cotyledon length (Caballero Deloya and Toral Chacon 1967). These differences proved more pronounced after the second month.

The certification of seeds by a qualified authority is essential for responsible forest plantings. Such certification must specify the species, variety, and provenance, as well as any tree-selection standards used; the date and specific locality of collection; the purity percentage; the moisture content; the number of seeds per unit of weight; and the most recent germination record with date and technique. It must also specify that the seeds are free from diseases and insects, with time and type of any fumigation technique used.

A standard seed-testing procedure that has been used in Malaysia for *P. caribaea* is of general utility (Paul 1972). Five attributes are evaluated: (1) the proportion of apparently full seeds (purity percentage), (2) the number of pure seeds per kilogram (seed weight), (3) the proportion of seeds containing kernels (full seed percentage), (4) the moisture content of pure seeds, and (5) the proportion of seeds that germinates.

Germination tests may be made on blotting paper, absorbent cloth, or a substratum of pure quartz sand of pH 6.0 to 7.0 (Paul 1972). A common sample size is 400 seeds, divided into 4 subsamples of 100 each.

Seed Storage. Because of the variability and uncertainties of seed production, at least enough seeds for next year's planting should be kept in inventory, where possible. Consequently, seed viability must be maintained for at least that period of time. How can that be done? Trials throughout the Tropics have confirmed Temperate Zone findings that temperature and moisture control are crucial to extending seed viability for most species.

Seeds of some tropical trees are capable of long storage life. Records exist of *L. leucocephala* seeds germinating after 99 years, *Albizia lebbek* after 30 years, *O. lagopus* after 24 years (Dent 1942b). Nevertheless, most seeds (particularly those of the humid Tropics) may lose their germinative energy within months.

Evans (1992) made two general points about seed-storage temperatures: (1) near freezing temperature usually prolongs viability, and (2) temperature fluctuations are less favorable than constant temperatures. He quoted Turnbull (1972b) to the effect that naturally dry seeds can withstand high temperatures much better than seeds with high moisture contents. Evans pointed out that seeds of certain pines and eucalypts, dried to a moisture content of 4 to 8 percent, retain viability for many years at temperatures below freezing, but most seeds are stored at 2 to 5 °C.

Anthocephalus chinensis seeds in Sabah generally showed poor germination unless stored for 6 months (Pollard 1969). Seeds that were air-dried, sealed, and stored at 5 to 10 °C retained good viability for 2 years; seeds that were unsealed did not.

Araucaria hunsteinii seeds perished in less than 1 month in the open at ambient temperature (Anon. 1958a, Havel 1965). But when seeds were dried, sealed, and kept at 3 °C, viability of 50 percent persisted up to 12 months. These same storage conditions, plus the use of blotting paper to humidify the seeds, resulted in 50 percent germination after 18 months.

Seeds of *C. equisetifolia* stored in the open in India remained viable no longer than 12 months (Sharma 1951).

In Merida, Venezuela, seeds of *Cedrela odorata* stored at ambient temperature, began losing viability by the 4th month, and all viability was lost by the 10th month (Lamprecht 1956). With open storage at 5 °C, the decline did not begin until after 12 months. When seeds were sealed at ambient temperature, a decline began at 4 to 6 months and only 25 percent germinated after 14 months. Sealed seeds kept at 5 °C retained their initial germination rate up to 14 months. *Cordia alliodora* seeds sealed at 12 to 18 percent moisture content and stored at 5 °C remained 50 percent viable after a year (Tschinkel 1967).

The dipterocarps as a group have relatively perishable seeds. Seeds of two species of *Shorea,* which are normally viable for only 1 week, were stored successfully 3 to 4 weeks by reducing their moisture contents from 40 percent to 20 to 25 percent and by storing them at 16 °C (Tang 1971).

Tests in Nigeria showed that, by reducing temperature to near 0 °C, the viability of seeds of *Khaya grandifoliola* and *K. ivorensis* could be extended from 6 weeks to 3 years, the viability of *Entandrophragma angolense* from 6 weeks to 6 years, and the viability of *Triplochiton schleroxylon* from 4 weeks to 2 years (Olatoye 1967).

Ochroma lagopus seeds, tested in India, were effectively stored up to 18 months when sealed (Nair 1953). Seeds of *P. merkusii,* tested in the Philippines, deteriorated after 3 to 4 months at ambient temperature (Gordon and others 1972). Stored at 2 °C with 6 to 10 percent moisture contents, the seeds remained viable up to 3 years. Applying dry heat for 5 minutes to fresh seeds of *O. lagopus* resulted in the following germination rates: 30 °C, 3 percent; 55 °C, 19 percent; 76 °C, 70 percent; 96 °C, 78 percent; 115 °C, 42 percent; and 135 °C, 1 percent (Vazquez-Yanez 1974). Boiling the seeds of *O. lagopus* not only increased germination but gave better results after storage (table 6–3; Vazquez-Yanes 1974).

Seeds of *Swietenia macrophylla* typically remain viable for about 3 months in the open. At 5 °C, the seeds remain viable for about 1 year. A test in the Philippines showed possible benefits from sealed storage in the ground (Lopez 1938). At 24 days, the germination rate

Table 6–3.—Effects on viability of immersing *Ochroma lagopus* seeds in boiling water

Immersion (seconds)	Storage time (% germination)		
	1 yr.	2 yr.	3 yr.
0	2	6	3
15	84	80	67
120	78	71	64
240	60	64	56
480	57	65	56
960	25	44	38
1,920	5	6	2

Source: Vazquez-Yanes 1974.

was 90 percent, compared with 86 percent in open storage above ground. After 132 days, germination was 72 percent with ground storage versus 4 percent with open storage.

Using a 0.1-percent solution of hydrochloric acid to sterilize *P. caribaea* seeds did not harm seeds immersed up to 20 minutes (Hong and Ivory 1974). A dip of 5 minutes increased germination 6 months later by 20 percent.

Seed Germination Factors. Germination of the seeds of most tropical tree species poses no special problems. Germination begins within a few days after sowing and is soon completed (table 6–4; Barrett 1973). *Leucaena leucocephala* is an exception, however. Because of some hard seeds, germination may not be completed for 1 to 4 years, as indicated by experience in Hawaii (Akamine 1952). Fresh seeds of this species germinated at a 44- to 80-percent rate in 4 months and at 73 to 80 percent in 8 months.

Most *Anthocephalus chinensis* seeds germinate in 4 to 14 days (Pollard 1969). Because of their small size, they should be pressed into wet soil, protected from rain by glass covers, and watered frequently. *Swietenia macrophylla* seeds typically germinate 13 to 27 days after sowing (Araujo 1970). Germination of bamboo seeds generally takes 2 to 6 weeks (Hadfield 1958).

The germination "potential" for most tropical tree species is high, 85 percent or more (Araujo 1970). Nevertheless, mishandling seeds during collection or fumigation, or drying seeds too late can reduce germination drastically. *Pinus merkusii* was reported to have typical seed germination of only about 10 percent (Anon. 1971b). However, improved handling increased this rate to more than 90 percent.

Table 6–4.—Seed germination periods for tree species in Zambia

Species	Germination (days from sowing)
Araucaria cunninghamii	7–19
Callitris spp.	21–57
Casuarina cunninghamiana	10–38
Cryptomeria japonica	20–83
Cunninghamia lanceolata	11–21
Cupressus lusitanica	21–63
Eucalyptus deglupta	19–117
E. grandis	7–54
Pinus elliottii	7–31
P. kesiya	9–46
P. patula	10–45
P. taeda	10–90
Tectona grandis	12–38

Source: Barrett 1973.

Seed dormancy must be understood if germination is to proceed as planned. The following three types of seed dormancy are recognized (Chapman and Allan 1978):

- Exogenous dormancy, related to seedcoat properties (mechanical, physical, or chemical)
- Endogenous dormancy, governed by the embryo or endosperm properties (morphological or physiological)
- Combined dormancy, caused by some combination of the other two.

After-ripening (continued maturation after the seeds leave the tree) is reported for some species. In what is now Sri Lanka, *Tectona grandis* seeds that were 9 months old germinated much sooner than fresh seeds (Fernando 1965); storage up to 18 months increased germination even more (Wood 1968). After-ripening of teak seeds was also reported from India (Gupta and Pattanath 1975). A water-soluble, germination inhibitor in the mesocarp was found to influence seed dormancy. Germination of *L. leucocephala* seeds 4 months after sowing has been as high as 80 percent with seeds 6 months old, compared with 50 percent for fresh seeds (Akamine 1952). However, by 12 months, the two seed groups had similar germination rates. Most other seeds, however, including those of *Cecropia negra* in Venezuela (Lamprecht 1955), can be sown promptly with satisfactory results.

Some shade-intolerant species do not germinate in the dark. One example is *Musanga smithii,* an African counterpart of *Cecropia,* which germinates up to 90 percent in the light (Ardkoesoema and Kamil 1955). Some other shade-intolerant species germinate well in the dark. One such species is *O. lagopus* (Vazquez-Yanes 1974). However, storage temperature is critical for this species. When seeds were subjected for 24 hours to constant temperatures of 16 °C, 26 °C, and 36 °C, *O. lagopus* germination did not exceed 4 percent, with or without light. With 20 hours at 25 °C and 4 hours at 45 °C, germination was 63 to 65 percent, regardless of light. In what is now Belize, observers concluded that, in nature, *O. lagopus* seeds germinate after fires (Stevenson 1940).

Seeds of *A. chinensis* in Costa Rica germinated better under an opaque metal roof than under a clear plastic roof (Gonzalez and Grijpma 1968). Light, temperature, and moisture were presumably all involved, but apparently light is not critical to germination of this species.

Presoaking seeds to stimulate germination is common in tropical areas. Soaking *P. caribaea bahamensis* seeds for 24 to 60 hours reportedly increases germinative energy (Anon. 1972c). Presoaking teak seeds for 48 hours has been practiced in India for a century or more (Laurie 1937). Another technique—daily soaking and drying for 3 weeks or more was also reported to give prompt, high germination (Bannerjee 1942). Another common practice is to soak the seeds 72 hours before sowing (Wood 1968).

Hot water stimulates the germination of some seeds. Germination of the seeds of *Prosopis juliflora* and several species of *Acacia,* for example, is increased by placing the seeds in boiling water and letting them cool to ambient temperature (Chapman and Allan 1978, Chatterji and Mohnot 1968). Soaking at 100 °C for more than an hour proved fatal. Soaking *Paraserianthes falcataria* seeds in water at 38 °C for 10 minutes raised the germination percentage from 36 to 72 (Valencia 1973). Seeds of *L. leucocephala* in India attained 85 percent germination when boiled briefly in water and then left to soak for 24 to 48 hours (Chaturvedi 1981).

Mechanical scarification (abrasion of the seedcoat) stimulates germination of some seeds. When *Prosopis juliflora* seeds, 40 percent of which are classified as hard, were shaken in a bottle two times per second for 15 minutes, their germination rate increased from 60 to 97 percent (Nambiar 1946). Shaking for 5 minutes produced prompt germination of 93 percent.

Tests with *T. grandis* in Thailand (Keiding and others 1966) showed that removal of the exocarps from the fruits by exposure to ants for 1 or 2 weeks accelerated germination. In a test in India, the endocarp was removed by splitting it on four axes with a sharp knife and then applying a fungicide; the result was rapid germination (Dabral 1976). Concurrent tests of nine mechanical treatments for teak seeds, however, gave such inconsistent results that more conclusive studies were recommended (Muttlah 1975).

An American tropical species, *Hernandia sonora,* normally has a germination rate of about 18 percent in 5 months (Anon. 1952l), but if the endocarps are perforated, germination may surpass 80 percent in 2 months.

Scarification with acid (usually concentrated sulfuric acid—H_2SO_4) accelerates germination of hard seeds. Tests with *L. leucocephala* in India gave good results after 20 to 40 minutes of soaking in concentrated sulfuric acid (Ramdeo 1971). Seeds of *Acrocarpus fraxinifolius,* normally with germination as low as 0.3 percent after 18 hours soaking in water, germinated at the rate of 90 percent after a 10-minute treatment in concentrated sulfuric acid (Rai 1976).

Direct Seeding. Sowing seeds directly, either broadcast or concentrated in spots, may cost only one-third to one-half as much as using nursery stock (Thomson 1968). With some species, including many with large seeds, this technique is also preferred because of seedling sensitivity to bareroot transplanting. Examples are *Calophyllum calaba, Hymenaea courbaril,* and *Manilkara bidentata.* Survival may be poor, however. Where seeds are scarce or expensive, broadcasting may be impractical because it tends to produce irregular stocking requiring early thinning of dense clumps.

Direct seeding is much less common than planting in the Tropics. The longer period of weeding required may make it more expensive than planting. Nevertheless, under some conditions, the technique is practical. Tests of *Eucalyptus saligna* in Australia have shown that direct seeding on burned land may produce abundant regeneration (Elliott 1956). Direct seeding of *Senna siamea* in India has been a standard method for establishing this species for fuel and fodder forests, particularly in the wet season (Guiscafre 1961, Prasad 1944b). This species is reputed to be capable of coming up through *Imperata* grass in Malaysia and killing it. *Imperata* grass has also been controlled in the Philippines by direct seeding of *L. leucocephala* (Buenaventura 1958). At the start of the rainy season, the grass has been burned to reduce the loss of tree seeds to rodents. The seeds were then broadcast either by hand or from the air or sown in cleared strips or spots. Brushing was done every 3 to 4 months for the first year and semiannually thereafter. Fire must be kept out for 2 years, after which the trees become fire resistant (Pendleton 1934). In one test of aerial sowing in heavy *Imperata* grass late in the season, 2.5 to 7 seedlings per square meter were found (San Buenaventura and Assidao 1957).

Direct seeding has been common in the arid regions of India. *Prosopis juliflora* has been sown in trenches to establish fuel and fodder plantations (Singh 1951); it has also been successfully established on shifting sands by sowing from the air (Singh 1954). Other species for which direct sowing has been successful include *Acacia auriculiformis, A. catechu, Anacardium occidentale, Azaderachta indica, Bauhinia* spp., and *G. arborea* (Goswami 1957). In a direct sowing of *G. arborea* involving the placing of 2 or 3 seeds on each of 5,200 mounded spots per hectare, survival after 1 year was 72 percent, despite a yearly rainfall of only 140 cm (Sabado and Asuncion 1970).

Direct seeding of *E. citriodora* and *E. saligna* is successful in Zambia only under certain conditions (Endean 1966). Seeding must be early in the rainy season, and a hot burn should precede sowing, followed by complete cultivation of seed spots. In Africa, *Cedrela odorata* produces adequate early height growth when direct seeded in cleared lines (Lamb 1969b).

In the Western Hemisphere, in addition to *Calophyllum* spp., *G. arborea* is direct seeded in Brazil and *O. lagopus* in Ecuador. In the latter case, seed spots are surrounded by plastic sheets for early weed control. Direct sowing of *Cupressus lusitanica* has also been successful on well-cleared, wet sites (Holdridge 1953). Direct sowings of *S. mahagoni* failed in dry forests of Puerto Rico because of extreme droughts that killed seedlings even in their second year. Direct seeding of *P. elliottii* in the southern United States requires burning the vegetation or disking the soil (Mann 1958). At Monte Dourado, Brazil, after years of planting *G. arborea* nursery stock on a large scale, the appearance of abundant natural regeneration from seedfall beneath the plantations led to direct seeding as a standard practice on all sites that had been burned (Woessner 1980a). By 1980, direct seeding had been successful on an area of 1,500 ha, with two seeds sown per spot.

The longer period of weeding generally required by direct seeding limits its use, even with species that otherwise are well suited for the technique. An example is seen in Colombia, where direct-seeded *C. lusitanica* and *P. patula* both survived well. But the cost of weeding made direct seeding more expensive than planting (Gutierrez and Ladrach 1978).

The future of direct seeding seems to depend on inexpensive control of competing vegetation and pests. As repellents are improved, direct seeding in the Tropics may be more widely practiced (Stuart Smith 1968).

Tree Nurseries. Where the use of neither wildings nor direct seeding is feasible, nurseries are required. These may vary from a few simple beds, used temporarily, to highly organized and technically advanced permanent operations. A few of the major considerations are detailed here. A technical guide for nursery management was published by Liegel and Venator (1988).

An ideal nursery site should (1) be near planting sites, (2) be accessible to both transportation and a labor supply, (3) have a continuous supply of good-quality water, and (4) have access to a well-drained, workable soil, either for direct rooting of stock or as a potting medium (fig. 6–2). The nursery site should be large enough to accommodate present and anticipated production. Within the nursery site, enough secure storage space for seeds, tools, and equipment is required. Generally, a partially shaded area protected from rainfall is needed for germination and early seedling development.

Timing is essential to tropical nursery management. Nursery operations must be scheduled to meet the dates when planting is proposed. If the planting season is

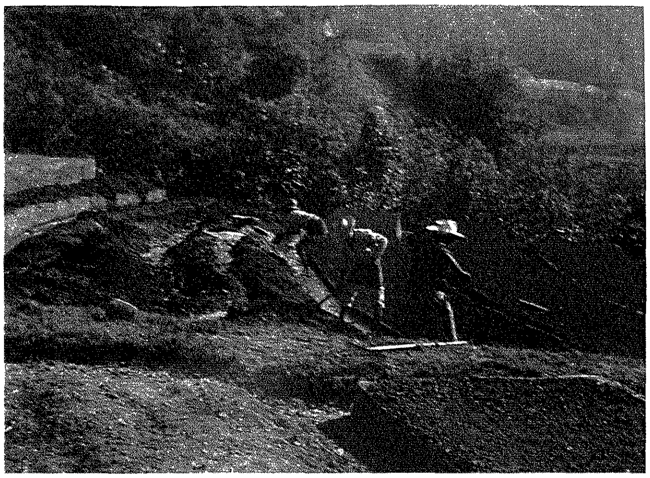


Figure 6–2.—*A typical small field nursery being prepared in Guatemala.*

several months long, a continuous flow of maturing stock will be needed throughout that period, requiring that all preceding steps be planned accordingly. Timing considerations in nursery operations include the following:

- The maximum length of the safe planting season for each tree species, scheduling planting according to when conditions may be favorable at different sites
- The period of production from sowing to lifting, together with variations possible through the use of stimulants such as pregermination seed treatment, the use of seedlings as substitutes for transplants, direct sowing in containers, soil enrichment, and the largest-to-smallest stock sizes that are safe
- Storage of seeds from seedfall to the sowing period
- Advance seed procurement, either from local or distant sources

Once these time-dependent steps are scheduled, less seasonal tasks, such as soil preparation and procurement of supplies and facilities, can be concentrated during slack periods. Timing also may be influenced by the seasonal availability of farm laborers.

Vegetative Propagation

The use of vegetative material rather than seeds for tree propagation is advantageous under some circumstances. In Ghana, it proved the only way to propagate *Triplochiton scleroxylon* during years of irregular seed crops (Nkansah-Kyere 1970). The height growth of cuttings rooted with hormones proved equal to the height growth of stumps or saplings during at least the first 4 years.

Vegetative propagation is relied on most commonly to control the genetic characteristics of propagules. Because the resemblance between ramets and ortets is likely to be greater than the resemblance between seedling progenies and parents, vegetative propagation increases the potential for genetic improvement of trees (Squillace 1970).

Because of this greater resemblance to the parents, trees produced from vegetative (nonsexual) propagation may differ from seedlings. For example, *P. radiata* from cuttings in Australia grew faster in height through 8 years than *P. radiata* from seeds (Fielding 1970). The cuttings also had thinner bark, less taper in the lower part of the bole, crowns that were less dense, and thicker and heavier roots. These differences were attributed to a carryover of the properties associated with the age of the parent tree or the developmental stage of the shoot. In the United States, 12-year-old *P. elliottii* trees produced from air layers did not differ significantly from trees grown from seedlings in terms of shoot growth and root surface area, but they lacked taproots (Schultz 1972).

Many tropical tree species have been reproduced vegetatively, providing great opportunities for genetic tree improvement. As early as 1953, 74 species were reported in India to reproduce by cuttings, 104 by root suckers, 11 by air layering (inducing root development on a plant's aerial portion), and 9 by budding and grafting (Rao 1953).

Under favorable conditions, vegetative propagation can be sufficiently successful for mass production of *Eucalyptus, Triplochiton,* and many other tropical genera (Heybroek 1978). All trees seem to have a juvenile stage during which they are easier to root than later. Clones of identical genetic characteristics have been developed as a result of large-scale vegetative propagation of eucalypts.

Leakey (1987) feared that clonal forestry could give rise to large, biologically uniform stands at risk to pests, diseases, and other hazards. He advocated retaining genetic diversity by using large numbers of clones to reduce risks. By continually producing new genotypes, diversity may in fact be more effectively maintained than in a seed stand/seed orchard. Leakey foresaw the selection of single-purpose clones of multipurpose, agroforestry species.

Stem and Root Cuttings. The first attempts to propagate trees vegetatively were usually by cuttings (sections of small branches) placed in the soil and kept well watered. Successful rooting of *Ceiba pentandra* by this method was reported early from the Philippines (Pacumbaba 1939–40). Roots of *Cedrela odorata* were struck from cuttings 5 to 15 cm in diameter driven into the ground (Castro 1951). Yet, tests in Ghana showed the rooting of cuttings from 9-year-old trees of this species to be unreliable even when the cuttings were treated with hormones (Britwum 1970). Tests in Taiwan with the related *C. sinensis* shed light on this variability in results (Huang 1967). Sprouting averaged 94 to 96 percent for cuttings taken in January and February, 90 percent for March cuttings, 82 percent for April cuttings, 31 percent for May cuttings, and 22 percent for June cuttings. It was concluded that sprouting was most vigorous before terminal growth started. Survival was similarly affected by the season the cuttings were set, being 35 percent in January, 55 percent in February, 32 percent in March and April, 20 percent in May, and 14 percent in June. The earlier cuttings also proved superior in height and diameter growth and root development. Cuttings from the base of the trees attained an 82-percent survival rate versus 65 percent for those from the terminals. The use of hormones improved the average survival from 63 to 72 percent.

Vegetative propagation of *Casuarina* has been reported. *Casuarina junghuhniana,* a Javanese species widely used in Thailand and introduced into India, was found to sprout from cuttings (Thirawat 1953).

Conifers are generally difficult to reproduce by cuttings. However, a test of branch cuttings of *Araucaria cunninghamii* in India produced roots on 50 percent and a 1-year survival rate of 17 percent (Dabral 1961).

The expense of cleaning *Prosopis juliflora* seeds in India led to tests with cuttings (Kaul 1956). Cuttings taken from natural seedlings about 1 m in height and 2 cm in diameter at the root collar sprouted and survived satisfactorily.

Eucalyptus deglupta cuttings can be easily rooted in water, and a 90-percent success rate has been reported (Davidson 1973c). However, rooting success greatly depends on the age of the ortet. Nearly all of the cuttings taken from the tops of trees up to 12 months old rooted, but none of those taken from 5-year-old trees did (Davidson 1974). It has been found that cuttings of most species of eucalypts will not strike roots once the plant is beyond the juvenile stage (Pryor 1978).

Stem cuttings of *Eucalyptus* have been used on a large scale at Aracruz, Brazil (Ikemori 1975, 1976). These cuttings have two pairs of leaves. The process has been successful with *E. grandis* and *E. urophylla.*

With many species, cuttings strike roots as readily with water alone as with hormone treatments. Topside branches of *Pinus caribaea* in Uganda performed as satisfactorily in water (24 to 26 percent) as with hormones (Tufuor 1973). Moreover, hormone treatments may vary in effectiveness with the chemical or its concentration. Tests normally compare more than one hormone and concentration. Yet, a test of indolebutyric and indoleproprionic acids with *P. caribaea hondurensis* in Brazil showed no difference in effectiveness at prescribed levels (Brandi and de Barros 1971).

In Costa Rica, *Acrocarpus fraxinifolius, Tabebuia rosea,* and *Toona ciliata australis* were rooted successfully with phytoregulators (Zanoni Mendiburu 1975). Failures included *Cordia alliodora* and *Swietenia macrophylla* (although rooted successfully elsewhere), *Cedrela odorata,* and *Simaruba amara.*

Root cuttings may prove superior to stem cuttings. The Temperate Zone species *Albizia julibrissin* reportedly has not been rooted from stem cuttings but has been rooted from root cuttings 2 cm in diameter and 8 cm long (Fordham 1968). The juvenile sprouts produced were, in turn, easy to root. The use of longer root sprouts (up to 30 cm) produced a larger number of sprouts. Greater rooting success with stump sprouts than with stem sprouts has also been reported for *Eucalyptus* (Pryor 1978).

In Papua New Guinea, a technique for reproducing *E. deglupta* by cuttings was 90 percent successful (Davidson 1973c). This and the stem practices used in Brazil can be expected to be applied more generally and to increase substantially the productivity of plantations of these species.

Air Layering. Where propagation by stem or root cutting is difficult, air layering has sometimes proved successful. In air layering, the outer bark of stems is severed, and the wounded area is moist-wrapped until rooting and separation can take place. Early efforts to air layer 42 species of tropical forest trees in India were successful (40 percent rooting or better) with *Casuarina equisetifolia, C. cunninghamiana, Chickrasia tabularis,* and *T. ciliata. Araucaria cunninghamii* and *Tectona grandis* rooted between 10 and 20 percent (Kadambi and Dabral 1954). The lower branches of *Casuarina junghuhniana* were also successfully air layered (Thirawat 1953).

The difference between young and old trees was found to be the same for air layering as for cuttings of *P. elliottii* (Hoekstra 1957). This difference was marked between trees 6 and 23 years old. With *P. roxburghii* in India, it was concluded that air layering should be done on the previous year's growth, just behind the apical bud (Chaudhuri 1960). This technique was found to be more successful if done when the apical buds were just opening in January. Rooting started in about 3 months and was adequate in 6. In another test in India, a 100-percent success rate was obtained in April and May for *P. roxburghii* and in June with *P. caribaea.* Two-year-old branches were found superior to 1-year-old branches (Kedharnath and Dhaundiyal 1963). Air-layering tests in Venezuela showed no problem using 8-year-old trees of *P. radiata* and 3-1/2-year-old trees of *P. oocarpa* (Melchior 1963). Use of indolebutyric acid accelerated root formation.

Grafting and Budding. Difficulty in propagating cuttings of many species has led to grafting and budding, the insertion of a bud or a terminal stem against the cambium layer of a rooted stock, as is commonly done with fruit and ornamental trees. A successful technique for budding *Ceiba pentandra* was reported early from the Philippines (Pacumbaba 1939–40).

Grafting of *P. radiata* with 8- and 3-1/2-year-old material of *P. oocarpa* was found to be easy in Venezuela (Melchior 1963). Field grafting of *P. caribaea* was developed by the use of plastic covering over top-cleft grafts (scion inserted within split terminal) (Nikles 1965). This technique improved the success rate from 66 to 91 percent. Use of the plastic enabled grafting to be done any time of the year. Plastic also made it possible to use dormant scions, which otherwise were 37 percent inferior to actively growing scions.

Top-cleft grafting was also successful in east Africa with *Araucaria,* an important finding because of the lack of local seeds (Willan and Salimu 1966). The scion must be from an apical leader to produce vertical growth. Decapitation was found to produce multiple leaders suitable for scions. Interspecific grafting of *Cupressus* was also developed (Dyson 1967).

Experience in Australia with *P. elliottii* showed grafting to be very satisfactory in view of the failure of cuttings (Slee 1967a). Under favorable conditions, top-cleft and whip grafting (side grafting at the terminal) proved satisfactory; bottle grafting (side grafting with the base of the scion retained in vessel of water) was better under difficult conditions. Protection from desiccation is important, and the summer months are to be avoided. However, young and old trees yielded the same results, and the use of auxins, basal wash, and antitranspirants showed no advantage.

Successful cleft grafting of eight species of *Eucalyptus* was reported from New Zealand in 1962 (Thulin and Faulds 1962). A root strike of 80 to 100 percent was attained. *Eucalyptus deglupta* was successfully bottle-grafted in Papua New Guinea shortly thereafter (Davidson 1968). Bottle and top-cleft grafts with this species were frequently found incompatible, a problem that was eliminated by the use of patch grafts (Davidson 1973a). Incompatibility remained a problem with many tropical species, however, requiring many replacements in seed orchards (Pryor 1978).

Grafting of *S. macrophylla* was tested in four seasons in Taiwan and found to be season sensitive; the best time for grafting there is the first 10 days of March (Liou 1969). Scions were soaked in one of three hormone solutions (50 ppm of indolebutyric acid, hapthalene, or indoleacetic acid) for 2 hours, on March 10 and March 30. Survival for all treatments was 80 percent or higher.

Teak budding on 1-year nursery stock showed promise as early as 1960 (Keiding and Boonkind 1960). Bud sprouts of teak from nursery stumps placed in a mist chamber gave an almost 100-percent rooting rate without hormones (Hussain and others 1976). The buds used had just put out two to three pairs of leaves when nipped off. Grafting of teak on 9-month-old plants achieved a 100-percent success rate in what is now Sri Lanka (Perera 1961).

Other Tree Propagation Practices. The use of tissue culture, growing and multiplying parenchyma in an artificial medium, shows great promise for large-scale vegetative propagation. It has been tested with several tree species in the Philippines (Crizaldo 1980), and promising results have been obtained with *Paraserianthes falcataria, G. arborea, P. caribaea,* and *P. kesiya.*

Skolmen (1985) points out that whereas tissue culture has the potential to produce enormous numbers of plants very quickly and efficiently, it has so far been successful only on species that can be readily propagated by conventional methods. Thus, it is not a method for overcoming propagation difficulties. In addition, the process is not simple or always successful. However, Skolmen anticipates that in the future it may be possible to outproduce conventional propagation methods at a greatly reduced cost by using tissue culture.

Bamboo is usually propagated vegetatively because of the infrequent periodicity of its flowering. Early experience with *Bambusa spinosa* in the Philippines showed that sprouting of vegetative material was most vigorous under direct sunlight (Mabbayag 1937). Also, it was observed that stem cuttings from the base of the culm grow faster early than do those from the middle or upper part of the culm.

Experience with bamboo propagation in Puerto Rico led to the recommendations that culms 2 to 3 years old be used, that all primary branches be pruned off, and that cuttings be buried in a furrow 15 to 20 cm deep (White 1948). *Bambusa vulgaris* cuttings 70 to 130 cm long often root when driven into the ground. For best results, the enlarged, congested nodes at the base of the culm were used. Similar recommendations have been made for *Dendrocalamus latifolius* in Taiwan (Lin 1962). Two-node cuttings were used, with the upper part of the culms avoided. Sprouting of this species in Taiwan proved best in March; April and May were the best alternatives.

Experience with *B. vulgaris* in the Sudan indicated that the best culm cuttings are three-node and from the middle third of the culm (Khan 1966b). Next are two-node cuttings from the same area. The third choice is three-node cuttings from other parts of the culm. The best month there for sprouting proved to be July. The cuttings were set in the ground on an angle, with one node buried. Sprouts appeared within 20 days. Two-year survival rate of the best type of cuttings was about 50 percent.

In the Philippines, young, 3-year-old seedling bamboos were divided to separate the 8 to 12 whippy shoots each had produced (Sunder 1970). These stood the shock well, and later each yielded more shoots. The practice in Bangladesh for thick-walled bamboos is to use culm bases, similar to offsets, about 50 cm long (Hasan and others 1976). When rooted, these develop good planting material in 20 to 24 months. This practice has been less effective with thin-walled bamboos.

Propagating Soil. Nursery practice throughout the world has produced a few axioms about soils used for propagation, whether it be by cuttings or by seeds. The soil should be light enough to provide free drainage and fairly easy lifting of stock without injuring the roots, yet heavy enough to hold water and nutrients and to cohere when containers are used. Once these conditions have been met, controlling the quality of the medium is chiefly a matter of chemistry, including regulating pH, ensuring the availability of existent nutrients, and correcting nutrient deficiencies.

As an example, river sand has been used as the basis for the potting medium in Nigeria (Lowe 1967b). Cocoa pod refuse, rice bran, and sawdust were added, primarily to assist in water retention. The addition of further organic matter proved undesirable because it reduced growth because of an adverse carbon (C)-to-nitrogen (N) ratio or increased mortality by disturbing the pH or nutrient balance. The use of relatively insoluble fertilizers was indicated.

Trials in Puerto Rico with *P. caribaea* showed sphagnum, if properly fertilized, to be better than sand and soil as a potting medium; the stock in sphagnum grew twice as rapidly as the stock in sand and soil (Marrero 1961). The best root development was in pots with a mixture of sphagnum, vermiculite, and loam.

The nutrient status of tropical tree nurseries must be diagnosed frequently (Swan 1969). Periodic foliar analyses are useful. Recognition of the need for phosphorus (P) and potassium (K) and other elements should prevent excessive attention to N alone, which may create or worsen an imbalance with other elements.

In some regions, filter-press cake from sugar mills has been a readily available organic supplement for nursery soils. Used as a bed dressing in Australia at the rate of

34 t/ha, it appeared beneficial, although 112 t/ha led to chlorosis (Anon. 1965g). In Puerto Rico, this treatment led to a pH increase to 8 or 9 from the Calcium (Ca) in the material, a threat of iron chlorosis.

South African practice recognizes a need to fertilize nursery stock well, even though the benefits may not continue after planting (Donald 1979). The use of organic additives for nursery soils is not practical everywhere in the Tropics. In parts of Brazil, where organic supplements are not readily available, inorganic fertilizers may produce a satisfactory medium (Simoes and others 1971). The application of N to nursery soil tends to shift blame for growth failure to some other factor. In Australia, neither N nor P alone commonly benefited propagation, but the two together may greatly stimulate growth (Simpson 1978). Studies of *E. saligna* nursery stock in Papua New Guinea showed stunted, purple-to-red seedlings resulting from a P deficiency (Reynolds and Lubres 1971). The condition was corrected by applying P, but high P fertilizer produced both a low root-to-shoot ratio and transplanting difficulties.

Seeds are usually covered with sand or a screened soil, although organic material such as peat moss is also used (Thomson 1968).

Symbiotic fungi that form mycorrhizae on plant roots and facilitate nutrient intake have proved crucial to the success of pine introduction in the Tropics. The fungi are generally introduced by inoculating nursery soils. Once established, their survival and future seem assured. Because their symbiosis is specific, they produce no environmental effect outside that of the pines themselves. The major danger is that of introducing unknown organisms in mycorrhizal soil.

Early attempts to introduce *P. merkusii* outside its natural range in Indonesia uniformly failed (Alphen de Veer 1954). Introduction of inoculated soil was unsuccessful. Then, small mother trees were planted at 1- by 1-m spacing, beneath which 6- to 8-week-old seedlings were transplanted. After 2 years, the beds had become uniformly inoculated, and the mother trees were no longer needed. The same technique was used for inoculating soils in Nigeria (Ekwebelam 1974). The addition of P appeared to stimulate the mycorrhizae.

Years were spent in Puerto Rico trying unsuccessfully to introduce conifers before the mycorrhizal fungi were introduced (Briscoe 1959, Hacskaylo and Vozzo 1967, Vozzo and Hacskaylo 1971). Introductions of fungi in culture initially failed. However, duff taken from pine forests elsewhere and worked into the soil around dying seedlings produced a spectacular response. Soil from inoculated plantations was then used to inoculate nursery stock. Subsequent use of inoculum of known fungi also proved successful. South African practice is to inoculate pines with ground sporophores or spores instead of infected forest soil (Donald 1979). The widespread occurrence of mycorrhizae in tropical forests is described by Janos (1975).

General Nursery Practices

Spacing of Stock. The spacing of seeds, transplants, or cuttings in the nursery is subject to few universal rules and generally must be determined for each species and local situation. A test of *G. arborea* spacing in India illustrates the main variables to be considered (table 6–5; Rajkhowa 1965). The number that survived and were usable increased with the number of seeds sown. The closest spacing may be considered best if there are plenty of seeds and the nursery area is limited. Wider spacing is better where seeds are scarce or expensive.

In Africa, pine sowings for later transplanting generally have aimed at a density of 2,000 to 6,000 seedings per m^2 (Allan and Endean 1966, Donald 1965). For *Eucalyptus*, a density of about 1,500 per m^2 is common.

Sowing directly in containers has many advantages, including faster growth and less danger of widespread

Table 6–5.—Effects of spacing on survival and yields of *Gmelina arborea* in India

Initial spacing (cm)	No. of seeds[a]	No. of survivors	No. of usable stumps[a]	No. of trees lost[a]
5 by 5	400	160	56	344
5 by 10	200	104	45	155
10 by 10	100	62	22	78
10 by 15	67	42	18	49
15 by 15	44	31	14	30

Source: Rajkhowa 1965.

[a] Per square meter.

damping off. But more seeds may be needed, because it is necessary to sow more than one seed per container and then thin out.

Transplanting. Transplanting nursery seedlings to prepared beds or to containers permits foresters to select a uniform crop of the most vigorous seedlings and to place them at their final spacing in the nursery. Pines were formerly transplanted several weeks after germination but are more commonly transplanted after only 2 to 4 weeks (Griffith and others 1962, Leuchars 1960). The advantages are higher survival rates and less post-transplant shock. *Eucalyptus* has been generally transplanted after the seedlings have three to four leaves (Anon. 1963c). In Malaysia, *P. caribaea* has been transplanted 4 to 6 days after germination (Paul 1972).

Shade. Shade over seedlings was once thought optimum for nursery stock because most forest species tolerate shade in nature. More recently, however, stock is shaded only when sensitive to high temperatures and desiccation, such as during germination and rooting of cuttings and transplants. Even species as shade tolerant as *Araucaria hunsteinii* have received half shade for only 6 weeks, about 10 percent of their time in the nursery (Havel 1965). At the other extreme, *Anthocephalus chinensis,* a very intolerant species, is at first lightly shaded because of its extremely delicate seedlings, but it soon bends toward the light it needs (Pollard 1969). *E. tereticornis* and most other *Eucalyptus* species only need about 2 weeks of shade (Lohani 1978). Well-established seedlings generally grow more rapidly and become more robust and woody under full light than under shade. Full light is desirable even for stock that is to be underplanted.

Root Pruning. Severing the deep roots of planting stock during growth in the nursery increases the compactness and density of the root system. Shorter taproot and increased fibrous roots reduce later planting shock and increase survival and early growth. This has long been standard practice. Common in small nurseries in the Tropics, such pruning may be done by pulling a wire stretched beneath the side boards under the beds. Experience with *S. macrophylla* in the Philippines recommended pruning at 60 days (Asiddao and Jacalne 1958). In what is now Zimbabwe, this has been considered an important advantage for pine and eucalypt stock to be used on grassy sites (Stubbings 1958).

Types of Planting Stock

As planting stock selection advances from species to provenance and then to progeny, intensification of investment in planting-stock quality becomes warranted. The production of seedling and transplant stock merits more study, not only to reduce planting costs and mortality but also to enhance the capacity of planted trees to adjust to field conditions and weed competition.

Bareroot Stock. Bareroot stock may die if the roots are exposed between lifting and planting. Even brief exposure to the wind or sun may preclude planting success, so moist packing material must be kept around the roots. Desiccation may also be reduced by stripping some or all of the leaves at the time of lifting.

In southern Brazil, *P. elliottii* and *P. taeda* have been planted bareroot only where rains are well distributed throughout the year (Simoes and others 1976). In Puerto Rico, bareroot planting of *P. caribaea* was discontinued partly because the rains were unreliable but also because of the long recovery period from planting shock, extending weeding by as much as 1 year.

Bareroot stock has been tested everywhere direct seeding, an initially cheaper alternative, has proved unsuccessful. Erosion-control plantings on poor soils in India have been done with bareroot transplants of *Albizia amara, A. lebbek, A. procera, Azaderachta indica, Dalbergia sissoo, Eucalyptus* spp., and *G. arborea* (Goswami 1957). On irrigated dry sites, *Casuarina equisetifolia* is planted bareroot (Venkatesan 1973).

In moist climates, bareroot planting is successful with many species. In Malaysia, the abundance of wilding stock made containerized trees too expensive (Gill 1970). *Cupressus lusitanica* has been successfully established bareroot in Guatemala when special care was taken to protect the roots (Holdridge 1953). *Virola surinamensis,* one of the trees with good potential in the moist forests of northern South America, has generally been bareroot planted (Schulz and Rodriguez 1966).

Swietenia macrophylla has been bareroot planted successfully in the Philippines (Santos and Rimando 1952). A test of *Terminalia ivorensis* in Nigeria, comparing potted stock with stumps, showed that during the 3- to 5-month rainy periods there was no need to use pots (Lowe and Dobson 1966). In Puerto Rico, *Casuarina* *equisetifolia, Cordia alliodora, Hibiscus elatus,* and *Swietenia* spp. have traditionally been bareroot planted. Both *Eucalyptus* spp. and *P. caribaea* have been bareroot planted experimentally, and there seems some prospect that this will continue under favorable conditions.

A planting of *P. caribaea,* both bareroot and in polyethylene containers, gave a survival rate of 99 percent for both methods at 30 days. After a subsequent 7-week drought, survival dropped to 88 percent for the bagged stock and to 45 percent for the bareroot stock. Yet, if all costs are included, it might commonly prove cheaper to replant than to use containers (Briscoe 1960).

A test in Florida with *Eucalyptus* seedlings raised in plastic bags showed no decline in the survival rate after soil was washed off before planting (Meskimen 1973). The treatment retarded growth during the first month, but transportation was simplified, and mechanical planting was made possible. The experiment also showed better results with woody than succulent stock.

Size of Stock. The size of planting stock has been standardized based on local conditions in tropical countries. This has led to the rejection of trees considered substandard, generally with little understanding of the significant criteria involved. The best seedling size for *Araucaria hunsteinii* in Papua New Guinea proved to be no taller than 18 cm (Havel 1965). In the Philippines, stock age was the criterion used. Eleven-month-old *Pinus kesiya* nursery stock grew much faster in height after planting than did stock that was 6 months old (Zamora and Agpaoa 1976). For planting of pines and eucalypts on grassy sites in what is now Zimbabwe, large bareroot stock 40 to 50 cm tall has been preferred (Stubbings 1958).

Size differences in nursery-produced planting stock are commonplace, yet whether there is genetic gain from taking the largest nursery stock to the field is questionable. For example, on the edge of a bed of polyethylene-bagged stock, shorter pines are common. However, this effect may be due to inhibition of mycorrhizae by lateral exposure to the sun, a phenomenon totally unrelated to the genetic potential of these trees (Jackson 1974). In fact, Sweet and Wareing (1966) concluded that size variations in nursery stock less than 1 year old are due almost entirely to small site differences occurring at (or soon after) the time of germination and are independent of genetic differences. Selection of dominants thus may not guarantee genetic superiority.

Isolated experiments would appear to support this conclusion. In Brazil, of the 9-month-old *P. elliottii* tree stems that grew best and appeared strongest, only 1 stem per 3,500 was chosen (Shimizu and others 1977). At the time of planting, the selected trees were 34 percent taller than the others. After 1 year, the difference was 46 percent. At the end of the second year, it had dropped to 31 percent, and by the end of the third to 12 percent, meaning that the benefit from selection had largely disappeared. In another case, tests of *P. taeda* in the United States disclosed genetic variation in the capacity of the trees to withstand transplanting shock (Beineke 1967). Tall trees were consistently the poorer survivors. These examples do not necessarily argue against nursery stock standards and selection, but they do suggest that stock that looks inferior may not really be so.

There is no reason, however, to reject seedling selection as a logical process for recognizing phenotypic vigor. A study of 45-year-old pines in the southern United States showed that trees from first-grade seedlings significantly outperformed those from third-grade seedlings (Wakeley 1969). The initial indications were vindicated by later performance.

Nursery workers commonly must decide whether to discard or hold over excess stock at the end of a planting season. Such stock normally will be larger and costlier to plant and perhaps less likely to survive. Probably not all such stock deserves to be saved, but results in Puerto Rico indicated that the capacity of *S. macrophylla* trees to survive planting need not decline over a few months (Marrero 1942). Overgrown stock 1 to 2 m tall cut back to 10 cm in height can survive well in the field. Small teak plants left over from a previous year are not necessarily inferior as planting stock (Venkataramany 1960a).

Stump Plants and Striplings. Large planting stock is ordinarily used in underplanting because it appears to have a head start on competitors. However, the other extreme, use of trees 1 to 2 m tall cut back to "stump plants," is also widely practiced. Stumping is probably most common with teak; the practice arose because many trees that were not cut back died back anyway after planting or sprouted at a point thought less desirable than the base of the stem. Teak stumps are cut back to about 2 cm above the root collar and usually have 15 cm of taproot below, with no lateral roots (Wood 1968). In a test in India, 2-year survival and height growth of teak increased with stump size (table 6–6; Anon. 1944, 1947a).

Stumps store well. A test in what is now Myanmar (Anon. 1947a) showed that *Toona ciliata* stumps left in the open air indoors had a 75-percent survival rate after 5 days of exposure, but none survived after 10 days. However, when stumps were stored in moist sacks, the survival rate was 90 percent after 25 days and 28 percent after 45 days. Oversized stumps may be halved by splitting without much loss, but if quartered, survival is lowered (Venkataramany 1960a).

On large projects, stumping offers such advantages that it will probably be used with more tropical species in the future. It has been used widely with *G. arborea* and on a large scale in Brazil (Woessner 1980a). The *G. arborea* stumps used are 4 to 6 months old and about 2 cm in diameter at the root collar. They are cut off about 4 cm above the root collar and have a taproot about 10 cm long. In India, stumps have been used under dry conditions with *Albizia lebbek, Bauhinia* spp., and *D. sissoo* (Singh 1951). A study of root systems in Ivory Coast indicated that stumping should be successful with *Tarrietia utilis, Terminalia ivorensis,* and, under favorable conditions, with *Entandrophragma utile* (Bonnet-Masimbert 1972). *Triplochiton scleroxylon* proved unsuited because it needs its entire fragile root system for survival. Stumps are not recommended for underplantings because of the need for maximum early height growth (Lamb 1969a).

Table 6–6.—Teak, *Tectona grandis,* stump diameter versus survival and early height growth in India

Root-collar diameter (cm)	1-yr. survival (%)	2-yr. height (m)
0.8–1.0	64	0.9
1.0–1.3	81	1.3
1.3–1.5	88	1.5
1.5–2.0	92	1.5

Source: Anon. 1944, 1947a.

At the other extreme are striplings, nursery stock 2 to 3 m tall stripped of most leaves but otherwise intact. These are used in areas where animal damage would otherwise be excessive, with species subject to stem pests, and in underplantings where weeding must be minimized (Parry 1956). Striplings have been used with *Gmelina* and the Meliaceae, chiefly in Africa, but also with *Swietenia* in Central America. Their usefulness depends almost entirely on local conditions. At best, the extra costs of longer production in the nursery and of planting can be recovered by an earlier "getaway" for the plantation.

Containerized Stock. The use of containers for forest planting stock has been much more common in the Tropics than in the Temperate Zone. The chief reasons are the lack of a dormant season during which transplanting shock would be minor and the need to facilitate early domination of planted trees over competing vegetation, particularly in underplantings (Lamb 1969a). Many tropical plantation failures have been blamed on rooting damage resulting from bareroot planting (Touzet 1972). Containers offer other benefits under special circumstances, such as a need to store the stock near the planting site.

Experiments in Puerto Rico compared the production and performance of *P. caribaea* stock in polyethylene bag containers, ball-rooted stock placed in bags the day before planting, and bareroot stock (Briscoe 1962). Both types of bagged stock required more space, more equipment, and more labor to produce than bareroot stock but were considered superior because of a higher survival rate and more rapid early growth.

The use of containers may require a large investment. Rooting media are expended with the planting and so must be procured continuously. In addition, the greater weight and bulk complicate transport. The containers themselves are generally expendable and costly, if filled by hand (as is usual). Large holes are required for planting, and planting machines are not widely used with container stock.

Containers have been made of bamboo, used tin cans, tarpaper, wastepaper tubes, milk cartons, specially made waxed-paper cartons, perforated polythene bags, and rigid plastic tubes (fig. 6–3). The most widely used container in the Tropics is the clear polyethylene bag, about 6 cm in diameter and 12 cm deep.

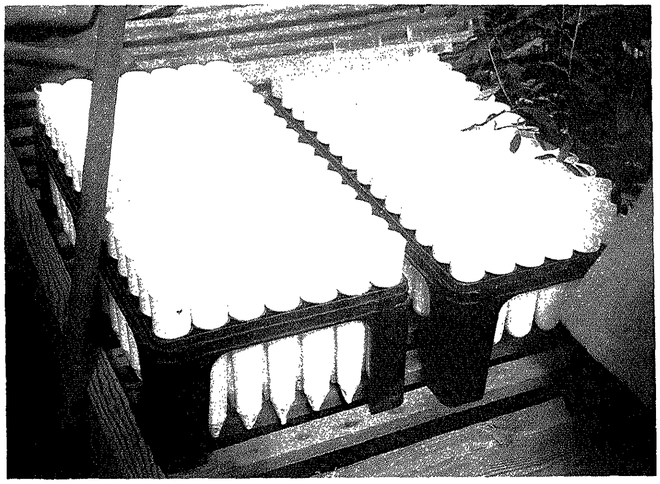


Figure 6–3.— *Reusable plastic containers have proved practical in some nurseries.*

For severely drifting sand in Madras, India, seedlings of *Prosopis juliflora* were produced in pots 7 cm in diameter and 15 cm deep to avoid field watering after planting (Rao 1951). *Casuarina equisetifolia* has also been potted in Orissa, India, for extremely dry, sandy sites where, even with potted stock and weekly watering for 2 years, casualties may be as high as 50 percent (Sharma 1951).

Rapid early growth of containerized *G. arborea* in low-rainfall areas in what is now Malawi replaced the use of stump plants (McEwan 1961). Tests in Tanzania (Wood 1966) with *Pinus caribaea* showed that containerized plants had significantly higher survival rates than bareroot stock. There was no difference in survival between 10- and 15-cm tubes, but at 1 year, the trees from the larger tubes were significantly taller, a difference of 1.4 versus 1.1 m. In Cuba, similar results were found (Acosta and others 1975). On one site, trees from containerized stock at 19.5 months averaged 88 cm tall compared with 59 cm for bareroot stock. In spite of the greater height growth, however, there was some question as to which practice yielded the most benefit for the investment. In Venezuela, some of the extensive pine plantings in the lower Orinoco have been established with bottomless tarpaper cylinders 6 cm in diameter (Lama Gutierrez 1976).

Eucalyptus planting in tropical America is generally containerized. Tests at Vicosa, Brazil, with seven species showed the planting survival rate with bareroot seedlings never to be above 29 percent (Brandi and de Barros 1970).

Soft plastic bags are difficult to fill rapidly and economically. Devices to facilitate filling them have been developed in Brazil, Venezuela, Puerto Rico, and elsewhere. The simplest of these is an appropriately dimensioned, metal funnel. Performed by hand, this process is still time consuming and, where labor is expensive or scarce, the cost may be prohibitive. A good mechanical bag filler has been used in Australia (Evans and Duyker 1965). The process requires bone-dry, fully pulverized soil.

Direct sowing of seeds into bags is much less expensive than transplanting. In Papua New Guinea, direct sowing of *P. caribaea* reduced growing time 28 percent and seedling cost 93 percent and produced a mean tree height advantage of 42 percent (Howcraft 1973). An alcohol-flotation technique was used to eliminate nonviable seeds. Two seeds were sown per bag.

Bag-filling problems, together with the expense of bringing large volumes of potting soil to nurseries and transporting the soil to the field, have recently led to the use of rigid containers, either disposable or reusable. Bottomless tarpaper pots, long used in Argentina, Venezuela, and elsewhere, can be filled rapidly. These pots stand upright in tight arrangement between bed sideboards and are filled collectively and quickly with a shovel.

Rigid plastic tubes no more than 3 cm in diameter and 15 cm deep with a conical, perforated bottom are being used in Florida and Hawaii and are being tested elsewhere. Typically, an artificial potting medium such as vermiculite or perlite is used. Therefore, there is no need to transport tonnes of potting soil each year. Moreover, the tubes can be placed in light frames for easy transport. They are reusable and can be removed and kept at the nursery if the medium is sufficiently cohesive to withstand rolling in burlap for the field.

Because desiccation kills many recently planted seedlings, chemical transpiration retardants have been tested as a preventive. However, in Hawaii, a test of *E. saligna* utilizing a captan-malathion solution and comparing dipping and spraying showed no superiority in either the survival or 1-year growth rate in the field (Walters 1971).

Insects and Diseases

The collection, storage, and production of propagating materials for tropical forest trees are not without insect and disease problems. These problems are diverse, usually local, and subject to rapid change. Some of the problems encountered are described here, but a detailed review of pest behavior and treatment recommendations is not attempted. The reader is referred to specialized reports on forest entomology and pathology for more information, some of which are cited in the bibliography. There is no comprehensive reference on forest insects of the Tropics.

An important category of nursery problems is termed "deficiency diseases," where stock has too little (or too much) of some abiotic component essential to its environment, such as moisture or nutrients. Excellent information now exists on these problems for agricultural crop plants, fruit trees, and ornamentals. This information is useful in diagnosing and correcting similar problems affecting forest tree, nursery stock. Specialists in entomology and plant pathology should also be consulted.

Most insect and fungal pests are host selective. Trees grown outside their native ranges may be spared from the pests of their home environments but may become new hosts for pests in their new locations. Making sure that the young trees introduced are kept healthy reduces the danger of pest attacks or infection (Chapman and Allan 1978). Control may be silvicultural, biological, mechanical, or chemical.

Silvicultural measures include control of tree spacing and the use of mixed plantings. Biological control involves coaction between two or more organisms favoring the desired crop. Mechanical control usually calls for removing infested material, including alternate hosts. Chemical control relies on insecticides and fungicides (Chapman and Allan 1978).

In the Tropics, the need to reduce or eliminate unwanted organisms from soil used for tree propagation is almost universal. Repeated cropping tends to attract such problems. An intensive practice in nurseries is to expose well-loosened soil to methyl bromide, a highly toxic (and dangerous) gas. This substance has been utilized for decades in *Eucalyptus* propagation. Methyl bromide's excellent properties as a sterilant, including the fact that it does not necessarily kill all organisms in the soil, were demonstrated in 1954 (Guimaraes and others 1954). The compound has been widely used in Brazil ever since. Its use became standard practice in *Eucalyptus* production in South Africa (Knuffel 1967), where it increased the number of plants by about 50 percent.

Insect problems may also be significantly reduced by treating nursery soil with insecticides. This is a standard practice with *E. tereticornis* in India (Lohani 1978). Ideally, treatment should be tried on a small scale to minimize unknowns before larger scale operations are undertaken.

The isolated locations of many forest nurseries in the Tropics means that common insect and disease problems can be handled only with common sense. An example is seen in a nursery of *Cedrela odorata* and *S. macrophylla* in Fiji (Anon. 1954d). An unknown Scolytid beetle attacked the seedlings of both species, boring into the stems near the root collars and laying eggs. The infested seedlings were quickly removed and burned, and the problem was essentially controlled. Such situations call for similar solutions because of lack of either precedent or access to specialists. Common-sense practices must continue, but because these generally neither identify the cause nor provide a scientific solution, the more serious or frequent problems of this nature sooner or later demand careful research. Biological controls are in many cases a research objective not yet attained.

Planting Techniques

Planting techniques in the Tropics vary so widely, and correctly so, that no practice is applicable everywhere. Standard manuals should serve merely as guides, being modified to suit the needs of each situation. Several compendia of planting experiences within the Tropics have been published that are useful for selecting planting practices. An excellent example by Chapman and Allan (1978) deals in detail with plantation planning; site preparation; direct seeding; planting and tending; special techniques for soil and water conservation, irrigation, sand dunes, wet or interlogged sites, and mine spoils; and protection of plantations from weather, insects and fungi, and fire.

The importance of site preparation where a tree is planted outside its natural range is shown by experience in Kenya (Schonau 1975). There, establishment techniques influenced the early growth rate of *E. grandis* more than did site quality. Where rainfall is limiting, complete site preparation, including plowing, fallowing, and harrowing, may be needed. The superiority of growth on sites so prepared was still apparent at age 7. The use of fertilizers, particularly P, may yield a financial return of 25 percent per year. A main need is for P, but the need for N increases with less site preparation.

Planting Season. Nearly all planting sites in tropical America are subject to seasonal rainfall variations. Rainfall occurring immediately before and after planting is critical to the survival of most tree species. Planting should begin at the onset of the normal wet season when maximum duration of adequate soil moisture is expected. Teak planted in India at the beginning of the rainy season invariably does better than if planted later (Laurie 1941g). Land preparation and digging of holes may be done months in advance to shorten the period required for planting (Lohani 1978). In west Africa, trees have been generally planted a full 6 months before the dry season (Groulez 1961a). For *E. deglupta,* a species that needs almost constant moisture, planting should not be done less than 1 month before a normally dry season (Dalton and Davidson 1974).

In Puerto Rico, the ideal times for planting seem to be months that average at least 15 cm of rainfall, preceded and followed by months averaging at least 10 cm (Marrero and Wadsworth 1958). In India, on sites where rainfall is less than 100 cm annually, direct seeding of *A. lebbek, Azadirachta indica,* and *Cassia fistula* may be done every month (Laurie 1941b). The seeds persist on the soil until the advent of the unpredictable rains.

Site Preparation. The preparation of the land is usually crucial to planting success. It may facilitate the planting job itself, but its primary purpose is to give the planted trees a head start over the natural vegetation and thus minimize weeding.

The general considerations in site preparation have been well described by Chapman and Allan (1978). Where vegetative cover can prevent successful plantation establishment, methods must be developed to eliminate or reduce such competition. Site preparation often constitutes a major proportion of total establishment costs. Therefore, efficient and economical methods that avoid undesirable ecological changes are required. Under favorable circumstances, little vegetation may need to be removed, and the soil may be left undisturbed. At the other extreme are rain forests with heavy residual vegetation and fragile soils.

Site-preparation costs are a major obstacle for planting on nonforested areas. Even on the grasslands of the lower Orinoco in Venezuela, land preparation has accounted for more than a quarter of the field cost of plantation establishment (Gutierrez 1970).

Land preparation is a twofold process: the elimination of competing vegetation and the preparation of the soil. Competing vegetation has been reduced on many sites by shifting cultivation. Remaining trees may be felled or, if large, girdled or poisoned. In dry areas, it is essential to prevent the consumption of scarce water by vegetation other than the planted trees (Cooling 1960). In a test in the miombo woodlands of Zambia, complete elimination of weeds resulted in a 14-month plantation survival rate of 95 percent compared with less than 30 percent where only spot weeding was done (Endean and Jones 1972).

Much of the land needing reforestation in the Tropics is poorly suited to mechanized site preparation because of steep or irregular terrain. Costs of personnel training, equipment maintenance, and parts and fuel inventories in remote locations may well exceed expectations. Even where mechanized techniques are feasible or less costly than hand methods, the social benefit of employment that using hand methods would provide should be weighed carefully before mechanization is considered.

Site preparation may not be required on eroding slopes, active dunes, and recently abandoned, cultivated fields. The less soil disturbance in such areas the better. What little weeding might be desirable can generally be done easily and by hand.

The contracting of shifting cultivators to prepare sites for forest planting and the initial sharing of the land by food and forest crops—the taungya system—has been and may in some places (such as Trinidad) (Lackhan 1976) remain a practical way to convert cutover forests to timber plantations where public control of forest land is adequate. At Monte Dourado, Brazil, where forests had recently been felled and burned, cultivation was contracted on a large scale to produce food crops and incidentally to weed planted trees. Site preparation by this method often left large, standing relics that later had to be felled with some damage to the plantation.

Where the taungya system is impractical, the removal of brush, low secondary forests, or recently logged stands is commonly done by hand with machetes, axes, and chain saws. Clearing high forests for planting is generally impractical by hand methods. At Monte Dourado (Jari), Brazil, high forests are felled, and up to 80 percent of the volume may be used for lumber and pulpwood. Most of the rest is used to fuel a pulpmill and generate electricity (Woessner 1980a). The harvest leaves chiefly branchwood to be burned in preparation for planting. This material is usually adequate to support a clean burn, allowing planting in the ashes immediately thereafter.

The use of fire for final site preparation is common in the Tropics. Where large volumes of debris cover the site and mechanical windrowing is impractical, using fire is the only way to provide the planters easy access. Where fire is not required for this purpose, however, it should be avoided, particularly on slopes, because burning releases nutrients (fig. 6–4). The N in the biomass is lost, and those nutrients remaining in the ashes may be lost to erosion. Allowing slash to decay in place, on the contrary, releases these nutrients to the soil at a rate roughly as fast as the new crop takes them up.

A less drastic method of converting secondary forests to plantations in the Tropics is by strip clearing and underplanting, a practice used widely in Africa but sparingly so far in America (see chapter 5). It was assumed that clearing lines about as wide as the crown diameters of mature trees would greatly reduce the site-preparation task, that species requiring early partial shade would be provided an environment similar to the natural one, and that most of the native forest might never need to be felled because the planted trees would soon dominate it. The technique proved to have merit, but it has not been as simple or effective as hoped. The shade left was initially too heavy, and planted species of slow-to-medium growth rates have required many years of tending, including liberation cutting, before their crowns were free. Subsequent emphasis has been on the use of fast-growing, intolerant species, requiring removal of the overstory (Lamb 1960). Thus, site preparation, even though the strips may initially be only 1.8 m wide (Lamb 1960), may be only slightly less costly than conventional plantings.

Figure 6–4.—*Site preparation by widespread burning 3 months after felling of the primary forest, an early practice at Jari, Brazil.*

Mechanized Site Preparation. Either manual or mechanized site-preparation methods may be used. On large planting projects in Brazil, land preparation has been generally mechanized (Simoes and others 1976). A thorough study of the relative social as well as economic advantages of manual and mechanized methods should precede any large planting project (Chapman and Allan 1978).

On flat land and slopes up to 30 percent that are free of surface irregularities or obstructions (the best sites available), machines may be used to topple trees, windrow debris, and plow and cultivate the soil for tree planting. Where labor is scarce or the planting season short, mechanization may be the only practical site-preparation option. The greater capability of machine operations may also provide employment opportunities that otherwise would not be available.

Mechanical removal of vegetation can damage the site, however. A study in Suriname revealed serious impacts on physical and chemical soil properties (van der Weert 1974). Heavy equipment may be detrimental to soil structure and may remove topsoil. Soil compaction may cause shallow and small root systems. Compaction is greatest when soil is wet, so clearing should be done during the dry season. To minimize repeated traversal of the land by machines, windrows should be closely spaced, at about twice the distance between the rows of the plantation.

Machines are commonly used for site preparation on the relatively level areas of cerrado forest being planted in Brazil (Brandi and others 1971). Small trees may be uprooted by chains drawn between heavy tractors, and the soil is usually thoroughly plowed and disked, not only for weed control but also to conserve soil water for the trees. Control of leafcutting ants with pesticides is an integral part of site preparation in Brazil. Plowing and disking on the altiplanos in Colombia produced faster growth of *E. grandis, P. kesiya, P. oocarpa,* and *P. patula* throughout their first 5 years (Cannon 1980; Ladrach 1978a, 1978b).

In the Tropics, site-preparation operations using mechanical equipment include the following:

Felling—Felling is usually done during the rainy season. In high or secondary forests, felling may be done with chain saws or cutting blades mounted on crawler tractors. Where trees are small, chaining with tractors in tandem may be done. In light brush, heavy, rolling choppers drawn behind crawler tractors may be used.

Windrowing—Windrowing is normally done shortly after the end of the rainy season. Heavy bulldozers or tractors with front rake blades are commonly used. Complete stump removal is necessary if the plantation is later to be machine tended. Large stumps that cannot be uprooted are surrounded with debris and burned.

Burning—Burning is done before the end of the dry season. Peripheral firelines are cleared with bulldozers, with workers standing by during the burning to consolidate incompletely burned material. Crews trained to control fires must be on hand.

Cultivation—Cultivation must be done immediately after burning. Soil is tilled only where heavy vegetative cover or a dry climate otherwise precludes successful plantation development. Heavy plows and disk harrows are drawn behind tractors.

Use of Herbicides. The use of chemicals involves hazards both to those who apply them and to the natural environment. It is necessary to remain informed of rapidly changing assessments of specific pesticides to avoid applying any that may unnecessarily harm the environment. The safety of workers exposed to these agents is of equal concern. Herbicide use calls for a number of important precautions. The manufacturer's safety instructions should be followed precisely. Many herbicides are irritating or toxic to mammals and may be absorbed through the nasal passages or the skin. Where sprays are used, protective clothing, including gloves and face shields, must be worn. Additional dangers arise from herbicides after application. Those that persist or that decompose into other dangerous or little-known chemicals must be kept from watercourses. This may call for minimum applications, avoidance of rainy weather, and tree injection in place of surface application.

Chemicals that kill plants are useful in preparing sites for planting under some conditions. Because they may kill grasses, weeds, and woody plants outright without the need for uprooting, herbicides can be superior to mechanical methods where site clearing is required. In areas with only grasses or weeds, herbicide treatment alone may be adequate. Where tree stumps remain, herbicides may be applied to prevent them from sprouting. Some herbicides kill vegetation upon contact; others must be translocated within the plant before they become effective; still others kill seeds in the soil. Herbicides are most effective when used in clear weather.

A few of the herbicides that have proved useful for tropical site preparation are listed below. The use of proprietary names is for clarity and conveys no greater endorsement than applies to any equivalents on the market.

1. Against grasses:
   a. Dalapon is a translocated herbicide affecting only monocotyledons. It is not known to endanger aquatic life.
   b. Paraquat is a translocated herbicide of extremely rapid action against grasses and fibrous-rooted or stoloniferous species. It defoliates (but rarely kills) woody species.

2. Against broadleaf, herbaceous weeds:
   2, 4-D (2, 4-dichlorohenoxyacetic acid) is a translocation herbicide applied as a foliar spray.

3. Against woody species:
   a. Picloram is a translocated herbicide that is extremely effective against woody plants and particularly useful in preventing coppice growth. Most grasses are tolerant.
   b. Ammonium sulphamate is a soluble, crystalline chemical that is applied to stumps in liquid or crystalline form to prevent sprouting.

4. Against seeds in the soil:
   Atrazine is an effective soil sterilant. It may be applied to low vegetation by manual or machine-powered, backpack sprayers or mistblowers. Trees may be treated by using basal spray (a mere wetting

of the bark around the stem), by wetting frill girdles, or by using injectors. Injectors deteriorate rapidly in wet climates and with the use of corrosive herbicides.

A combination of traditional methods for vegetation removal and chemical arboricides is found effective where low, dense, woody growth must be removed. Control of the introduced, leguminous, shrub marabu *(Dichrostachys glomerata)* in Cuba, found impractical by mechanical methods, has been successful with arboricide spraying at the beginning of the dry season and again during moist weather (Kudela 1978).

Special Site-Preparation Considerations. On soils susceptible to serious erosion because of texture, slope, or rainfall intensity, less complete site preparation may be appropriate. It is particularly important that the natural protective cover on such sites be preserved to the degree compatible with successful plantation establishment. This could mean leaving natural grasses, herbaceous cover, or low, woody growth between trees in contour rows. Sites must also be protected from damage by fires, grazing, and cultivation.

Large areas in tropical America that are unsuited to agriculture are poorly drained and may be low in timber productivity as well. At least some of these areas, and possibly all mangroves, have important water-conservation or wildlife-habitat values that may preempt their use for wood production.

In dry climates, the use of contour structures to trap needed rainwater, as is common in the Eastern Tropics, deserves further testing in America. Trenches with cross barriers apparently can be effective in such climates. Several of these traps have been tested in Mexico. The survival rate of *Chilopsis linearis* was increased in Coahuila from 20 to 100 percent by using such trenches (Zapien Barrogan and others 1978). Outlets must be carefully engineered, because a breakthrough may so concentrate waterflow that an entire slope is damaged. Under extreme conditions, the setting of wide, wooden sticks 30 cm long into the ground at the base of recently planted trees and slanting them perpendicular to the prevailing rains directs added rainwater to the trees.

Preparing sand dunes for fixation is a special case. Unstable, sharp, sand particles may be blown at high speed along the land surface, presenting a particularly adverse environment for the establishing plant cover. The nature of the substrate on these sites is also adverse, with low moisture retention and nutrient levels. Any natural vegetation present is usually desirable and should be left. Where sand movement is greatest, physical barriers of wood or other material can be used to slow the movement and build up the surface level. It may be necessary to increase the height of such barriers progressively as they become covered. This can be followed by planting shrubs or trees. Trees such as *Acacia* and *Pinus* are preferred for their crown densities near the ground. *Casuarina* proved successful near Veracruz, Mexico. Complete protection of exposed dune areas from grazing and fire is essential.

In much of tropical America, chemical treatment against leafcutting ants is also crucial to plantation success. In *Eucalyptus* plantations in Minas Gerais, Brazil, ants can reduce survival rates by as much as 15 percent (Simoes and others 1976). Treatment must extend to major ant colonies some distance from the planted area.

Vegetation that has been killed may also have to be removed in preparation for planting. The most common method has been burning. Many years ago in India, it was recognized that light burns do not necessarily destroy organic components of the soil (Griffith 1946). Burning was also found to reduce the acidity of the topsoil and to release significant amounts of nitrates. In fact, burning alone significantly increased the early height growth of planted trees, even into the second year. Burning has been a traditional site-preparation practice for *Eucalyptus* plantings in India (Lohani 1978).

General burning after tree harvesting in the miombo woodlands of what is now Zambia favors aggressive grasses (Cooling 1962a). For land preparation, it has proved better to uproot the large trees with tractors, dig out the smaller ones, and let charcoal burners clean up. The land is then plowed and harrowed at the end of the rainy season and fallowed over the dry season to prevent depletion of soil moisture.

The study of burning in preparing planting sites has shed more light on its effects (Anon. 1949a). Burning destroys organic acids and liberates bases, tending to neutralize acid soils, thus possibly improving conditions for plant growth. Burning has been seen as favoring bacteria rather than fungi, thereby changing the balance of nutrients available to plants. Burning also increases the soluble mineral nutrients in the soil for a protracted period after the burn. However, burning may destroy some of the organic matter in the immediate surface soil and can destroy all surface seeds. The released nutrients tend to be concentrated in the ash, so regeneration may do best where ash is concentrated. One of the benefits of burning may be the replacement of Ca in the ash.

The adverse effects of burning may show up in crop performance. In Papua New Guinea, burning of moist forests after logging depressed early height growth of a subsequent plantation of *E. deglupta* (Lamb 1976). Planted trees in unburned areas had an average height superiority of 2.6 m at 9 months and of 2.9 m at 15 months; the differences were significant at the 5-percent level. Foliar nutrient concentrations, including manganese (Mn) and boron (B) but excluding P and K, were up to 24 percent higher in the unburned area, the differences being highly significant. Phosphorus and K were significantly lower (at the 5-percent level). Growth inferiority in burned areas was blamed on the loss of N through fire, followed by only gradual recovery.

Once vegetation has been treated, the soil may also be prepared to conserve moisture, eliminate competitors, and improve texture for root penetration. In a planting in the savanna areas of northern Nigeria on land devastated by tin mining, the application of subsoilers to loosen the surface soil was important to the success of *E. camaldulensis* (Wimbush 1963). The soil was disked to control weeds. Tractors and subsoilers have been used also for *P. patula* plantings on the mountain grasslands of Madagascar (Vignal 1956). Disking for a plantation of *P. elliottii* in the Southeastern United States doubled the root surface at a 30- to 45-cm depth in the soil at 4 to 6 months in comparison with sites where no disking was done (Schultz 1972).

The use of machinery in soil preparation is advantageous only on good terrain and large planting areas (Letourneux 1960). The technology used must be justified not only financially but also socially, in view of trade balance and employment needs. It must also be recognized, however, that on many sites intensive soil treatment may greatly increase productivity. In the cerrado of Brazil, brush cutting with a heavy roller knife resulted in *E. saligna* plantations with 50 percent more early height growth than sites that were only plowed and harrowed (Mello and Rodriguez 1966). Even underplantings responded significantly to thorough ground preparation (Danso 1966).

In dry areas, soil preparation may be done chiefly to reduce water loss through runoff and evaporation. In areas of India with annual rainfall of less than 100 cm, the soil may be worked to a depth of 15 cm along planting lines, and rockwork bunds (ridges) may be constructed for erosion control (Laurie 1941a). Trenches about 4 to 6 m long, 60 cm wide, and 45 cm deep were dug in red soils, and the dirt was heaped to form a mound (Muthanna 1941). The seeds were then sown on the mounds. In a test with *A. arabica,* the use of contour bunds almost doubled the early height growth (Ahmad 1957). Elsewhere, the trenches have been refilled with the loose earth where the sowing is then done (Singh 1951). On barren areas planted with *Anacardium occidentale,* pits 50 by 50 cm were dug, and the soil was exposed a month before being replaced for planting (Iyppu 1957). Complete land clearing and deep plowing in advance of tree planting in India have long been done to prevent water loss (Shetty 1973). Full soil preparation, with disking, is done in the cerrados of Brazil for the same reason (Ayling and Martins 1981, Simoes and others 1976). In India, where the annual rainfall is less than 50 cm, taungya farming may begin 3 years before tree planting (Sweet 1946).

Under extremely dry conditions, pits to capture water may be dug well in advance of planting to take advantage of short moist periods. In India, ditches have been dug 30 to 40 cm deep before the rainy season either on the contour or spaced about 3 m apart (Sahai 1945). Seeds of *Acacia, Dalbergia,* or *Prosopis* were sown, and the earth was replaced loosely at the beginning of the rains (Krishnaswamy 1960).

Spacing of Planted Trees. Tree spacing affects planting costs, the need for later silvicultural treatment, and ultimate yields. Chapman and Allan (1978) listed factors influencing the choice of spacing in tropical plantations:

- Growth rate (the closer the spacing, the slower the rate)
- Tree form, crown shape, and degree of self-pruning
- Weed hazard and need for mechanized weeding, side shade from natural intergrowth, and taungya weeding
- Prospective rooting depth (wider spacing is needed where rooting depth is shallow)
- Marketability of early thinnings, and final d.b.h.
- Costs of culture and of carrying investments.

Evans (1992) listed some of the effects (good and bad) of wide spacing, including: cheaper ground preparation, fewer trees required, higher survival rates, mechanization of planting and tending favored, longer tending and fire-hazard period before stand closure, thicker and more persistent branches to prune, less need for precommercial thinning, and fewer trees to harvest per volume unit.

For field planting, the spacing most commonly used ranges from 1.8 by 1.8 to 2.5 by 2.5 m, but there are many exceptions. In one area of Madras, India, spacings of *Casuarina* as close as 1 by 1 m have been used for fuelwood production; yields were 200 to 250 t/ha of dry wood after 4 years (Kaul and Gurumurti 1981). Even closer spacings (0.9 by 0.9 m) have been used with *Sesbania grandiflora* for 3-year fuelwood rotations. On favorable sites, the trees reach 8 m in height and an average d.b.h. of 10 cm with yields to 40 t/ha/yr air-dry (Bhat and others 1971).

In southern Brazil, *Eucalyptus* for cellulose has been commonly spaced at 2.5 by 2.5 m or 2 by 3 m and *Pinus* at 2 by 2 m for pulpwood or 2.0 by 2.5 m for sawtimber (Simoes and others 1976). For *P. caribaea* in Venezuela, a common spacing has been 2.5 by 2.7 m (Lama Gutierrez 1976). Plantings of *Cupressus lusitanica* in Costa Rica have been spaced at 1.5 by 1.5 m to foster natural pruning (Holdridge 1953).

In the Amazon plantings at Monte Dourado, Brazil, *G. arborea* has been spaced 3.5 by 3.5 m and *P. caribaea* at 4.0 by 2.5 m to provide access to the trees (Woessner 1980a). Spacing for *Anacardium occidentale* on barren areas in India may be as wide as 10 by 10 m (Iyppu 1957).

Studies of *P. elliottii* in southern Queensland, Australia, over a 20-year period show the greater value of wide spacing for the long rotation, despite the lower yield, a reflection of the importance of tree diameter (table 6–7; Anon. 1972a).

Studies of *P. elliottii* grown for sawtimber in southern Brazil show that at spacings as wide a 2.8 by 2.8 m too few well-formed trees were available for final crop selection (Fishwick 1976). In addition, the number without growth defects increased with closer spacings.

Plantations of *O. lagopus,* a tree requiring very wide spacing, were tested in what is now Sri Lanka at 3 by 3 m and 4.6 by 4.6 m; the latter proved better (Parsons 1943, 1944). In India, balsa spacing has varied with the site, from 3.7 by 3.7 m to 4.6 by 4.6 m on poor sites to 5.2 by 5.2 m on good sites (Nair 1953). In Papua New Guinea, initial spacing has been at 2.1 by 2.1 m, but thinning has been done after 1.5 years to an average spacing of 3.9 by 3.9 m (White and Cameron 1965).

Table 6–7.—Spacing effects on *Pinus elliottii* in Queensland, Australia

	Productivity (m^3/ha/yr)		Relative value per yr.[a] (%)	
Spacing (m)	Age 12	Age 20	Age 12	Age 20
2.1 by 2.1	13.7	19.5	41	92
3.0 by 3.0	11.1	16.3	39	100

Source: Anon. 1972b.

[a] As a percentage of the relative value of the 3.0- by 3.0-m spacing at age 20.

Wardle (1967a) has shown that in England tree spacing can be prescribed on an economic basis with some certainty and that a range of spacings from close to wide may affect total volume production by less than 10 percent. There, 2.4-m spacings were at one time found to yield about 95 percent of the maximum in net discounted revenue. Closer spacing increased volume but sharply diminished monetary returns. Wardle points out that physical production in the narrow sense is generally just one objective of a spacing decision. Others may be the value at the time of harvest, the net discounted value, or the risk of loss.

Comparisons of four species of *Eucalyptus* near Sao Paulo, Brazil, showed that a spacing of 1.5 by 3.0 m yielded more stacked wood (and bark) for particleboard at 5 years than a spacing of 2 by 3 m, but the mean diameter was significantly smaller (Simoes and others 1976). For paper manufacture, the wider spacing yielded the greater volume of usable wood.

Evans (1992) concluded that for field plantings, three ranges of spacings are desirable: (1) for fuelwood with maximum yield per year and no small-size limit, 1 to 2 m; (2) for pulpwood logs from 10 to 40 cm in diameter, 2 to 3 m; and (3) for sawtimber and veneer requiring logs 30 cm or more in diameter from trees selected by thinnings, 2.5 to 4.5 cm.

The effects of extremely close spacing of plantations of *L. leucocephala* are apparent in a Taiwan study by Wang and others (1984). The "Salvadorian type" of *L. leucocephala* was used, and density ranged from 2,500 to 40,000 trees per hectare. The yield at 4 years is shown in table 6–8. The high biomass production shown for the 40,000-per-hectare spacing is deceptive. Mortality eliminated 12,000 trees per hectare, and 74 percent of the survivors were less than 4 cm in d.b.h. and so could not be used for pulpwood, reducing the ultimate size of the crop to 7,000 trees per hectare.

A similar experiment with *S. sesban,* conducted in India, showed that the d.b.h. decreased with closer spacing but yield increased (table 6–9; Dutt and Pathania 1986). Although the last column in table 6–9 may exaggerate the results because it does not include mortality, it suggests an inevitable contrast between tree size, which is significant not only to utilization but also to the cost of handling.

In taungya plantings, where trees are interplanted with food crops, tree spacing has been wide to ensure a cropping period long enough to reward the cultivator for land preparation. Thus, in India, taungya plantings of *Acacia arabica* and *D. sissoo* have been at 3.7 by 4.6–m spacings (Sahai 1945). In what was formerly Zaire, where *Terminalia superba* has been interplanted with bananas, the tree spacing ranged from 3.7 to 5.5 m (Baur 1964a). At Monte Dourado, Brazil, plantings of *Eucalyptus, Gmelina,* and *Pinus* have been spaced 2.25 by 4.00 m to prolong forage production where grazing is planned (Woessner 1980a). *Pinus caribaea* taungyas in Trinidad have been planted at a spacing of 2.7 by 2.7 m (Lackhan 1976).

Table 6–8.—Spacing effects at 4 years on *Leucaena leucocephala* biomass yields in plantations in Taiwan

Tree component	Biomass of trees planted (t/ha)		
	N = 2,500	*N* = 10,000	*N* = 40,000
Stems	36	50	83
Branches	8	6	11
Leaves	3	3	6
Roots	11	13	24
Total	**58**	**72**	**124**

Source: Wang and others 1984.

Table 6–9.—Spacing effects on tree volume at 30 months for *Sesbania sesban* in India

Spacing (trees per ha)	Mean d.b.h. (cm)	Yield (m^3/ha/yr)	No. of trees per cubic meter[a]
2,500	7.7	21	48
5,000	6.5	29	69
10,000	5.3	39	103
20,000	4.0	41	195
40,000	3.1	45	356

Source: Dutt and Pathania 1986.

[a] No mortality assumed.

Spacing of underplantings has been wider still. In fact, the need for few trees per unit of area has been an important argument for the practice. Because the natural forest is left between the rows, close spacing is not required to ensure good tree form. In the Central African Republic, spacing of *T. superba,* has been 12 by 12 m, compared with francophone Africa, where spacing has ranged from 5 to 20 m between lines and from 3 to 7 m within the lines (Aubreville 1958; Baur 1964a; Catinot 1965, 1969a).

Underplantings in Malaysia have been spaced at 2 m in lines 10 to 12 m apart (Tang and Wadley 1976a, 1976b). In Fiji, underplantings of *Swietenia macrophylla* have been spaced about 3 by 12 m (Busby 1967). In Papua New Guinea, *Araucaria hunsteinii* has been underplanted at a spacing of 3 by 7 m (Godlee and White 1976).

Spacing for underplanting may be a function of the crown diameter of the trees at maturity. In Africa, it is recommended that spacing between lines be at least equal to final crown diameter or slightly wider to permit persistence of natural trees (Dawkins, cited by Lamb 1969a). Within the lines, the trees have been spaced about one-fifth of the distance between the lines, providing for a good selection of final trees.

Final crown width has been measured on uncrowded trees. As an example, in Malaysian lowland dipterocarp forests, *Dyera costadata* has a crown-diameter-to-bole-diameter ratio of about 17, considered remarkably low for a fast-growing tree (Wong 1966a). The distance between the lines for this species at 60 cm in d.b.h. at maturity, using triangular spacing, becomes 0.60 x 171/155 = 8.8 m. Other Malaysian trees have a crown diameter-to-d.b.h. ratio ranging from 16.5 to 25 (10 to 15 m for trees 60 cm in d.b.h.), and line spacing is frequently calculated at 1.5 times this amount, with initial spacing within the lines at 1.8 m (Tang and Wadley 1976b).

Widely spaced, group plantings have been tested extensively in the Tropics. They are frequently associated with the name Anderson because of his description of early group plantings in Scotland and northern England (Anderson 1953). The Anderson concept is that a group of trees, rather than a single tree, is the planting unit and that the units are spaced widely enough that much of the area between the units remains unstocked until the planted trees mature. There are variations in the initial number of trees per unit, the composition of the unit, the spacing within the unit, the spacing between units, and the species mixture. The number of trees per unit has ranged from 3 to 25, spaced 1 m or less apart; inferior trees are thinned out early to favor the best. Species mixtures may be alternated within or between groups. Spacing within units has varied from 30 to 150 cm and between units from 2.8 to 7.5 m. In Uganda, the method has been used successfully with 5- by 5-tree squares with internal spacing of 1 m (Lawton 1976).

Advantages attributed to the Anderson pattern are facility in relocation for weeding, thinning, and harvesting; relative freedom from branches on interior trees; and wind stability. There is a tendency for the outer trees to dominate, but this may not be an important drawback because early thinning can favor the best trees. In Brazil, it was noted that damage from Meliaceae shootborers was seldom spread throughout each unit; in other words, some trees in each group tended to escape attack.

An adaptation of the Anderson pattern has been tested in Suriname with *Cordia alliodora* (Vega 1977). There, trees are planted 1 m apart in triangular spacings in secondary forests at the time of overstory poisoning. The units are spaced 5 by 10 m apart, or 200 per hectare, with an expected harvest of 130 to 150 trees. Tests in Brazil are using closer spacings within the unit, but the units are separated by 20 m.

Spacing involves much more than the number of trees required and the ease of early tending. Equally important are its effects on stem straightness, natural and artificial pruning, stem taper, diameter growth, and the size of the trees when a first thinning might be required.

Studies of these relations have been made under tropical conditions or where conclusions may be applicable to the Tropics. An early fuelwood production experiment with *E. saligna* in Sao Paulo, Brazil, illustrates the results of different spacings (table 6–10; Guimaraes 1957, Navarro de Andrade 1939). The return on the investment probably favored the wide spacing even more than is shown because a constant value per cubic meter was used, without taking into account the probable lower cost of handling the fewer, larger pieces yielded by the wider spacing.

A spacing test in Kenya with exotic softwoods compared 10-year growth at 1.8- by 1.8-m, 2.1- by 2.1-m, 2.4- by 2.4-m, and 2.7- by 2.7-m spacings (Anon. 1962a). Mean branch size and the mean height of all trees was depressed by close spacing, but for the 250 largest trees per hectare, mean height was slightly greater at close spacing than at the wider spacings. The diameter of the largest 250 trees per hectare was about the same regardless of spacing. The widest spacing produced many poorly formed trees, some of them large; therefore, thinning them out left the mean diameter of the remaining crop smaller than the mean diameters of the two intermediate spacings.

In a study of *E. saligna* in Hawaii, the diameter-growth rate of dominant and codominant trees was less affected by spacing than that of the entire stand (table 6–11; Walters 1973, Walters and Schubert 1969). Dominance continued to benefit growth to the 10th year.

Another study in Hawaii involved *P. taeda* (Whitesell 1974). Crown closure occurred by the 4th year for the 1.8- by 1.8-m spacing, by the 7th year for the 2.4- by 2.4- and 3.0- by 3.0-m spacings, and by the 11th year for the 3.7- by 3.7-m spacing (table 6–12). The progressive effects of spacings are again apparent. The benefits of wide spacing on diameter growth continue to increase with time. The decline in basal-area growth at close spacing is indicated by the relative increase in the basal area at the wider spacings.

A study of the same species, *P. taeda,* in the Southeastern United States shows the influence of spacing on harvestable volume (Balmer and others 1978). The age of the plantation (15 years) is not indicative for the

Table 6–10.—Spacing effects on tree yields at 8 years for *Eucalyptus saligna* in Sao Paulo

Spacing (m)	Trees per hectare (thousand)	Mean d.b.h. (cm)	Yield (m^3/ha/yr)	Return on investment (%)
1 by 1	10.2	7.2	33.4	–3.7
1 by 2	5.2	8.6	33.2	3.4
2 by 2	2.6	11.8	30.8	15.8
2 by 3	1.7	12.5	25.8	20.4

Source: Guimaraes 1957, Navarro de Andrade 1939.

Tropics, but the relationships are (table 6–13). The 3.0- by 3.0-m spacing yielded more than three times as many trees larger than 20.3 cm in d.b.h. than the 1.8- by 1.8-m spacing.

Triangular spacing has its proponents who see it as a way to distribute space more uniformly among planted trees. Each tree is placed at the center of a hexagon of six other trees and thus equidistant from each of its neighbors. Triangular spacing allows 15 percent more trees per unit of area than square spacing, or a 7.5-percent greater minimal distance between trees (Wakeley 1954). Triangular spacing is of special interest in experimental studies of spacing, but requires more care in alignment than may be justifiable in large-scale plantings.

Looking to the future, Lewis (1968) concluded that the advantages of a small core of juvenile wood and perhaps smaller branches, which have long been reasons for close spacing, will probably have to be foregone in an era when quantity will be more important than quality.

Planting Guidance. The layout of plantings requires forethought and planning. Access to the area must be provided, and protection from fire and animal damage may be needed from the outset. Tree alignment is important on all but the roughest terrain. Straight rows make row thinning possible (Brown 1965) and facilitate the use of mechanical equipment for culture and harvesting. They also foster uniform spacing and, therefore, fullest use of the site. Plantings have been commonly laid out by means of two long tapes marked with the planting distance. The tapes are laid out at right angles to each other and moved progressively over the terrain for staking each planting spot. This task should be completed before good planting weather arrives. In rough terrain in Mexico, the edge of the plantation has been marked, allowing the planters to use the spacing of the first row as a guide for spacing the trees in each subsequent row (Martinez McNaught 1978). Use of a single tape is normally adequate for mechanized planting.

Planting on all but the most favorable sites in the Tropics is done by hand. The large project at Monte Dourado,

Table 6–11.—Spacing effects and tree growth at 5 years for *Eucalyptus saligna* in Hawaii

Spacing (m)	Mean d.b.h. (cm)		Basal area (m^2/ha)	Comparative 5–10/0–5yr. basal area growth per tree[a] (%)	
	Dominants and codominants	All trees		Dominants and codominants	All trees
2.4	19.0	15.7	33.6	0.98	0.51
3.0	21.3	17.8	27.6	1.01	0.54
3.7	21.8	18.8	20.3	1.05	0.64

Source: Walters 1973, Walters and Schubert 1969.

[a] Basal area growth between the 5th to 10th year as a percentage of the growth for the first 5 years.

Table 6–12.—Influence of spacing on growth of *Pinus taeda* in Hawaii

Spacing (m)	Comparative plantation development[a] (%)					
	Stem diameter			Basal area per hectare		
	4 yr.	7 yr.	11 yr.	4 yr.	7 yr.	11 yr.
1.8	100	100	100	100	100	100
2.4	107	117	119	62	72	79
3.0	107	128	136	43	59	67
3.7	117	143	153	35	51	60

Source: Whitesell 1974.

[a] Relative to 100 for 1.8-m spacings.

Brazil, at least until 1980, has been planted entirely by hand (Woessner 1980a, 1980b). Most tropical sites appropriate for forest plantations do not favor the use of machinery nor do conventional types of containerized planting stock. The trees are carried along the planting lines in trays with wet packing or other containers to protect roots from exposure. Holes are opened in the soil of a size and shape to accommodate the root systems of the trees in a natural position. For bareroot stock, the hole may be made with a bar with a narrow, spadelike blade or with a conventional spade. A danger here is that in an effort to minimize the work, too small an opening is made, and the roots are cramped when the hole is tamped closed. Whatever tool is used, the tree should be set at about the same depth as in the nursery (the root collar at the surface level).

Tamping of planted trees is normally done with the heel of the planter's shoe, firmly on at least two sides. Air pockets must not be allowed to remain in the soil near the roots. Hard-packed, tamped, clay, surface soil should be mulched around the trees with litter to prevent high surface temperature and rapid evaporation.

Table 6–13.—Spacing and yield at 15 years for *Pinus taeda* in the Southeastern United States

Spacing (m)	Trees per hectare	
	D.b.h. > 15.2 cm	D.b.h. > 20.3 cm
1.8	1,373	111
2.4	1,388	496
3.0	1,008	652
3.7	699	642

Source: Balmer and others 1978.

Except when it is in small, rigid tubes, containerized stock requires larger planting holes than bareroot stock. These holes are commonly made with a pick-mattock. This process tends to mix both surface and subsoil and may expose hard clods. When the containers have been carefully opened or removed, it is best to place topsoil against the root mass and then fill the rest of the hole with subsoil, breaking up any large clods. Tamping should be done gently near the root mass, but repeatedly as the planting hole is filled. In dry areas of the Tropics, the holes are sometimes opened early in the wet season to capture moisture before planting (Mathus Morales 1978b).

A major advantage of small, tubular containers is that they require only small, cylindrical holes for planting, which can be made with a pointed metal bar. Special care is needed to ensure that the depth is correct and that tamping eliminates air pockets.

Newly planted trees must be easily identified so the site can be weeded. The use of large planting stock may make this easier, but placing a stake next to smaller trees may be advisable. Ease of relocating trees is a major reason for planting in straight rows.

The use of planting machines has greatly accelerated planting rates on suitable sites. Machine use is limited to large, relatively flat sites that are neither swampy nor rocky and in climates where bareroot seedlings can be expected to survive. Machines use a vertical blade to cut the soil to a desired planting depth. Then, a wedge-shaped blade opens the slit wide enough to allow manual placing of tree roots in the opening. The slit is closed by pressure from two rubber-tired wheels mounted side by side, forming a "V." Two lines may be planted behind a single tractor. As many as 12,000 trees may be planted per machine per day (Chapman and Allan 1978). Machines have been utilized effectively in eastern Venezuela and southern Brazil. The largest mechanized-planting project in the region may be one that involves *P. caribaea* planted on savannas in Venezuela's lower Orinoco basin. Some planted bareroot stock has been lost as a result of unexpectedly dry weather, but subsequent replanting has also been done by machine because of the large scale of the operation.

In Malaysian mangroves, *Rhizophora mucronata* is planted by manually pushing the already germinated hypocotyls deeply into soft mud (Walker 1938).

Some foresters have assumed that under dry conditions, planting stock should be set deeper than in the nursery. But tests in the Sudan with *Azadirachta indica* indicate that on dry sites trees should be planted at the same depth as in the nursery, that is, with the root collar at the surface (Reynders 1965). Also, the desirability of removing the plastic bags from the roots under such conditions has been questioned. Test results with *E. microtheca* in the Sudan suggest that leaving the bags on seriously delays root development and lowers drought and wind resistance of the trees (Wunder 1966). On the other hand, in the miombo woodland region of what is now Zambia, *Eucalyptus* stock has been successfully established leaving the bottomless, black, polyethylene tubes about 9 cm in diameter and 15 cm deep attached around the roots (Cooling 1962a).

Tests of direct seeding in Kenya with *Cupressus lusitanica, P. patula,* and *P. radiata* proved the efficacy of using bamboo slats to direct rainwater to the tree (Howland and Hosegood 1965). Slats 1 m long and 2.5 cm wide were placed in the soil so that each slat stood up at an angle perpendicular to the usual slant of the rainfall; each tree was also surrounded on its lower side by a sleeve of bamboo to retain surface water. The sticks and sleeves proved vital for survival, providing 60 percent more water to the trees.

The cost and quality of the planting job depend on the expertise of the planters. For hand planting, a supervisor is generally needed for every 10 to 16 workers. Worker time must be judiciously balanced between transporting and planting. "Lining out" (the location of tree sites to be planted), if it is to be done at the same time, is better organized as an independent operation, ahead of the planters. Trays that shelter the stock from sun and wind may be carried by the planters themselves, each planter making the planting hole, planting the seedling, and covering the roots. On difficult terrain, one worker makes holes and a partner plants seedlings. The supervisor should check not only for tightness of the soil but also for planting depth and root-system spread.

In tropical America, most trees have been planted by unskilled rural workers. The assumption is that those who plant other crops know what to do, an assumption close enough to the truth to have yielded many successful plantations. One result of such an assumption, however, is unexpected losses from improper care in planting. Initial training should include indoctrination in the purposes and importance of the work, demonstration of each practice, and close observation of initial performance. Instruction in accident prevention and first-aid is also essential. Minimum safety equipment includes special footwear, shinguards, gloves, headgear, and first-aid kits.

Crew training for mechanized planting must be more intensive, involving the use, care, and maintenance of mechanical equipment; inherent and avoidable hazards; accident prevention; and response in case of accidents. Access to safety equipment and first-aid materials is particularly important.

Soil Additives. Trees, like any other crop, require a balanced intake of 13 essential elements for satisfactory growth (Swan 1968). These include the macronutrients—N, P, K, Ca, magnesium (Mg), and sulphur (S)—and the micronutrients or trace elements—B, copper (Cu), iron (Fe), zinc (Zn), Mn, molybdenum (Mo), and chlorine (Cl) (Chapman and Allan 1978). Nutrient deficiencies are common in the marginal soils planted to trees. Tropical forests commonly grow on nutrient-deficient, siliceous sands or highly leached clays. After deforestation, these natural soil deficiencies can be ameliorated only by fertilizing.

Fertilizer use in forest plantations has been much less general in America than elsewhere in the Tropics, although its benefits have in some instances been impressive. Fertilizers have proved capable of increasing the site adaptation of different tree species as well as improving their resistance to pests and diseases (Baule 1979). A worldwide Food and Agriculture Organization (FAO) study of 13,000 fertilizer trials showed an average increase in growth of 73 percent with the application of fertilizer and an increased value-to-cost ratio (Phillips 1972).

Adding nutrients to the soil may spectacularly accelerate tree and stand growth in tropical forests, and the response may last for many years (Swan 1968). The potential gains to be realized by the correction of forest-soil deficiencies in the Tropics are more immediate and substantial than gains produced by other forms of intensive silviculture (Assman 1970). For most end uses, wood produced by trees receiving supplemental nutrients is little, if at all, inferior in quality to wood produced by trees not so favored.

The process of preparing for forest planting accentuates the prospects for nutrient deficiencies. Wholetree logging, clearing, and burning drain nutrients from the site and cause deficiencies just when the new trees most need nutrients—immediately following tree planting (Waring 1972). Studies in Kenya show that planted trees of *E. saligna* begin downward root growth into the moist lower soil layers within 2 weeks of planting (Griffith and Howland 1962). The response of newly planted trees to soil additives has confirmed their almost immediate need for nutrients (fig. 6–5).

Weed control and nutrient supply are the keys to early tree growth in the Tropics. The production gain is permanent, and the full growth potential of the site is directed to the tree at the earliest time (Waring 1972). Increased nutrient levels can also increase the number of tree species or provenances that can be grown as well as their resistance to pests and diseases (Baule 1979). Rational use of mineral fertilizer, selection of appropriate geographic provenances, and procurement of good-quality seeds are considered Brazil's three most important silvicultural requirements (Golfari 1977). Notwithstanding these many benefits, only a negligible area of the land planted to trees in the Tropics has been fertilized (Baule 1979).

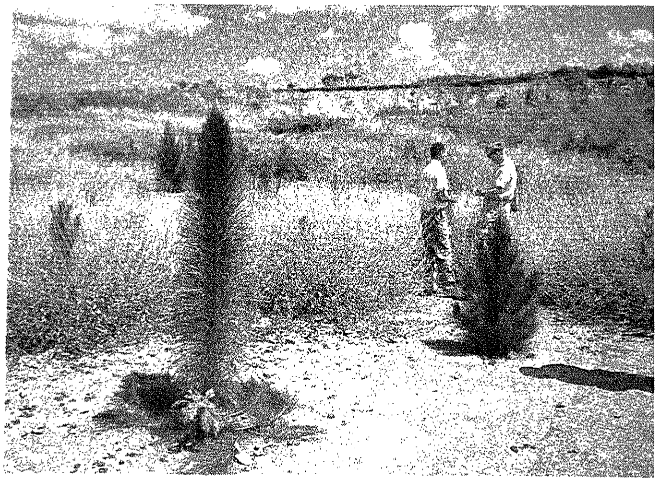


Figure 6–5.—*First-year growth of* Pinus caribaea *was induced by placing fertilizer in the bottom of the planting hole at the time of planting on a poor site in Jamaica.*

The best time for fertilizing is at planting. Fertilizer should be placed in the bottom of the planting hole beneath the reach of the roots of most weeds. Mixing the fertilizer with a small amount of soil may be desirable to avoid "burning" the tree roots. The amount and mix of nutrients or fertilizers should not be haphazard. One source of guidance is local agricultural practice. Another possible source is soil analysis. Yet another is to test in representative areas the early growth responses of trees to different amounts of each nutrient and nutrient combination, with unfertilized trees as controls.

Chemical fertilizers represent but one source of plant nutrients. For centuries farmers have been applying organic residues to their crops. Trees benefit from any residue left from previous forests or crops.

Attention to soil nutrients began early in India, where leguminous *Ipomaea* vines were interplanted in *Casuarina equisetifolia* plantations on beach sands to supply N (Sharma 1951). This practice was later found to be of no significant benefit, evidently because *C. equisitifolia* fixes much of its own N.

On land devastated by tin mining in northern Nigeria, reforestation with *E. camaldulensis* on bare subsoil was tried; a half shovel of compost and about 90 g of ammonium sulphate were added to each tree (Wimbush 1963). The trees grew to 3 to 4 m in height the first year. Without compost application, height growth was half as great.

The use of green manure or plant nutrients in tropical plantations began early with teak in Java (Alphen de Veer 1958b, Sieverts 1958). Teak was growing unsatisfactorily on poor soils. *Leucaena leucocephala,* considered a purveyor of N, was interplanted about 1 month after the teak was planted. But the *L. leucocephala* tended to compete with the teak at the latter's expense. However, heavily pruning back the *L. leucocephala* three times each year and placing the branches around the teak proved a very effective stimulus to the teak (Alphen de Veer 1958b).

Putting mixed, inorganic fertilizers in the planting holes at the time of planting has generally accelerated initial height growth. *Eucalyptus* planted in tubes on poor sites in Hong Kong attained high survival rates, but early growth was slow (Anon. 1954f). The addition of 15 to 30 g of ammonium sulphate per tree at planting time increased height growth by a meter or more within a few months.

In Colombia, poor growth of *Cupressus lusitanica* was found to be due to deficiencies in P and N (Tschinkel 1972b). Application of P fertilizer alone increased stand volume growth by 53 percent. Addition of N alone increased it 58 percent. Applied together, they increased stand volume growth by 230 percent. In the Philippines, application of 12-12-12 and 16-20-0 fertilizer to *E. deglupta* increased tree height by 2 m at 6 months; there was no marked difference between the responses to the two fertilizer mixes (Tagudar and Gianan 1970). In Brazil, the application of NPK greatly increased 1-year *Eucalyptus* height growth, and a difference of as little as 1 m repaid the fertilizer cost (Foot 1968a).

A test treatment of *E. saligna* in the savannas of Minas Gerais, Brazil, showed significant returns from applying 60 g of N, 80 g of P, and 20 g of K to each tree (Knudson and others 1970). Two-year heights for the treated trees averaged 7.2 m compared with 4.2 m for untreated trees. Adding small quantities of B and Zn further raised the mean height of treated trees to 9.1 m. In another experiment with *E. saligna* in the state of Sao Paulo, Brazil, the initial application of 5-17-3 fertilizer yielded, at 5 years, 266 stacked cubic meters per hectare versus 150 for the untreated controls (Simoes and others 1976). Fertilizers increased mean yields of eucalypts in Brazil to 35 m^3/ha/yr (Golfari 1977).

Fertilizer-growth acceleration with *P. caribaea* and *P. patula* in Uganda was limited to trees on sandy and highly leached red soils (Karani 1976b). Fertilizer was no substitute for clean weeding in terms of survival and initial growth. Pines, particularly, have responded unpredictably to fertilizer under many conditions. In Uganda, *P. caribaea* and *P. patula* responded to various fertilizers only on the poorest sands and leached clays (Karani 1976b). On one site, highly significant growth responses were attributed to Mg and K.

The use of slow-release fertilizers has recently been tested as a method of prolonging the stimulus to early growth. Placing such fertilizer about 8 cm from the tree roots in the planting hole at the time of planting resulted in a significant growth difference at the end of the first year for *Toona ciliata* grown in Hawaii (Walters 1975). This test was made in heavy grass, which also grew better because of the treatment, but the tree seedlings outgrew the grass.

Nitrogen has proved to be a key element in most fertilizer trials in the Tropics. The main effect of N is to increase the leaf area (Helms 1976). In a test with *E. deglupta* in Papua New Guinea, height growth increased with foliar N (Lamb 1977). In fact, foliar N accounted for 72 percent of the height variation at 15 months.

Nitrogen usually stimulates growth more than other minerals. Width of growth rings of pines in the Temperate Zone increases with the N content of the needles (Assman 1970). A test with *E. camaldulensis* in the Philippines, using N, P, and K, showed a growth response only to N (Mendoza and Glori 1974).

Light application of N fertilizer (34 kg/ha) at the time of sowing *L. leucocephala* in Papua New Guinea aided growth without inhibiting nodulation (table 6–14; Hill 1970). Note that N applications aided the *L. leucocephala* whether or not plots were weeded, but the higher fertilizer level was no more beneficial in the weeded plots than the lower level.

The scarcity of N in nature may limit the natural occurrence of some tree species. On the coastal lowlands of Queensland, Australia, hoop pine, *Araucaria cunninghamii,* does not occur naturally (Richards 1962). On lateritic and podzolic soils, plantings of this species failed and were replaced with *P. taeda*. After the latter became established, the surviving hoop pines improved. Apparently, hoop pines need N that the *P. taeda*

Table 6–14.—Nitrogen application and weeding benefits to *Leucaena leucocephala* in Papua New Guinea (kg/ha)

Nitrogen application	9-week green wt. of forage	
	Unweeded	Weeded
0	750	960
34	830	1,650
68	1,090	1,650

Source: Hill 1970.

somehow supplies (Richards 1962). This theory is supported by the fact that pure plantings of hoop pines do better with applications of 120 kg/ha/yr of fertilizer (Richards 1967). However, N fixation by pines, although claimed by some, is unsubstantiated. The N might come from other organisms favored by the pines. Native legumes do not supply enough N for hoop pines. Pine litter does not appear to be the source of this N because the hoop pines do well in openings in sparse pine stands that are beyond the littered area but not beyond the root spread. It was postulated that the *P. taeda* might also repress some organisms antagonistic to the hoop pines (Richards 1962). Site "preparation" by the *P. taeda* takes 5 to 6 years. Underplanting *P. taeda* with hoop pines gives promise of success.

Nitrogen-only applications can be chancy (Swan 1969). Many experiments have shown varied results of such treatments, and the equal importance of P and K has repeatedly been demonstrated. Research is needed to clearly distinguish causes of problems.

Growth of *P. caribaea* plantings on coastal sands in Tanzania decreased where N fertilizer was applied without P (Dick 1969). The cause was concluded to be a serious P deficiency. A similarly weak growth response was reported from a controlled experiment of *P. caribaea* in Queensland, Australia (Cameron and others 1981). Application of N plus trace elements led to reduced dry weight after 238 days. These same additives stimulated growth in the presence of P.

A more elaborate study with *P. radiata* in Australia shed additional light on the interaction between N and P (Waring 1968). Applications were made five times during the first 4 years of a plantation's life. Nitrogen, in the form of urea, was applied at the rate of 50 g per tree, or 600 kg/ha. Phosphorus (dicalcium phosphate) was applied at the rate of 20 g per tree, or 235 kg/ha. Nitrogen and P together produced about three times the height growth and five times the basal area growth of the controls. Phosphorus alone almost doubled the N uptake from the soil over that of the controls. Trees receiving both N and P took up more than six times as much N as the controls, or about 25 percent of the applied N. The trees receiving N and P took up 18 percent of the applied P compared with only 3 percent for trees receiving the same quantity of P without N. The addition of P raised N intake by 50 percent, apparently because of an increase of N mineralization or better exploitation of the soil by stimulated root growth. Phosphorus uptake with added N (but no added P) was only 60 percent of what it was without added N, indicating an increased P deficiency in the presence of N.

An Australia-wide test of N, P, and K application at the time of planting showed *E. globulus,* one of the species most planted in western tropical America, to be more responsive to fertilizer than several other *Eucalyptus* species (Cromer and others 1981). The application of N and P greatly affected the N-to-P ratio of the leaves. A ratio of about 15:1 seemed right for *E. globulus* because above that level the response was to P application, below it, the response was to N.

Although foliar analysis has been useful for measuring nutrient deficiencies in the Tropics, Evans (1992) cites data collected from *G. arborea* that indicate a great need for standardizing procedures in collecting leaf samples for comparative analysis (table 6–15).

A test with *P. caribaea bahamensis* on a cerrado site with poor, acid soil in the State of Sao Paulo, Brazil, showed a 1-year height growth of 1.3 m versus 0.8 m for the control; apparently, the difference was due chiefly to the addition of P and Ca (Simoes and others 1976). Experience in Colombia appears to confirm the importance of these two nutrients (Ladrach 1974). *Cupressus* was similarly stimulated by Ca. Tests with *E. grandis* have shown a need for B (Chapman and Allan 1978). Without it, no salable wood yields were produced, but with it, yields reached a mean annual growth of 25 m^3/ha. Studies in

Table 6–15.—Foliar nutrient variation in the leaves of a single *Gmelina arborea* tree

Location of leaves	Nutrient (% oven-dry wt.) N	P	K	Ca
Upper crown				
Topmost	2.10	0.11	1.5	1.0
Outer	1.86	.11	1.6	1.0
Inside	1.69	.10	1.1	1.8
Lower crown				
Outer	1.79	.11	1.5	1.5
Inside	1.39	.08	1.6	1.7

Source: Evans 1992.

Note: N = Nitrogen. K = Potassium.
P = Phosphorus. Ca = Calcium.

Colombia have also shown benefits from B applied to *E. grandis* (Cannon 1981).

In Australia, where the productivity of successive crops of *P. radiata* has been under intensive study, the use of fertilizers has become a necessity. It has been concluded that any decline in soil fertility can be arrested by judicious use of legumes and N fertilizers (Waring 1968).

Irrigation of fuelwood plantations is not uncommon in dry areas throughout the Tropics. At Changa Manga, Pakistan, plantations of *D. sissoo* have received about four times the amount of water used locally for agriculture (Tahir and Ali 1974). After a century of fuelwood production, surface soil had four times the organic matter content of virgin soil and five times its N content. Both P and K content, however, were less than in the virgin soil.

This chapter has presented a variety of experiences with nutrient requirements for planted trees, some with apparently conflicting results. What is illustrated is the great variation in conditions and corresponding needs. Application of inorganic fertilizers should normally be considered only as a supplement to the natural level of nutrients. To the degree that these are unknown, the application of fertilizers can be expected to produce unexpected results, either positive or negative. Trial-and-error at an experimental scale has been the basis for many findings in the past. In the future, fertilizer applications must be based more on prior soil studies.

Chapter 7
Plantation Culture

This chapter, following the chapter that deals with the generation of forest plantations, covers cultural practices designed to make and keep these plantations productive. Experience is called upon from both hemispheres of the Tropics—experience with many different sites and with many different species. Little is said about the economics of plantation culture, the details of which are influenced by local conditions. For this reason, a number of specific cases are presented in the appendices G through M.

Chapman and Allan (1978) offered the following list of necessary planning considerations for managing a timber plantation:

1. *Policy and Objectives*—Those instructions received by the project manager from higher authority as to what the project is to accomplish.
2. *Basic Information*—The project environment, history, land availability and suitability, facilities, institutional framework, and staff.
3. *Future Management*—Future operations to be carried out, working circles, plantation operations, equipment, financial resources, current budget, maintenance, administrative control, and records.

Evans (1992) outlined a sequence of decisions and operations for which planning must be done (table 7–1).

Table 7–1.—Sequence of industrial plantation decisions and operations

Usual silvicultural operation	Main decisions	Crop
Obtain seeds	Species?	Not applicable
Produce planting stock	Season? Containers? Size?	Seedlings Transplants
Prepare ground	Intensity?	Not applicable
Planting	Spacing? Fertilizer?	Young trees
Tending	Frequency? Methods?	Saplings
Low pruning	Need? Partial?	Small poles
Thinning	Timing? Intensity?	Large poles
High pruning	Need? Height?	Large poles
Harvesting	When?	Mature trees
Replant	Changes in species or culture?	Second crop

Source: Evans 1992.

The goal of plantation culture is to increase the volume or quality of the wood produced. The manager, therefore, needs a way to estimate the potential productivity and a means of assessing the effects of treatments on growth. The first may be obtained from volume tables and site-index curves if already published for the region. The second—assessing annual growth—can be difficult. Because growth in the moist Tropics is generally not distinctly seasonal, the growth of most tree species can be ascertained only by repeated measurements. Even with *Pinus caribaea hondurensis,* a species that in sharply seasonal climates forms annual growth rings in its wood, the growth of adjacent trees is highly variable (Slee 1972).

A compendium of the performance of 129 of the best timber plantations in Latin America, classified by approximate life zone, was published in 1960 (Wadsworth 1960). More recently, a summary of plantation performance through the 1980s was issued by the Food and Agriculture Organization (FAO) (Anon. 1985f) to serve as a guide for plantation practices throughout the region.

In summarizing the yields of plantations on grasslands or tropical, high-forest sites, Wood (1974) concluded that the greatest productivity is at medium altitudes; lowland, upper montane, and dry sites are less productive. The faster growing trees can sustain growth rates of 2 m in height per year and 1 cm in diameter at breast height. Production of 35 to 50 cubic meters (25 to 40 tonnes) per hectare per year is well documented. These high yields are limited largely to conifers or eucalypts.

Assessing plantation performance requires average tree sizes at different ages and volume tables or equations to convert these averages into quantities of usable products. An example of the former is a recently published set of site-classification curves for teak *(Tectona grandis)* (fig. 7–1) based on measurements in Colombia, Venezuela, Central America, and the Caribbean (Keogh 1982). Height here refers to "top height," or the height of the largest (in d.b.h.) 100 trees per hectare. Similar curves are also available for *P. caribaea* from Indonesia, Jamaica, and Suriname. Typical cellulose volume tables for *P. elliottii* and *P. taeda* have been produced for southern Brazil (tables 7–2, 7–3; Hosokawa and others 1979).

Site Quality

Plantation performance is a response not only to culture but also to site quality, a complex of climatic, edaphic, and biotic factors. Site quality may be influenced by cultural practices to some extent, but the manager must recognize the limitations. Identifying favorable and unfavorable sites for most tree species is no problem. At one extreme, the tree may not even survive—and at the other, the growth rate culminates (figs. 7–2, 7–3).

A clear site-to-growth relationship exists for teak, as shown in yield data from Java (table 7–4; Alphen de Veer 1958b). Trees on a site V were nearly twice as tall as those on a site II, and their productivity was nearly three times as great. The use of poor sites is costly to volume production. The effects of the site are cumulative, increasing with time.

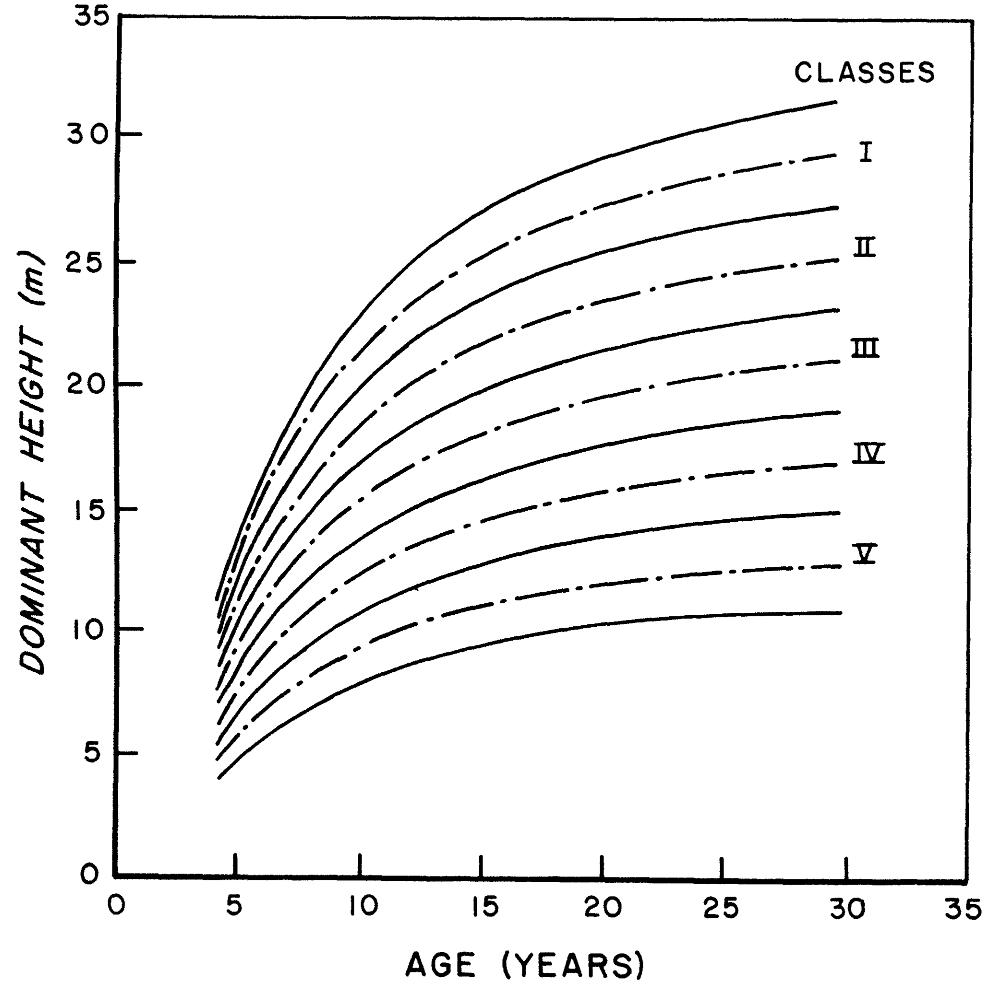


Figure 7–1.—*Site classes for teak in tropical America (Keogh 1982).*

Table 7–2.—Usable cellulose volume of *Pinus elliottii* in Parana, Brazil (m^3)

D.b.h. (cm)	Commercial height (m) 8	10	12	14	16	18	20
16	0.05	0.07	0.10	0.12	0.14		
20		0.12	0.16	0.19	0.23	0.26	
24			0.23	0.27	0.32	0.36	
28				0.37	0.42	0.47	0.52
32				0.47	0.53	0.58	0.64

Source: Hosokawa and others 1979.

Note: Volumes to 6 cm in diameter inside bark.
Regression equation: $V = 0.03096d + 0.0008d^2 - 0.02435h + 0.00291dh + 0.00004d^2h + 0.25225$, where V = volume, d = diameter in centimeters, and h = height in meters.

Wide variation in productivity of *Eucalyptus globulus* was found between sites classified in Madras, India (table 7–5; Krishnaswamy 1957b). *Eucalyptus globulus* in El Salvador is also very responsive to the site (Burgers 1960). Productivity is affected sharply, and the first coppice, which is at least as productive as the seedling crop on good sites, tends to fall behind on the poor site (table 7–6).

Pinus caribaea is very responsive to site quality in Suriname (Vincent 1970). Predicted yields at age 30, based on early growth, are shown in table 7–7. Suriname's site class I is mesic with sandy-loam soil on gradual, lower slopes, well drained but near streams. Site class III is midway between streams and uplands, with loamy-sand soil. Site class V is xeric upland savannas on coarse, white sands. The same species *(P. caribaea),* under premontane humid conditions in Costa Rica, with elevations between 600 and 1,100 m and annual rainfall of 220 cm, produced yields of wood inside bark averaging 45 m^3/ha/yr on 16 sites (Salazar 1976).

The much lower volumes produced in young plantations on relatively poor sites are illustrated in a *P. caribaea* plantation in southern Queensland, Australia (Anon. 1972b). At age 8, the volume of the site-90 plantation was only 22 percent of the volume on site 110 (table 7–8). At age 20, it was 62 percent. Current annual growth also culminates later on the poorer site.

Site-Quality Improvement in Plantations. Site quality and productivity can be improved in plantations. Such improvement is particularly marked on soils that have been degraded by cultivation, grazing, or fire. Litterfall

Table 7–3.—Usable cellulose volume of *Pinus taeda* in Parana, Brazil (m^3)

D.b.h. (cm)	Commercial height (m) 8	10	12	14	16	18	20
16	0.06	0.08	0.10	0.12	0.14		
20		0.14	0.17	0.20	0.23	0.26	
24			0.26	0.30	0.35	0.39	
28				0.39	0.45	0.50	0.56
32				0.51	0.58	0.64	0.70

Source: Hosokawa and others 1979.

Note: Volumes to 6 cm in diameter inside bark.
Regression equation: $V = -0.0140 + 0.0003d^2 - 0.0159h + 0.017dh - 0.000000009d^2h + 0.12766$, where V = volume, d = diameter in centimeters, and h = height in meters.

Figure 7–2.— *Disregard for site qualities such as soil depth or moisture level may lead to poor tree form, as illustrated by this* Gmelina arborea *in Peru.*

beneath a 10-year-old pure teak plantation in west Africa decomposed within 6 months during the dry season and within 1 month during the rainy season (Egunjobi 1974). Significant increases in organic matter on the soil surface were found in teak plantations in Thailand that were only 4 years old (Wasan and Bunwong 1975). By the 15th year, increases were also found in the pH, the cation exchange capacity, phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), but these were not statistically significant, even though they increased site quality.

Figure 7–3.— *A good site produces trees of both good form and rapid growth, as illustrated by these 1-year sprouts of* Paulownia tomentosa *in the Philippines.*

Table 7–4.—Teak *(Tectona grandis)* yields by site quality in Java

Site quality class[a]	Height of tallest 100 trees per hectare (m)		Mean annual increment including thinnings (m^3/ha/yr)	
	30 yr.	80 yr.	30 yr.	80 yr.
II	16	21	3.9	2.9
III	20	27	5.4	4.0
IV	25	33	7.6	5.8
V	29	39	10.5	8.1

Source: Alphen de Veer 1958b.

[a] Classes are defined locally on the basis of tree height at a selected age.

Studies of 23 *P. ponderosa* sites in the United States have shown that tree height increases with soil nitrogen (N) (one component of organic matter) (Zinke 1960). In fact, it was concluded that tree height is an index of total soil N. Presumably, *available* N would show a still stronger relationship. It therefore follows that plantation development that increases soil N should improve the site.

Site-quality changes effected by plantations are not fully understood. The common phenomenon of a coppice stand outproducing the plantation that preceded it suggests that the site may be actually improving. In Kenya, for example, in a first coppice stand of *E. grandis* at rotation age, 20 percent of the stems were larger than 15 cm in d.b.h. compared with only 4 percent in the previous seedling stand (Howland and Freeman 1970). An unknown (but probably significant) proportion of this increase is due not to site improvement, but to the established root systems inherited by the coppice stand.

Site Deterioration in Plantations. Unless compensating measures are taken, site productivity will decline sooner or later where timber crops are being removed. Some indication of this drain is seen in the aboveground biomass of plantations of *P. radiata* in South Africa (table 7–9; van Laar 1982).

The problem of the pure teak plantation, debated in India from the 1930s to the 1950s, reflected preoccupation with the repeated extraction and removal of nutrients from sites that were marginal at the outset. Deterioration of "laterite" soils in India, caused by clear-felling teak and subsequent burning, reportedly could change sites

Table 7–5.—Site effects on productivity of *Eucalyptus globulus* in Madras, India

Age (yr)	Mean d.b.h. (cm)		Mean height (m)		Annual increment (m^3/ha/yr)	
	Site I[a]	Site III	Site I	Site III	Site I	Site III
5	21.0	12.1	21.9	11.3	10.6	5.0
10	31.5	21.0	31.4	15.8	11.3	5.2
15	39.6	25.9	37.8	24.4	10.4	5.0
20	46.1	29.9	41.8	28.0	9.9	4.6

Source: Krishnaswamy 1957b.

[a] Site classes are defined locally on the basis of tree height at a selected age.

from eminently suitable to absolutely unsuitable for teak (Davis 1940). Even the good teak sites that had supported tall trees were poorer for the next crop.

Site deterioration has been documented during the life of closely spaced teak plantations subject to repeated burning of the litter (Bell 1973). In Trinidad, an 11-year-old plantation spaced 2 by 2 m, repeatedly burned over and without undergrowth, was compared to a natural forest. The plantation yielded 25 percent more runoff per unit of rainfall than the forest and eight times as much soil loss per unit of land area (5.6 versus 0.7 t/ha). It was clear that the rate of erosion had to be reduced to the equivalent of the nutrient input rate to maintain site productivity.

Much concern has been expressed recently regarding a prospective decline in site productivity under pines, particularly pure plantations of *P. radiata* in Australia. An early review of possible causes by Florence (1967) deserves mention here. His study pointed out that under mixed species, the forest soil develops properties that vary according to the species of understory trees growing in it; there is wide variation in the chemical composition of the litter and the nature and rate of decomposition. Productivity may depend in part on the accumulation by a single species of a nutrient that might otherwise be limiting. The fact that soils under oaks (*Quercus* spp.) have much higher nutrient-supplying power than those under pines suggests that pine productivity might be increased by the presence of other species.

Florence (1967) further pointed out that soil N content under mixed pines and nonconiferous species is much greater than it is in pure stands of either group. He concludes that this excess N may be the result of a more suitable environment for microbial activity. He cited the work of Tarrant (1961) in *Pseudotsuga menziesii* plantations in the northwestern United States, where the interplanting of *Alnus rubra* greatly increased total N in the soil and in the foliage. Pine plantations in Nigeria reportedly have not changed the physical condition of the soil but have increased the organic matter at the surface and reduced it in the deeper soil layers (Iyamabo 1970). The N level in the soil beneath the pines averaged 24 percent less than on sites without the pines. Florence (1967) also

Table 7–6.—Site effects on productivity of 8-year-old *Eucalyptus globulus* in El Salvador

Site class[a]	Mean height (m)		Yield (m^3/ha/yr)	
	Seedling	Coppice	Seedling	Coppice
I	18	21	9.8	9.8
III	16	17	5.2	5.5
V	14	13	2.8	1.1

Source: Burgers 1960.

[a] Classes are defined locally on the basis of tree height at a selected age.

Table 7–7.—*Pinus caribaea* performance at age 30 in Suriname by site class

Site class[a]	Mean annual increment (m^3)		
	Sawtimber	Pulpwood	Total
I	10.2	5.5	15.7
III	8.4	4.6	13.0
V	0.0	3.3	3.3

Source: Vincent 1970.

[a]Classes are defined locally on the basis of tree height at a selected age.

noted that a number of the introduced timber species that have been outstandingly successful have attributes that ameliorate site adversities.

Evidence of an apparent decline in productivity of *Pinus radiata* in South Australia has appeared as reduced basal area (Bednall 1968). Plantations repeated on the same site gave basal areas of 20 versus 29 m^2/ha at age 15. Bednall determined that none of the factors suggested was conclusively related to the decline. These factors included the soil-water regime, soil type, slash burning, the interval between felling and replanting, and site preparation. He suggested that the following factors deserve study as possible causes of decline: nutrient depletion, depletion of water supply, toxic residuals from the first crop, reduction in the genetic standard, and changes in establishment practices because of residual stumps.

Hatch and Mitchell (1972) suggested that N loss as a result of thinnings may have diminished the growth of subsequent crops of *P. radiata*. This study found that repeated thinnings alone could remove as much as 470 kg/ha of N during a typical pine rotation.

Decreased productivity of second-rotation *P. radiata* has also been reported from New Zealand (Whyte 1973). There, marked declines in height, basal area, and volume growth were apparent in a few areas, whereas in most other areas the declines were minor, and in still others, not apparent. A complication was that comparisons had to be made between plantations that were in close proximity but not in precisely the same location. Some of the declines appeared to be permanent, but most were transitory, limited to the first 5 to 8 years of the second crop.

Whyte (1973) concluded that the declines were enough to extend rotations by 2 years to attain the height of first-rotation crops, by 8 years for the same basal area, and by 5 years for the same total stem volume. He noted that reduced productivity was particularly noticeable on ridges and upper slopes, whereas on valley bottoms the second crop was often better than the first. He recommended shortening the regeneration period and preventing sheet erosion on ridges and slopes.

The complexities of proving a productivity decline were pointed out by Chaffey (1973), who called for long-term plots and detailed stem analyses. He assumed that almost certainly no single cause was at work. The abiotic factors, chemical and physical soil changes, may be

Table 7–8.—Site effects on *Pinus caribaea* in Queensland, Australia

Age (yr)	Standing volume (m^3/ha)		Current annual increment (m^3/ha/yr)	
	Site 90[a]	Site 110	Site 90	Site 110
8	17	76	—[b]	—[b]
10	40	117	11.8	20.7
12	75	172	17.5	27.3
14	123	234	23.9	30.9
16	175	293	25.9	29.8
18	214	343	19.3	24.8
20	241	386	13.7	21.4

Source: Anon. 1972a.

[a]Site quality measured by tree height at a locally selected age.

[b]Insignificant.

Table 7–9.—Aboveground biomass in a 40-year-old *Pinus radiata* plantation in South Africa

Tree d.b.h.	Oven-dry biomass per tree							
	Stemwood		Bark		Branchwood		Needles	
(cm)	(kg)	(%)	(kg)	(%)	(kg)	(%)	(kg)	(%)
30	344	87	36	9	7	2	7	2
60	1,499	81	168	9	138	8	35	2

Source: van Laar 1982.

cyclic. Climatic fluctuations are difficult to assess. The role of the living component of the soil in decomposition cannot be ignored in investigation. Mycorrhizal antagonisms could be responsible in some situations.

A study of logging residues in *P. radiata* plantations in southwest Victoria, Australia, suggests an important source of site deterioration (Flinn and others 1979). The residue on the surface after logging was 796 t/ha. When burning was done to prepare for replanting, 84 percent of the dry matter was lost. Other losses from the residues included 72 percent of the N, 27 percent of the P, 21 percent of the K, 31 percent of the Ca, 16 percent of the Mg, 40 percent of the sulfur (S), 30 percent of the iron (Fe), and 34 percent of the manganese (Mn). Under these circumstances, the recommendation was not to burn.

A review of second-rotation productivity declines in 53 pairs of plots matched on the same site in Swaziland was undertaken by Evans (1978). His results from 14-year-old plantations appear in table 7–10. Evans believed the climate to be the primary cause of the decline. Poorer weather prevailed during the second rotation, particularly shorter wet seasons during the last 3 years. He concluded that the climate obscured (and probably transcended) other site trends. Early volume growth in the second rotation was better than in the first at ages 5 to 6 by a margin of 10 to nearly 25 percent, but declined to 7 percent below the first rotation at age 14. Evans suggested that the constantly increasing constraint might not be climatic. He concluded that neither alarm nor complacency is warranted, but the need for more information is critical.

In a subsequent review, Evans (1980) concluded that evidence is still not adequate to prove a decline in monoculture yields in plantations. He pointed to the confounding factors of improved genetics and management with each rotation, coppices versus seedlings, and cumulative mortality with successive coppice crops. He considered results with *P. radiata* to be confounded by improvements in practice. He found no evidence of decline in *P. elliottii* yields in east Africa, where seeds were collected from the same parent trees. He concluded, however, that trends might still be found that

Table 7–10.—Comparative productivity of first and second rotations of 14-year-old *Pinus patula* in Swaziland

Item	Mean height (m)	Mean volume per tree (m^3)	Volume per hectare (m^3/ha/yr)	MAI[a]
Rotation				
First	18.1	0.243	299	21.4
Second	17.5	0.226	276	19.8
Percent decline	3.4	6.9	7.6	7.5

Source: Evans 1978.

Note: Significance level = 5 percent.

[a] Mean annual increment.

could relate to climatic variation, genetic improvement, direct plantation effects, or silvicultural practices such as thinning, skidding, debris disposal, burning, and fertilizing.

There remains cause for concern over productivity where crops are repeatedly harvested. A net loss of nutrients is inevitable, and sooner or later, compensation must be made if productivity is not to decline. Soil studies alone will not adequately account for the important trends because much of the nutrient supply is in the biomass (Fearnside and Rankin 1980).

The effect of harvested plantations on site quality is further illuminated by studies of the nutrient content in eight plots of *Gmelina arborea* and four of *P. caribaea* in plantations (Chijioke 1980). For both species (tables 7–11, 7–12), stemwood had the lowest percentage of nutrients, but when combined with the bark, it contained more than half the aboveground nutrients of the plantation. Whole-tree harvesting caused 25 percent more nutrient loss than leaving the slash on the site. Leaving the bark would have saved 5 to 10 percent more.

Chijioke's studies provided no evidence that monocultures per se deplete soil nutrient reserves faster than mixtures, *other things being equal.* Rapid nutrient depletion, however, is clearly associated with rapid growth, short rotations, and whole-crop harvesting.

Chijioke concluded that the nutrient immobilized most depends on the age at which the crop is harvested. For example, the quantity of nutrient elements immobilized in *G. arborea* trees 13 to 15 years old is only 6 to 9 percent greater than it is in 5- to 6-year-old trees, yet the biomass is 25 to 66 percent greater. Producing five 5- to 6-year-old crops of *G. arborea* during a 30-year period would be more than twice as demanding as producing two crops 13 to 15 years old during the same period.

According to Chijioke, any decline in tree growth in later rotations on the soils of the Tropics will most likely be the result of the soils' incapacity to convert nutrients from unavailable to available forms at the pace of tree demand, or slow mineralization. He did not foresee any decline as a result of the absence of essential nutrients. In pine plantations, he found no evidence to suggest decline in later rotations to be a result of soil-nutrient losses due to harvesting. He suspected that lowered soil moisture could be more of a limiting factor. He recommended (1) leaving slash, (2) doing no burning, (3) continuously monitoring soil nutrients, and (4) conducting fertilization tests of marginal soils.

Genetic Relationships

Plantation managers must recognize that their crop is highly variable, not only from site to site and species to species but also from tree to tree. Tree species vary in differentiation by provenances. Wide-ranging species are usually less uniform than those with a narrow native

Table 7–11.—Nutrient levels in 6-year-old *Gmelina* plantations in Nigeria and Brazil

	Major nutrients				
Index	N	P	K	Ca	Mg
			Kilograms per hectare		
Nutrient content					
Aboveground (live)	128–352	22–63	93–208	42–185	39–79
Stem and bark	90–182	14–38	71–136	34–108	31–51
			Percent		
Dry weight					
Aboveground	3.49	0.35	2.55	1.64	0.83
Stem and bark	0.71	0.08	0.96	0.86	0.25

Source: Chijioke 1980.

N = Nitrogen. K = Potassium. Mg = Manganese. P = Phosphorus. Ca = Calcium.

Table 7–12.—Nutrient levels in 6-year-old *Pinus caribaea* plantations in Suriname and Brazil

Index	Major nutrients				
	N	P	K	Ca	Mg
	Kilograms per hectare				
Nutrient content					
Aboveground (live)	197	33	46	78	25
Stem and bark	99	21	31	25	17
	Percent				
Dry weight					
Aboveground	1.93	0.13	0.60	1.05	0.28
Stem and bark	0.37	0.03	0.17	0.22	0.08

Source: Chijioke 1980.
N = Nitrogen. K = Potassium. Mg = Manganese. P = Phosphorus. Ca = Calcium.

range (Lines 1968). Exploiting this variation to improve future crops is a management responsibility.

Genetic manipulation, termed "tree improvement," has much to offer the plantation manager. The genetic potential of tree populations varies so widely that tree improvement can often produce trees with characteristics not found in nature (Zobel 1972). Tree improvement may lead not only to higher yields but also to greater tree adaptability to marginal sites and resistance to pests and diseases. Once the genetic makeup of the trees has been improved, genetic manipulation need not be repeated, but further manipulation may result in additional gains.

The Nature of Genetic Variation. Tree form is apparently more heritable than growth capability. Studies of *Cupressus lusitanica* in Kenya (Dyson 1966) indicated that tree size was a poor criterion for selection of crop trees. A study of 11 provenances of *Tectona grandis* in Tanzania showed that straightness and tree height at age 5 were related to source, whereas d.b.h. was not (Persson 1971). Had Trinidad's first teak seeds come from Travancore, India, instead of Tenassarim, in what is now Myanmar, the species might well have been judged a failure because of poor form, heavy branching, and slow height growth (Beard 1943). *Gmelina arborea* in west Africa (such as at Enugu, Nigeria) is reportedly much better formed than in other locations (Anon. 1959d). Tests of 22 provenances of *Swietenia macrophylla* and *S. humilis* in Puerto Rico showed interprovenance differences at age 4 (Geary 1969).

An ingenious study of teak in Nigeria further demonstrated the impropriety of selecting parent trees solely on the basis of their apparent vigor (Wyatt-Smith and Lowe 1972). Thirty-four pairs of dominant and subordinate teak trees were selected from a 14-year-old, unthinned plantation. The dominants had a mean d.b.h. of 23.8 cm; the subordinates, 13.6 cm. Each was budded on teak stocks, and height growth was compared after 1 year. After eliminating variation in the vigor of stocks and mortality, no significant differences in clone heights were found.

Wyatt-Smith and Lowe concluded that the heritability of vigor is low and that if it cannot be demonstrated in vegetative material, it is even less likely to show up in seedling progeny. They further concluded that apparent vigor is not an effective indicator of a superior genotype because inherited differences are almost entirely overwhelmed by environmental influences on vigor.

This low heritability of apparent vigor has important implications (Wyatt-Smith and Lowe 1972). If the environment is almost all important in determining the growth performance of a tree, silviculturists should be able to select and culture the trees they wish to become dominants without fear of dysgenic stand deterioration. A corollary is that harvesting what are apparently the "best" trees in a natural stand may not leave subordinate trees that are genetically inferior.

Evidence that tree characteristics other than apparent vigor may be heritable is seen in the early discovery in

India that the phenomenon of twists in teak stems is independent of any influences soil and treatment may exert (table 7–13; Champion 1930).

The occurrence of branchless leaders (foxtails) in pines in the Tropics is influenced by climate and other site conditions but is also due in part to genetic factors (Anon. 1960b). Under favorable conditions for *P. merkusii* in Indonesia, foxtailing ranged from 0 to 30 percent and was due to soil characteristics (Hamzah and Natawiria 1974). In Malaysia, Greathouse (1973) found foxtailing of *P. caribaea* to range from 30 percent on a good site to 47 percent on a poor one. Yet, the heritability of the foxtailing trait in *P. caribaea* is sufficient to preclude selecting it (Ledig and Whitmore 1981). Also, forking and branch diameter increase with foxtailing.

Foxtails are generally considered inferior trees and are thinned out. Their large, widely spaced branch whorls make them susceptible to wind damage. Nevertheless, in a study of *P. caribaea* in Malaysia, trees with a foxtail of 2.15 m or longer were larger at age 6 on good sites than normal trees (Greathouse 1973); the reverse was true on poor sites.

A common observation in provenance testing is variation in the time of foliage flushing, presumably reflecting climatic differences at the points of origin. A trial in Nigeria of *Cedrela* from Argentina, Belize, Brazil, Costa Rica, Cuba, Jamaica, Mexico, and Puerto Rico showed such variation and led to the hypothesis that it might affect growth rates because of the gains from correlating flushing with the rainy period in the area of introduction (Omogiola 1972).

Table 7–13.—Twisting in teak progeny as related to seed source in India

Seed source		Progeny twisted 7°+ in region of extreme twisting (%)
Parent tree	Surrounding trees	
Imported		
Straight	Straight	1
Local		
Straight	Straight	25
Straight	Twisted	36
Twisted	Straight	59
Twisted	Twisted	65

Source: Champion 1930.

Note: Natural regeneration of twisted trees in forest = 72.

Even the mass collection of seeds from successful local plantations may produce better results than the first generation of imported seeds. Identifying the best local seed sources should be a priority for the plantation manager. The possibility of different responses by individual eucalypts to fertilizer treatment has been suggested as a result of the large variability observed in Zambia (Hans and Burley 1972).

Hybrids of species brought together in plantations are not uncommon, particularly in *Eucalyptus*. Some show hybrid vigor superior to either parent, but variability in all characteristics is a frequent result that is accentuated in later generations (Hans 1974). Strongly inherited *Eucalyptus* characteristics include rate of growth (in contrast to findings with teak) (Wyatt-Smith and Lowe 1972), character of wood (Pryor 1956), and resistance to the large numbers of leaf-eating insects of their native land. In Australia, many species of *Eucalyptus* cover a wide range but occur as small isolated groups, probably crossing within (but possibly not between) groups. This suggests a source of diversity worth investigating (Pryor 1956).

Variation in wood properties among trees and the prospects for their genetic improvement are commonly taken for granted or are expected to result from improvements in other properties such as tree form. Although increased volume production is generally more important than improved wood quality, the two can be manipulated independently, so there is no reason not to improve them simultaneously (Zobel and Kelliston 1973). For example, specific gravity and cell-wall thickness of latewood tracheids (imperforate wood cells) are both important to wood yield and quality for pulp and paper manufacture, and both are heritable enough to permit economically important gains through their genetic manipulation. With *P. caribaea*, there is potential for an increase in specific gravity of from 50 to 80 kg/m^3 through manipulation (Zobel and Kelliston 1973).

When *S. macrophylla* and *S. mahogani* are grown together, as in Cuba and Puerto Rico, an intermediate form (or race) develops that is reportedly a hybrid; it in turn produces an F2 generation with segregated *S. mahagoni*, *S. macrophylla*, and the F1 hybrid (Marquetti and others 1975). The intermediate race is considered superior to the others on certain dry sites (Briscoe and Nobles 1966). Natural variation in the wood of *S. macrophylla* in Bolivia has led to recognition of four different races with a range of specific gravities from 0.55 to 0.71 (Irmay 1949).

Wide variability within the genus *Prosopis* is to be seen in the following examples, all from the closely related species *P. chilensis, P. chilensis glandulosa, P. glandulosa,* and *P. juliflora* (Magini and Tulstrup 1955). Of these, the species that are from arid areas are useful under very dry conditions; those from Mexico are frost hardy; those from Argentina produce the best fodder; those from Peru require good drainage; and those from Argentina are best for irrigated plantations.

Not only is the durability of teak wood variable, but the variability in trees tested from throughout its natural range suggests that genetic factors are largely responsible (Da Costa and others 1961).

Provenance trials of *P. caribaea* in Transvaal and Zululand, South Africa, at age 16 and 17 showed that trees from seeds originating at higher latitudes produced less wood volume but had superior form (Falkenhagen 1979).

Potential Genetic Gains. Attempts at tree improvement in tropical forest plantations have been localized and relatively recent, so the gains that can be achieved by genetic manipulation are yet to be realized. How great those gains might be is suggested by limited data.

Mass selection from 6- to 9-year-old plantations of *P. elliottii* in Queensland, Australia, led to clear improvements in the progeny, both in volume and straightness (Nikles 1966). Phenotypic selection of parent trees proved to be very reliable. Only rarely did mass-selected parents (the 400 most vigorous and well-formed trees per hectare) produce progeny without significant gains over the checks. And in no case have such progeny proven inferior to the checks. While useful gains were obtained from progeny of open-pollinated, selected parents, spectacular gains came from controlled pollination of the same trees.

Thirteen-year-old *P. elliottii* in Australia from closed-pollinated, selected trees showed a gain of 6 percent in total height, 21 percent in straightness, and 22 percent in volume per unit of area (Anon. 1972a).

A resume of genetic gains from tree breeding in the Tropics has been presented by Venkatesh (1976). He listed as types of gains clean cylindrical boles, stem straightness, timber and pulp quality, thinner branches, compact crowns, and less reaction wood. He pointed out that mass selection alone nearly doubled *Eucalyptus* yields in Brazil, from 60 to 112 m^3/ha/yr. Merely converting plus stands (of already selected stock) into seed-production areas by eliminating all undesirable trees can increase productivity 5 to 10 percent. Seed orchards established from outstanding plus trees may increase productivity 10 to 20 percent in the first rotation. Plus-tree seed orchards of *P. caribaea* have provided a gain of up to 50 percent in the proportion of straight stems.

The selection of 25 plus trees of 8 species in Tanzania led to seed crops that yielded 10 percent faster growth than did trees from unselected seeds (Vaclav and Skoupy 1973).

Venkatesh (1976) pointed out that seed orchards started with seedlings were much easier to establish but gave only half the gain of first-stage, clonal orchards. Orchards of progeny-tested trees are likely to gain an additional 35 to 45 percent. Crossing of two closely allied species is another approach to genetic gain. Hybrids of *E. camaldulensis* and *E. tereticornis* in India have shown 30 percent more height growth and 80 percent more d.b.h. growth than either species at 4 years. Hybridization also promises better adaptability to poor drainage, salinity, and drought as well as resistance to pests and diseases. A crossing of *P. caribaea* and *P. elliottii* in Australia produced an F1 hybrid better adapted to swamp sites than either parent (Slee 1969). Moreover, the cross retained the rapid growth rate of *P. caribaea.* Gains in 6-year volume growth due to hybrid vigor are reported from Australia (table 7–14; Anon. 1971–72). Interestingly, the greatest percentage hybrid gains are for unfertilized trees.

Selection of plus trees of *Cupressus lusitanica* in Kenya at the rate of 1 plus tree to 206,400 trees planted led to a 125-percent increase in stem growth and corresponding improvements in other tree characteristics (table 7–15; Dyson 1969).

Further gains are to be expected by crossbreeding superior stock. For example, *Cedrela* grafted onto *Toona* stock resists the shootborer *Hypsipyla grandella* (Grijpma

Table 7–14.—Hybrid vigor in *Pinus caribaea* and *P. elliottii* in Australia

	Mean volume (m^3/hundred trees)			
Stock	No fertilizer	P	NP	NPK and Cu
P. elliottii and *P. caribaea*	3.8	38.9	34.0	38.4
Hybrid	9.6	60.0	59.5	43.6
P. elliottii and *P. hondurensis*	3.3	43.5	39.2	30.9
Hybrid	14.7	75.6	68.0	53.2
P. caribaea and *P. hondurensis*	1.7	33.4	25.6	20.2
Hybrid	6.5	52.7	38.8	34.0
Mean gain, *percent*	250.0	63.0	68.0	46.0

Source: Anon. 1972b.

Note: NPK and Cu = Nitrogen, phosphorus, potassium, and copper.
P. caribaea = P. caribaea caribaea. P. hondurensis = P. caribaea hondurensis.

1976). Because the larvae of the insect die when boring into the tissue of *Toona,* a toxicant is postulated as the source of resistance.

However, genetic gains, if accompanied by a narrowing of the diversity of germplasm, may increase the risk of pest and disease problems (Gibson and Jones 1977).

Economic Considerations in Genetic Tree Improvement. The key controllable plantation expenditures are establishment costs, crop security, and time. Genetic tree improvement could benefit all three. If a tree species is sufficiently variable to respond to selection and is widely used, tree-improvement costs may be greatly exceeded by even minimal benefits (Carlisle and Teich 1975).

From the viewpoint of wood utilization, a good case can be made for investing in tree improvement. For kraft pulp and paper manufacture in the Southern United States, specific gravity is the most important wood property (van Buijtenen and others 1975). With short rotations, tree breeding for high specific gravity is desirable. Modifying paper properties by refining or using additives is generally more expensive than achieving the same result by using genetics or silviculture.

An important economic aspect of tree improvement is the early ability to predict later tree performance. In provenance trials with *P. caribaea* in Transvaal and Zululand, later genetic traits were strongly correlated with those traits visible at age 8 (Falkenhagen 1979). Therefore, it may prove justifiable to wait for the results of progeny tests before embarking on large planting programs (Champion 1943).

Tree Improvement as an Aspect of Management. Tree improvement must be considered to be as integral a part of forest management as is silviculture. Breadth of the genetic base is as important as phenotype performance. Silvicultural practices focusing primarily on rapid growth could compromise productivity in the long run by excessive production of wood with juvenile characteristics and unfavorable earlywood-to-latewood ratios (Bevege 1976).

Pinus caribaea trees in plantations in Australia develop little latewood compared with naturally occurring trees and are, therefore, often of much lower density (Hughes

Table 7–15.—Selection gains with *Cupressus lusitanica* in Kenya

Character	Gain (%)
Stem volume	125
Stem straightness	30
Reduction of canker and fluting	85
Reduction of branches per stem	13
Improvement in branch angle	42
Knot index	45

Source: Dyson 1969.

1968a). This may reduce their value for heavy construction, but it makes them more suitable for joinery. Pulpwood from fast-growing *P. caribaea* plantations is markedly superior to pulpwood from natural forests. The wide natural variability exhibited by this species is partly genetic. It is the task of management to sort out and control these genetic properties for improved utilization (Hughes 1968a).

Plantations will become more important sources of genetic material as dependence on planted trees for future timber increases. As collections of genetic material become more complete, the best sources of genes will be the resultant plantations. "Storage" of different sources in 10-ha plots has been suggested as integral to management (Willan 1973). Because of the value of this material for future production, it probably will be safer in the care of plantation managers than in the wild. Although an attempt to save everything will fail, more than only the best trees must be conserved (Zobel 1978a). The *characteristics* of each provenance as a unit should be preserved through the conservation of many representative trees.

Undertaking Tree Improvement. Before tree breeding proves practical, silvicultural practice must apply interspecific selection to eliminate undesirable parental stock at the species level. Then, within species, genotype and phenotype characteristics may be related and thus reward the selection for good visible traits.

Tree improvement can best be undertaken in a sequence of progressively more intensive steps, including some or all of the following (Cooling 1967; Jones, N. 1967):

- Identify seed origin of established trees.
- Secure from a range of provenances a genetic base adequate for sound selection.
- Compare performance of trees from different provenances.
- Select superior stands.
- Use rogued superior stands as interim seed-source areas.
- Select superior phenotypes.
- Use controlled-pollination seedlings from numerous superior phenotypes to establish interim seed orchards.
- Screen controlled-pollination seedlings or vegetatively propagated progeny (including tissue culture) of superior phenotypes; preserve the best in a clonal collection.
- Use either seedling or vegetative propagation to develop (from progeny screening) clonal seed orchards that are adequate for large-scale planting.
- Continue to search for outstanding phenotypes for future improvement and inclusion of new and better genes in the clonal collection and seed orchards.
- Test crosses to determine the potential of hybrids.

An early and important stage in the development of superior trees calls for the interim seed-source areas mentioned above (Kelliston 1969), which serve until seed orchards attain commercial production. These are plus stands from which undesirable phenotypes have been removed and around which isolation barriers against foreign pollen have been established. The progeny from such areas usually have not been tested, so proof of superiority is lacking. However, experience has shown that trees from seeds collected in such areas are superior to those from commercial lots in uniformity, form, and pest resistance (Kelliston 1969).

Wherever there is a prospective plantation of 75,000 ha or more, seed orchards designed to maximize matings among trees selected for desirable characteristics should be established to supply planting material. In a seed orchard, at least 25 clones are required, and 50 to 100 are preferable. They should be planted at twice the density that is ultimately desired and in a random arrangement to ensure separation of the ramets of each clone. Fertilization can promote flowering, and irrigation is also stimulating.

All traits are not 100 percent inherited, as the example of vigor in *Tectona grandis* indicates (Wyatt-Smith and Lowe 1972). Therefore, if optimum results are to be achieved, the degree of heritability of different traits must be determined as early as possible in the selection process because selection for some characteristics may unfavorably affect others.

In east Africa, the selection process began with pine plantations that were at least 10 years old and 10 or more meters tall (Dyson and Paterson 1966). Field personnel made the first selection, based on straightness and circularity of bole, narrowness of crown, freedom from disease, fertility, and size relative to five free, neighboring trees. Other characteristics considered valuable were persistence of the leader, symmetry of the crown, smallness of the branches, flatness of the branch angle, good natural pruning, slight taper, freedom from epicormic branches, and minimal buttressing (Jones, N. 1967). Cores may also be checked from randomly selected trees for ring width, percentage of latewood, fiber length, density, and grain angle. Wood quality is as important a selection criterion as are form and branching habit (Hughes 1973).

Selection criteria for *P. caribaea* in Suriname (Teunissen and Voorhoeve 1973) have included the following:

- Habit, straightness, lack of forks, full crown, diameter, and height above the average of nearby trees
- Branches with an angle of about 90° to the bole
- Nodes not excessively protruding
- Full flowering later than average and of medium abundance
- Few whorls per meter of bole
- Few branches per whorl
- Low ratio of branch diameter to stem diameter
- High ratio of girth at midlength to girth at one-tenth of length.

In Australia, selection criteria have included acceptable wood properties, including minimal spiral grain, moderate basic density, and long fibers (Anon. 1968b).

In Ghana, the search for plus trees of export quality among indigenous genera, such as *Afrormosia, Entandrophragma, Khaya, Tarrietia, Terminalia,* and *Triplochiton,* has been guided by the following criteria (Britwum 1970): (1) bole with minor buttresses and free of fluting, sweep, and other irregularities; (2) bole clear for 30 m or more; (3) no sign of spiral grain; (4) branches small with good natural pruning; and (5) freedom from disease or injuries. From the trees so selected, seed orchards based on grafting were proposed.

Tree-improvement efforts with *E. deglupta* began with seed collection from all apparent variants (throughout the natural range) (Davidson 1973b). When provenance trials reached 11 to 20 years old, superior trees were selected on the basis of vigor, form, and wood density. Seed orchards were then established from seeds from the selected phenotypes, after heavy culling in the nursery. The orchard spacing was wide to foster seed production. Clonal orchards using cuttings and grafting from outstanding phenotypes were also set up.

Experience with *E. deglupta* led Davidson (1973b) to several conclusions that may prove generally useful. Because the growth potential of the species seemed already adequate, the goal was uniformity. Because low cellulose yields had been reported, there seemed a logical opportunity to increase the cellulose percentage in the wood. Wood density varied widely, presenting another opportunity for genetic improvement. However, because wood density is affected by growth rate, the primary goal would be uniformity. Fiber length was found insufficiently variable to warrant much attention.

The timing of flowering and other factors favors self-pollination of eucalypts (Eldridge 1976). Almost all species tested are self-fertile to some degree. Until eucalypt breeding systems and selection consequences are better known, breeders should assume that a lot of nonrandom mating and low heritabilities occurs, and consequently, breeding programs should emphasize family selection rather than selection of individual phenotypes (Eldridge 1976).

The intensity of mass selection should vary with the size and quality of the seed source and the purpose of the collection. From small plantation areas (or within those already improved and made more uniform genetically), as many as one fifth of the trees may be selected (Nikles 1973). On the other hand, selection from unimproved plantations to establish untested clonal seed orchards may require only 1 in 24,000. Such selections for clone banks and open-pollinated progeny tests with *Cupressus lusitanica* and *P. patula* in Colombia have been as selective as 1 in 82,000 (Gutierrez and Ladrach 1978).

Tree spacing in seed-production areas is critical to yields. In 13- to 16-year-old *P. taeda* plantations in Australia, pollen production was greatest at 262 trees per hectare and lowest at 608 trees per hectare (table 7–16; Florence and McWilliam 1956).

Cone production reflects not only pollen availability but also successful pollination. Florence and McWilliam (1956) found that cone production in *P. taeda* in Australia responded significantly to site quality. The effects of spacing on cone production in 13- to 16-year old plantations of *P. elliottii* and *Araucaria cunninghamii* in Australia are shown in table 7–17. The number of *P. elliottii* seeds per cone varied with pollen availability, decreasing in dense stands where little pollen was available. At densities of 140 to 450 trees per hectare, the number of seeds per cone averaged about 100. In contrast, at a density of 790 trees per hectare, there were only 86 seeds per cone (Florence and McWilliam 1956). These studies led to a recommended spacing in thinned, seed-production areas or seed orchards of 7.3 by 7.3 m, or 187 trees per hectare. At age 20, plus stands thinned to this spacing should yield 62 *P. elliottii* cones per tree and 28 kg of viable seeds per hectare, and 70 *A. cunninghamii* cones per tree and 1,120 kg of viable seeds per hectare (Florence and McWilliam 1956).

Orchards may be planted densely with a plan to rogue out some of the genotypes (Shelbourne 1973). Once progeny tests have been completed, a new orchard may be established with those trees of best potential for the combined traits under selection.

Table 7–16.—*Pinus taeda* pollen production as related to tree spacing in 13- to 16-year-old seed orchards in Australia

	Male amenta[a]	
No. of trees per hectare	Per tree (thousands)	Per hectare (hundred thousands)
128	60	78
163	57	93
262	50	132
403	24	95
608	3	19
1,902	2	42

Source: Florence and McWilliam 1956.

[a] Amenta are spikes of unisexual unpetaled flowers.

Tropical America is deeply involved in screening tree provenances. By 1962, air layering of *P. caribaea* was in progress in Trinidad as a beginning of clonal trials (Chalmers 1962). By 1976, Brazil was testing the 3 varieties of *P. caribaea,* as well as *P. elliottii densa, P. kesiya, P. oocarpa,* and *P. pseudostrobus,* some 31 provenances at 13 locations within 3 states. Tests are also in progress in many other countries of the region; Mexico has a program that apparently is comparable to Brazil's (Patino 1976).

Rotation

Selecting a rotation is basic to plantation planning and management. It reflects the tree size needed for the ultimate yield and the expected growth period required to achieve that size. Nevertheless, in the Tropics, plantings have seldom been established fast enough to meet future requirements; therefore, planting has proceeded at a feasible rate, leaving ultimate tree size and rotation tentative because of unforeseeable market changes, economic fluctuations, and unproved growth rates. This uncertainty does not argue against rational planning but merely confirms that a first crop on any site may not grow at the rate predicted by the best informed sources. Added to this uncertainty is the ever widening range of tree diameters as the plantation grows, suggesting different growth periods for different stand components. Market limitations for small trees, long an obstacle to intensive silviculture throughout the Tropics, have been reduced to a point where some rotations have been shortened drastically.

Several types of rotations are recognized (Fenton 1968). A physical rotation is intended to fill any real or anticipated need. A silvicultural rotation optimizes natural regeneration. A technical rotation serves the requirements of given products. A maximum-production rotation provides the greatest mean annual yield of marketable volume. A financial rotation produces the greatest return from a forest area.

The financial rotation tends to be longer than the maximum-production rotation for fuelwood because large trees are cheaper to harvest than small trees. But it tends to be shorter than the rotation of maximum production of large trees because of the cost of carrying investments. The financial rotation length may be extended by a sharp increase in the value of large-diameter trees.

Table 7–17.—The effect of tree spacing on cone production of *Pinus elliottii* and *Araucaria cunninghamii* in Australia

No. of trees per hectare	No. of cones per tree	Cones per hectare (thousands)
P. elliottii		
148	40–120	5.5–16.5
198	32–85	6.4–17.6
445	8–45	3.6–20.8
790	2–14	1.6–16.2
A. cunninghamii		
247	54–85	13.2–21.1
445	32–65	12.1–28.9
692	11–44	6.8–30.1
939	11–18	9.4–17.2
1,423	5–8	5.3–10.8

Source: Florence and McWilliam 1956.

Selecting a rotation is desirable at the outset, but at that time it may be an arbitrary decision because few studies document the costs of and responses to various practices such as thinning and the effects of tree-size distribution and tree age on product quality and value (Fenton 1968).

The variety of markets has led to widespread differences in rotation length. Where fuelwood is the product, rotations not much longer than the time needed to reach the culmination of mean annual increment may be used. The chief constraints here are the high proportion of bark and the cost of handling small trees. For *Leucaena leucocephala,* rotations as short as 2 to 3 years were recommended long ago (Matthews 1914), with the mean d.b.h. as small as 5 cm and the height only about 3 m. More recent studies of the giant varieties of *Leucaena* show a threefold increase per tree in biomass from the 3rd to the 4th year (1.7 to 5.5 kg), suggesting later harvesting if the growth per unit of area is sustained (Pathak and others 1981).

Casuarina equisetifolia, commonly used as fuelwood in the eastern Tropics, has been managed on a rotation of 6 to 10 years (Raghavan 1947). At the other extreme was the rotation set for teak in what is now Myanmar during the 1950s, 150 years for trees 70 cm in d.b.h. on moist sites and 60 cm in d.b.h. on dry sites (Aung Din 1957). Two factors have tended to reduce long rotations. The growing scarcity of large timber in natural forests has adjusted the market to smaller trees. Also, increasing populations and local demand for less specialized wood products have permitted intermediate cuttings that make up more of the yield and thus decrease the average rotation length.

The African species *Aucoumea klaineana,* a source of prized veneer wood, has been planted widely in Gabon (Catinot 1962). Thinnings led to strong sprouting and to studies of the wood for pulp. In plantations of 750 trees per hectare, the wood volume doubled from the 7th to the 10th year and again from the 10th to the 18th (Leroy-Deval 1975). However, because current growth began dropping after the 11th year, it was concluded that the best pulpwood rotation was 11 to 12 years.

Wood Quality. As the rotation increases, there is a decrease in the percentage of the low-quality corewood and the percentage of wood with sloping grain, particularly in pines (Fielding 1967). Increases occur in the average cell length, the average specific gravity (although this may decrease in certain broadleaf species), and the percentage of heartwood. These trends all favor longer rotations for wood quality.

For paper production, there are some drawbacks to short-rotation wood from broadleaf trees. Juvenile wood has more reaction wood, although in rotations of at least 8 years, the specific gravities and pulp yields may equal those of mature wood (Einspahr 1976). Beating-energy requirements and cooking times are less for the short-rotation wood, but for conifers, chemical requirements may be higher. However, the presence of more bark can reduce paper yield and tearing strength.

Rotations used in South Africa with *Eucalyptus* (mostly *E. grandis*) have been 6 to 10 years for posts, pulpwood, and mine timbers; 10 to 14 years for utility poles; and 14 to 30 years for saw and veneer logs (Poynton 1981).

Tree and stand growth provide guidance for determining the optimum rotation. They vary according to site, stand condition, species, and measurement method. Some universal sources of variation, following, have been listed by Assman (1970):

- The age of trees determines not only the growth rates and yields for limited growth periods but also the average yield for the mean tree age.
- Age for age, there are more trees on poor sites.
- For any given mean height, there are fewer stems per unit of area on poor sites.
- At the same crop height, light-demanding species have fewer trees per unit of area than do shade-tolerant species.
- Mean tree diameter is really the quadratic mean, corresponding to the tree's mean basal area. (This mean is also approximately that of a stem with the mean volume.)
- Top height, a useful measure for volume estimates, is the average of the 100 largest trees in d.b.h. on a hectare.
- Basal area growth may culminate and decline before yield becomes important.
- Height growth decreases regularly with age. Site quality should be determined by tree height rather than by crop yield.
- Form factor, a value that converts the product of d.b.h. and total height into tree volume, increases with age as a stand mean.
- Volume growth results from the combined effects of basal area and height growth in addition to changes in the form factor.
- Mean annual volume increment (MAI) of the stand begins to decline well before the MAI of the individual trees.

Usually, the interaction of several parameters that change with the plantation's age determines the rotation. Height, diameter, basal area, and volume all increase, and each culminates later in the life of a plantation than its predecessor. Means culminate still later.

Rotation is often based on the age at which current growth falls to a point equal to the MAI, obviously the culmination of the latter. However, two economic parameters may influence the rotation decision. For most uses, the larger the tree, the more valuable the wood per unit of volume, meaning that the current and mean increases in value culminate later than the increase in volume. On the other hand, carrying charges rise ever more rapidly with cumulative interest, tending to shorten rotations for maximum returns. To these factors must be added local influences, such as risk of blowdown, price fluctuations, yield versus frequency of regeneration costs, and special needs of the owner.

A study in Nigeria with the principal broadleaf species showed that current basal-area growth culminates long before merchantable timber sizes for quality woods are attained (Lowe 1970). For *Tectona grandis, Terminalia ivorensis,* and *Triplochiton scleroxylon,* stem basal-area growth per tree culminates at 7 to 8 years. For *Nauclea diderrichii,* the culmination was between 10 and 12 years.

A number of examples of dates from plantations significant to selection of a rotation are presented in appendix I.

Growth Prediction. As noted before, theories of energy fixation suggest that the maximum potential synthesis of dry wood might reach 60 t/ha/yr (Dawkins 1964b). In actual practice, however, the maximum aboveground production of dry wood, including branches, appears to be 20 to 40 t/ha/yr for *E. grandis, E. regnans, E. saligna, P. merkusii,* and *P. radiata* at high elevations with favorable rainfall and soils (Dawkins 1964b). Comparable limits were 20 t/ha/yr for *Agathis* and *Swietenia* and 10 to 15 t/ha/yr for *Simarouba* and *Tectona*. Generally tropical angiosperms, such as *Aucoumea, Maesopsis, Schefflera,* and *Triplochiton* are not expected to yield more than 5 to 10 t/ha/yr of dry wood. Dawkins (1964a) concluded that for these genera, 11 t/ha/yr was never exceeded, and the usual maximum, with 90-percent crown cover (the greatest practical crown freedom), was less than 8 t/ha/yr. Such yields reflect the effects of using the best available genotypes and microsites, better than management could ever hope for within the existing range of genotypes. Intolerant and light-wooded species showed the lowest yields (Dawkins 1964b).

Many of the data presented in this section are taken from yield tables. Their derivation and use deserve some description. The discussion that follows is adapted from Vuokila (1965). Yield tables deal with attainable yield, not necessarily harvestable yield. They are models and do not necessarily fit any specific stand. They show the progressive development of stands at periodic intervals covering the greater part of their useful life on a specific site. They generally show the number of trees, d.b.h., tree height, basal area, and yields, including thinnings.

Normal yield tables deal with fully stocked natural stands that have never been cut. These tables are useful as a basis for comparison. Empirical yield tables concern average actual stand conditions; some provide yields from residual stands after harvesting. Preliminary or provisional yield tables present single sets of figures for each site under average treatment. Multiple yield tables indicate how stands develop under various degrees of intermediate cutting, usually specifying light, heavy, or low thinnings. These may need revision as practices change.

Variable-density yield tables or functions are more versatile, because they enable the forester to predict the results of any intermediate treatment. They are based on studies of trees rather than stands, where data are required on tree growth under a great variety of conditions. The development of the stand is then derived from that of the trees in it. When properly prepared, these yield tables can be adapted to any stand and any thinning regime.

In the Temperate Zone, the following criteria have been established for predicting volume and growth (Assman 1970):

1. Tree volume, from d.b.h. and total height (R, the coefficient of determination or the correlation coefficient squared = 0.99, meaning that 99 percent of the variation is explained)

2. Stand volume, from stand basal area and height of the 100 largest trees per hectare ($R = 0.99$)

3. Diameter growth, from stand age, height of dominants, d.b.h. of trees, mean d.b.h. of stand, thinning interval, and percentage of basal area removed in thinning ($R = 0.93$)

4. Height growth, from initial mean stand d.b.h., initial tree height, initial age, and initial tree d.b.h. ($R = 0.94$)

5. Basal-area growth, from initial stand age, height of 100 largest trees per hectare, initial basal area per hectare, percentage of basal area removed in thinning, thinning interval, and initial mean d.b.h. of the stand ($R = 0.96$)

6. Volume growth, from MAI in tree d.b.h. between thinnings, initial tree age, initial tree d.b.h., initial height, and mean height of 100 largest (in d.b.h.) trees per hectare ($R = 0.93$).

When comparing volume in the field, workers commonly assume a single form factor for all trees. In East Africa, the same form factor was found applicable to *Cupressus lusitanica, E. saligna,* and *P. patula* (Osmaston 1961). Thus, a "silve" was developed in Uganda for rapid volume comparisons. It was equal to d.b.h.^{2} (in inches) times total height (in feet) divided by 500 (Osmaston 1961). This equation gives a range from 0.96 for a tree 4 inches in d.b.h. and 30 feet tall to 138.24 for a tree 24 inches in d.b.h. and 120 feet tall. In the metric system, the corresponding silve is d.b.h.^{2} (in centimeters) times total height (in meters) divided by 1,000, or 1.0 for a tree 10 cm in d.b.h. and 10 m tall, and 144 for a tree 60 cm in d.b.h. and 40 m tall.

Plantation Treatment

Planting is merely a prelude to plantation establishment. Only in exceptional areas does planting alone ensure survival and development of a satisfactory plantation.

Protection. The first requisite for plantation success is protection from hazards, such as fire, grazing or other animal damage, and human trespass. Local inhabitants can play a key role in preventing, reporting, and controlling problems of this sort. Involving them in the planning and in the employment opportunities offered by plantations is one way to encourage their support. If fire is a serious problem, residents may need to be educated or convinced as to its consequences and trained and equipped to fight fires on a volunteer basis.

Vegetation Control. Worldwide experience has shown that there is a need to control growth of unwanted vegetation (weed growth) on most forest sites. Recently planted trees have small root systems and have just suffered planting shock. In wet climates, herbaceous growth and vines tend to smother even fast-growing trees planted on well-prepared sites. In dry climates, such plants compete with the planted trees for scarce water. Some vegetation control is vital to the success of most plantations. Under adverse conditions, entire plantations may be destroyed by uncontrolled growth.

Weeds in the moist Tropics are so serious a problem that one of the foremost requirements for tree species to be planted in the region is rapid early height growth. First-year height growth of as much as 1.5 m has been specified as a minimum in some places (Lamb 1969b).

The invasion of young plantations by fast-growing, pioneer vegetation may be either harmful or beneficial. The entry of *Musanga cecropioides* into *Aucoumea* plantations in Gabon has been considered harmful and its elimination has been recommended (Deval 1967). In contrast, however, the invasion of *Cecropia* and *Simarouba* into plantations of *Swietenia macrophylla* in Martinique practically eliminated attacks by the mahogany shootborer, evidently because of the added shade provided by these species (Marie 1949).

The optimum weeding intensity must be determined locally. Excessive weed growth in a teak coppice reduced productivity (Laurie 1934a). But keeping rubber plantations continuously weed free resulted in soil erosion and reduced productivity (Haines 1934). On the other hand, clean weeding of *G. arborea* planted at 1.2 by 1.8 m in what is now Malaysia permitted development of a closed canopy within 18 months (Anon. 1948c).

Weeding-intensity requirements vary with the site. On wet sites, competition may be for nutrients or light, so illumination from above must be ensured. Weed growth is rapid and must be set back enough to free the trees for 4 to 6 months or longer. Aboveground growth (and preferably roots) of weeds and vines should be set back or destroyed for a radius of at least 1 m around each tree. At some spacings, this is almost equivalent to complete weeding. This intensity of weeding should no longer be necessary when the trees reach 2 m in height.

On dry sites, competition is chiefly for moisture, so weeds must be removed for a distance beyond that of aboveground contact with the seedling, to a radius of 1.5 m or more, meaning complete weeding. Weed roots should be grubbed out (Dawkins 1955b, Laurie 1941a). In Zambia, spot weeding around each *P. kesiya* on miombo dry forest sites did not stimulate early growth (Endean and Jones 1972). On the other hand, teak in Tanzania showed a 57-percent increase in height during the first year after clean weeding (Bryant 1968).

The intensity of the weeding that is required also depends on the tree and weed species present. For example, *P. caribaea* in Puerto Rico came up through matojo grass *(Andropogon licormis)* after only an initial weeding around each tree, but with grasses such as *Panicum maximum* and *Pennisetum purpureum,* as many as six weedings during the first 17 months were required (Geary and Zambrana 1972). Clearly, the ease of weed control is an important criterion for classifying planting sites.

An early experiment in what is now Sri Lanka shed light on how much weeding was needed for *Eucalyptus* and other broadleaf species (Holmes 1941). Three patterns of weeding were compared: clean weeding, covering the entire area; strip weeding, limited to the planting lines; and patch weeding, only surrounding each tree. The *Eucalyptus* species were considered established at a height of 2 m and the other species at 3 m.

Clean weeding showed a slight advantage over the other methods at the outset, but by the end of the first year, the strip-weeded trees had caught up. During the second year, patch-weeded trees caught up as well. The best combination of methods was clean weeding the first year followed by strip weeding the second. The trees so treated usually became established in 2 years but always by the third year.

The need for weeding does not cease so promptly everywhere. A 3-year-old plantation of *Cupressus lusitanica* in Colombia had attained an average d.b.h. of 2.8 cm and had long overtopped the herbaceous vegetation, but it lacked vigor and appeared chlorotic. When a dense stand of *Melinus minutifolia* grass was eliminated, the trees so treated increased 50 percent in diameter growth over the untreated trees.

To determine the need for replanting, initial plantation-survival data are needed promptly as well as subsequently, because progressive mortality may result from weed competition. Too often, assessment is done in a slipshod fashion, yielding no reliable information about either the percentage of trees that survived or when or why mortality occurred. Permanent sample rows with a fixed number of trees in each should be selected at random in sufficient numbers to ensure coverage of the range of site conditions. Observations should note possible causes of mortality as well as numbers of living and dead trees. The frequency of survival assessment can best be decided locally. The first assessment should precede the end of the planting season to afford an opportunity to fill gaps. Extra checks might be needed to detect effects of abnormal weather.

Some tree loss at the time of planting or immediately thereafter is to be expected, so provision for replanting should be included in initial project budgets. Trees may be lost through exposure at the time of planting, treatment during planting, or adverse weather shortly afterwards. Because far more trees are planted than may eventually be harvested, such losses are tolerable to some degree. In Mexico, evenly distributed losses as high as 75 percent have been accepted (Martinez McNaught 1978). However, failed patches large enough to allow serious weed invasion usually merit replanting. This should be done during the first year to avoid a permanent age disadvantage for the replanted trees. Replanting represents added investment, generally costs more per tree than initial planting, and may lead to higher weeding costs. Therefore, the causes of mortality in the initial planting bear investigation, and their elimination, where possible, is usually justified economically.

Experience in southern Brazil has shown that eucalypts commonly require weeding for 2 to 3 years (Simoes and others 1976). On the other hand, where their growth is rapid (up to 4.5 m in height at the end of 12 months), no further weeding may be needed. Slow-growing pines are better able to compete with weeds in southern Brazil, so weeding may not be as necessary. Eucalypts are weeded twice per year; pines, four or five times in all.

At Jari, along the Amazon in Brazil, the most serious weeds in plantations are the trees of *Cecropia* spp., which have been poisoned or harvested for cellulose (Woessner 1980a, 1980b). In Trinidad, *P. caribaea* plantings have undergone weeding and vine cutting for 3 years (Lackhan 1976). The need for weeding persists longer on moist sites. Weeding for up to 7 years is required in pine plantations in the wet mountains of Costa Rica (Salazar 1978).

On the grasslands of Papua New Guinea, pine plantations require three weedings the first year, two during the second, and one during each of the third and fifth years (Lamb 1974). In India, plantations of *E. tereticornis* are commonly weeded two to three times per year for 3 years (Lohani 1978). In Fiji, weeding and vine cutting in plantations of *S. macrophylla* are necessary for up to 5 years (Busby 1967).

Natural forest is sometimes retained between rows of underplanted trees to reduce the problem of weed control. But it is a common mistake to assume that underplanted trees will generally come through without weeding. If the planted trees are to grow, they require direct sunlight, which can be rapidly obscured by weeds.

In fact, weeding planted trees within a natural forest is a task almost equivalent to weeding plantations in the open. Openings above the planted trees that are adequate to stimulate their growth will also stimulate herbaceous vine growth. Although the weeds may not be as exuberant in a natural forest as in the open, tending (particularly vine cutting) may be required for 5 years or more. Overhanging crowns must also be cut back.

In Uganda, the limitations of clearing in corridors above underplanted trees were shown in a study by Dawkins (1956). Clearing the entire understory of trees up to 10 m tall was twice as costly as clearing only corridors. However, the corridors closed over in 18 months, almost completely suppressing the planted trees. Removing all of these overlapping branches would almost require clear felling.

Weeding may be done by hand, by machine, or with herbicides. Evans (1992) found that manual methods require the least skill and supervision, and chemical methods, the most. Where dense grass must be completely removed, the labor cost (or employment value!) was 25 worker-days per hectare for manual weeding, 6 to 15 for mechanical, and 1 or 2 for chemical.

Traditionally, plantations that are small or on rough topography are weeded by hand, with machetes and hoes. The machete, probably the most common tool in the region, is skillfully used by most workers. Nevertheless, it is dangerous and is frequently the cause of injuries, both to planted trees and to workers. Training workers in the use of such a tool may seem redundant, but even experienced machete handlers benefit by learning safety techniques. One technique is to hold down vegetation with a forked stick while chopping. Another is constant vigilance for obstructions and other workers while chopping. Safety shoes and shinguards are rarely used and may appear impractical, but they prevent injuries. Crews should be trained and equipped to apply first aid.

In southern Brazil, mechanized weeding using disks and rototillers has been common (Simoes and others 1976). Spacing between the rows must be wide enough to admit the machinery. However, even where mechanical equipment may prove suitable, cleanings between machine-weeded strips may have to be done manually.

Herbicides are frequently more effective than mechanical weeding. A drawback of some herbicides may be the difficulty of transporting the solvent (oil or water) to the site. Nevertheless, herbicides require less human effort and provide longer weed-free periods. Herbicides can kill both excess trees over underplantings and vines and weeds at ground level. Their effectiveness is proved, and when publicly sanctioned chemicals are used as instructed and the process is properly monitored, there should be little cause for environmental concern. The decision to use herbicides hinges largely on a complex of political, economic, and social factors. A rational decision requires a full appraisal of all risks involved, an estimate of the cost of other weeding treatments (Newton 1975), and public sanction.

Herbicides are most commonly applied with hand-operated, knapsack sprayers. Great care must be taken in spraying around recently planted trees, because they, too, are susceptible to some herbicides. Workers must be trained to prevent herbicides from being inhaled or contacting their bodies. The most hazardous stage of the spraying operation in new plantations can be eliminated by placing a conical or cylindrical shield over each tree as nearby weeds are sprayed.

The cost of weeding, which may exceed that of land preparation and planting several times, is a major deterrent to reforestation (Gutierrez 1970, Salazar 1978). On lowland rain forest sites, even *Eucalyptus* may require 17 to 49 days of weeding labor per hectare (Lamb and Bruce 1974). This requirement argues for selecting tree species for planting that are capable of rapid early height growth. Production of trees that are so slow growing that semiannual weedings are required over a period of several years may never be profitable.

Project budgets must provide for weeding; otherwise, funds for new plantings may be reduced by the cost of weeding recent plantations (Iyamabo and Ojo 1972). Any project should also compare the cost-effectiveness of different weeding techniques and intensities. Total weed control may look good but it is not generally necessary. Therefore, significant cost savings may be possible through less frequent or less complete weedings.

Weeding of *Eucalyptus* can be avoided on some sites in South America if the land is completely cultivated and fertilized at the outset (Donald 1971). Fertilizing is not yet common in tropical forests, but agricultural experience suggests that tests are worthwhile.

Cover Crops. Cover crops have been planted under a variety of tropical tree plantations. Indigenous groundcover species have commonly been used in rubber plantations in what is now Malaysia (Haines 1934). They reduce erosion and runoff by increasing percolation of rainwater into the soil, lower soil temperature and thus reduce evaporation, and add organic matter to the soil surface (Haines 1934). Nevertheless, cover crops make demands on the soil. Early experience with leguminous cover crops showed that their greatest benefits came only after they were worked into the soil (Becking 1951).

An exhaustive report (Watson 1973) presents more evidence regarding leguminous groundcovers in rubber plantations. If the cover crop is planted at the same time the rubber is planted, the groundcover may develop rapidly for 3 years and then drop off as the canopy closes. Pot trials indicated that legumes may fix as much as 235 kg/ha of excess N during 5 months. However, legumes may cause a heavy drain on P, requiring the equivalent of 280 kg/ha of rock phosphate in the first

12 months and 110 kg/ha annually thereafter. Nevertheless, legumes grow vigorously and provide a rapid buildup of organic matter on the soil surface (Watson 1973).

Studies in Oubangui-Chari, Central African Republic, indicated that for soil and water conservation, the best cover beneath young coffee plantations was mulch, but this alternative was considered too costly (Forester 1959). Clean-weeding led to excessive soil erosion. Covers of *Paspalum* grass, sweet potatoes, and *Leucaena* were not compatible. *Pueraria* (kudzu), if controlled, was found low in nutrient drain and had about the same beneficial effect on the coffee as clean-weeding.

In tests in southern Queensland, Australia, a perennial leguminous groundcover under *P. caribaea* and *P. elliottii* began to deteriorate after 3 years (Richards 1967). Such covers depressed the yields of exotic pines but stimulated those of native conifers (*Agathis robusta* and *Araucaria cunninghamii*), while increasing the N content of the native conifers and having no effect on the N content of the pines. Nevertheless, the pines still outgrew the natives.

In summary, there has been little conclusive experience concerning good groundcovers under timber plantations. In Puerto Rico, soil and water conservation seems assured if thinning is sufficient to keep the canopy open between the tree crowns. Native herbaceous vegetation provides at the surface a continuous cover that is sufficient to control erosion.

Interplanting. Multiple cropping with timber trees and the use of the taungya system are treated in detail in the next chapter. This section is primarily concerned with interplanting to benefit established timber crops.

Early studies of teak in India showed that the species tolerated *Leucaena* and *Syzygium jambolanum* beneath it (Laurie 1934b). In fact, underplanting bamboo was recommended because where bamboo grows with teak, there is no epicormic branching of the teak.

The role of *Leucaena* in teak plantations was ascertained early in Java, well before the present century (Becking 1951). Teak grew slowly on poor sites and failed to get away. *Leucaena* was found to be an excellent understory. It covers the ground quickly and completely, remaining green during the dry season and thus preventing weeds. It is easy to sow, tolerates teak shade, and can be planted sufficiently close to the teak to favor good trunk formation. *Leucaena* may increase teak productivity 50 percent by increasing soil porosity, humus content, and nutrient levels. It sprouts after fires, prevents erosion, and produces excellent firewood and charcoal. On poor soils, *Leucaena* will outgrow teak and so must be pruned back. Maximum benefits accrue if pruned foliage is placed about the teak trees. Cattle eat the foliage, so other species (such as *Acacia villosa*) have been substituted in some locations.

In India, underplanting teak with trees or shrubs to maintain or improve soil or prevent otherwise inevitable weed growth has reduced basal-area growth of the teak by as much as 33 percent (Venkataramany 1956). This loss must be offset by compensating products from the interplanted crop. Valuable woods, or specialty trees like *Rauwolfia* and *Cinnamomum,* have been recommended for such situations.

Leucaena has been interplanted with *P. merkusii* in Java (Alphen de Veer 1954). While the pines are young, the *Leucaena* must be pruned down, but it dies as soon as the pines close.

Soil Cultivation. The soil under plantations is seldom cultivated after planting except where other crops are interplanted. An experiment with *E. alba* in Brazil showed that annual soil cultivation for 1 to 3 years after planting had no effect on tree development (Guimaraes and others 1959).

Cultivating other crops within tree plantations, however, has been done with some success for over a century. The practice arose in response to two problems: (1) the high cost of tending young plantations limited plantation establishment, and (2) land suitable for agricultural crops was in short supply. The practice, called "taungya," a joint effort by tropical forest landowners and farmers, originated in what is now Myanmar in 1866 (Blanford 1925). Taungya is defined as the establishment by a farmer of a forest crop by planting trees within an agricultural crop and weeding the trees for the duration of the agricultural crop (Dawkins 1958c).

Baur (1964b) pointed out that because taungya is normally associated with a low standard of living, it is sometimes criticized. Yet, in a world facing a population explosion, it may ultimately prove to be the only way for much of the world's population to have any living whatsoever.

The practice has been applied mostly in seasonal forests. It began in India by 1914 and has spread throughout the Tropics since. By 1961, there were 78,000 ha of taungya plantations in Ghana (Danso 1966). There, the timber was first felled by the government; then the villagers cleared, burned, and prepared the area for planting. The government may plant the trees, and afterwards, the farmer intercrops the area for 1 to 3 years.

The discovery in the State of Bombay, India, that natural regeneration of teak was not satisfactory led to the use of taungya there (Kaikini 1960). Also, in the dry forests of Madras, cashew *(Anacardium occidentale)*, which commonly turned yellow and grew slowly, shot forth and grew rapidly when intercultivated with *E. tereticornis* (Rajasingh 1968). One or two food crops have been interplanted with *Eucalyptus* in some parts of India (Lohani 1978).

In what is now Myanmar, taungya proved useful with natural regeneration (Kermode 1952, 1955). When there was more regeneration of valuable tree species in dry and semi-evergreen secondary forests than had been expected, taungya planters were allowed to cultivate between the young trees. Enough teak survived for an average tree spacing of less than 1.8 by 1.8 m. Only one farm crop was generally harvested before the teak took over.

In Malaysia, taungya was tested with *P. caribaea* and apparently was successful (Ramli Mansor and Ong 1972). Results with dipterocarps were reported to be "variable." Experience there emphasizes a need for developing clear working plans before introducing taungya to protect conservation areas and to define agreement terms and the level of tending to be done (Fielding 1972).

At Mayumbe, in what was formerly Zaire, a taungya practice developed with *Terminalia superba* and banana culture (Dawkins 1955b). In this taungya practice, known as "uniformisation par le bas," the farmer, who pays rent for the use of the land, plants bananas a year after forest harvesting; the next year, he or she plants trees supplied by the government. By the end of the fourth or fifth year, the trees are established. Taungya was reportedly successful in Uganda with *Terminalia, Triplochiton,* and several Meliaceae (Lawton 1976).

Taungya was introduced into tropical America in Trinidad for teak planting (Cater 1941). Two agricultural crops were produced before the teak was growing freely. Crops that outgrew the teak were prohibited, including cassava, pigeon peas, okra, and taniers. In Suriname, the system has been used to establish *Cordia alliodora* (Vega 1978). Corn, rice, bananas, and cassava are used with certain restrictions. Cultivation lasts 2 years on sandy soils and 3 years on clay. The farmer continues to care for the trees until the fourth year, at which time they may be 8 m tall. In Puerto Rico, under the name of the "parcelero system," thousands of hectares of worn-out land were reforested successfully with mahogany (*Swietenia* spp.), *Eucalyptus* spp., and other species from 1935 to 1945.

Experience in India has led to several conclusions about the advantages and limitations of taungya (Kadambi 1957). The system may permit cheap plantation establishment and gainful employment (fig. 7–4). Properly managed, the system can also meet at least part of the demand for tillable land. On the other hand, taungya works only in areas where there is a demand for agricultural crops. It also requires sufficient land to ensure continuous rotational cropping for the planters. On the marginal land that is usually available, it exposes the soil and robs it of some fertility. Moreover, taungya does

Figure 7–4.—*Early vegetation control using taungya in Java, interplanting* Leucaena leucocephala, Tectona grandis, *corn, and rice.*

not necessarily substitute for all tending because further care is usually needed after the farmers leave (Danso 1966). An early but profound observation about taungya was that success depends on making it attractive to the farmers and showing them that it is in their best interests (Kennedy 1930).

Irrigation. Irrigating timber trees may seem a questionable investment. Yet because trees are desperately needed in tropical dry regions, many irrigated plantations have been established in the Eastern Hemisphere.

Some of the earliest and most successful irrigated plantations are in Punjab, India (Kitchingman 1944), where desert receiving 20 to 50 cm of rainfall annually was converted to forest yielding 2.2 to 3.4 t/ha/yr of firewood. The species planted is chiefly *Dalbergia sissoo,* spaced at 1.8 by 3.0 m. At age 6, tree diameters range from 5 to 10 cm and heights to 10 m. At that time, a thinning yields 28 to 35 steres of stacked fuelwood per hectare. At 12 years, a second thinning takes an equal volume, and the final felling is in the 20th year. The four major irrigated plantations in the region in 1944 are described in table 7–18 (Kitchingman 1944).

A more recent trial of irrigated plantings for wood was started in the Sudan (Booth 1965). Early results were promising with *Acacia farnesiana, Albizia lebbek, Casuarina cunninghamiana, Conocarpus latifolius, D. sissoo, Eucalyptus* spp., *G. arborea, L. leucocephala, Melia azedarach, Prosopis juliflora,* and the bamboo, *Dendrocalamus strictus.*

The water requirements for irrigated plantations are indicated by a test in Pakistan (Sheikh and Masrur 1972). These requirements were summed for a 7-month growing season by three irrigation techniques: drip, trench, and flood. Amounts needed proved to be 2.2 m^3 per tree for drip, 9.9 m^3 for trench, and 14.9 m^3 for flood. Corresponding mean seasonal height growths were 61 cm, 66 cm, and 81 cm, respectively. Height growth per cubic meter of water by the three techniques was 28 cm, 7 cm, and 5 cm, respectively, indicating that drip irrigation was the most efficient.

Burning. Burning litter beneath established plantations releases N and may add ammonium nitrogen to the underlying humus and mineral soil layers (Wollum and Davey 1975). Subsequent nitrification may result from increased availability of substrate ammonium and essential elements.

A long-term test of annual burning in wattle plantations (*Acacia* spp.) in Natal, South Africa, showed no adverse effect on the quality or yield of this legume (Beard and Darby 1951). Nor was there any measurable decrease in the humus content of the soil, its water-holding capacity, or stored moisture. The pH increased slightly, but no adverse effects were apparent. Ten years later it was concluded that burning adversely affected crop performance only when the ash was lost by water or wind erosion (Beard 1961).

It is common for coniferous plantations to be burned inadvertently. They tend to be well adapted to fire and thus resist fairly well. In fact, controlled burning in pine stands, a common practice in the Temperate Zone, has been recommended in Brazilian plantations of *P. elliottii* and *P. taeda* to reduce the fire hazard from a fuel buildup (Soares 1975).

Fertilizers. Tree plantations capture, conserve, and recycle large volumes of nutrients; so fertilizer needs, if any, are much less than for agricultural crops. The nutrient return through litter from a *Eucalyptus* hybrid plantation in India illustrates this point (table 7–19; George

Table 7–18.—Area and growth of irrigated plantations in India in 1944

Plantation	Year begun	1944 area (ha)	Mean annual increment (m^3/ha/yr)
Changa Manga	1866	4,200	20
Chichawathi	1913	3,620	10
Khanewal	1915	6,300	6
Daphar	1919	2,670	8

Source: Kitchingman 1944.

Table 7-19.—Nutrient return through litter in a *Eucalyptus* hybrid plantation in India

Plantation age (yr)	Annual return of nutrients from litter (kg/ha)				
	N	P	K	Ca	Mg
5	29.8	1.6	15.0	40.2	5.0
10	59.2	3.9	30.6	73.2	9.3

Source: George 1982.
N = Nitrogen. K = Potassium. Mg = Manganese.
P = Phosphorus. Ca = Calcium.

1982). The plantation, located in a climate with 200 cm of annual rainfall, averaged 11.1 cm in d.b.h. and 14.6 m in height at age 5, and at age 10, it averaged 14.4 cm in d.b.h. and 19.0 m in height.

Wild plants devote about 2.5 percent of their photosynthetic energy to fixing atmospheric N and another 5 percent to reducing recycled nitrate previously fixed through decay (Gutschick 1978). Sooner or later, the exhaustion of fossil fuels will require reliance on photosynthesis for the world's energy requirements. However, because even legumes do not fix all the N they need and N fertilizer may increase crop yields fivefold, greater fertilizer use in agriculture is an attractive, near-term alternative to destroying more forests for intermittent cropping.

There are at least three major reasons, which follow, for using fertilizers in the Tropics:

- Increased food production, which is currently attainable chiefly through the use of fertilizers, is the best hope for soon reducing the pressure to lay waste to the rest of the forests of the Tropics.
- Neither N fixation nor decay can be increased sufficiently, and soon enough, to provide nutrients for the foreseeable food needs of tropical peoples.
- Production and use of fertilizers to produce more food for the Tropics in the near term may well be the highest use of fossil resources.

Gutschick (1978) pointed out that crop rotation with legumes cannot provide even half the yield that current fertilizer use does. The return of all sewage N to fields would offset only about 10 percent of current fertilizer use, and the cost of transportation would negate all but a small fraction of this amount. Moreover, the hydrogen (H) for the ammonia in fertilizers can be generated by the use of abundant coal as well as by limited petroleum.

The need for fertilizers in tropical forest plantations is described well by Lundgren (1978); his arguments are summarized in the paragraphs below. His conclusions, based on experience in Tanzania, appear to be generally applicable to the inherently infertile soils of the humid and subhumid Tropics, regardless of the species planted.

Conversion of natural vegetation to man-made forests using today's management techniques will inevitably deteriorate the soil by decreasing organic matter and nutrient levels, damaging topsoil structure, and reducing porosity. The magnitude and speed of this deterioration will depend on the climate, soil conditions, management practices, and species used.

Any soil deterioration will retard the growth of the trees. It may appear quickly, as a result of soil compaction or erosion, or more slowly, as a result of decreased water-retention capacity. The decline may not be significant during the first two or three tree-crop rotations on favorable sites. It may also be temporarily offset by improved seeds and silvicultural methods; but, because these will increase the demand on soil fertility, the benefit will probably not last beyond one or two rotations. On poor sites, growth may decline late in the first or second rotation.

These concerns, however, are no argument against intensive forest production. Forestry may still be a more ecologically sustainable form of land use than farming. At least some types of site deterioration can be controlled once they are identified.

The fact that site deterioration is likely is less a source of anxiety than is the failure of forest managers to recognize that such a prospect exists. Soil-management research is considered much more important by tropical agriculturists than by foresters. Without much larger investments in site maintenance, long-term forest-yield forecasts could prove illusory.

Most foresters question the urgency of applying soil amendments. Reasons include the fact that trees can utilize existing site resources better than other crops, the belief that sustained productivity can be met through genetics, and the lack of local evidence that forest crops respond to fertilizers (Nwoboshi 1968). As a consequence, investment in fertilizers is not seen as justifiable.

Although the cost of fertilizers is expected to rise, their use in forestry will doubtlessly increase. For one thing, the competition for land may force the need for the higher yields produced by fertilizers (Swan 1965). Moreover, wood scarcities should increase the value of increased yields attributable to fertilizer use. Potential productivity gains from fertilizing appear greater and more immediate than can be expected from other silvicultural practices. Jari now fertilizes 3 times per 5–7 year rotation.

Each of the primary nutrients has a distinct effect on plant development (May 1954). Nitrogen contributes chiefly to vegetative growth, the formation of stems and leaves. Phosphorus encourages root development and hastens seed ripening. Potassium is necessary for assimilation and increases disease resistance. Of these three primary nutrients, none is effective in the absence of the other two.

A worldwide study of 13,000 fertilizer trials was conducted by the Food and Agriculture Organization (FAO) from 1961 to 1964 (Phillips 1972). In tropical America, the tests showed an average growth increase of 95 percent. The value of the added growth in comparison to its costs also generally increased more with time. The study showed that in humid and subhumid areas, the main increase in yield is produced by added N, but this effect may be increased more economically by the addition of P. The addition of K to N and P increased yields in most of the trials. For each of the three nutrients, the largest growth increase is brought about by the first 20 kg/ha. Gains generally culminate at 60 kg/ha, and such applications might be economically sound with genetically improved trees.

Fertilizer application has proved necessary for the survival of many tropical plantations (Ojo and Jackson 1973). Pines in one area of Nigeria grow poorly unless given superphosphate. Eucalypts in parts of Africa suffer severe dieback unless borate fertilizers are applied. Phosphorus is the element that most often generates responses in field trials. In fact, N without P often produces no reaction at all, and N alone can injure pines. Favorable responses to K alone are few.

Nitrogen fertilizers affect both tree form and uniformity (Schultz 1976). Fertilizers increase tree d.b.h. more than height and thus increase taper, reducing the form factor. They also reduce the variability of tree d.b.h. within the plantation (Schultz 1976).

The effects of fertilizers on wood properties not only vary from species to species but also appear to vary from tree to tree (Zobel and others 1961). The treatment of a 16-year-old *P. taeda* plantation in the United States with 180 kg/ha of N, 90 kg/ha of superphosphate and 90 kg/ha of potash for 3 consecutive years produced wood during the subsequent 7 years that was significantly lower in specific gravity (up to 16 percent) than was the wood 7 years before treatment (Zobel and others 1961). Other studies suggest that *P. palustris* and *P. taeda* wood may increase in specific gravity following fertilizer use and that there is no decrease in the quality of the juvenile heart wood or the summerwood percentage (Schmidtling 1973). Any reduction in specific gravity is more than compensated for by the increase in volume production resulting from fertilization and improved culture. Another benefit can be less heartwood at the pulpwood stage.

The common sources of nutrient elements contain about the following percentages of N, P, and K (May 1954):

Nutrient	Percent
Nitrogen	
Sodium nitrate	15
Ammonium sulphate	20
Farmyard manure	0.4–0.7
Phosphorus (P_2O_5)	
Superphosphate	20
Double or triple superphosphate	40
Farmyard manure	0.2–0.4
Potassium	
Potassium sulphate	50
Muriate of potash	48
Wood ash	5–15
Farmyard manure	0.1–0.7

Fertilizer application must be viewed in the context of nutrient balance. The outgo through leaching, erosion, or harvesting must be at least compensated for by additions. A historic example of the consequences of ignoring this need is to be seen in the case of litter removal for fuel from a forest in Germany over a 25-year period

Table 7–20.—Nutrient flux in a *Pinus radiata* plantation on a 35-year rotation in New Zealand

	Nutrients (kg/ha/yr)			
Index	N	P	K	Ca
Input (rainfall)	—[a]	1.1	21.8	3.9
Removal (two thinnings)	6.6	0.9	8.1	5.4
Net balance	—[a]	+0.2	+13.7	−1.5

Source: Will 1968, cited by Schultz 1976.
[a]Data not available.
N = Nitrogen. K = Potassium.
P = Phosphorus. Ca = Calcium.

(Bray and Gorham 1964). This drain reduced the basal-area growth of the forest about two-thirds, and after the practice was discontinued, the forest took 30 years to recover.

The significance of the N balance to wood production is evident in a closely monitored forest in central Europe (Wehrmann 1961). Nitrogen input from precipitation was between 3 and 7 kg/ha/yr, and absorption of ammonia from the air added another 4 to 7 kg/ha/yr. Leaching losses were 2 to 4 kg/ha/yr. Harvesting of "derbholz" (the usable trees, without bark, in excess of 7 cm in diameter) removed N at the rate of 10 kg/ha/yr. Also, harvesting branches, bark, and roots increased N removal to about 20 kg/ha/yr. It was concluded that no form of economic wood production would yield sufficient N to balance these removals even though the use of N-fixing species would be beneficial. Adding needed N by fertilizing would not only eliminate the deficiency but reduce the susceptibility of the forest to fungi and pests (Wehrmann 1961).

Table 7–21.—Net nutrient demands of *Pinus radiata* in New Zealand

	Nutrients demand (kg/ha)			
Period	N	P	K	Ca
First 10 years	493	41	308	201
Next 25 years	0	12	84	90
10 years, second rotation	246	20	199	99

Source: Will 1968, cited by Schultz 1976.
N = Nitrogen. K = Potassium.
P = Phosphorus. Ca = Calcium.

The natural replacement of soil nutrients has not been measured widely in the Tropics. Evidence from Puerto Rico, however, suggests that the K-supplying power of certain common soils may be adequate to sustain forest crops indefinitely. Tests of sandy Ultisols, using 4 years of intensive grass cropping to reduce the K to the replacement level, showed a natural input of about 35 kg/ha/yr of K (Abruna and others 1976). In the uplands, the mean for 17 soils was 90 kg/ha/yr. For six Oxisols, it was about 50 kg/ha/yr. And for seven Inceptisols, ranging from loams over tuffaceous shale to loams derived from coarse diorite, K input averaged 106 kg/ha/yr.

A much larger than average increase in the N content of young planted pines in the United States and Europe, on the order of 50 kg/ha/yr (Richards and Voigt 1965), is not readily explained by the contribution from precipitation (10 to 12 kg/ha/yr). Free-living, N-fixing bacteria contribute less than 10 kg/ha/yr. Experiments using the isotope N^{15} suggest that the soil is the site for fixation of the rest (Richards and Voigt 1965).

Plantations naturally tend to conserve and recycle nutrients, possibly resulting in a larger residual supply for subsequent rotations. About half of the N, P, and K in the needles of *P. taeda* is translocated to other organs immediately before abscission (Schultz 1976). The less mobile elements, Ca and Mg, remain in the needles when they fall. The net demands of *P. radiata* in New Zealand are shown in table 7–20 (Will 1968, cited by Schultz 1976). Table 7–21 suggests that subsequent crops may demand much less from the soil than did the first crop.

This average nutrient balance does not reflect conditions during the early age of the plantation when uptake greatly exceeds return through litterfall. It is at that time that fertilizer may do the most good. The fertilizer need varies with the nutrient requirements of each species. For example, in Australia in a 2-year-old plantation, nutrient uptake by *E. grandis* exceeded that of *P. elliottii* by these percentages: N, 86 percent; P, 197 percent; K, 366 percent; Ca, 1,243 percent; and Mg, 347 percent.

The return of nutrients through litterfall from plantations is a significant source of further growth (table 7–22; Egunjobi 1974).

The amounts of nutrients removed through timber harvesting and the amounts left behind were determined for *Eucalyptus* in the Mediterranean region (Philippis 1966, cited by Singh 1967). There, the average annual rate of removal of P_2O_5 was 8.6 to 10.8 kg/ha, whereas 6.4 to 16.6 kg/ha were left. For K_2, the amounts were 34.5 to 289.3 kg/ha removed and 78.8 to 296.1 kg/ha left. For calcium oxide, they were 70.2 to 136.5 kg/ha removed and 277.7 to 478.1 kg/ha left. The residues left are generally more than the removals.

The significance of new, more intensive timber-harvesting methods on nutrient levels has been studied in the Temperate Zone. In Finland, whole-tree skidding removed half the slash that would have been left by traditional methods and thus removed almost twice as much N and P (Malkonen 1972). Whole-tree chipping in the forest removes 50 percent more N and P. Moreover, loss through logging is not limited to direct removal because leaching is also increased. The prospect of nutrient deficiency becomes greater as forest plantations are relegated to poorer soils so that agriculture can be expanded on the better areas.

Nutrients lost through harvesting will probably eventually have to be replaced by fertilizers, and amounts will have to exceed losses because much of the applied fertilizer leaches.

Studies in Casamance, Senegal, showed that teak litter decomposes rapidly, organic carbon (C) mineralization is active, and N mineralization is restrained (Maheut and Dommergues 1960). Mineral fertilizers will eventually be needed to sustain productivity. It was suggested that this prospect could be ameliorated by mixing species. Species that mineralize C slowly, such as *K. grandifoliola,* might reduce the rate of drain of organic matter. Species that produce organic matter capable of increasing mineralizable N might also improve the nutrient balance.

The nutrient content of five *E. globulus* trees in Italy shows tree-harvesting effects that are relevant to tropical forests (table 7–23; Lubrano 1968). These trees averaged 24 cm in d.b.h. and 21.6 m in height. The percentages in table 7–23 show that removal of the stem and bark in tree harvesting takes more than half the nutrients bound up in the aboveground biomass. In plantations yielding 15 m^3/ha/yr, this would mean an average annual removal of 8.2 kg/ha/yr of N, 2.9 kg of P, 9.9 kg of K, 50.4 kg of Ca, and 4.0 kg of Mg.

Where adding N to a site at the time of planting does not greatly stimulate growth, it may be that competing vegetation is better prepared than freshly planted trees to take advantage of the added N (Wollum and Davey

Table 7–22.—Return of nutrients through litterfall from a 10-year-old teak *(Tectona grandis)* plantation and from natural forests in west Africa

Source	3-year average annual return (kg/ha) N	P	K	Ca	Mg
Teak plantation, Nigeria					
Leaves	82.0	8.4	63.5	179.0	20.0
Seeds, floral parts	6.5	.7	5.6	3.8	.9
Twigs	2.0	.4	2.6	3.5	.6
Total	**90.5**	**9.5**	**71.7**	**186.3**	**21.5**
Moist evergreen forest, Burkina Faso	164.0	11.0	54.0	73.0	—[a]
Moist deciduous forest, Ghana	199.0	7.0	68.0	206.0	—[a]

Source: Egunjobi 1974.

[a] Information for these items not available.

N = Nitrogen. K = Potassium. Mg = Manganese. P = Phosphorus. Ca = Calcium.

Table 7-23.—Nutrient content of five *Eucalyptus globulus* trees grown in Italy

Element	Dry biomass (g/tree)	Aboveground biomass (%)		
		Stem and bark	Branches	Leaves
Nitrogen	672	59	13	28
Phosphorus	57	71	14	15
Potassium	306	60	14	26
Calcium	1,808	68	24	8
Magnesium	301	82	13	5

Source: Lubrano 1968.

1975). Even where competition is controlled, the response to large doses of N is short lived. It is not possible to build long-lasting reserves of N in the soil, as can be done with P and K. Therefore, the amount of N fertilizer needed depends heavily on the plant's *current* requirements (Wollum and Davey 1975). Also, eliminating vegetation that apparently is competing with very young forest trees may not always be beneficial. Some types of vegetation may sufficiently improve the N economy that they more than compensate for any detrimental effects they might otherwise have.

Variable results are surely confounded by the natural supply of nutrients, many applications possibly being made where the nutrient supply was adequate or excessive. Also, in unthinned, established plantations, the trees may be too crowded to react (Schultz 1976).

The long-term benefits of P application are to be seen in a study with *P. radiata* in Australia (Turner 1982). The plantation was treated at age 4. At age 16, the plantation that had been treated with 100 kg/ha of P had 3.2 times the basal area and 4.5 times the volume of the untreated control. After 30 years, the respective mean d.b.h. of the two plantations had reached 38.8 cm and 26.5 cm, and the net returns from the crop were A$8,600 per hectare and A$3,195 per hectare. All treatments except the lowest (25 kg/ha) were profitable.

Still another source of inconsistency in the results of fertilizer tests is the interaction of multiple nutrient deficiencies. Positive results using N and P together, where N alone is either ineffective or detrimental, are common. Such results have been reported with neem *(Azadirachta indica)*, eucalypts, pines, and *Gmelina* (Jackson 1973). Such confusion can be eliminated by including in every test one or more treatments in which all nutrients other than the one being tested are present in available form in abundance.

Even though many tests of fertilizing *Eucalyptus* have produced inconsistent results, there is evidence that optimum nutrient conditions can be achieved and apparently are worth the effort (Cromer and Hausen 1972). In Victoria, Australia, the application of 101 kg/ha of N in the form of ammonium sulphate and ammonium nitrite and 45 kg/ha of P proved optimum, doubling height growth in the subsequent 2 years and increasing wood production tenfold, without any major adverse effects on wood density, extractives, lignin, or pentosan values.

Results of selected fertilizer tests around the world suggest treatments both worthy and unworthy of trial elsewhere. Numerous tests have been made with *P. caribaea*. An early test in what is now Belize compared the effects of applying 14 g, 28 g, and 56 g of triple superphosphate per tree (Anon. 1959g). The smallest amount had a marked effect on height growth, and the larger amounts were only slightly better.

Fertilizer treatments applied to *P. taeda* in south Queensland, Australia, at age 3 showed that the response to P depended on the N status (Richards and Bevege 1967a). To guarantee an immediate response to P, N must be added as well. The benefit-to-cost ratio with fertilizer was 1.33 versus 1.03 without fertilizer. Part of the benefit is that with added nutrients, 2,220 stems per hectare can be sustained until a pulpwood thinning at age 7; without fertilizer, only about 1,000 stems per hectare can be carried.

In Brazil, complete fertilizer applications to *P. caribaea bahamensis* at the time of planting increased first-year height growth by 67 percent, but in the second year the effects of N were no longer significant (Simoes and others 1970). In contrast, applications of P, K, and Ca continued to be beneficial.

In Australia, P applied to 8-year-old *P. taeda* produced remarkable results 4 years later (Anon. 1952a). The volume underbark to a minimum diameter of 7.6 cm at age 12 was 88 m^3/ha or 11 per year, compared to only 7 m^3/ha/yr without fertilizer. With 213 kg/ha of superphosphate broadcast at age 8, the 12-year volume increased 49 m^3/ha, or 12 m^3/ha/yr. With 430 kg/ha of superphosphate, the increase was 84 m^3/ha, or 21 m^3/ha/yr. With 918 kg/ha of superphosphate, the increase was 155 m^3/ha, or 39 m^3/ha/yr. The application of 1,774 kg/ha of superphosphate increased yield 157 m^3/ha, about the same as the next lighter application. These highest yields, five times those without fertilizer, probably cannot be maintained, but they do indicate a strong P deficiency.

Application of fertilizer to *E. saligna* on red-yellow Latosols in Sao Paulo, Brazil, produced spectacular growth increases over 5 years (Mello and others 1970). The application was 53 kg/ha of N, 172 kg/ha of P_2O_5, and 25 kg/ha of K_2O. The yield of the fertilized plantation at 5 years was 50 steres/ha/yr compared with 30 steres/ha/yr for the unfertilized plantation.

In Darwin, Australia, irrigating *Anthocephalus chinensis* with sewage effluent led to growth up to 10.6 cm in d.b.h. and 8.2 m in height in 18 months (Cracium 1978).

These examples of responses to fertilizer have not been presented in complete detail because their significance is qualitative rather than quantitative. Furthermore, for many of these studies, the initial availability of nutrients was unknown as was the amount of the fertilizer actually consumed by the plants. One is left with the clear impression that whatever the local fertilizer use for agricultural crops, the extent of nutrient deficiencies and the response of trees to supplementary nutrients merit study, in nurseries and in young and established plantations, particularly where growth problems exist.

Thinning

Wood products such as lumber and plywood can be made only from trees of certain minimum dimensions. As trees grow above these dimensions, their output and value rise, and the proportion of usable material declines. Even for pulpwood, tree size is important because industrial wood processing is linear; costs are affected more by the number of units handled than by their size. Some 15 to 20 trees 10 cm in d.b.h. must be felled and handled to provide the volume of a single tree 30 cm in d.b.h. Large trees are also more valuable because of the superior quality of their wood for most products. Therefore, forest-production goals, rotation lengths, and silvicultural practices all focus on tree diameter. Diameter growth is generally favored over wood volume or biomass growth as an index of timber-quality production. In most timber plantations, trees are planted too close for all to grow to a large diameter concurrently. These excess trees cost money and they compete for light, nutrients, and moisture. However, their presence accelerates the rate at which the canopy closes and suppresses weed growth. They may also encourage vertical, straight, tree stems and shade out lower branches. They also provide a selection of trees for the final crop.

Effects of Spacing. Under most conditions, initial spacing influences final yield more than does thinning. For example, an unthinned *P. taeda* plantation in the Southern United States spaced at 2.4 by 2.4 m yielded 256 m^3/ha at 34 years compared with 306 m^3/ha from a comparable plantation spaced at 1.5 by 1.5 m (Wakeley 1969). However, thinnings, which took 30 percent of all trees at 15 to 19 years, had no significant effect on 30-year yields at either of these spacings. The wider spacing is considered preferable because of its lower initial cost.

Early observations on spacing effects in the eastern Tropics led to the following conclusions (O'Conner 1935):

- The size attained by a tree at a given age must be related to the growing space previously at its disposal; all other factors influencing its size are fixed by the locality.
- Planted trees, until they start to compete with each other, will exhibit the absolute or normal growth standard for the species and locality.
- Planted trees left to grow unthinned will exhibit the absolute or normal growth standard for the species, locality, and stocking density.

The space required for each tree increases with tree size. For example, *Shorea robusta* trees 10 cm in d.b.h. need only a 2-m triangular spacing to ensure free growth (Suri

1970b). Their needs, as they grow, and those of *A. chinensis* and *Tectona grandis* (Fox 1968b), an extreme light demander, appear in table 7–24.

The effect of initial spacing on the quality of yields is demonstrated by two plantings of *E. camaldulensis* in Israel (Karschon 1960). The stand with the wider spacing showed a marked superiority in quality of yield even at a younger age (table 7–25).

Where biomass rather than tree size or form is the main objective, the highest yields will coincide with the culmination of basal-area growth. In pine plots in Queensland, Australia, spaced to allow free growth, the annual basal-area growth in plantations with 1,360 trees per hectare culminated between 11 and 13 years (Trist 1956). With 620 trees per hectare, basal-area growth culminated in the 13th to 16th year. With 320 trees per hectare, it culminated at 16 to 19 years.

The ratio of actual crown diameter to d.b.h. affects tree growth, and the ratio is partly defined by tree spacing. For example, spacing of *P. elliottii* has been positively shown to be related to the crown diameter-to-d.b.h. ratio (Harns and Collins 1965). Eucalypts do not tolerate interlocking crowns, and therefore, their required crown diameter-to-d.b.h. ratio is an indicator of the needed spacing (Lane-Poole 1936). A ratio of 18 was derived for many *Eucalyptus* species, suggesting that full stocking corresponds to that shown in table 7–26.

Studies in the Temperate Zone with *P. banksiana* and *Populus tremuloides* verify that crown overlap affects growth (Bella 1969). By using the crown-diameter-to-d.b.h. ratios of open-grown trees as a control and measuring the influence of competition on close-grown trees (the summed zone of overlap for competing trees), Bella determined that crown overlap is responsible for 70 percent of the variation in basal-area growth per tree.

Table 7–24.—Spacing requirements in meters for free growth of three tropical tree species by d.b.h.

D.b.h. (cm)	*Anthocephalus chinensis*	*Shorea robusta*	*Tectona grandis*
10	2.0	3.5	9.4
20	4.1	5.1	11.0
30	5.7	6.7	12.3
40	6.5	7.6	13.8
50	—[a]	8.9	15.4
60	—[a]	—[a]	17.0

Source: Fox 1968b, Suri 1970b.

[a] Information for these items not available.

Table 7–25.—Spacing of *Eucalyptus camaldulensis* and resultant tree quality in Israel

Spacing (m)	Age (yr)	Wood suitability (%)		
		Poles	Posts and pulpwood	Chipwood
2 by 2	8	2	57	41
3 by 3	6	6	80	14

Source: Karshon 1960.

Studies have indicated the natural range of crown diameter-to-d.b.h. ratios for many species (Sandrasegaran 1966a): *E. robusta,* 17 to 19; *E. grandis,* 17 to 26 (the low end of the range for large trees 60 cm in d.b.h.); *E. saligna,* 18 to 26; *Swietenia macrophylla,* 18 to 21; *G. arborea,* 18 to 32; *T. grandis,* 22 to 30; and *Maesopsis eminii* (an extreme light demander), 36 to 39.

As an even-aged plantation grows, competition affects trees in several ways (Catinot 1969a). Average tree growth decreases. Three "stories" of trees generally form: dominant, dominated, and overtopped. This stratification results from a differential decrease in the water at the disposal of each tree, correspondingly lower transpiration, a decrease in photosynthesis (because the stomata are less open), and less H, decreasing cambial activity.

Table 7–26.—*Eucalyptus* stocking limit derived from crown-diameter-to-d.b.h. ratio

D.b.h. (cm)	No. of trees per hectare	Basal area (m^2/ha)
10	1,950	16
20	600	19
30	290	21
40	170	22
50	110	22
60	80	22

Source: Lane-Poole 1936.

The minerals available must be allotted more stringently to the ever larger biomass, and fewer constituents are available for new wood. These limitations are seen in the development of four, unthinned, 12-year-old plantations of *P. caribaea* in Puerto Rico (table 7–27; Whitmore and Liegel 1980).

Even where plantation spacing is uniform, local soil variations affect the extent and health of the tree root systems. These influences during establishment and shortly thereafter, before competition among trees sets in, significantly affect the initial and later growth rates of individual trees (Day 1966). The continuing effect of early advantage has been demonstrated in several studies. For example, in a *Triplochiton scleroxylon* plantation in Nigeria, 70 percent of the variation in basal-area growth per tree was related to the basal area of the tree at the beginning of the period (its former relative advantage), and only 11 percent was due to the current proximity of neighboring trees (Lowe 1967b). In a comparable study of *Shorea robusta,* 77.5 percent of the diameter variation was explained by initial size (Suri 1970a).

Tree height at a given age, a standard measure of site quality, is presumed to be essentially unaffected by tree spacing. This assumption is generally true in widely spaced plantations but not in closely spaced ones. A study of *P. elliottii* in the United States showed that in an unthinned plantation, tree height after the 11th year increased with spacing (Harns and Collins 1965). At age 14, the height of the dominant and codominant trees averaged 12.2 m with 2,470 trees per hectare and 9.8 m with 14,820 trees per hectare (Collins 1967).

Table 7–27.—Effects of spacing on unthinned, 12-year-old *Pinus caribaea* in Puerto Rico

Mean triangular spacing (m)	No. of trees per hectare	Mean d.b.h. (cm)	No. of stems per cubic meter
1.6	4,090	15.0	6.3
2.7	1,370	24.1	2.6
3.5	840	27.8	1.6
4.3	550	29.3	1.5

Source: Whitmore and Liegel 1980.

Reasons for Thinning. Thinning may be done to achieve the following (Fraser 1965):

- Accelerate diameter growth (shorten the rotation)
- Increase the percentage of trees reaching maturity
- Improve wood quality (fig. 7–5)
- Provide intermediate yields
- Increase light penetration to develop larger crowns
- Raise the temperature at the forest floor to accelerate decomposition
- Increase internal air currents
- Reduce humidity
- Encourage root development
- Maintain ground cover for erosion control (fig. 7–6).

There is ample evidence that thinning accelerates diameter growth. For example, *E. deglupta* that was thinned 60 percent at 3.5 years of age averaged 18 percent larger in diameter than unthinned trees within a year afterward (Ugalde Arias 1980). But thinnings usually reduce subsequent volume growth; therefore, where usable biomass is the desired product (as is characteristic

Figure 7–5.—*Thinning of* Araucaria angustifolia *in northern Argentina leaves the best trees for the later harvest.*

Figure 7–6.—*Early thinning of pine plantations for posts and poles allows enough light through the canopy to maintain a protective vegetative cover on the ground beneath the trees.*

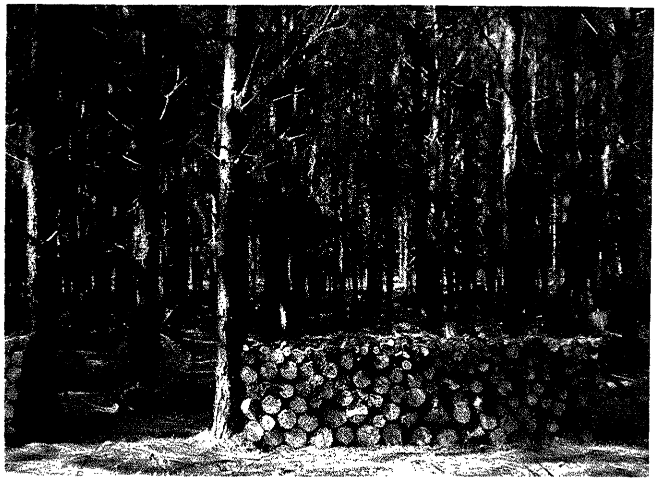


Figure 7–7.—*Thinnings for pulpwood provide early partial retirement of investments in plantations.*

of most *Eucalyptus* plantations), thinning may be counterproductive. Spacing of plantations for biomass is commonly wide enough to permit trees to attain harvestable size without thinning. Spacing may be 2.5 to 3.0 meters, and the trees are harvested at 5 to 12 years for the first crop and every 6 to 8 years thereafter. Genetically improved trees may attain pulpwood size earlier.

In addition to accelerating diameter growth, thinning may offer economic benefits. The early yields generated by thinnings, if marketable, may significantly offset carrying charges of plantations (fig. 7–7). The more rapid growth resulting from thinning should reduce rotation periods. The quality and sale value of the final crop should be near the maximum.

Experience with thinnings under local conditions should reveal the costs and benefits of alternative practices. When these are known, the plantation manager can plan a balanced culture, selecting an optimum combination of spacing, weeding, pruning, thinning, rotation, and yield.

The final product desired profoundly affects thinning practice, as seen from studies of *P. resinosa* in the United States (Lundgren 1981). The optimum residual basal area, regardless of product, proved to be 28 to 32 m^2/ha. For maximum usable biomass, the optimum number of trees was 3,950 per hectare. For usable roundwood volume, it was 1,970 to 2,470 trees per hectare. For sawtimber, it was 500 trees per hectare.

Thinning principles developed many decades ago in India are generally applicable (Singh 1955). These principles call for focusing on the number of trees left, not on the number of trees removed, the freedom of the crowns of the remaining trees, or the size of gaps created.

South African thinning experience led to the development of two coefficients as a basis for thinning regimes (O'Conner 1935). The coefficient of suppression is the quotient of the volume of any tree divided by the volume of a tree of the same age that has been free growing on the same site. The coefficient of response is the quotient of tree growth after thinning divided by that of a comparable unthinned tree. With these coefficients for different tree ages and growing conditions, it is possible to derive the following:

- The best spacing for growth of trees of any size
- The best spacing and rotation for maximum volume production regardless of tree size
- The relative effects of different thinning intensities on tree and stand growth
- A thinning regime for the production of trees of any mature size.

To sustain rapid diameter growth and yet fully use the site for optimum production, three basic thinning decisions must be made: when to thin, how many trees to leave, and which trees to leave.

When to Thin. Thinning should not be done so early in a plantation's life that it favors weed growth or branchiness. On the other hand, once crowding has already reduced diameter growth, thinning will not recover the loss. As trees grow and require more space, thinning should be repeated, leaving progressively fewer trees.

A general case can be made for thinning early in the life of the plantation. If done before competition is severe, thinning can prevent a lasting imbalance between the root systems and crowns of the trees (Day 1966). The idea is reflected in the recommendation for thinning southern pines in the United States while the crowns of the dominant and codominant trees are still 35 to 40 percent of their total heights (Wakeley 1954). Fast-growing, light-demanding *E. deglupta* has been thinned as early as the second year, the thinning yielding 22 m^3/ha, of which 6 m^3 was in poles (Rappard 1951).

Early thinning leads to an early peak in the growth rate as well as an early growth decline (Assman 1970). Stands thinned early may eventually be surpassed in growth by stands subjected to later, lighter thinnings that produce a lower peak but a longer period of growth acceleration.

Early thinning is particularly important with very rapidly growing species such as *Ochroma lagopus.* When *O. lagopus* was planted at 4.3 by 4.3 m in Malaysia, without thinning, only 45 percent of the trees met the prescribed diameter growth rate of 9.7 cm/yr the first year, 13 percent in the second, and none in the third (Wycherly and Mitchell 1962).

Studies of thinning *P. caribaea hondurensis* in Queensland, Australia, showed that as standing basal area increased (up to 60 m^2/ha) basal-area growth also increased, indicating that thinnings confer no benefit to total volume production (Anderson and others 1981). Nevertheless, it was suggested that a single, precommercial thinning at about age 5 to 750 stems per hectare could have other values: eliminating the worst trees, increasing windfirmness, and accelerating the growth rate, yet reducing final yield only about 10 percent. Little mortality is expected before stands reach 70 m^2/ha at rotation age.

How Many Trees to Leave. Desirable plantation spacing may be derived from the unrestrained crown diameters characteristic of different bole diameters. Crown diameters of such trees, a crude index of photosynthesis potential, relate closely to d.b.h. Conifers and eucalypts need crown diameters about 14 times their d.b.h. Most other tropical species need crown diameters about 18 times their d.b.h. These relations suggest maximum basal areas of about 40 and 24 m^2/ha for conifers and eucalypts versus others, respectively, with square spacing. Thinning intensities for plantations of various stem diameters that would leave adequate crown space between each 15-year thinning are given in table 7–28.

Basal area has been used in Trinidad as a guide for thinning *P. caribaea* (Lackhan 1976). In the absence of markets for products of early thinnings, only 1,330 trees are planted per hectare. When the stands reach a basal area of about 25 m^2/ha, at age 10 to 15, about 7 m^2 are removed. When the remaining basal area reaches 26 m^2/ha, another 5 m^2 are removed.

Guiding thinning intensity by crown diameters in reality addresses crown areas, assuming that a crown area adequate to support acceptable diameter-growth rates must be accommodated. Theoretically, the tree crowns could develop so that they complement each other perfectly and utilize the entire area. This would mean that the maximum number of trees per hectare to be accommodated (just before thinning), using triangular spacing, might be 10,000 divided by 0.866 multiplied by the crown area per tree in square meters.

Which Trees to Leave. The third basic decision, which trees to leave, focuses on the final product. Because thinning is usually practiced only where large, well-formed, clean stems are the goal, the trees left to grow must include those that potentially meet these standards. Ideally, the largest and straightest, equally spaced trees should be left. Such thinnings are termed "from below," because it is chiefly the small trees that are removed. In Trinidad, for example, thinnings of *P. caribaea* plantations have concentrated on dying, diseased, and suppressed trees; whips (slender-crowned trees damaged by neighboring tree crowns); wolf trees (broad-crowned trees of poor form); badly compressed subdominants; and codominants that interfere with good dominants (Lackhan 1976).

A technique widely used in young plantations because of the ease of supervision is mechanical or row thinning, that is, removing alternate rows. Among young trees, row thinning does not remove so many potentially good

Table 7–28.—Fifteen-year thinning regimes for tropical tree species based on the relations between crown diameter and d.b.h.

D.b.h. (cm)	No. of trees per hectare[a]		No. of removals per hectare	
	Conifers and eucalypts	Others	Conifers and eucalypts	Others
15	1,300	1,100	740	760
30	560	340	310	190
45	250	150	250	70
60	0	80	0	80

Note: For triangular spacing, divide the number of trees per hectare by 0.866 and increase removals accordingly.

[a] Desirable plantation spacings: conifers and eucalypts, 14 × d.b.h.; others, 18 × d.b.h.

trees as to preclude later selection of a quality crop. Where removal of alternate rows is inadequate for the first thinning, additional trees within the remaining rows may be removed from below. Another approach is to set a minimum crop-tree diameter and remove trees of lower diameters. A marked tape or fixed caliper can facilitate their identification.

A study of 6-year-old *P. patula* in Colombia (Ladrach 1979) showed that after mechanical (row) thinning, 50 percent of the trees immediately increased their mean d.b.h. from 10.4 to 10.9 cm. Thinning by individual tree selection from below raised the mean d.b.h. from 10.9 to 12.7 cm. Four years later, a difference of 1.5 cm in diameter growth favored thinning from below.

Thinning from below automatically boosts mean tree diameter because the smallest trees are removed. This increase, of course, is not a reflection of growth. A spectacular illustration of the instantaneous gains available from thinning is apparent in data for *Anthocephalus chinensis* from Sabah (Fox 1968b) summarized in table 7–29. These data show that selecting the larger trees for the crop can increase the mean diameter by 50 percent or more. Studies of growth stimulation should relate to mean diameters after (rather than before) thinning. This relation to growth rate is apparent in data from 30-year-old plantations of *Swietenia macrophylla* and *Tarrietia utilis* in Ivory Coast (Martinot-Lagarde 1961), as summarized in table 7–30.

The importance of distinguishing spacing effects on the size of final crop trees (most of which are dominants) from the effects on the average tree is illustrated by studies of *Cupressus lusitanica* in Kenya (Pudden 1959). Regression analysis of data from thousands of hectares of plantations showed stand density to have a negligible effect on either the diameter or height of the final crop trees. This raises a basic question as to some of the purported benefits of thinning.

Recommendations from Uganda on thinning (Lamb 1968e) focus on the quality of the trees to be left rather than on the deficiencies of those to be removed. The form and height of residual trees have been considered more important than stem diameter. Selecting the best trees requires the weighing of other characteristics, such as: the absence of crook or sweep; the lack of bole fluting; the size, angle, and persistence of branches; their apparent immunity to fungi and insect attacks; and their height and d.b.h. excess over their nearest five neighbors. Isolated plantations thinned once or twice using these criteria are potentially superior seed sources. Especially outstanding trees could serve for vegetative propagation of selected clones.

Generally, trees are selected for removal as much to upgrade the remaining crop as to obtain an intermediate yield. For this reason, the best trees are left and the worst removed. Dead and dying (or totally oppressed) trees are removed if marketable, but otherwise their removal is of little or no significance to future productivity. Trees with form too poor to yield primary products, regardless of their vigor, are generally next in priority for removal. And finally, the remaining trees may be thinned to release those most promising. The degree of intervention should seek the most favorable relation between cost and reduction of competition (Schulz and Rodriguez 1966).

If thinning is to maximize acceleration of the more desirable trees left, thinning from below is not sharply focused on this objective because some of the less

Table 7–29.—Size differentiation for unthinned *Anthocephalus chinensis* in Sabah (d.b.h. in cm)

	Spacing			
	3.6- by 3.6-m		6.1- by 6.1-m	
Age (yr)	Mean	Best 50 trees per hectare	Mean	Best 50 trees per hectare
4.0	—[a]	—[a]	12.8	19.9
6.0	—[a]	—[a]	19.0	26.5
8.0	14.0	25.5	—[a]	—[a]
11.8	18.0	29.7	—[a]	—[a]

Source: Fox 1968b.

[a] Information for these items not available.

desirable large trees may be competing with the best. An approach being tried with *P. caribaea* in Puerto Rico is to identify and paintmark a generous number of trees for the sawtimber crop (about 300 per hectare). Then, at age 7 to 9, thinning removes as posts only the trees that are adjacent to those that are as tall as or taller than the sawtimber trees yet are not crop trees (those considered to be the only competitors). It is assumed that no further release of the crop trees will be needed but that remaining noncompetitors (those not expected to compete in the future) may be removed for posts before the canopy closes above them, as needed for intermediate products, with little significance to the progress of the crop.

Economic Considerations. To a large extent, practical considerations dictate thinning practice. Thinnings cost money and initially may yield small material for which there may be no market. Plantations where spacing is wide enough to obviate the need for precommercial thinnings may require a longer weeding period and special attention to pruning. Frequent, light thinnings appear to be ideal from the standpoint of sustained, rapid diameter growth but may yield so little usable material that they are impractical. Yet, less frequent thinnings must either be heavier (leaving the forest open and less productive during the period immediately following) or will allow the forest to become too dense for rapid diameter growth before the next thinning.

In Australia, harvesting costs for *P. caribaea* are about double production costs, so substantial savings can be expected from fewer and heavier thinnings (Hanson 1966). For economic reasons, thinning *P. taeda* in the United States for pulpwood is thought to offer no advantages in pulpwood production, and thinnings for sawtimber are considered beneficial chiefly to shorten the rotation (Goebel and others 1974).

Thinning in tropical America is not yet widely justified on economic grounds (Wadsworth 1978) and may not become commonplace until more demand appears for the products of small trees. Production is currently highly oriented toward fiber (Bryant and Williston 1978). Both social and economic goals might be better served by considering lumber and plywood as primary (high-value) products, and pulp, composition boards, and fuelwood as secondary products, however great the proportion of the wood volume entering into the latter.

Table 7–30.—Diameter growth relative to tree size for *Swietenia macrophylla* and *Tarrietia utilis* in Ivory Coast

	Mean annual diameter growth (cm)	
Portion of stand	*S. macrophylla*	*T. utilis*
All trees	0.68	0.63
Largest 300 trees per hectare	1.02	0.80
Largest 150 trees per hectare	1.20	0.96
Largest 50 trees per hectare	1.39	1.14

Source: Martinot-Lagarde 1961.

Effects of Thinning on Wood. To understand how thinning affects wood properties, it is necessary to know how these properties are related to tree age, growth rate, and position of the wood within the stem. For example, it was concluded many years ago that teak timber with fewer than 1.6 rings per centimeter is weak; the strongest wood has 2.0 to 2.4 rings per centimeter (Limaye 1942).

Studies of softwoods grown in the United Kingdom have shown that wood density varies with tree age (Rendle and Phillips 1957). Wide-ring wood formed in middle life is denser than wood of similar ring width laid down in early life. The higher density of later wood does not depend, as has been assumed, on the usual decline in diameter growth. After a certain age, even rapidly growing trees can produce wood of reasonably high density. It would be misleading, however, to assert that wood density depends almost entirely on the age of the tree when the wood is laid down.

Boyd (1968) reported that with age, *P. caribaea* in South Africa rapidly increases in wood density and strength up to about 22 years. The strength of *P. radiata* wood formed during the first 5 years may be less than half the strength of wood formed after 15 to 20 years. The large core of juvenile wood in rapidly grown conifers generally has a low percentage of latewood, low specific gravity, short tracheids, high longitudinal shrinkage, and often spiral grain and compression wood. Nevertheless, conifers (as well as *Eucalyptus*) may at an early age produce wood that is better for papermaking in terms of yield, bursting strength, sheet density, and tearing strength than at a later age. Heavy thinning of pines leads to lower wood density and shorter tracheids. Uneven spacing that may result from thinning can cause asymmetrical stem growth.

Boyd points out that the effects of thinning on angiosperms tend to be more varied. With some species, slow growth leads to lower specific gravity, but the opposite may be true for others. Rapid wood production tends to adversely affect uniformity, texture, dimensional stability, machinability, and wear characteristics. The properties of eucalypt woods tend to vary in proportion to density. Wood from fast-growing plantations is slightly lower in density than the corresponding wood from native forests. Wood from fast-growing eucalypts in Australia is subject to severe manufacturing problems because of growth stresses, but its low density leads to easy seasoning and good machining properties.

Experience with *P. patula* in South Africa has shown a number of defects in wide-ringed timber (Villiers and others 1961). Included are excessive longitudinal shrinkage, uneven texture, knottiness, compression wood, and spiral grain. The first few inner rings invariably contain wood of this type, and the opportunity for restricting the diameter of this core is limited. A spacing of 2.4 by 2.4 m resulted in cores that were only about 2.5 cm smaller than those in trees grown at a spacing of 3.5 by 3.5 m. Close spacings are said to increase the contrast between the corewood and the later wood.

Although rapidly grown conifers tend to have longer tracheids than slowly grown trees, thinning may cause sudden growth rate increases that reduce tracheid length in the new wide rings (Fielding 1967). Silvicultural practices that promote dense, deep crowns on conifers tend to increase production of earlywood and thus reduce specific gravity of the wood near the crown. However, differences in growth rates generally have little if any effect on the specific gravity of the corewood.

Heavy thinning of *P. taeda* in the Southern United States at age 9 increased ring width nearly threefold during the ensuing 4 years, from 0.26 to 0.71 cm (Smith 1968). The percentage of latewood declined from 36 to 28, and specific gravity dropped from 0.45 to 0.42; both decreases were statistically significant.

Effects of Thinning on Yields. Deciding whether or how much to thin has important yield implications. The manager needs to know in advance the magnitude and timing of the potential benefits. Some of the pertinent ways thinning can affect yields—and thus the return on investment—are discussed in more detail in appendix J.

The reduced number of stems limits tree selection for the final crop and the quantity and quality of the product at various stages, including log size, taper, ring width, wood density, fiber length, and the characteristics and distribution of knots (Wardle 1968).

Thinning is based on the premise that beyond a certain limit, increased stand density diminishes usable volume production per unit of forest area. Average stem diameters, branch sizes, and taper all increase with spacing. Susceptibility to fire and to disease and insect attacks may also be reduced by thinning.

Thinning affects not only the remaining trees but also the site. The contribution of litterfall to soil nutrients is closely related to the basal area of the forest and, therefore, is reduced in proportion to the thinning intensity (Bray and Gorham 1964). The residue from thinnings may add a large volume of C to the site, increasing the C-to-N ratio (Wollum and Davey 1975). Exhaustion of N by decomposing organisms might be expected but has not been reported.

Thinning Systems. Thinning systems involve intensity, tree selection, and assessment. The intensity of thinning has often been expressed in terms of the number or percentage of trees removed; the emphasis was thus on intermediate yields. A standard classification of thinnings applied widely by the British throughout the Tropics (Champion and Seth 1968) was as follows:

Thinning class	Trees removed
A. Light	Moribund, diseased, and suppressed
B. Moderate	Class A trees plus defective subdominants, whips, and branchy advance growth
C. Heavy	Class B trees plus all subdominants and defective codominants that can be removed without leaving a permanent gap in the canopy
D. Very heavy	Class C trees plus any dominants and codominants that can be removed, yet also retaining a well-spaced, evenly distributed stand of trees with good boles and crowns.

A measure that reflects both the trees and basal area removed is the Queensland thinning ratio (Bevege 1972):

$$\text{Ratio} = \frac{\text{(basal area removed divided by initial basal area)}}{\text{(stocking removed divided by initial stocking).}}$$

This ratio is sensitive to the size of the trees removed. Removing numerous small trees (a high percentage of stocking) produces a high denominator relative to the numerator and thus a low ratio. Under Queensland conditions, cleanings of the understory yield ratios of less than 0.43. Conventional low thinnings range in ratio from 0.43 to 0.56. Severe low thinnings to light crown thinnings range from 0.57 to 0.81. Severe crown thinnings yield ratios of more than 0.81.

Basal area, because it reflects tree size as well as number, is a better measure of the intensity of tree competition than is the number of trees. It is also simple to derive from tree-diameter measurements. As a measure of stand volume growth, however, basal area is insensitive to tree height. Use of basal area to compare volume in early and late thinnings may be biased if the trees removed early are shorter than those removed later (Assman 1970). However, merchantable height of tropical broadleaf trees for timber tends to be fixed early in the life of the tree by branching, making basal area and volume thereafter directly related.

However, if the main benefits from thinnings are to be increased quantity and quality production for the residual stand, it seems more logical to classify thinnings by the number or percentage of trees retained rather than removed. Thus, one early thinning classification proposed for India was as follows (Sagreiya 1944):

Type of thinning	Percentage of stems retained
Very light	50 to 75
Light	33 to 67
Moderate	25 to 50
Heavy	11 to 33
Very heavy	6 to 25

Thinnings have also been classified according to crown freedom (Singh 1947, 1960). Classes may be based on the percentage of the trees remaining that have free crowns.

Thinning intensity is in part dictated by the frequency of thinnings. The longer the interval, the more space should be left for each tree. To determine the appropriate spacing in India, crown spread of free-growing trees has been measured; a cord and plumb bob are used to assist the eye in determining the points on the ground that are vertically beneath the edges of the crown (Suri 1970a, 1975). Once crown spread is related mathematically to tree diameter, the spacing required between trees of any size can be determined for any projected future growth. For thinnings of *Shorea robusta* and *Tectona grandis,* made at a frequency designed to maintain 5 cm in d.b.h. growth, the required spacing for a range of mean diameters was then calculated and reduced 15 percent for triangular spacing (table 7–24).

If plantations with trees of a specified mean d.b.h. are thinned to an average triangular spacing, as shown in table 7–24, they presumably would grow well until the average d.b.h. is 10 cm larger. The differences between the two species reflect differences in their natural ratios of crown diameter to stem diameter in free-growing trees. *Tectona grandis* has a larger crown and needs wider spacing.

The crown-diameter-to-bole-diameter ratio indicates the needed intensity of thinning, but appropriate ratios must be determined not only by species but also by tree size. Studies of the rapidly growing, light-demanding tree *A. chinensis* in Sabah bear this out (Fox 1968b, 1971). Trees 10 cm in d.b.h. had a ratio of crown diameter to bole diameter of 93. At 20 cm in d.b.h., it was 52; at 30 cm in d.b.h., 39; and at 60 cm in d.b.h., 28. Nevertheless, a ratio as low as 18 has been found conducive to rapid growth of this species on the best sites.

Mathematical guides to thinning intensity have been sought for many decades. In preparing the all-India teak yield tables, Laurie (1938) derived a nearly linear formula for desired spacing as follows:

$$S = 0.2472\,d - 0.0014\,d^2 + 0.8656$$

where S = mean tree square spacing in meters and
d = mean diameter of crop trees in centimeters.

Thus, a stand with a mean crop-tree diameter of 15 cm should have an average spacing of approximately 4.25 m. For thinning, Laurie recommended that the minimum spacing be roughly 1.5 times the average so derived, which would be 6.4 m in the example used. A later formula for the spacing to leave after thinning, also derived for teak, was $S = 0.2\,d + 2.25$ (Takle and Muyumdar 1956). For the 15-cm mean diameter of the example, this formula gives a minimum spacing of 5.2 m. Matthews' spacing factor (1935) has been converted to the metric system for deriving mean tree distances as a guide to thinning regardless of species (Burger 1975):

D=d multipled by the square root of 7854 over BA

where D = mean distance between trees in meters
d = mean d.b.h. of the stand in meters
BA = mean basal area of the stand in square meters per hectare.

For a plantation with a mean d.b.h. of 30 cm and a mean basal area of 20 m²/ha, the mean distance between trees is 5.95 m. The formula is obviously useful for determining the distance between crop trees that will be needed in the future to correspond to specified goals in terms of mean diameter and basal area. For example, if a mature stand is to average 50 cm in d.b.h. and have a basal area of 30 m²/ha, the number of trees per hectare derived from the spacing distance (8.1 m) would be 175 with triangular spacing (153 × 1.15). An amount larger than this number (to allow for possible future losses) would apparently merit selection as crop trees, with corresponding release and possibly pruning.

Hart's spacing factor (Hart 1928) has been widely used as a guide to thinning. It is designated "S%" and expresses triangular spacing between trees as a percentage of "top height," the height of the tallest or largest 100 trees per hectare. The standard index of stocking (1.0) is S% = 20. Variants that have been used in the United Kingdom include the mean height of the largest 250 trees per hectare and square spacing instead of triangular (Hummel 1953). A number of stocking levels have been derived using the United Kingdom modification (table 7–31).

Through the use of Hart's factor, the frequency and intensity of thinnings can be guided by a fixed increment in height or by a fixed percentage of the trees removed at each thinning. Thinning according to height is illustrated in table 7–32, in which it is assumed that thinnings are to be made with each 2 m in height growth and that residual stocking is to correspond to S% = 20 (Hart 1928, Hummel 1953b). When thinning is being done according to the percentage of trees removed, with S% of 20 the maximum stocking allowed, removals may be pegged at 33 percent, as indicated in table 7–33.

Hart's spacing factor has been used in thinning teak plantations in Indonesia (Sudarmo 1957) and for *E. saligna* in South Africa (van Laar 1961). For *P. caribaea* in Suriname, thinning derived from S% is presumed to decline with age (Vincent 1970). A provisional practice for site I, starting when S% reaches 20 to 23, is illustrated in table 7–34.

Studies in Queensland, Australia, with *P. elliottii* and *P. taeda* led to the conclusion that basal area was a better basis than Hart's spacing factor for developing thinning regimes (Robinson 1968). When thinning is being done from below, there is a wide range of standing basal areas that yields maximum basal-area growth. Therefore, high volume production can be obtained from less growing stock than is generally considered necessary. The objective is to manage the stand at or below the lower limit of this basal-area range. This approach may lead to

Table 7–31.—Stocking levels adapted from Hart's spacing factor

S%	Stems per hectare at corresponding top heights (m) 10	15	20	25	Stocking
10	1,250	556	312	200	Very light
15	1,875	833	468	300	Light
20	2,500	1,111	625	400	Traditional
25	3,750	1,666	938	600	Heavy
30	6,250	2,778	1,562	1,000	Very heavy

Note : Hart's spacing factor (S%) expresses mean triangular spacing between trees as a percentage of "top height"—the height of the largest 100 trees per hectare (Hart 1928). This adaptation substitutes the mean height of the 250 largest trees (in d.b.h.) and uses square instead of triangular spacing.

unmerchantable thinnings or may lower the age of the first merchantable thinning.

Stands should be held at or near the "limiting basal area" until only the final crop trees remain, after which the basal area may be allowed to build up to any level desired (Bevege 1972). Thinning schedules allow stand density to oscillate about the limiting basal area so that basal-area growth over the thinning interval is near the maximum. An example would be to allow basal area to build up to 110 percent of the limiting level and then to thin it down to 90 percent of that level. The limiting basal area appears to be independent of age but varies directly with site for *P. elliottii* in Queensland (table 7–35).

Table 7–32.—Thinning regimes according to height growth

Top height (m)	Trees left (no./ha)	Trees removed (no./ha)	Percent removed
10	2,500	0	0
12	1,736	764	31
14	1,276	460	26
16	977	299	23
18	772	205	21
20	625	147	19
22	517	108	17
24	434	83	16
26	370	64	15
28	319	51	14
30	278	41	13

Source: Hart 1928, Hummel 1953.

Tree Selection. The natural approach to selecting trees to be thinned would be to leave those that appear most promising. However, identifying the most promising trees may call for more expertise than is generally available, so systematic tree selection deserves consideration.

Systematic thinning, removing trees in accordance with their location rather than their quality, proved about as satisfactory as selective thinning with *Araucaria angustifolia* in Misiones, Argentina (Cozzo 1958). Part of an 8-year-old plantation with a basal area of 22 m²/ha was reduced to 20 m² by selective thinning and another part to 17 m² by systematic thinning. Six years later, both treatments had a basal area of 42 m²/ha, indicating 14 percent faster basal-area growth for the systematic thinning. Mean diameter was also 1 cm greater for the systematic thinning than for the selective thinning. There is no reason to conclude that systematic thinning is better, but it may produce results as good as those produced

Table 7–33.—Thinning regime according to 33-percent tree removal (no./ha)

Top height (m)	Trees left	Trees removed
10.0	2,500	0
12.2	1,675	825
14.9	1,122	553
18.3	748	374
22.4	499	249
27.4	333	111

Source: Hart 1928, Hummel 1953b.

Table 7-34.—Provisional S% thinning for *Pinus caribaea* in Suriname

Age (yr)	Top height (m)	S% residual (%)	Trees left (no./ha)
6	14.7	29.2	625
9	20.0	26.0	425
14	24.5	25.3	300
20	27.3	24.8	250
30	30.1	0	0

Source: Vincent 1970.

Note: S% = Hart's spacing factor (Hart 1928).

by selective thinning and, therefore, may be more practical under some circumstances. Such circumstances seem to exist in plantations where survival is high, rows are well laid out, tree form is good, and there are plenty of good crop trees. Row thinning 14-year-old *P. taeda* in the Southern United States was superior to selective thinning simply because it was much easier to apply (Grano 1971).

Triangular spacing can be adapted to facilitate row thinnings (Wong 1966a). The distance between final lines should be 0.866 times the final crown diameter, and the spacing within final rows should equal the final crown diameter. If, for example, the final d.b.h. of the crop trees is to be 0.6 m and the crown-diameter-to-bole-diameter ratio is 20, the final crown diameter would be 12 m. This amount multiplied by 0.866 gives a line spacing of 10.4 m. Within rows, the spacing would be 12 m, making the final spacing 10.4 by 12.0 m. Initial spacing on these lines can be one-fourth of these distances (2.6 by 3.0 m), allowing for early systematic and later selective thinnings.

Selective thinnings generally are "from below," that is, trees that have the poorest performance (the slowest growth) and that are likely to continue to be outstripped by the larger trees are removed. The removal of suppressed and dominated trees can normally be expected to increase the growth of the residual trees, because those removed are heavy respirers (Assman 1970). The result is more uniform stand structure. However, in plantations that have a very irregular upper story or that are so young that only the large trees are marketable, there may be reason to thin "from above" rather than from below. Such thinnings may influence basal area more than those from below. In first-generation plantations, variation in tree quality is so great that selection by form is desirable, removing abnormal trees whether large or small.

In a study of *P. taeda* in the Southern United States, 20-year-old plantations were thinned to 16, 20, and 23 m^2/ha of basal area, some from below and some from above (Bassett 1966). Yields at age 35 were nearly the same in volume and quality for the various treatments. Thinning from above left only 40 to 54 percent of the former dominants or codominants as crop trees versus 98 to 100 percent in plantations thinned from below. Thinning from above led to a slightly smaller mean final d.b.h., shorter merchantable heights, and smaller crowns, but no difference in mean form class.

A hybrid system of selecting crop trees is termed "eclectic." It utilizes plantation rows in one direction. Groups of trees within rows are selected to ensure relatively uniform distribution. The original system, called the Scottish Eclectic System, has been adapted and modified in Queensland and elsewhere. The eclectic system only selects crop trees. The degree to which they are then released may be decided concurrently but as a separate process.

Table 7-35.—Site effects on limiting basal-area growth of *Pinus elliottii* in Queensland, Australia

Site index[a]	Limiting basal area (m^2/ha)	Maximum basal-area growth (m^2/ha/yr)		
		Age 10 yr.	Age 20 yr.	Age 30 yr.
15	21.6	1.4	1.0	0.5
21	27.1	3.1	1.3	0.8
27	32.7	3.8	1.7	1.0

Source: Bevege 1972.

[a] Site index is defined locally by tree height at a selected age.

The process of tree selection under the eclectic system involves walking down each plantation row and selecting crop trees within groups of adjacent trees (including blanks) within each row; groups number four or five, depending on the number of crop trees desired (Pudden 1955, Sawyer 1962). Using the quartet system, the best tree in the first group of four is tentatively selected. Trees are selected according to size, merchantable height, straightness, lack of stem fluting, number of small branches, and absence of injuries. If it is tree number 1, the selection is final, and the next quartet (trees 5, 6, 7, and 8) is then reviewed. If the tree selected in the first quartet is number 3, the selection is only tentative until it is compared with the additional members of its quartet in a forward direction, namely trees numbered 4, 5, and 6. If number 5 or 6 is superior (number 4 having been already found inferior), it substitutes for number 3 as the final select tree. If not, number 3 serves as the final selection, and the next quartet then begins with tree number 5. If tree 5 or 6 is selected, the next quartet begins with the next tree (or blank) in line, and the procedure continues as for quartets 1 through 4.

The next step in the Scottish Eclectic System is choosing the crop trees from among the selected trees. About 150 stems per hectare are so designated, the most promising spaced about 10 m apart (MacDonald 1961). Dominant trees competing with them are marked for removal. From among the smaller trees closely surrounding the crop trees, a few healthy, straight poles are selected, which, if given sufficient light, are likely to follow behind the crop trees. These followers are "relieved" by removing any larger or equal-sized trees (other than those selected for the crop) that would compete seriously with the selected trees.

Crop trees may be marked permanently to eliminate needless repetition of the selection process. However, some managers prefer periodic reselection to consider changes in the vigor of individual trees (Assman 1970).

Another systematic way to release crop trees within a plantation is based on their spacing and diameters. Sagreiya (1946b) long ago proposed this formula for releasing teak crop trees: If the distance between a crop tree and its neighbor (in meters) is less than the sum of their d.b.h. (in centimeters) times 0.12 plus 1.2, the noncrop tree should be removed. For example, if a crop tree is 25 cm in d.b.h., and its neighbor is 21 cm in d.b.h., multiplying their sum (46) by 0.12 and adding 1.2 gives 6.7 m as their necessary separation. If spaced closer, the neighbor is removed.

The number of crop trees to select will vary with the desired tree sizes of future harvests, intermediate and final. If 100 trees per hectare are wanted for a final harvest of sawtimber, about twice as many pole-sized trees should be selected (Assman 1970).

Thinning practice in the plantations of South Africa attracted wide attention as a result of conclusions reached in a series of experiments by Craib (1939). It has since continued to provide guidance wherever intensive thinning is appropriate. Although the densest stands always show the highest mean total annual growth, marketable growth (that above a certain stem diameter) is more important (Marsh 1957). Evidence that the production of small trees in plantations was wasteful, because they did not yield much revenue even where marketable, led Craib to recommend heavier and earlier thinnings than were traditional.

Research on thinnings of *P. patula* in 20 areas throughout South Africa showed that in plantations of 3,000 trees per hectare, the dominant trees suffered from suppression from the third year on (Anon. 1947c). In plantations of 1,500 trees per hectare, suppression of the dominants began in the fourth year. With 750 trees, suppression began in the sixth year; with 500, in the seventh; with 370, in the eighth; and with 250, in the ninth. These findings support Craib's recommendations for early and heavy thinning.

Later, Craib (1947) concluded that neither species nor site influences the age at which nutritional competition in a stand of a given density commences. He suspected that even climate makes little difference. He also concluded that as density of stocking decreases, mean diameter increases. This increase, due to increased growing space, is small during youth and increases with advancing age. As stocking density decreases, mean height increases—but only slightly. As stocking density decreases, total volume production per unit of land area also decreases. Maximum sawtimber volume is generally produced by stockings of 750 to 1,250 trees per hectare, or initial spacings of 2.7 by 2.7 m to 3.7 by 3.7 m. Maximum early sawlog returns come from wide, not close, spacing. The goal has been uniform ring width, about 2.4 cm without knots, grown over an unpruned core of wide-ringed wood. Even where the aim is for maximum sawtimber volume, the bulk of the yield is in stems of lower value.

Craib (1947) further concluded that the longer thinning is delayed, the greater will be the loss in total volume growth thereafter. Under local conditions, financial returns from heavily thinned stands were likely to be much greater than those from lightly thinned stands. For *P. caribaea,* he recommended the schedules shown in table 7–36.

In a review of Craib's methods, Hiley (1948) concluded that such early thinning removes the option of selecting trees for quality and requires much pruning; but under South African conditions, these were not serious problems. The thinnings prescribed were so early that they yielded little or no marketable wood. Nevertheless, Hiley concluded that wood quality does not suffer, because it is a function of age, not growth rate.

South African thinning practice has been defended because of a lack of markets for small material (Villiers and others 1961). Wood defects, such as high longitudinal shrinkage, uneven texture, knottiness, compression wood, and spiral grain, all exist to some degree, but occur chiefly in the first 5-year core of juvenile wood. Planting at 2.7 by 2.7 m instead of 3.7 by 3.7 m reduces the diameter of this defective core by only 2.5 cm. Moreover, the lower yield (17 percent) with the wider spacing is more than compensated for by a 76 percent higher value for the total harvest at 40 years.

Table 7–36.—Thinning schedules for *Pinus caribaea* in South Africa

Age (yr)	No. of trees to leave per hectare	
	Site I[a]	Site III
0	1,310	740
6	all	440
8	740	all
12	490	all
18	320	all
20	all	all
25	230	all
30	0	210
35	0	0

Source: Craib 1947.

[a] Site classes are defined locally on the basis of tree height at a selected age.

The appearance of pulpwood markets in South Africa changed the emphasis on large diameters recommended by Craib (Johnston 1962). Craib's stands, about 65 percent sawlogs, yielded too little pulpwood to support processing facilities. The new pulpwood markets dictated less concern with spiral grain and knottiness than with fiber length and fibril angle. Spacing was reduced to 2.1 by 2.1 m to increase selectivity for the final crop, to provide more pulpwood, to reduce taper and knot diameter, and to help suppress the ground vegetation. Closer spacing does not reduce the amount of juvenile wood but merely puts it on more trees (Johnston 1962).

By 1971, further market shifts toward smaller trees had led to closer spacing and lighter thinnings (Villiers 1971). More recent practice in South Africa with *E. grandis* for sawlogs and veneer logs has been to plant at 2.7 by 2.7 m, or 1,370 trees per hectare, thin to 750 per hectare at 3 to 5 years, then to 500 per hectare at 7 to 9 years, and to 300 per hectare at 11 to 13 years; the rotation length is 14 to 30 years (Poynton 1981).

Thinning studies with teak date back to 1900 (Krishnaswamy 1953). Teak is intolerant of crown "friction" and incapable of maintaining a closed canopy except early in life (Mirchandani 1941). A mixed understory normally develops and does not interfere with the growth of the teak. On good sites in India, teak has been thinned at 3, 6, 10, 18, 30, and 44 years (Krishnaswamy 1953). Heavy thinnings are recommended. Examples of thinning schedules are presented in appendix J.

Pruning

Pruning, removing branches to improve tree form or wood quality, has most often been done in the Tropics in conifer plantations. Other timber species, whether in natural or planted forests, tend to self-prune at conventional spacings and thus seldom require artificial pruning.

To improve wood quality, pruning must be done early, before the stems are so large that little knot-free wood can be produced before maturity. A good guide is the diameter of the knotty core that will be acceptable, generally 10 to 15 cm. Achieving this goal requires not only early pruning but also progressive pruning as the trees grow in height and as the critical diameter rises up the stem. In reality, the knotty core may be up to 5 cm larger than 15 cm when the pruning is done because of the area of occlusion (wound healing) over pruned stems (Robinson 1968). For early pruning of *C. lusitanica* in east Africa, a U-shaped stem caliper (or pruning gauge) was developed to facilitate locating the upper limit of the prescribed knotty core (Graham 1945).

For most conifers in east Africa, the best time to start pruning is at age 5 to 7 (Pudden 1955). With *Cupressus,* pruning may begin as early as the second year and be repeated every 2 years thereafter. Rapidly growing trees such as *E. saligna* must be pruned more than once per year (Luckhoff 1967). Less frequent, heavier prunings tend to set up undesirable wood stresses in this species.

Early pruning also promotes rapid occlusion. In South Africa, *P. caribaea* at age 4 heals over to straight wood on 84 percent of the wounds in 5 years and 100 percent in 10 years (Anon. 1954c). When trees were pruned at age 15, only 30 percent of the wounds healed over in 5 years and only 80 percent even after 11 years.

The time of year that pruning is done affects the rapidity of wound occlusion and rebranching. In Kenya, rapid occlusion occurs when pruning is done just before the rainy season (Anon. 1954i). In Puerto Rico, epicormic branching in teak resulting from pruning is most vigorous in the dry period immediately preceding leaffall (February) and least vigorous during the rainy period (August) (Briscoe and Nobles 1966). The influence of the season of pruning on the rapidity of wound occlusion is seen in data from a 3-year-old *C. lusitanica* plantation in Kenya (Anon. 1954i):

Month pruned	Months to occlusion
February	41
March	41
April	18
June	18
August	25
October	29
December	40

Because trees will benefit from pruning only if they are allowed to grow a long period thereafter, trees soon to be thinned should not be pruned, except perhaps to a height of about 2 m to provide easy access. Higher (and more costly) pruning should be limited to the potentially final crop trees. For example, pruning *A. cunninghamii* in Queensland, Australia, has been restricted to 620 trees per hectare to a height of 3 m, and 400 trees per hectare to 6.7 m, for a final crop expected to be 185 trees per hectare (Grenning 1957). For the southern pines of the United States, pruning of 370 to 490 trees per hectare has been recommended (Wakeley 1954).

Pruning intensity has been widely studied. When pruning is done earlier and higher, the prospect for reducing tree growth is greater, but the proportion of knot-free wood is also greater. It was concluded long ago that pruning southern pines in the United States to 5 m when the trees are 10 m tall promises greatly increased profits from plantations producing sawtimber and veneer bolts (Wakeley 1954).

A. cunninghamii has commonly been pruned to 7 m in height in Queensland (Grenning 1957) as have other conifers in South Africa (Johnston 1962). Even at this height, much of the wood in mature trees 30 m tall is still knotty.

Pruning intensity is usually measured in terms of the percentage of the tree's total height. A test of *P. elliottii* in Misiones, Argentina, showed that pruning 5.5 m tall trees to half their total height did not reduce diameter growth during the subsequent 3 years (Molino 1972). Even pruning to three-quarters of the total height prompted no significant reduction. In Kenya, *C. lusitanica* has been pruned to about 60 percent of the total height; on pines, one whorl has been left below the 60-percent level (Pudden 1955). The standard of half-tree height has also been used with *G. arborea* at Monte Dourado, Brazil (Anon. 1979e). South African experience suggests that the guide there should be mean tree height, not height of the dominants (Sherry 1961).

Experience with *P. elliottii* and *P. patula* in South Africa showed that pruning up to one-third of the live crown at age 4.5 years caused only a small loss in d.b.h. growth, and this decline lasted only 15 months (Sherry 1961). *Eucalyptus saligna* is capable of surviving after pruning up to 40 percent of the live crown, but wood stresses may result. Studies with *P. elliottii* and *P. taeda* in Queensland indicate that if significant losses in diameter growth are to be avoided, a knotty core of less than 15 cm in diameter is unattainable (Robinson 1968). In Kenya, the same conclusion was reached where pruning of conifers was no more than half the total height (Pudden 1955).

Pruning of *Simarouba amara* in Suriname was limited by a tendency for new branches to develop immediately above the uppermost whorl that had been pruned (Schulz and Vink 1966).

In a study of *P. elliottii* in southern Brazil, Fishwick (1977a) set, as a primary standard, a maximum diameter outside bark of stem core within which all knots (branch stubs) must be confined. Having set two of these maximum diameters, 10 and 15 cm, he applied the necessary treatments, attempting to keep the prunings to a reasonable number and to avoid excessive removal of the live crowns. He concluded that the time to prune should be dictated by the average total height of the 500 best trees per hectare. To confine knots to a 15-cm core, the first pruning should be done to a height of 5 m when the total height reaches 9 to 10 m (age 6 to 7 years), and the second and final pruning should be done to 7 m when the total height is 12 to 13 m, about 2 years later. For a 10-cm core, four prunings would be needed, to 2 m (total height 5 to 6 m), 4 m (total height 7 m), 5.5 m (total height 9 m), and 7 m (total height 11 to 12 m).

The response of plantations to pruning is complex. A few general observations from South Africa follow (Craib 1947):

- Pruning live crowns retards diameter growth much more than height growth. Removing 25 percent of a vigorous crown has no effect on diameter or height growth.
- Removing 50 percent of a vigorous crown has a significant effect only on diameter growth.
- Removing 75 percent of a vigorous crown significantly affects both diameter and height growth.
- Recovery of normal growth is rapid, even in the worst case, by the fourth year.
- Loss of volume as a result of pruning is never regained.

Similar observations were made on *P. elliottii* in the Southeastern United States (Bennett 1955). Diameter growth decreased very gradually after the elimination of up to 50 percent of the live tree crowns, but as pruning intensity progressed from 50 to 90 percent, diameter growth decreased rapidly. However, height growth was little affected by the loss of up to 80 percent of the live crown. Studies of the 2-year response of a 4.5-year-old plantation of *A. cunninghamii* in Nigeria produced similar results (Anon. 1961a).

Pruning in a 7.5-year-old plantation of *P. patula* in Malawi (Foot 1968b) led to the growth responses summarized in table 7–37.

Experience in South Africa has shown that selective pruning puts the pruned trees at a disadvantage relative to their unpruned competitors (Luckhoff 1949). Selective pruning also much more severely affects growth of 4-year-old trees than the growth of 8-year-old trees. If all the trees are pruned, even to the extent of 75 percent of their live crowns, diameter growth recovers in only 2 years. But with selective pruning, recovery may take 5 years or longer. The effect of selective pruning on diameter growth and the delay in recovery is less on poor sites than on good sites.

The detrimental effect of pruning on diameter growth can be greatly reduced by thinning just before pruning (Sherry 1961). In South Africa, it is recommended that plantations of *P. elliottii* and *P. patula* be reduced to 860 to 980 stems per hectare before the first pruning. After pruning, the radial stem growth was greatest immediately below the lowest branch and decreased with distance from the crown. The heavy pruning thus reduced taper. A pruning schedule proposed for *P. elliottii* and *P. patula* in South Africa is summarized in table 7–38 (Sherry 1961).

Studies of *P. patula* in South Africa have shown that pruning to 7 m does not increase branch size above the level of pruning, which is from 8 to 12 m above the ground (Villiers and others 1961). Pruning 30 to 50 percent of the live crowns of *E. grandis* in South Africa had no effect on the specific gravity of the wood but did prevent trees from attaining pole size by age 10 (Schonau 1974).

Although pruning *C. lusitanica* in Kenya was found to depress d.b.h. and height growth, it appears that more high-pruned trees can be carried than low-pruned trees (Pudden 1957b).

Pruning practice is straightforward. Where low branches are persistent, all trees are generally pruned to head height for easy access as soon as this can be done without exceeding half their total height. Thereafter, the selected crop trees are pruned repeatedly to the established standard (Pudden 1955). Thinning is generally

Table 7–37.—Growth responses to pruning of 7-1/2-year-old *Pinus patula* in Malawi

Yrs. since pruning	Pruned to 18% of height (control)	Pruned to 42% of height	Pruned to 57% of height	Pruned to 77% of height
	Basal area growth			
1	100	81	52	14
2	100	84	60	21
3	100	96	87	49
4	100	112	126	92
	Height growth			
1	100	88	82	64
2	100	95	95	81
3	100	101	94	81
4	100	107	99	100

Growth response as percentage of control.

Source: Foot 1968b.

concurrent, confining pruning to the most promising trees. Pruning is normally done manually with curved pruning saws mounted on long poles. The final pruning height is usually less than half the total tree height. Pruning clearly should stop where the stem ceases to be straight. A practical limitation of 5 to 7 m on pruning height is dictated by the pruning pole length. Pruned limbs should be removed from the base of crop trees to reduce fire risk. Pruning is done close to the stem to minimize the size of the knotty core and to accelerate occlusion. Special care is required with some genera such as *Cupressus* and *Tectona* to minimize wounds that expose wood to insects and decay.

Coppice

The capacity of many plantation species to sprout vigorously after harvest to an advanced age can minimize the cost of regeneration and has led to various forms of coppice management. Not only is such regeneration less expensive, but coppice crops may produce higher yields sooner. Early experiments with 13 species of *Eucalyptus* in Guarani, Brazil, yielded 15 to 33 m^3/ha/yr from the seedling crop at age 7, whereas the first coppice crop, at age 6, yielded 17 to 42 m^3/ha/yr (Navarro de Andrade 1939).

The advantages of coppices are clear with Mysore gum, a variety of *Eucalyptus* with morphological characteristics of *E. botryoides, E. camaldulensis, E. robusta,* and *E. tereticornis* that is widely planted in India. Because the species is grown mostly for pulpwood and firewood, its productivity is measured in terms of biomass. At a rotation of 8 years, a test plantation yielded a mean annual increment of 19.6 t/ha/yr green weight (Singh 1967). At 14 years, the growth was 14.5 t/ha/yr. However, if the plantation is cut at 8 years and coppiced for 6 more, the 14-year yield averages 20.7 t/ha/yr; the coppice rotation averaging 22 t/ha/yr.

Coppicing proved highly productive in *Eucalyptus* shelterwood plantations that covered more than 22,000 ha at Belgo Mineira, Brazil (Osse 1961). The practice was to make a first cut at age 8 or 9, yielding 210 m^3/ha, or 23 to 26 m^3/ha/yr. The second cut, made 7 years later

Table 7–38.—Pruning schedule for *Pinus elliottii* and *P. patula* in South Africa

Tree height (m)	Pruning height (m)	Living crown removed (%)
4.9	1.8	37.5
7.3	3.7	33.3
9.1	5.5	33.3
11.0	7.3	33.3
12.8	9.1	33.3

Source: Sherry 1961.

at age 15 or 16, yielded 250 m^3/ha, or 36 m^3/ha/yr. The third cut, at age 22, yielded 200 m^3/ha, or 29 to 33 m^3/ha/yr. The aggregate 22-year yield was 30 m^3/ha/yr.

An extensive test with more than a thousand growth plots in the Brazilian States of Paraiba and Sao Paulo showed superior coppice yields on a variety of rotations for *E. alba, E. grandis, E. rostrata, E. saligna,* and *E. tereticornis* (table 7–39; Heinsdijk 1972). Yield tables shed light on wood production potentials of *Eucalyptus* for both the seedling crop and the first coppice. Note that MAI culminates earlier and higher in coppices than in the first crops. The initial difference was due chiefly to the number of stems, not differences in diameters. At 4 years, the coppice stands had about 25 percent more basal area, an excess that disappeared in about year 8. By year 14, the coppice basal area was 10 to 15 percent less than that of the first crop, and MAI was declining much more sharply because of slower diameter growth.

Coppicing has long been applied to *Senna siamea* and *T. grandis* in the Ibadan fuel plantations of Nigeria (Collier and Lockie 1940). Started in about 1924, these plantations were managed for decades by clearcutting and coppicing on a 10-year rotation.

The early sprouting vigor of *L. leucocephala* was illustrated by a test in India (Pathak and others 1981). The mean annual increment in bole and branch biomass per tree of the seedling crop at age 3 was 1.73 kg, but that rate was equalled by coppice trees in half that time.

The number of coppice crops that may be obtained from a planting depends on the longevity of the coppicing power of the stumps. The Ibadan fuelwood plantations in Nigeria have produced in some areas as many six successive coppice crops over 53 years (King 1966). Tests with blue gum *(E. globulus)* in Madras, India, showed the cost in terms of reduced yield of continuing coppice rotations for many years. With 15-year rotations for fuelwood, the yield dropped 9 percent in the third rotation and 20 percent in the fourth (Krishnaswamy 1957b). In Brazil and South Africa, the third coppice crop of *Eucalyptus* is generally the last, each crop being made up of fewer trees. The same three-crop scheme was proposed for *G. arborea* at Monte Dourado, Brazil (Anon. 1979e).

Early Brazilian experience with an 8-year-old coppice of eight species of *Eucalyptus* at Rio Claro indicated that the number of sprouts left had little effect on yield (Navarro de Andrade 1939). Coppices where only one sprout was

Table 7–39.—Wood production potentials of *Eucalyptus* spp. in Brazil

	No. of trees per hectare		Mean d.b.h. (cm)		Mean annual increment (m^3/ha/yr)	
Age (yr)	1st crop	1st coppice	1st crop	1st coppice	1st crop	1st coppice
			Site 1 (24–28 m at 8 yr)			
4	1,640	2,170	10.0	9.9	34	36
5	1,340	1,570	12.4	12.4	42	66
8	980	1,340	16.6	13.7	56	65
11	860	1,180	19.1	15.0	56	58
14	790	1,100	20.4	15.9	54	54
			Site 3 (16–20 m at 8 yr)			
4	1,760	2,580	9.2	8.6	16	28
5	1,430	1,880	11.1	10.8	20	33
8	1,060	1,600	15.0	12.1	26	32
11	920	1,400	16.9	13.4	26	29
14	850	1,310	18.1	13.8	25	26

Source: Heinsdijk 1972.

left per stump produced trees 21 to 25 cm in d.b.h. and a basal area of 34 to 70 m²/ha. Coppices with several sprouts per stool produced trees 18 to 21 cm in d.b.h. and a basal area of 20 to 72 m²/ha.

In Kenya, the usual practice with *E. saligna* fuelwood coppices has been to thin to two sprouts per stump (Dyson 1974). Leaving three sprouts gives a higher gross yield, but where the size of the fuel billet is important, two sprouts are preferable (Howland 1969). In one test, stumps were thinned to one sprout, three sprouts, or left unthinned (an average of 5.5 sprouts) and growth was compared at age 6-1/4 years (table 7–40).

With *E. saligna* in South Africa, leaving only two shoots per stump can obviate the decline in volume production that occurs with an increasing number of coppice generations (van Laar 1961). Another factor affecting the number of shoots left per stump is harvesting efficiency. In Australia, the use of mechanized systems may favor the single stump even if yields are lower (Carter 1974).

A special type of coppice has been applied to *Shorea robusta* in Indian taungya plantings (Huq 1945). The tree commonly puts up several basal shoots, particularly when fully exposed to side light. It was found that cutting the sprouts back at age 5 produced a single straight sprout without extra shoots. Coppicing of *Paulownia tomentosa* in the Philippines by cutting back the 1-year leaders also subsequently leads to an extremely straight stem.

South African coppicing experience with *E. grandis* for short-rotation crops has led to the following conclusions (Stubbings and Schonau 1980):

- For high yields, initial survival must be 95 percent or higher. If less, immediate replanting is necessary.
- High stumps lead to poor coppice attachment.
- Stump mortality averages about 5 percent per rotation. It is greater if felling is done during the driest part of the year.
- Shoots should not be thinned during the windy season.
- Shoots should be thinned in two steps, once when dominant height is 3 to 4 m and a second time when dominant height is 7 to 8 m.
- Retained shoots should be dominants of good form arising as low on the stump as possible.
- If more than one shoot is selected, the diameters should differ by no more than 1 cm. A wide range in shoot diameters cannot be evened up.

A special case of coppice management has been the production of pitprops of *G. arborea* in eastern Nigeria. About 6 months after harvesting, all but the best three or four shoots per stump are removed (Pringle 1950). Six months later, these are reduced to one per stump. The rotation is 10 to 15 years, and four-fifths of the remaining sprouts have been of pitprop quality.

The coppice-with-standards method (leaving superior trees after an early selective harvest) has been tested in what is now Rwanda and Burundi, with *E. maideni* and *E. saligna* on sites too poor for high forests (Reynders

Table 7–40.—Thinning effects on a *Eucalyptus saligna* coppice in Kenya

Index	Unthinned	Three sprouts per stump	One sprout per stump
Basal area (m²/ha)	5.9	5.5	3.6
Volume by d.b.h.[a] (m³/ha)			
>5 cm in d.b.h.	32.8	34.9	24.6
>10 cm in d.b.h.	27.2	31.1	24.1
>15 cm in d.b.h.	3.0	2.1	9.6

Source: Dyson 1974.

Note: Stand age = 6.25 years.

[a] Inside bark to a 5-cm top diameter.

1963). The products were used for house posts and other local timber needs, including fuel. The best cutting treatment left 200 to 250 standards per hectare. The standards were later thinned to stimulate further coppicing.

Bamboo Management

Experience in managing natural and planted bamboo groves has led to a few conclusions applicable to *D. strictus,* by far the most widely distributed and important of all bamboo species (Dass 1960). Harvesting can begin 8 to 15 years after planting from seeds (Singh, S. P. 1973). This species responds well to heavy thinnings (table 7–41; Wilson 1936). Felling cycles range from 2 to 4 years (Prasad 1948). New culms are not felled, and some old culms are retained. The life of this species (between flowerings) varies by locality from 21 to 38 years. The stems are suitable for pulp and make good paper up to 4 years after flowering.

Experiments in India with *Dendrocalamus* harvesting from 1934 to 1947 led to the following conclusions (Krishnaswamy 1956a):

1. Felling cycles of 2, 3, and 4 years produced about the same number of new culms. The poorest performance came from the 2-year cycle, which is also the most costly.

2. With a 3-year felling cycle, the quality of both the harvested and new culms was unaffected by cutting intensity, which ranged from leaving only the same number of old culms as new culms to leaving eight times as many old culms as new.

3. With a 5-year felling cycle, when no old culms were reserved, the new culms were fewer in number and inferior in quality to those produced in areas where one to eight times as many old culms as new were preserved.

Table 7–41.—Postthinning recovery of *Dendrocalamus strictus*

No. of culms per clump		
Before Thinning	After thinning	New in 4 yr.
19	7	20
68	13	45
96	13	64
105	13	45
146	24	96

Source: Wilson 1936.

The advantages of longer felling cycles became apparent with later growth studies in India (Kaul 1963). The number of new culms per clump in the fourth year after felling was almost triple the number in the second year. By 1967, the felling cycle was generally 3 to 4 years, and about 66 percent of the existing culms were removed in each felling (Zakiruddin 1967).

Another commonly planted species of bamboo is *Bambusa vulgaris.* There are two periods of growth each year, and the culms reach full height in 12 to 13 weeks, assuming their normal appearance in 8 to 9 months. The first partial harvest should be delayed 6 or 7 years and could be scheduled every 2 to 3 years thereafter (Groulez 1966). In what was formerly Zaire, the species has been planted at 5 by 5 m and produced from 22 to 31 t/ha/yr fresh weight (11 to 16 dry weight). The cellulose yield is from 6.6 to 9.4 t/ha/yr. Under optimum conditions, production might be increased 50 percent (Maudoux and Abeels 1958).

Bambusa tulda matures from seedlings in 8 to 10 years and lends itself to a 4-year felling cycle (Prasad 1948). Culms that are less than 1 year old should not be cut, and at least six mature culms per clump should be left. No culm with rhizomes should be removed. Stumps should be less than 30 cm in height.

Bambusa arundinaria is similarly managed (Prasad 1948). Mature culms are ready by the fifth year. Selection felling—a thinning out of the older culms—is the only practical method of management. Cutting more than half the culms jeopardizes the health of the clump and requires a recovery period of several years. The cutting cycle is 3 to 4 years, and the life cycle is 30 to 32 years. Felling should leave stumps no higher than 30 cm, take no culms less than 18 months old, and leave at least eight culms per clump plus the exterior shoots.

Harvesting

In forest plantations, the current annual growth of usable wood volume generally rises sharply in the early years and then drops gradually as the canopy closes and the trees compete for space or as thinning progressively reduces the stand volume. The mean annual volume growth—derived from total volume (plus thinnings) divided by age—rises more slowly. The curve of mean annual value growth (or prospective financial returns) rises more slowly still, but the greater value per unit of volume sustains the curve longer.

The curves of production and economic yields are flat enough that they rarely affect the decision concerning precisely when to harvest most plantations. They are most significant for large-scale, cellulose operations, where extensive planted areas provide a sustained supply to a large industry. Even there, however, fluctuations in the market (or temporary social conditions) may influence the precise timing of the harvest more than volume production or stumpage return.

If plantations are normally harvested after the culmination of mean annual volume growth, harvesting should be done before the culmination of mean annual value growth, that point where decline in vigor offsets increasing value per unit of volume because of tree size. For pulpwood, the limit is more likely to be decided by such factors as the maximum diameter acceptable to chippers. For larger products, the capacity of logging equipment and carrying charges may dictate the upper tree-size limit.

The task of moving harvested material to an all-weather road is so large a part of production costs that feasibility and practical alternatives should be explored before planting sites are chosen. Mechanized equipment is virtually essential. If the terrain and layout of the plantation permit the equipment to be operated between the rows, both thinning and harvesting are greatly facilitated. Otherwise, winching with cables, either ground lines or some form of skyline, is needed. Both of these systems operate best at relatively short distances from haul roads and with large volumes of high stumpage value per unit of land area.

Yields

The volume yield standards by which plantations in the Tropics are generally judged are those of eucalypts and pines. Extensive research in Brazil (Heinsdijk and others 1965) indicates that first-crop eucalypts at age 8 produced on the four best site classes an MAI ranging from 16 to 52 m^3 (without bark). An example is seen in table 7–42, based on plantations in Sao Paulo (Simoes and others 1980). Clones of *E. grandis* and *E. urophylla* in Espiritu Santo have yielded as high as 73 m^3/ha/yr (Rance 1976), and higher yields are reported from specially selected clones of Aracruz, near Victoria, Brazil.

Yields of 10 species of *Eucalyptus* in Brazil averaged as follows: seedling rotation, 7 years—18.3 m^3/ha/yr; first coppice, 7 to 14 years—17.0 m^3/ha/yr; and second coppice, 14 to 21 years—14.7 m^3/ha/yr (Ayling and Martins 1981).

Gmelina arborea at Jari, in the Amazon Basin, attains a maximum MAI of 38 m^3/ha of pulpwood at age 6. For *E. deglupta,* the comparable yield at the same age is 42 m^3/ha. For *P. caribaea* at age 12, it is 25 m^3/ha (Woessner 1980a)

Information on plantation yields of a few species common throughout the Tropics has recently been compiled (Lugo and others 1988). Data of general interest from that study, arranged by Holdridge's life zones (Holdridge 1947), appear in table 7–43.

Regeneration

Plantations seldom regenerate naturally, except by coppice, although seedlings of many genera, such as *Gmelina* and *Swietenia,* may appear in abundance beneath old plantations after thinning. These new trees may benefit from natural mass selection in the previous crop but should sooner or later be surpassed in quality by intensively selected and bred progeny. Both *Gmelina* and *Swietenia* have been successfully grafted. The high cost of plantations demands the use of such superior stock.

Plantations should be regenerated at least partly with the best trees in existing plantations. These are of proven adaptability and, if from selected seed sources, should provide superior genotypes as well as phenotypes. Superiority may be in growth rate, form, disease and insect resistance, and wood quality. Improvement of 50 percent or more may be expected.

Genetic quality may be improved in several ways, as is exemplified by Cuba's program with *P. caribaea caribaea* (Betancourt-Barroso 1972), which began in 1965. Included in this program are provenance studies, mass selection, superior-tree selection, progeny studies, vegetative reproduction of superior genotypes, and clonal seed orchards. At the time of this report, 11 provenances had been compared, 1,100 ha of seed source areas had

Table 7–42.—*Eucalyptus* plantation yields in Sao Paulo, Brazil

Species	Age 5 yr.		Age 9 yr.	
	1.5 by 3 m	2 by 3 m	1.5 by 3 m	2 by 3 m
	Steres per hectare per yr			
E. grandis	74	69	59	60
E. saligna	68	59	45	42
	Tonnes per hectare per yr			
E. grandis	21	22	17	17
E. saligna	20	19	13	13

Source: Simoes and others 1980.

been mass selected, and 118 superior phenotypes had been identified. The Forestry Division of Trinidad has been working along similar lines with *P. caribaea hondurensis* since 1959 (Lackhan 1976). Vegetative propagation for seed orchards has been done chiefly by grafting.

Mass selection of nursery seedlings of *P. elliottii* in Brazil led to more rapid early growth in the forests (Shimizu and others 1977). Nine-month-old seedlings were selected in the nursery at the rate of 1:3,500. Their superiority in height increased to 45 percent in the second year. This advantage could be important in reducing the period of weeding.

Insects and Diseases

No attempt is made here to describe plantation pests and diseases or to prescribe treatments. They are important nevertheless. Locally, pathologists and entomologists at agricultural research stations are available to foresters in the Tropics. Several publications listed in appendix K may also prove useful.

In summary, it should be evident that plantation management is a necessary obligation after the initial investment in establishment. It should also be apparent that there are many options and intensities to choose from. Despite vast experience gleaned under many different conditions, foresters must test new projects before applying practices that have been successful in other places.

Table 7–43.—Typical plantation yields of tropical species by Holdridge's life zones

Mean temperature, annual rainfall	Species	No. of plantations	Yield at 10 yr. (m³/ha/yr)	
			Maximum	Average
>24° C, 2–4 m	*P. caribaea*	47	31	22
>24° C, 1–2 m	*P. caribaea*	89	25	13
18–24° C, 2–4 m	*P. caribaea*	194	40	25
18–24° C, 1–2 m	*P. caribaea*	112	38	20
	P. patula	79	40	21
	Eucalyptus grandis	18	21	15
	Cupressus lusitanica	24	21	10
12–18° C, 1–2 m	*P. patula*	100	33	20
	C. lusitanica	88	24	13

Source: Holdridge 1947, Lugo and others 1988.

Chapter 8
Agroforestry

The information presented thus far on culture and management has been concerned almost entirely with trees, assuming that production of trees is the primary land-management objective. Such singular emphasis is attractive because of its simplicity. Concrete results and high timber yields are possible, because this type of management makes the most of available and appropriately forested sites in the region. In most tropical countries, it is only by such concentrated production that the foreseeable national requirements for wood products can be met without increasingly costly imports.

However convincing or obvious the arguments for such focused production may seem, no tropical country is dedicating enough land exclusively to forests to meet its needs. The lead time that is necessary before management produces wood yields may cause serious local deficiencies in timber supplies in most tropical countries.

The reasons for this anomaly are many. Not the least is the sharp divergence between the views of proponents of intensified forest production and those who live on or near the land involved. Implementation of long-term forest management affects the land in ways that may be new, unexplained, and constraining to an affected rural community. The fact that employment opportunities may result does not, in the eyes of tropical people, necessarily compensate for perceived restrictions imposed on them by forest regulations.

These and other factors restrain government forestry investment in what should seem to all as both a social and an economic good. Private investments in plantations are likewise frustrated by a lack of popularity and public support. The crux of the matter is that benefits are seen to accrue to someone else, somewhere else, some time in the future; in short, the benefits are not for the immediate "public." This feeling of remoteness is most acute among rural populations far from the decision-makers whose choices affect local welfare.

Therefore, the integration of forestry and agriculture in the Tropics is commonly seen as an underexploited opportunity to bring forestry "to the people." In its broadest sense, this concept includes upstream trees that protect downstream farmlands. It includes trees on farms that protect food or forage crops growing beside or beneath them. Also included is the practice of intercropping to control weeds in tree plantations.

The combination of forests and other crops may not be an equal partnership. Usually, the coexisting crops are unequal in their respective economic yields, and the trees generally produce the lowest. Therefore, the introduction of trees into crop mixtures must generally be done at little cost to the yields of the other, more appreciated crops. Thus, the task of integrating forestry and agriculture involves not only forestry technology but also agronomy, knowledge of rural social traditions, and skill in human relations. These disciplines are still slighted in forestry curricula.

This chapter is devoted primarily to what is known in the Tropics about agriculture that can be considered pertinent to forestry. The practice of shifting cultivation that is so prevalent in and adjacent to tropical forest areas is reviewed. Its adaptation for tree-plantation establishment through the taungya system is also described. Then, experiences with the additional practices defined as agroforestry are explored.

Shifting Cultivation

Shifting cultivation (rotation of tree and agricultural crops), possibly the oldest of agricultural systems, is a source of livelihood for more than one-quarter of a billion people throughout the Tropics. Application varies from place to place, but several shifting-cultivation practices are nearly universal (Blaut 1960). Among them are rotation of fields, clearing by fire, exclusion of draft animals and manuring, exclusive use of hand labor, planting by means of dibbles, and short periods of crop production alternating with long periods of fallow. The system developed under conditions of low population density, subsistence orientation, the presence of forests, and the concurrent production of many crops with different times of harvest. Fertility is restored by the long fallow, and little if any weeding is necessary in the first planting season.

Custom and Precedent. In what is now Zambia, shifting cultivation has been intimately interwoven with the lives and customs of the native people. For instance, trees have been cut and burned only on certain days (Endean 1960), and after 4 to 6 years of cultivation, land lay fallow for 20 to 30 years. Managed in this way, as many as 50 to 80 ha of land have been needed to sustain one family. Rural people in the Philippines are also sentimentally and psychologically bound to the forest (Maturan 1976). Their attitudes, motivations, and aspirations are deeply involved in their use of virgin forests,

Figure 8–5.—*An important secondary crop of anthuriums marketed for export is produced beneath the wet lower montane forests of Dominica.*

secondary forests, and logged areas for shifting cultivation.

It has only been a few millennia since settlers came as hunters and fishermen to the Amazon (Sioli 1973). They collected wild food plants and adapted farming practices, planting only enough to satisfy home needs. As their numbers were small, they did not significantly influence the structure and dynamics of the forests as a whole. Later, European colonists discovered that cultivation was practical for only 2 successive years; if the fallow was recut at 10 years, only one more harvest was possible. The terra firme soils lacked the colloids needed to fix minerals; even adding minerals from outside sources did no good (Sioli 1973). Only where annual flooding replenished these minerals was continuing cultivation possible.

Primary forests offer the most fertile areas for shifting cultivation, but secondary forests have proved easier to clear and more productive per unit of labor. The optimum forests, then, are in some stage of secondary succession. To compensate for the lower nutrient base of these secondary forests the farmer has simply used more land.

The fallow forests differ markedly from the original forests but seem to adequately restore the sites (Blaut 1960). The forests need not return to their primary condition. Even a permanent deflection toward fewer species, more fire-resistant species, or fewer stories should not substantially affect the crop yields after subsequent burning. Nor is soil structure worse or nutrient supply much lower under a secondary forest than under a primary forest. To a point, yields overall may increase by shortening the fallow.

Environmental changes can diminish or eliminate shifting cultivation. For example, increased population density, access to outside commerce, or the introduction of more intensive technology all tend to shorten the fallow period and thus reduce the forest proportionately. As the fallow period shortens, more labor is required for tillage and weeding, and yields decline. There is also a tendency toward fewer, hardier, and more salable crops and the fixing of property boundaries. All these factors work against the duration of the forest fallow.

As the process breaks down, new crops and drastic changes in techniques may be required. New crops must not compete for labor during periods when other activities peak. The soils may deteriorate under more intensive use as crop marketability becomes more of an objective.

The problems arising from progressive land shortages are not solved simply by intensifying cultivation (Blaut 1960). Erosion control and fertilizers may be required. Tree crops may provide more permanent income but less income per unit of area than ground crops. Converting an area of shifting agriculture to purely commercial forest or pastureland is no solution unless an alternate means can be found to support the people forced out by the reduced employment.

In dealing with the problems of shifting agriculture, Blaut (1960) points to certain fallacies that in the past have led to misunderstanding and misdirected efforts. These are as follows:

- Shifting agriculture is the only system suited for the Tropics.
- Shifting cultivation cannot sustain an equilibrium.
- Villages must eventually move because of land impoverishment inherent in shifting agriculture.

Traditional Practices. The shifting cultivation systems of the Amerindians in the Orinoco Basin of Venezuela evolved into complex polycultures of manioc, yams, gourds, cotton, and tobacco (Harris 1971). Such mixtures utilize both vertical and lateral light. The Waikas cultivated these mixtures for 5 to 6 years, until reclearing and weeding became difficult; then, a gradual transition to fallow permitted continued harvesting of fruits. Their monocultures, in contrast, could be farmed for only 2 to 4 years and were abandoned abruptly because of fertility loss rather than weediness. The fallow started with pioneer shrubs and trees such as *Aegiphila, Cecropia, Clidemia, Miconia, Palicourea, Psychotria,* and *Trema.*

Carib polycultures in the Amazon region involved fields of 2 to 3 ha where 12 species of food plants were mixed (Smith 1978). This approach provided a ground layer, middle layer, and top layer, the latter usually composed of small trees such as *Bixa.* Individual fields were 2 to 3 km apart, a distance that reduced the danger of pest buildup. Simultaneous cultivation for 2 to 5 years permitted a sequence of crop maturation.

In Papua New Guinea, the reuse of organic wastes has been a striking feature of shifting agriculture (Kingston

1960). One result is that in the uplands, as little as 0.04 to 0.09 ha of garden per capita has been required. Pits were used to store organic matter while it decomposes. *Casuarina equisetifolia,* a nitrogen (N)-fixing species, may be planted a year or two before farm cropping ceases. It is easier to clear away than natural regrowth and provides timber and firewood. The branches can be used as stakes for erosion control, and the leaves are either composted or burned.

Native forests were converted to what appears to be permanent cultures of coffee more than a century ago in Mysore, India, on steep slopes with rainfall up to 380 cm/yr (Mayne 1947). The basis for the system was the introduction of an economic crop, coffee, within the existing plant association, evergreen forests. The natural regrowth was cut and allowed to decay, usually without burning. The coffee was planted close, never at more than a 1.8- by 1.8-m spacing, to produce a quick cover like that of the former undergrowth. Canopy density was maintained well below the optimum for maximum cropping, ensuring maintenance of the mulch and protecting the soil from the impact of the heavy rains. Managing the shade proved one of the planter's most exacting tasks.

This successful technique was generally ignored in the eagerness to expand coffee culture in south India and what is now Sri Lanka after 1860. The forests were felled and burned, and coffee was subsequently planted in the open. All that remains of this early practice is poor secondary forests and thickets of *Lantana.* On the other hand, where there was partial clearing and light burning, shade was provided, using both leguminous and nonleguminous species. The use of genera such as *Erythrina* and *Grevillea* deviated widely from the native forest composition. The success of this venture suggests that other species may also serve as a permanent culture.

In what was formerly Zaire, shifting cultivation developed to a complex degree, extending the period of cultivation on good soils up to a total of 9 years (table 8–1; Henry 1952). The difference in the lengths of the cultivation cycle reflects soil quality.

A study of the Bantu cultivation systems in what was formerly Zaire led to a number of conclusions (Coene 1956). In high-forest areas, burning alone was sufficient site preparation. Clearing of stumps and roots was not necessary for bananas, cassava, and yams. On the forest edge, however, the crops were mainly maize, sorghum, and millet, which require more complete cultivation. As a result, fields were worn out; they were cultivated until repeated burning turned them into savannas.

The growth of urban communities in tropical areas and the consequent introduction of economic crops such as cotton, rice, and peanuts encouraged farmers to lengthen the cultivation period or return to field crops too soon. Inadequate restoration during the fallow progressively deteriorated the soil. The intensified search for fresh soils often meant a nomadic way of life, declining income, and a search for work in the towns.

Several characteristics of shifting cultivation have hindered its practice. Polyculture is one; mixed plantings are incompatible with high yields of the most profitable crops, but clearing of bush fallow for monocultures is difficult to mechanize. Deep plowing and leguminous fallow have produced deplorable results. Heavy mulching and composting favor productivity but are not feasible for the average cultivator. The prevalence of the tse-tse fly in west Africa has meant no dung or draft animals.

Shifting cultivation systems, those requiring fallows and including tree crops, may survive where permanent agriculture cannot, but they yield so little per unit of land area that they may not support such community services as roads and schools (Holdridge 1959).

The length and shape of the clearing for cultivation in the forest are of paramount importance. The long axis should be east-west for maximum light. The optimum breadth is about 100 m. Under these conditions, loss of yield along the borders amounts to 10 percent in heavy forests but only 3 percent in secondary forests (Coene 1956).

Two weeded crops with short cycles may generally be grown in the same field in the same year. Annual weeded crops, such as maize, peanuts, soya, and cotton, are very sensitive to competitors; therefore, before they are planted, the soil should be exposed to the sun and rain. When planted immediately after removing the heavy forest, these crops do not usually yield well. Cutting the fallow a year before cultivation for annual crops increases yields greatly. Complete clearing, however, eliminates tree stumps as a source of sprouts for the subsequent fallow. Perennial crops such as bananas and

Table 8–1.—Past shifting cultivation regimes in what was formerly Zaire

Sequence (yr)	Location Bambesa	 Gandajika	 Yangambi
1	Deforest, maize, rice	Deforest	Deforest, maize
2	Cotton	Cotton	Maize, rice, manioc, bananas
3	Manioc, bananas	Maize, root crops	Bananas, manioc
4	Manioc, bananas	Maize, peanuts, root crops	Bananas, manioc
6	Fallow	Maize, manioc	Bananas, manioc
7	Fallow	Manioc	Legumes
8	Fallow	Manioc	Legumes
9	Fallow	Manioc	12-year fallow
10	Fallow	Fallow	6-year fallow

Source: Henry 1952.

cassava ordinarily do not require this treatment. They protect the soil better and have little effect on residual fertility.

Perennial crops are well suited to newly cleared areas and are an excellent precursor for annual crops. They increase the pH of the soil and favor decomposition and mineralization of organic residues from land clearing. The pigeon pea *(Cajanus indicus)* has proved to be a good crop to sow before a farm is abandoned (Page 1948), and its stems are large enough to use as fuel.

In the Philippines, shifting agriculture (referred to as "swidden") can produce rice yields double the national average (Conklin 1957). The system uses 2 ha of cultivable land per person on a 12-year cycle. The intensity of management varies. At one extreme, the vegetation is cleared each year; at the other, plentiful tree crops are established with little or no clearing of the climax forest.

During its first (and most active) year, an average swidden may have up to 40 different basic crops and 85 to 150 crop types at the same time (Conklin 1957). By the beginning of the second year, there was a shift toward tree crops, including bananas, fruits, and bamboo. When all cultivated crops were exhausted, a forest fallow may already be well advanced. The fallow period is two-thirds to three-fourths of the total swidden cycle.

The swidden system is land extensive and labor intensive (Harris 1972). It involves 500 to 1,000 hours of labor per family per year; however, no concerted action by large groups is generally required. Although the system is inefficient in terms of the amount of land cultivated, the yield per unit of labor expended can equal or even surpass some types of permanent field agriculture. It is the fallow, not the productivity, that restricts the capacity of swidden cultivation to support concentrated populations. The number of people living in swidden areas seldom exceeds 60 per square kilometer and is usually less than 40.

Shifting cultivation in Venezuela has been practiced on all humid lowlands (Watters 1968c). Above 1,600 m, decomposition is slower, and agriculture tends to be more continuous. Shifting cultivation is not the most productive system on poor soils, but it is the best available to people without implements or fertilizer. The first two crops may equal those of better land without fertilizer but are much less than what could be achieved with fertilizer.

Because shifting cultivators move to new areas when yields drop 50 percent, the practice is a principal cause of deforestation (Watters 1968c). Although primary forest areas permit a shorter cycle, cultivators will normally select secondary forests if they are more accessible. The system is hard to beat in terms of yield per unit of work. The labor input ranges from 32 to 86 d/ha.

In central Brazil, a village of 145 people that has been stable for 90 years cultivates a gross area of 5,500 ha, or nearly 40 ha per capita (Watters 1974). But at any one time, the area in use is less than 3 ha per capita. Half the food produced is sold. Only 3-1/2 hours each day are spent on subsistence, and of these, only 2 involve agriculture. The system has been a reasoned approach in that it has made lavish use of the resource that was available (land) while economizing on capital that was in short supply.

Shifting cultivation in what is now Sri Lanka has depended greatly on the products of burning for its nutrients and was therefore not necessarily a heavy drain on the soil during short cultivation periods (Joachim and Kandiah 1948). Intrinsic soil composition is restored in 5 to 10 years.

An unusual dry-climate variant of shifting agriculture has been described in the Sudan (Jackson and Shawki 1950). Here, the scrubby native vegetation was cleared from sand dunes, and sorghum was cultivated for 4 to 10 years, during which time the soil becomes exhausted. Natural revegetation with *Acacia senegal* and *A. seyal* followed, and after 8 years, the trees were ready to be tapped for gum arabic. Tapping continued for 6 to 10 years, during which time the trees wear out and die. The area was then burned and cultivated again.

Shifting cultivators are usually at least partially concerned with subsistence; therefore, their cultivated patches are normally a complex mixture of plants. The mixture is apparently chosen to satisfy the diverse needs of the family table and to give the farmer the relative security that comes from crop diversity. However, as would be expected, mixtures give lower yields per unit area for each crop than pure cultures (table 8–2).

Table 8–2.—Comparative yields from shifting cultivation in what was formerly Zaire (t/ha)

Crop	Mixed yield	Pure yield
Rice	1.5	2.5
Manioc	15.0	25.0
Bananas	4.0	15.0

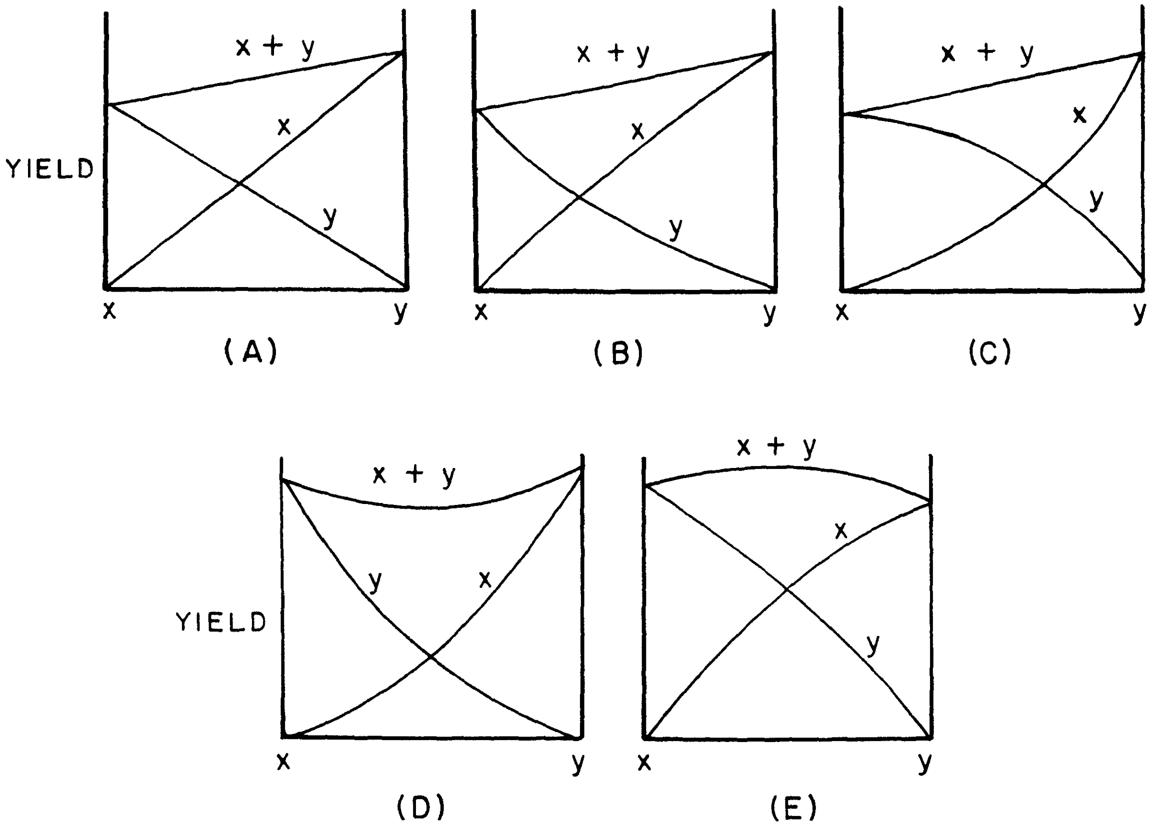
Source: Henry 1952.

The diversity of natural vegetation in the Tropics, a product of long evolution and succession, has suggested other reasons for the use of crop mixtures by farmers, and much research has been undertaken on this subject. Some hold that interspecific interactions not only protect mixtures from pests and diseases more than they do pure cultures but also can make mixtures equally (or even more) productive. However, studies have shown that most crop-mixture yields are intermediate between those of each component as a monoculture (Trenbath 1974). The yield totals tend to be nearly equal. Trangressive yields (above the limits of any component alone) are few and seldom significant or repeated. Such yields occur only in mixtures of similar components and, thus, are not to be expected with wide differences within subsistence cropping mixtures.

Mixed cropping systems have dominated northern Nigeria (Baker 1975) and are justified by their dependable return per unit of land or per June-July hour of work, which is higher than for pure crops. To obtain gains from mixtures over pure crops, the constituents must have complementary growth cycles. Intercrop competition must be less than intracrop competition. The arrangement and relative numbers of the different plants in mixtures will influence the degree of competition. Factors that may produce a gain from mixed cropping are differences in light interception (because of different canopy heights and structures) and differences in water utilization. These factors themselves change over time because of different growth periods for the mixture's constituents.

The theoretical significance of mixtures has been explored by Harper (1977) (fig. 8–1). In case "a," species "x" and species "y" compete with more or less equal effect on each other; so, yields are directly proportional to their relative representation. In case "b," species "x" is more aggressive than species "y"; so, mixtures of the two lead to greater than proportional yields from "x" at the expense of "y." For case "c," the opposite is true; the yield of species "y" is greater than its proportional representation in the crop. When, as in case "d," each crop is recessive relative to its level of intraspecific competition, mixtures yield less of each than their proportional representation and total yield is less than each species could produce alone. In case "e," both are more aggressive against each other than they are intraspecifically. Thus, each permits greater yields of the other species than their proportional representation would suggest, and their overall yield in a mixture is greater than the sum of their respective yields alone. Only in this instance is transgressive yield to be expected.

However, it is generally not true as alleged that yield capacity is correlated with aggressiveness, that mixtures always outyield pure stands, that mixtures have the mean yields of pure stands, that competitive capacities are additive, or that competition is more intensive between members of the same species (Harper 1977). Each of these statements can be true in specific cases, but can be clearly untrue in others.



Mixture	Mixture, x & y	
	crop x	crop y
(A)	equal	equal
(B)	aggressive	recessive
(C)	recessive	aggressive
(D)	recessive	recessive
(E)	aggressive	aggressive

Figure 8–1.—*Prospective yield effects of crop mixtures (Harper 1977).*

A study of 572 crop mixtures showed that two-thirds had total yields close to the sum of their separate yields (Trenbath 1974). Another 20 percent exceeded that sum by as much as 70 percent. About 14 percent produced less in mixtures than as pure crops.

Nine mixed cropping systems outproduced a monoculture of yams in Jamaica (Schroder and Warnken 1981). They required more labor and more capital, including fertilizer, but produced a 50-percent increase in farm income, three to four times what is typical for hill agriculture. Apparently, fertilizer helped, but most of the benefit seemed to arise from multiple cropping.

The following advantages and disadvantages of multiple cropping have been described (Gleissman 1981b):

Advantages

- Better use of time and vertical space, capture of solar energy and nutrients, crop overlapping
- Pumping of nutrients from deep in the soil
- Less vulnerability to climatic extremes and wind
- Less vulnerability to pests and diseases
- More flexible distribution of labor through the year.

Disadvantages

- Competitive constraints on short crops
- Limitations from species incompatibilities
- Damage from partial harvesting
- Inconsistency with a fixed fallow period
- Limited volume of each crop
- Unsuitability to mechanization and crop uniformity for marketing
- Greater complexity, making it little understood agronomically and biologically
- Incompatibility with prevalent social, economic, and political systems.

Although shifting cultivation has been an ingenious use of labor and resources in the Tropics to sustain primitive cultures, its limited capacity to support expanding populations has resulted in extensive land destruction. By 1952, shifting cultivation in west Africa was presenting a tragic picture. In the Sudan, all attempts to prevent widespread annual fires had failed. The lack of fuelwood had led to the plundering of the forests, and shifting cultivation with a shortened fallow was destroying the soil (Faure 1952). In Niger, the fallow stages had already become too short to restore the land between cultivation periods, and the entire territory was burned every year (Jorvanceau 1952). In Chad, the soil "discipline" formerly enforced had disappeared (Anon. 1952j). As a result, some 150,000 ha of forests were being cleared annually, fires were everywhere, and shifting cultivation was wearing out the soil.

In what is now Burkina Faso, forest exploitation for fuel and charcoal and the impossibility of protecting the country from fires led to a proposal to give the forest reserves to the people to farm (Civette 1953). In Ivory Coast, native farming practices were formerly kept in balance with the woodlands, but this balance was upset by overpopulation, emphasis on industrial development, changes in diet, and migration (Piolant 1952).

In Sierra Leone and The Gambia, the balance between cultivation and fallow had been upset by 1952, and the fallow was shortened to less than 7 years (Anon. 1952m). All unreserved forests were being released for more agriculture. In Togo, firebreaks to protect forests were thought to be too expensive, and the government was considering releasing the forests to farmers (Chollet 1952). In what is now Ghana, inadequate patrol of unreserved forests had led to trespass and illegal exploitation. All such forests were soon to be transferred to agricultural use (Anon. 1952i).

Soil destruction caused by shifting cultivation has been documented in the Western Ghats of India (Satyanarayan 1960). Soil depth ranged from 150 cm under teak *(Tectona grandis)* forest to 15 cm under poor grass. The pH of the latter decreased 0.8, the sand content doubled, and organic matter dropped to one-third, N to one-sixth, exchange capacity to one-third, and calcium (Ca) to one-fifth.

Studies in what is now Malaysia have shown that shifting cultivation persisting after 18 months wipes out all tree sprouts from the former forest (Wyatt-Smith 1958c). A shift there from millet to hill rice extended cultivation into the second year, wiping out most forest sprouts (Carey 1960). Even the isolated relics left as possible seed bearers were soon gone (Wyatt-Smith 1960d). Soil degradation continued because the people were unwilling to return to millet for a year; the soils were considered too poor to warrant the expense of their conservation and the area too remote for fertilizer or cash crops (Carey 1960).

The destruction of forests by shifting cultivators in Thailand has been spectacular. By 1958, two-thirds of the forests above 1,000 m were gone (Loetsch 1958). The waste was obvious because the timber was burned, yet there was reportedly little sympathy for forestry in the Parliament.

Burning, almost universally associated with shifting cultivation, causes some nutrients to be lost to the atmosphere or released in ashes lying loosely on the surface exposed to runoff water. Yet, studies in Ghana showed that after forest clearing and burning, almost all the potassium (K), Ca, and magnesium (Mg) in the first 30 cm of soil was retained (Nye and Greenland 1964). There was a marked rise in the pH. An increase in the soil N and carbon (C) was due to a mixture of parts of the vegetation with the soil. There was no net loss of humus in the soil as a result of burning. During the subsequent year, organic matter was lost as a result of oxidation of unhumidified material; however, the rate of loss was much lower the second year. In general, there was a rapid loss of nutrients through leaching and erosion during the first year. Burning accentuates these losses, particularly when repeated, after which grasses may take over and preclude further cropping (Frissel 1977).

Further light was shed on the results of burning in a study on yellow Latosols in Amazonia (Brinkman and Nascimento 1973). After burning, the pH, Ca, Mg, and K had increased in the top 20 cm of the soil (table 8–3). Thereafter, K, which is relatively mobile, declined.

In 1957, the Food and Agriculture Organization (FAO) detailed the shortcomings of shifting cultivation (Anon. 1957b) as follows:

- The fallow is not subject to control; therefore, site improvement is impossible.
- Fire and erosion are destroying the soils.
- Nomadic life offers no inducement to intensify management or make long-term improvements.
- Shifting cultivators accumulate no material wealth as a reward for good practices.
- When population exceeds the sustainable limit, all of the soil becomes degraded, and famines disperse the population.
- No prospect for specialization or progressive change is possible.
- The trend toward cash crops destroys the soil.

The causes of low efficiency in subsistence farming were listed by Phillips (1961). Among them, the following still seem especially important: poor land use; poor soil husbandry; poor seeds; insufficient tools and implements; and inadequate weed, pest, and disease control.

These factors differ in importance, and some are debatable. There is little question that the subsistence farmer, when not subject to outside influences, has made good use of the land, available crop plants, labor, and ingenuity in spacing and timing crops. There is also no doubt that the practices of the subsistence farmer are as durable as those of modern agriculture in the absence of fertilizer. The difficulty comes with the desire to produce more than is needed for subsistence purposes. This goal requires larger crop yields and usually a departure from mixed cropping and the multistoried cover. It also demands competitive production, involving fertilizers or a high return on hand labor. Efficiency, then, must be judged not solely by unit production costs but also by how well the yield serves the needs of the rural community that produces it.

One of the most common criticisms of shifting cultivation is that it seems to support only 8 to 12 persons per square kilometer (Nye and Greenland 1964). However restrictive this may sound, the system could thus support a village of 630 to 950 people using land within a 5-km radius. The fact that shifting cultivation does not necessarily dictate low population densities or a lack of social development is indicated by actual cases (Rebugio 1976). In Campeche, Mexico, more than 20 people have been supported per square kilometer. The Uaxactum culture has supported up to 40. In Indonesia, as many as 50 people have been supported. In parts of Africa, the

Table 8–3.—Burning effects on soil properties in Amazonia

		Days after burning		
Soil property	Before felling	14	148	290
pH	3.70–4.10	4.30–4.80	3.50–3.80	4.10–4.50
Calcium and magnesium (meq%[a])	0.30–0.50	1.00–1.60	0.50–1.00	1.00–1.40
Potassium (meq%)	.06–.09	.17–.31	.08–.12	.15–.09
Phosphorus (meq%)	.46–.67	.69	.69	.69
Aluminum (meq%)	1.20–2.10	.50–.90	1.10–1.80	.40–1.10

Source: Brinkman and Nascimento 1973.

[a]meq% = milliquivalents per 100 g.

number is 90 or higher, and in highland New Guinea, nearly 200 persons are supported per square kilometer.

The culture of the Xingu in Brazil, involving 3-year shifting cultivation of 0.3 ha per person and a 25-year fallow, has sustained a village of 145 people on 385 ha (Carneiro 1961b). A village of 2,000 could be supported at this intensity on 5,400 ha, all within walking distance.

Although under certain circumstances these shifting-cultivation systems can support dense populations, no convincing evidence appears to confirm that they can sustain a complex, stratified society concentrated in large villages or towns. In fact, some suggest that the shifting cultivation that led to the Mayan civilization was also the cause of its downfall (Rebugio 1976). People in small, dispersed settlements face a difficult transition to dependency on remote, centralized-market control. Support of large populations may be facilitated by concentrating cultivation on vegetables and root crops that remove only a small fraction of existing nutrients in their harvests. These and other crops, such as the peach palm *(Guilielma gasipaes)* and *Brosimum alicastrum,* may have supported the Mayan civilization (Harris 1972).

The Fallow: Nutrient Conservation. Cropping can deplete plant nutrients, which may seriously threaten productivity, even under shifting-cultivation systems. A significant portion of available plant nutrients may be stored within the fallow vegetation. Destruction of the fallow predisposes these nutrients to loss during decomposition through runoff and leaching. The rapidity of this loss is seen in the results of a study in Ghana where nutrient levels 3 years after forest treatment were compared (Cunningham 1963). In an area reduced to half the forest density, the decline in the top 5 cm of soil was 47 percent of N, 44 percent of phosphorus (P), and 48 percent of organic C. Where the forest was cleared, the corresponding percentages of loss were 53, 50, and 57.

In the Venezuelan Amazon, a decline in the cassava crop from 4.3 t/ha in the first year to 2.8 t/ha in the second was attributed to loss of soil fertility (Uhl and Murphy 1981). During the first year after cutting and burning the fallow, the cassava crop produced nearly five times as much dry matter as the secondary forest. In the second year, however, the productivity of the secondary forest (the fallow) rose to 2.7 times that of the cassava crop.

Runoff and erosion increase dramatically after conversion from primary forests to cleared cultivation (table 8–4). But a secondary fallow at 6 years is almost as effective as a primary forest. These data from Mindanao, Philippines, were collected on slopes of about 25 percent and for a period of 227 days (Kellman 1969).

Table 8–4.—Runoff and sediment losses with clearing of forests in Mindanao, Philippines

Forest type	Rainfall runoff (%)	Mean daily loss (kg/ha)	Annual organic matter loss (kg/ha)
Primary forest	26	200	45
6-year secondary forest	26	290	65
10-year abaca	64	590	133

Source: Kellman 1969.

Fallow systems do not markedly accelerate liberation of nutrients from primary sources in the soil, but the capacity of fallows to capture and immobilize released nutrients is unique. The following two factors help enhance soil productivity during the fallow (Bartholomew and others 1953):

- Accumulation of plant nutrients in organic combinations and prevention of nutrient losses by plant immobilization
- Improvement of soil structure by both biological activity and rest from cultivation.

Total dry-weight biomass accumulation in fallows was shown by early studies at Yangambi (table 8–5; Bartholomew and others 1953). The chemical composition of this biomass further indicates the immobilization rate of nutrients by the fallow (table 8–6). Immobilization of nutrients by 3-year-old grass cover in the same area produced a total biomass averaging 86.1 t/ha dry weight, 418 kg/ha of N, 46 kg/ha of P, 348 kg/ha of K, and 201 kg/ha of Ca and Mg (Bartholomew and others 1953). Obviously, grasses may initially immobilize more nutrients than does the forest fallow, but the latter eventually immobilizes far more.

Tree and shrub crops that keep the soil covered, such as rubber, oil palms, coconuts, and tea, produce significant leaffall and may support a cover crop beneath them that can be managed to sustain the level of organic matter (Young 1976). However, for the culture of annuals, there appears to be no practical means of maintaining organic matter in humid areas other than by extended fallows or supplementary soil treatments.

Table 8–5.—Dry-weight biomass accumulation in forest fallows in Yangambi, in what was formerly Zaire (t/ha)

Tree component	Dry weight of fallow		
	2 yr.	8 yr.	17–18 yr.
Leaves	5.6	5.3	6.4
Wood	5.4	116.3	114.6
Roots	6.9	22.7	31.2
Litter	1.9	8.0	22.8
Total	**19.8**	**152.3**	**175.0**

Source: Bartholomew and others 1953.

A benefit from fallows not generally recognized is their relative resistance to burning. Even where fallows are frequently subject to fire, all organic matter is rarely consumed, and their residual root systems and capacity to sprout favor prompt immobilization of a maximum of the released nutrients.

There is evidence that the pioneer tree species that naturally come up after clearing are superior to others in their capacity to immobilize nutrients (Kellman 1969). Most of the soil recovery takes place during the life of these pioneers, be it 5, 10, or 15 years. During this period, soil-surface conditions are restored, and runoff and erosion are reduced to levels similar to those of older forests.

The length of the fallow period that is necessary to restore forest sites for further food crop production has become a problem where population density or increases in demand have pressed for expanded agriculture. Many estimates of this time period have been made from general observations. Early estimates suggested a fallow of 15 years in North Borneo (Coene 1956, Lee 1961) and 5 to 10 years in what is now Sri Lanka (Rosayro 1961). In Trinidad, the fallow period required after clearing, burning, and 1 year of cultivation is directly related to steepness and wetness because of the great propensity to erosion and leaching (Cornforth 1970b). Increases in K, Ca, and Mg and decreases in N resulting from burning disappeared in about 4 years. Nitrogen reached its original level in about 10 years. Phosphorus decreased for 7 years and never regained its original level, remaining about 25 percent lower. In Sarawak, estimates of site recovery time range from 7 to 12 years (Cramb 1978, Hatch 1980).

Studies in Central America further detail the effect of fallow length on-site recovery (Ewel 1976, Ewel and Conde 1978). Litterfall in secondary forests in Guatemala equals that of the mature forests by the 14th year. Equality of cycling for some nutrients was reached earlier. Litterfall may be even greater in secondary than in primary forests because of more deciduousness and the successional changes in species.

In eastern Guatemala, with 200 cm of annual rainfall, organic matter accumulation after clearing was found to reach half that of the undisturbed forest in less than 1 year of fallowing and to equal that rate in 3 to 5 years (Ewel and Conde 1978). Litter production peaked at 21 years and declined to the natural level at 30 to

Table 8–6.—The chemical composition of forest fallows in Yangambi, in what was formerly Zaire (kg/ha)

Tree component	Nutrient	Nutrient content		
		2 yr.	8 yr.	17–18 yr.
Leaves	Nitrogen	80.0	120.0	143.0
	Phosphorus	10.7	6.6	7.5
	Potassium	80.0	79.0	80.0
	Calcium, magnesium	63.0	87.0	76.0
Wood	Nitrogen	18.0	206.0	301.0
	Phosphorus	6.2	15.3	62.2
	Potassium	37.0	579.0	305.0
	Calcium, magnesium	34.0	344.0	378.0
Roots	Nitrogen	76.0	152.0	146.0
	Phosphorus	4.9	9.1	34.0
	Potassium	65.0	100.0	200.0
	Calcium, magnesium	42.0	127.0	266.0
Litter	Nitrogen	15.0	101.0	11.0
	Phosphorus	0.4	13.2	4.1
	Potassium	4.0	81.0	16.0
	Calcium, magnesium	21.0	110.0	102.0
Total	Nitrogen	**189.0**	**579.0**	**701.0**
	Phosphorus	**22.2**	**44.2**	**108.0**
	Potassium	**186.0**	**839.0**	**601.0**
	Calcium, magnesium	**160.0**	**668.0**	**822.0**

Source: Bartholomew and others 1953.

35 years. Organic matter decomposed more slowly in cleared areas than in areas covered by vegetation.

Nitrogen, probably more than any other element studied, reflects the benefits of fallowing. Inputs of N are age dependent and are never higher in secondary than in primary forests (Ewel and Conde 1978). Phosphorus in a secondary forest dropped to one-half the former level in 5 weeks and to one-fourth in 6 months. Returns of P were closely related to litter production and probably reached a peak at about 20 years. Potassium declined 5 percent in 3 weeks or less and 10 percent in 6 weeks. Ensuing losses were slower. Subsequent K levels did not correlate well with forest age nor did those of Ca and Mg, both of which were relatively stable.

Where long fallows cannot be allowed, it is generally agreed that some fertilizer, especially N, P, and K, will be necessary (Kanehiro 1978).

The difficulty of procuring fertilizers in many tropical areas has led to the use of leguminous plants to fix N. Nitrogen in the atmosphere is stable and inert and cannot be used directly. Fixation involves splitting dinitrogen into two N atoms that react with hydrogen (H) to form first ammonia and then a range of compounds (Halliday 1981). Rhizobia bacteria penetrate the roots of some legumes and other plants and give rise to highly specialized organs referred to as root nodules, which are capable of fixing N. Some tropical legumes associate with only a few bacteria, others with many. They may fix up to 100 kilograms per hectare per year of N; *Leucaena* has the highest rate of N fixation, up to 350 kg/ha/yr.

Although some legumes can *in some circumstances* contribute N to the soil (Halliday 1981), many cannot (Kellogg 1963). Of 68 native and exotic leguminous species studied in Peninsular Malaysia and Singapore, 37 (more than half) did not have root nodules (Lim 1977). For the

Caesalpinioideae, only 4 of 27 had nodules; for Mimosoideae, only 5 of 13; and for Papilionoideae, 22 of 27. An absence of nodules in a natural habitat, however, does not prove a lack of nodulating capability. But there is no convincing evidence that even nodulated legumes excrete significant amounts of N from their roots or nodules. A crop fixing 100 kg of N per year excretes only about 0.5 kg to the soil (Halliday 1981). Even on poor soils, only a part of the N accumulated by legumes comes from biological fixation. The main N benefit to associated plants is considered to be indirect, through the loss and decay of shoot, root, and nodule tissue. But even then, 5 t of green matter add only 40 kg/ha of N to the soil, of which only about half would mineralize to the benefit of the other vegetation.

These findings contradict many widely made claims about the capabilities of N-fixing plants. Nevertheless, such plants clearly have a place on poor soils where other N is limiting; and, in association with other plants, those that fix N presumably compete less for N than do other species.

Ameliorating Shifting-Cultivation Effects

Shifting cultivation has been so widely criticized, particularly from distant sources, that many have concluded it should be eliminated. Under some conditions, shifting cultivation undeniably creates many serious problems. However, elimination of the practice is, in most of the Tropics, neither feasible nor necessarily desirable. Rather, the practice of shifting cultivation must be adapted to the productive capacity of the environment. This calls for an understanding of both the human needs involved and the techniques that might alleviate the problems.

Because of the need to support growing populations in the Tropics, Gourou (1956) believed forest production should be relegated to slopes and plateaus. Concentrating agriculture on the lowest, richest, and wettest areas would increase output per hectare of land, output per hour of labor, and the total mass of food produced. This trend, however, would not necessarily mean abandoning shifting cultivation, because in the absence of manure, it yields more per day of work than paddy rice.

In contrast, Watters (1968a) observed that increases in production per unit of work seldom result in corresponding increases in investment in further production. Rather, such increases result in more leisure. Nevertheless, he recommended solving the problems of shifting cultivation by increasing output per unit area in densely populated places and per hour of work in sparsely settled areas (Watters 1971). He further concluded that while many technical problems remain, most are relatively simple to solve. The real difficulty lies in implementing the solutions, that is, inducing rural people to accept them. Development should be not so much *for* the people as *by* the people. Governments must recognize that what is ultimately involved is the conservation of people; their very lives and cultures are at stake (Watters 1974). These historic and rightful owners of the land have every right to participate in the decision making that will affect their future lives and the future use of the forest. Unfortunately, their needs and desires are not often considered. For example, policymakers in North Borneo recommended controlling shifting cultivation by limiting population density to 10 families (57 people) per 4 km^2 (Lee 1961). Such proposals suggest a wide gulf between decision making and those affected by decisions.

Shifting cultivators are wary of attempts to change their practices. Thus, in what is now Malaysia, although technicians agreed that the only real "remedy" for shifting cultivation was more permanent methods of husbandry that involved cooperative production and that permitted fencing of animals, the cultivators did not accept the change until it could be proved to their benefit (Arnot and Smith 1937).

Among the Bantu in what was formerly Zaire, the value of shifting cultivation was seen, partly, to be its guarantee of economic stability (Tondeur 1955). The system operates on family labor, providing the families with food and protecting them from the economic troubles caused by fluctuations in the produce and labor markets. Any more elaborate system of agriculture could be much more vulnerable.

It is commonly said that the prospect for protecting and managing forests in the Tropics depends on intensifying farming and stock-raising elsewhere, thus relieving forests of the pressures of extensive farming (Fontaine 1976). This approach undoubtedly has merit, but intensive farming will generally not employ all those previously dedicated to extensive farming. Also, because intensive farming requires more specialization and skills, the people it does employ may not be the shifting cultivators.

Replacing primitive agricultural systems with more intensive techniques must be examined in the light of economics. Shifting cultivators start with nothing, and changing their methods could mean an enormous investment in land improvement, irrigation, drainage, implements, sheds, roadways, machines, vehicles, cattle and draft animals, and pest control. Because native agriculture cannot bear even a slight increase in costs, intensification would be advisable only if the net crop return were clearly greater as a result. The economy not only must be capable of absorbing the investment, but the cultivator, who has no capital, must have a source of credit (Tondeur 1955).

The scientific principles on which agricultural practice is based may be universal, but individual practices must be tested locally (Greenland 1975). It cannot be assumed that new methods of agriculture developed by the industrial countries are unconditionally superior to local methods (Egger 1981). Industrial and developing countries have different goals and different resources. In the Tropics, emphasis has been on subsistence rather than production for the market, on security and stability rather than maximum yield, and on great diversity in husbandry rather than mechanized and chemical aids. One approach to changing that emphasis might be to adopt advanced methods in use in neighboring regions. Another might be to adopt carefully selected modern methods capable of increasing the efficiency of traditional systems without endangering their basic structure (Egger 1981). The best strategy would be to balance population factors with the technological potential of shifting cultivation rather than eliminating or rigidly controlling the practice (Rebugio 1976).

Promoting changes in shifting agriculture requires rare combinations of tact and expertise. Raghavan (1960a) concluded that in India, those who attempt it should be not only scientists but also practical sociologists with missionary zeal. Even for those with experience in practical economics and organization, the task requires time, patience, and persistence (Jurion and Henry 1967). Conventional schools are not providing the type of education needed to change the practice of shifting agriculture (Raghavan 1960b). To help meld the rural population with the forest environment, forestry curricula must stress the importance of forests for a host of allied farming opportunities, such as poultry raising, pasture management, production of dairy products, woodcarving, basketmaking, and carpentry.

In Thailand, stabilization of shifting cultivators has been attempted through broad rural development (Samapuddhi 1974). The forest is divided into large tracts for each village, as much as 96,000 ha for 100 families. The community leaders are provided with educational material that emphasizes ways the organized village may help the people. Village improvements (water, electricity, and education) may be supplied. Forestry tasks are a source of part-time employment. A taungya system is organized to produce significant income to the community.

Improved Local Planning. Agricultural settlement schemes commonly have goals that assume the cessation of nomadic agriculture. As an example, in what was formerly Zaire, two systems were applied (Coene 1956). In one, families were initially assigned a tract within which they worked in a small area at one time. In another, farmers were assigned strips of land in sequence. In both systems, the land remained communal property. The first alternative resulted in better care of the soil because the farmer always worked the same land.

Where pure subsistence farming has given way to cash-crop farming, any previously harmonious relation with the environment has usually become strained. It is generally neither desirable nor possible to re-create the old relations (Watters 1960). The task is rather to establish new relations that do not violate the "design of nature" and yet are consistent with modern needs.

Where tree crops, such as rubber, oil palm, nuts, and fruits, are appropriate on rainy slopes and marginal soils, both the initial investment required and the delay in returns make the proposition unattractive for private landowners (Santiago 1961). Public participation may be needed in the form of at least temporary, direct administration or continuing governmental incentives.

Government participation calls for recognizing a dual role in forest production. Assistance to rural communities and particularly to farmers who can benefit from better practices on land requiring special conservation measures may appear to be the primary public goal. However, the government must also stimulate production of enough industrial timber to satisfy national requirements. To ensure both objectives, public planning must identify permanent forests as well as those forests whose primary function is as fallows to sustain the production of other crops.

An example of local planning is seen in Madras, India (Venkataramany 1960c). The community consisted of 100 families (500 people) and 400 cattle. Annual domestic fuelwood consumption was 1/6 t per capita, or a total of 83 t. On a 30-year rotation, this called for about 100 ha of forest. In addition, the cattle needed 80 ha of pasture, for a combined total of 180 ha. This is equivalent to 0.36 ha per person, more than triple the land generally available at that time throughout India. Recommendations to remedy this deficiency included reducing the number of cattle and shifting from manure to chemical fertilizers, dedicating fallows to intensive production of fuelwood and fodder, and dedicating part of the nearby forest reserves to fuel and fodder.

In a 1960's survey, tropical land managers agreed that combined tree and food crops could prosper on land not capable of supporting continuous cultivation (King 1968a). Fallows of either secondary forest or planted trees were seen as a key to success. As a result, village projects were proposed in which land use would be closely controlled and production supplemented by sustained taungya crops within reserved forest land. The attraction was the advantages over alternative systems such as frequent moving, expensive monocultures, and tree planting with paid crews (King 1968a).

Land Use. A wide array of techniques, some proven but largely unused, offers hope for improving and stabilizing land use where shifting cultivation precludes sustained productivity. Some of the current practices are no more pleasing to the cultivators than they are protective. It was pointed out in India (Sagreiya 1946a) that peasants use cow dung for fuel only as a last resort. The recommended alternative was the establishment of "fuel cum fodder" plantations, using rapidly growing, hardy tree species, such as *Acacia* spp., *Dalbergia sissoo, Melia* spp., *Prosopis* spp., and *Senna siamea,* thinned to 5 by 5 after 2 to 3 years and interplanted with fodder grasses.

The corridor system developed in what was formerly Zaire was designed to stabilize the boundaries between each cultivator (Kellogg 1963). The entire area was managed on a rotation based on the number of years cropped plus the number of years of fallow. Appropriate amounts of land were planted and fallowed each year. Supplemental permanent crops were planted nearby. Wood ashes, manures, and composts were used. Tall crops not requiring clean cultivation, such as cassava and bananas, were used during the last year before fallowing to give the trees a better start. Each cultivator worked strips 100 m wide along the contour, and a protected strip was left in between (Nath 1968).

"Alley cropping" is a practice developed by agriculturists in which food crops are grown in alleys between hedgerows of trees or shrubs. Food cropping may be only periodic, with the hedgerows pruned only during food-cropping periods. Hedgerow species must be easy to establish, grow rapidly, develop deep roots, produce heavy foliage, and coppice well. Hedgerows are spaced 2 to 4 m apart, with trees or shrubs spaced 25 to 100 cm apart in the rows. During cropping periods, the trees are pruned every 5 to 6 weeks to a height of 2.5 to 7.5 m. Five prunings of *Leucaena* per year on mildly acid soils yielded 160 kg of P, 100 kg of K, 40 kg of Ca, and 15 kg of Mg per hectare. Over 4 years, the application of these prunings to maize tripled the yields.

Changes in the shifting cultivation system considered in India include longer fallows (taungya) with tree crops, such as *Alnus, Gmelina, Leucaena,* or *Sesbania,* and shifting to better land for continuous cultivation with fertilizer, crop rotation, or bench terracing where necessary (Nath 1968).

Where shifting cultivation is wearing out the soil, intensifying treatment has been widely recommended. This includes fertilizer use, plowing as soon as stumps decay, more efficient use of forage and tree crops, and the use of fungicides and pesticides (Watters 1974). These, however, are departures from subsistence farming and the dual economy. Such intensification has not generally helped the peasant farmers as much as it has enslaved them to one or a few crops at the expense of their subsistence needs. Unless the government can compensate with community-development benefits, small farmers on marginal land generally lose out to competition from production on better land.

Whatever the apparent obstacles to betterment of shifting cultivation, the natural primary productivity of the humid Tropics remains among the highest in the world (Lieth 1976). Although this productivity may be reduced substantially by conversion from natural ecosystems to cultivated crops and although fertilizers may be needed for sustained production, there remain many areas of great promise and a vast number of untried native crop species that should prove widely adaptable.

In both natural and agricultural systems, high biological activity is almost always achieved with the aid of energy subsidies from outside the system (Odum 1972). However, attempting to force too much productivity from the land could lead to pollution from heavy chemical use, unstable one-crop systems, and increased vulnerability of plants to disease if their protective mechanisms are genetically suppressed in favor of yield. Young ecosystems are high in production, growth rate, and quantity of yield. Mature ecosystems have high protective values, stability, and quality. Some of these traits from both systems need to be conserved.

For any agricultural system to be stable, the physical condition of the soil must remain suitable. Maintaining arability involves control of erosion, acidity, and toxicity. The soil must be protected against the direct force of falling rain; therefore, a continuous or intermittent cover crop is required. The nutrients removed by cropping must be replenished, and there must be no weed or pest buildup (Greenland 1975). Under shifting cultivation, these conditions can be met only with a fallow that may be 1 to 20 times as long as the cropping period. Reducing the fallow and lengthening the period of cultivation induce site deterioration.

A cultivation system potentially beneficial to the small farmer could include zero tillage, mulching, use of mixed crops of high-yielding varieties that are pest and disease resistant, application of P and possibly other fertilizers, addition of legumes, and control of acidity by ash and mulch. To be practical, alternatives to shifting agriculture should require minimal capital investment. This combination should reduce or eliminate the fallow and increase productivity at least fourfold (Greenland 1975). However, the possibility always exists that intensive cropping may exacerbate soil degradation. Therefore, organic matter levels and structure should be monitored to foretell any need for corrective measures (Young 1976).

Traditional farming can often be improved by adopting methods used in neighboring regions (Egger 1981). Examples of such methods include the use of tree crops, cover crops, weed management, mixtures, and staggered rotations. These practices tend to lead from subsistence agriculture toward marketable crops, something best done gradually.

Improved Fallows. A great potential for increasing agricultural production lies in the intensification of fallow systems (Greenland 1974a). This could lead to a shorter fallow or a longer cultivation period. Fertilizing during cropping will always be necessary and should significantly stimulate production. Ammonium fertilizers tend to acidify, eventually calling for costly liming; fallowing followed by burning adds nutrients largely in the form of carbonates and, thus, economically counteracts acidification (Greenland 1974b). Nevertheless, protection from burning may be critical, otherwise the fallows may not accumulate enough nutrients to support subsequent crops. This problem, which is widespread, arose years ago in what was formerly Zaire and led to the practice of leaving strips of native forest throughout agricultural regions as fuelbreaks (Collin 1952b). Protecting the fallow from fire by itself can greatly increase its effectiveness.

Woody fallows on savannas store far more K, Ca, and Mg than do grass fallows (Nye 1958). Even pigeon peas are greatly superior to native grasslands as fallows.

Different tree species may be equally valuable as fallows, yet vary widely in usefulness for other purposes. *Acioa barteri,* a shrubby tree of the Chrysobalanaceae family native to west Africa, was tested because it coppices well (Nye and Hutton 1957). After 4 years, it had stored less N, P, and K than the natural regrowth but had produced nearly double the aboveground phytomass (table 8–7). Thus, in the long run, it may be as beneficial as the natural fallow.

Another alternative for fallows is rapidly growing tree species (Young 1976). Promptly introduced at the end of the cropping period, they may be as effective as natural fallows in restoring soil humus. A 6-year-old fallow of

Table 8–7.—Four-year nutrient storage of an *Acioa barteri* fallow in west Africa (kg/ha)

	4-yr. storage in stems, leaves, and litter	
Nutrient	Natural fallow	*A. barteri* fallow
Total dry matter	24,800	46,700
Nitrogen	382	310
Phosphorus	52	27
Potassium	367	174
Calcium	168	230
Magnesium	104	147

Source: Nye and Halton 1957.

such trees on a 25-percent slope in Mindanao, Philippines, kept sediment and organic matter losses to only 45 percent above those of a primary forest and rainfall runoff to only 2 percent above that of a primary forest (table 8–8; Kellman 1969). Short-cropping and skillful utilization of fast-growing softwood fallows might keep the rate of site deterioration below what is common to traditional, periodic logging of forests and at the same time provide optimum fallow benefit to the cultivation cycle (Kellman 1969).

Improved Cropping Practices. There seems to be a fund of local knowledge in the Tropics suggesting that increasing the use of food crops could prolong the cropping period. For prolonged cropping, two cropping sequences were recommended for what was formerly Zaire, considering the compatibilities of different crops (Coene 1956):

Heavy forest areas:

1st year:	bananas and rice, then cassava after rice harvest
2nd year:	bananas with cassava, harvest beginning near the end of the year
3rd year:	bananas and cassava harvested
4th year:	maize, pumpkins, and beans, followed by cotton
5th year:	peanuts, followed by cotton
6th to 19th year:	bush fallow.

After bush fallow:

1st year:	rice on 20 percent of the land; maize, beans, and pumpkins, followed by cotton on the other 80 percent
2nd year:	peanuts on 100 percent of the tract, followed immediately by cotton on 50 percent; 2 months later, cassava interplanted with the cotton
3rd year:	bananas and cassava not weeded
4th and 5th years:	bananas and cassava harvested
5th to 17th years:	bush fallow.

The balance between subsistence and cash crops is critical but varies widely from place to place. As communication and transportation improve, the shift toward market crops and a money economy for rural populations is increasing. This trend accentuates a need for recognizing and developing superior varieties of the crop plants. Of course, many improved varieties depend on fertilizers for highest yields. However, often overlooked but gaining recognition are those crops that are most efficient when fertilizers are used sparingly.

A shift to more permanent crops, such as forage and trees, has been recommended as one way to increase the stability of shifting cultivators. Certain tree crops, carefully husbanded, have sustained their productivity for decades.

Table 8–8.—*Soil effects of cropping in Mindanao, Philippines*

Index	Primary forest	Cleared, abandoned for 7 yr.	Cleared, in abaca for 12 yr., abandoned for 7 yr.
Nitrogen (percent)	1.1	0.6	0.4
Phosphorus (ppm P_2O_5)		8.0	24.0
Potassium (meq%)[a]	0.4	0.4	0.4
Calcium (meq%)	2.6	3.3	3.9
Magnesium (meq%)	1.0	0.8	1.0
Carbon (percent)	8.5	9.0	4.0
Sodium (meq%)	0.1	0.04	0.1
pH	4.7	5.2	5.5
Cation exchange capacity	76.7	46.5	43.3

Source: Kellman 1969.

[a] meq% = milliquivalents per 100 g.

Crop improvement might well include better use of legumes. Although legumes differ widely in their ability to fix N (Halliday 1981), this capacity can be improved significantly by inoculating with selected strains of Rhizobia. The result can be not only less drain on soil N but better use of the N. Nitrogen-fixing legumes take up less soil N than do nonlegumes. If the nonleguminous species outlive the legumes, they benefit by the release of N from the legume decomposition. In addition, 60 to 90 percent of the N in leguminous grains can be harvested for human food, a contribution far more important than the benefit to neighboring crops (Halliday 1981).

Nitrogen fixation by legumes is largely a complement to N fertilizer rather than a substitute (Halliday 1981). Any suggestion of replacing N fertilization of cereal and root crops by biologically fixed N is unrealistic because these crops need much more N than could be supplied through N fixation by legumes.

The future of legume usage, however, may well be bright. Legumes are not yet widely produced because of low volume yields (Halliday 1981); cereal grains yield four times as much. Legumes, however, may yield five times as much protein as cereals, and thus, techniques that increase legume yields deserve investigation. A list of tree species appropriate for agroforestry appears in appendix L.

Fertilizer Use. The shift from subsistence farming to market crops has brought to the forefront the need to compete with farm produce from other areas where fertilizers are used. There seems little doubt that more fertilizer application will eventually prove both productive and profitable for small farmers despite currently perceived financial and balance-of-payment limitations. Use of small quantities of fertilizers and chemicals can greatly increase growth. There is no logic in foregoing fertilizers for the sake of tradition. If the fertilizers are justifiable economically and applied properly, there should be no ecological reservations against using them or other chemicals (Egger 1981).

In the Campo Cerrado of Brazil, where felling and burning have reduced the former moist evergreen forest to scrubgrass savanna, shifting cultivation cannot succeed without fertilizers, including P, Ca, sulphur (S), and minor elements (Hardy 1962a).

Government subsidies have been proposed to encourage the use of cash crops and fertilizers in tropical America as a remedy for the ills of shifting agriculture (Watters 1971). The supposition is that only through such financial assistance can the small farmer benefit fully from participation in national economies.

Intensification of small farming in the Tropics must count on the use of fertilizers, both to lengthen cropping periods and to increase yields to competitive levels (Greenland 1974b). Improved cultivars of crops (including the so-called high-yielding varieties) require more nutrients than lower yielding varieties (Young 1976). The potential nutrient deficiencies are not remedied solely by fertilizers; other good soil management practices are required. The key to providing plants with adequate N is to maintain reasonable levels of organic matter by applying fertilizers supplemented with compost.

The objective of fertilizer use should be to maximize the output-to-input ratio rather than to maximize yield alone (Liebhardt 1981). Small amounts of fertilizer may greatly increase production. On the high-base soils that cover 18 percent of the Tropics, small amounts of N, P, and micronutrients should be sufficient. On low-base soils, which cover 51 percent of the Tropics, high acidity, aluminum (Al) toxicity, and P deficiencies may have to be corrected by adding lime, P, and possibly S. Fertilizer requirements may be reduced by using crops that tolerate adverse conditions, such as upland rice, cassava, sweet potatoes, cowpeas, some grass species, and legumes (Liebhardt 1981).

Taungya Systems

Taungya systems involve using farm crops to render the land suitable for starting a forest plantation. The word, meaning literally "field on the hill" in Burmese, became "kumri" in India, where the system migrated from what is now Myanmar in 1870 (Clarke-Butler-Coke 1943, Raghavan 1960b).

In Java, the taungya system had been used to plant 40,000 ha of teak *(Tectona grandis)* by 1891 (Becking 1951). The total had risen to 190,000 ha by 1920 and to 312,000 ha by 1952 (figs. 8–2, 8–3; Wepf 1954). There were 40,000 ha of teak and mixed plantings under the taungya system in what is now Myanmar by 1962 (Hundley 1962). In 1977 alone, 132,000 ha of teak were planted in Java using the system (Atmosoedarjo and Banyard 1978). The taungya system spread throughout much of India after 1914, including the dry fuel forests planted throughout the 1920's. It reached west Africa by the late 1920's (Brookman-Amissah 1976). By 1935, the

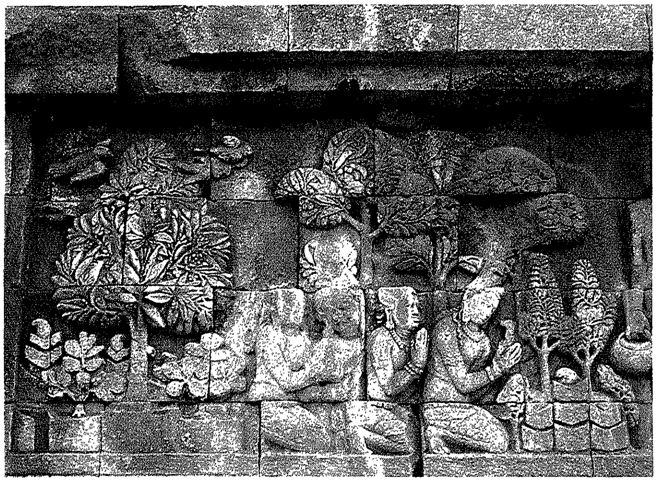


Figure 8–2.—*An indication that agroforestry may not be so new after all is depicted on the wall of the 8th-century Boburadur Temple in Java.*

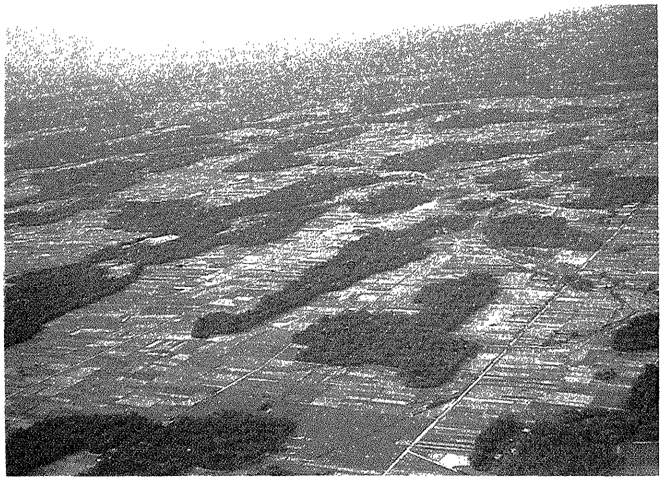


Figure 8–3.—*Rich, level land in eastern Java is heavily populated and intensively cultivated, yet trees have been maintained for centuries for vital fruits, poles, and fuel for the farming population.*

native authority of what is now Benin agreed to make available 400 ha of reserved forest each year for taungya (Clarke-Butler-Coke 1943).

To be successful, the taungya system must be applied where a need for land exists, where soils are adequate to yield reasonable food crops temporarily without excessive soil deterioration, where tree species in demand are of proven adaptability, where a willing farming population exists, and where a local staff is trained to operate the system (Clarke-Butler-Coke 1943, Raghavan 1960b, Raynor 1941).

The system was introduced into West Bengal, India, because natural regeneration had proven unsatisfactory there (Talukdar 1948). Each cultivator was given 0.4 to 0.8 ha to work. In some areas, the cultivator collected the tree seeds, sowed them, and cleaned the plantation for 2 years at no cost to the government. However, in addition, the cultivator was offered up to 2 ha of lowland for a paddy and was allowed to graze two work animals and one cow on the forest land. The cultivators were also permitted forest products for construction and might be loaned food grains until harvesting time. They were paid wages for additional forest work.

A combination of taungya with village forests and grazing has been described as successful in India (Smythies 1938b). An area of some 15,000 ha had historically been used by 86 villages living within 5 km of the forest boundary. Unlimited grazing and wood utilization had deteriorated the forest until 1947, when 5,700 ha were protected from grazing; they subsequently improved. The plan classified 6,700 ha for timber, of which 5,700 were to be established using the taungya system, and 8,700 ha were for village use, of which 6,500 ha were to be fuelwood plantations established by the taungya system.

In Java, the taungya system was used simply because of a need for food crops (Wepf 1954). Corn, peanuts, and peppers were planted (Becking 1951). Manioc and castor oil plants were considered too tall. *Leucaena* was interplanted with the food crops, producing increased litter and N. More recently, dryland rice has been raised with teak in Java, using N and P fertilizer (Atmosoedarjo and Banyard 1978). The fertilizer increased crop yields more than 50 percent and appeared to stimulate the teak as well.

By 1952, the taungya system had been tested in most of west Africa. In The Gambia, Ivory Coast, and Sierra Leone, taungya had proved successful with teak *(Tectona grandis)* and *Senna siamea* (Anon. 1952n, Piolant 1952). In what was formerly Zaire, two types of taungya were used (Collin 1952a). On government reserves, parcels of 5 ha were given to cultivators and prepared for planting by the government. The farmer raised bananas for export at an 8- by 12-m spacing while caring for trees planted by the forest department. On tribal lands, natural regeneration of timber species was allowed to come up between the crops at a wide spacing, averaging 20 m. In Nigeria, two similar systems have operated, depending on ownership; farms range from 0.5 to 2.0 ha per family (Olawoye 1975). There, the taungya system became an important source of both food and employment.

In dry areas of Africa, such as the Sudan, the taungya system has been practiced using corn for 1 year, interplanted with *Acacia arabica* (Jackson and Shawki 1950). Corn, sorghum, and short grasses have also been maintained under *Eucalyptus microtheca* in the Sudan for 3 years without apparent detriment to tree growth. Mean tree height after three growing seasons was more than 3 m (Khan 1966a). Where subsurface water is not too deep, *Azadirachta indica* (neem) has been interspersed successfully with such crops as millet and beans. When trees are planted at 2.4 by 2.4 m, the canopy closes in 3 years (Mackay 1952). In Pakistan, interplanting of *D. sissoo* with cotton proved inexpensive for the government and produced good cotton after 13 months (Khan 1957).

Experience with the taungya system in east Africa (the *shamba* system) showed that cultivators get less harvest from second-rotation cropping than from the primary forest areas cropped the first time (Anon. 1968d). However, repetition of the practice was considered necessary even if nutrients eventually had to be added.

In Trinidad, where the taungya system was long practiced with teak, annual leases have been given for cultivation. The normal practice was to crop areas for 1 to 3 years before abandonment (fig. 8–4; Goodlet 1953).

The taungya system has been used successfully elsewhere in tropical America. In what is now Belize, corn has been raised in young mahogany *(Swietenia macrophylla)* plantings (Flinta 1960). In southern Brazil, rice and beans have been cropped for 2 years in *Cunninghamia lanceolata* plantations. In Sao Paulo, rice and cotton have been raised with eucalypts. A test of a *Eucalyptus* taungya system with corn in Brazil showed the significance of spacing (table 8–9; Gurgel Filho 1962). Three rows of corn between the eucalypts produced the most value per unit of land, but because the soils were poor, one row of corn was considered preferable.

In 1968, a worldwide questionnaire about the taungya system (King 1968a) reported that more than 60 percent of the forest departments in tropical countries had planting programs designed to assist farmers. These programs listed 79 tree species and 39 agricultural crops as being used. Crops not generally used included bananas, corn, rice, sugarcane, tobacco, and yams, usually because these produced excessive shade, had too long a cropping period, or tended to climb on the trees. Yields reportedly declined after the first year because of crown closure.

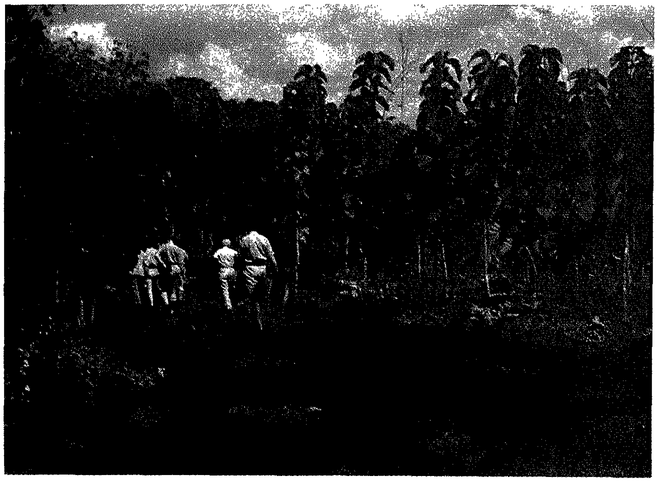


Figure 8–4.—*A successful result of taungya planting of teak* (Tectona grandis) *in Trinidad; the agricultural cropping has ended and the teak trees have taken over.*

The taungya system has been spectacularly successful as a means of establishing tree plantations under a number of conditions. In the dry zone in what is now Myanmar, with 45 to 110 cm of rainfall annually, village forests were established using 2- to 3-year taungya systems to provide fuelwood from *Acacia* spp., *Albizia lebbek, Senna siamea, D. sissoo, M. azedarach, Prosopis* spp., and eucalypts (Aung Din 1954). The taungya system has also been used successfully to raise four species of pulpwood. For their work, cultivators receive incentives such as credit and grazing privileges. In Brazil, some of the Jari pulpwood plantations of *Gmelina* being established used the taungya system.

This system is not without problems. In some areas, it is difficult to exclude cultivators from a tract once they are working it (Civette 1953). In India, cultivators have been criticized for neglecting the trees and then claiming the site for permanent agriculture (Banerji 1960). At the other extreme, where there is plenty of land, there is little interest in the practice (Anon. 1952h, Cristovao Henriques 1952).

Three factors are seen as increasing the need for the taungya system (Wyatt-Smith 1979): (1) the population explosion in the developing world, (2) recognition that industrial development is not a panacea, and (3) the

Table 8–9.—Yields of *Eucalyptus* and corn from a taungya system in Brazil

Spacing	Corn (kg/ha)	Mean tree size at 18 months D.b.h. (cm)	Total height (m)
E. alba alone 1.5 by 3.0 m	0	5.3	7.0
E. alba separated by 1 row of corn 1.0 by 1.5 m	4,600	4.9	6.5
E. alba separated by 2 rows of corn at 1.0 by 1.0 m	5,400	4.0	5.9
E. alba separated by 3 rows of corn at 1.0 by 1.5 m	6,700	3.2	5.1

Source: Gurgel Filho 1962.

need to arrest the undesirable population drift to urban centers by greatly improving the quality of rural life.

The Development of Agroforestry

Agroforestry has suffered from many conflicting definitions. The term appears to have arisen from "agrisilviculture" (Townshend 1952). Subsequently, King (1979a) went on to define "agrosilvicultural systems" as cultivated crops plus trees, "silvopastoral systems" as fodder crops with trees, and "agrosilvipastoral systems" as all three in three-tiered combinations.

Wyatt-Smith (1979) considers "agroforestry" to be an umbrella term that includes agrisilviculture as well as other systems. Richards (1982) used narrower limits than some others by confining agroforestry to practices in which trees are vertically integrated with other crops, that is, one above the other; systems with horizontal integration, such as windbreaks, he termed "farm forestry." This distinction appears to have merit.

Classification of agroforestry systems and accumulated experience have been compiled in an FAO regional office publication (Anon. 1984e), "Sistemas agroforestales en America Latina y el Caribe." The state-of-the-art information about using and producing multipurpose trees in Asia, with many practices of universal applicability, was laid out in the proceedings of a 1984 planning workshop at Kandy, Sri Lanka (Burley and Stewart 1985).

Conceptual Variables. Much of what is being said about agroforestry is merely promotional. True, there are some cropping techniques for rubber, cocoa, and lowland mixed crops (in Indonesia) that for decades have embodied permanence, continuous cropping, and trees as components. But the technology has not yet been fully developed for annual crops on the much larger areas of wornout, marginal, tropical lands.

Recent enthusiasm for agroforestry does not mean that foresters in tropical countries have heretofore ignored the welfare of rural people in forested areas (Wyatt-Smith 1979). They have been preoccupied with creating large, compact, forest estates with sustained management for the benefit of the economy of entire countries and for providing foreign exchange.

With the recent great need to justify reservation of good lands, forestry is being assigned lands that are submarginal for agriculture. Much is also poor for timber production. At the same time, demand for both timber and fuel is increasing. The only solution is to increase the productive capacity per unit of area by better protection and by reducing the production period for new crops through plantations (Wyatt-Smith 1979). Forest departments and the forestry profession have been profoundly affected by these trends.

Typically, forestry planning at a national scale has involved setting goals in terms of future requirements of what have been considered "major" wood products, such as lumber, plywood, particleboard, and pulp and paper (Mackney 1968). Other roundwood products and fuelwood have been considered secondary.

Agroforestry is seen by some as a system for breaking down the false dichotomy between agriculture and forestry (Adeyoju 1980). The broader values of rural development transcend those of conventional forest production and should be incorporated into the training of foresters.

A characteristic of agroforestry that distinguishes it from other forestry is its multidisciplinary complexity. This complexity does not arise chiefly from technical problems, such as those of conventional tree plantations, but rather from the fact that agroforestry's success or failure is largely out of the hands of foresters. Agroforestry is generally practiced on agricultural lands where agricultural crops eclipse tree crops in productivity and importance, and by farmers whose main goal is to produce farm rather than forest crops. Therefore, the forester must deal effectively as a minority partner with agronomists and the farming community. To do so, he or she must learn more about the science and practice of agriculture and the traditions and motivations of farmers. In the final analysis, the future of agroforestry depends more on acceptance and effective efforts by agronomists and farmers than on the convictions of foresters.

All these facets of agroforestry point to one important preliminary and continuing requirement: careful observation. Agroforestry is the work of rural communities as a whole, not just professionals. Its proponents must be involved with and accepted by the community. They must come to know the motivations and aspirations of the people in the community.

Trees, if already in use as a part of local agriculture, may offer a significant starting point. Current practices for producing food crops or forage must be considered, and the role of soils in limiting farm and possibly tree crops must be understood. Current seasonal patterns of mixed cropping must also be explored, as well as the balance between direct consumption and cash crops. Local interrelations between subsistence and commercial agriculture may well parallel the interrelations between agroforestry and commercial timber production.

Whether or not trees are actually a component of local agriculture, current farm practices are probably deeply ingrained, usually for valid reasons. The foremost of these may be security, assurance that a familiar level of yield is certain for farmers who apply timeworn practices. Where livelihood is precarious, security is more attractive than promises of something new. The significance is that new practices should be merged with traditional ones, so they do not merely substitute something unknown for what is known. Gaining acceptance of agroforestry techniques thus must be a gradual process.

Agroforestry systems may be categorized on the basis of their functions and the nature and arrangement of their components (Nair, P.K.R. 1985). Their protective functions include soil conservation, moisture conservation, soil improvement, and shade and windbreak maintenance. They may produce food, fodder, wood, or other products (fig. 8–5). Their components may be crops and trees; pasture and trees; crops, pasture, and trees; or other combinations including aquaculture and apiculture with trees.

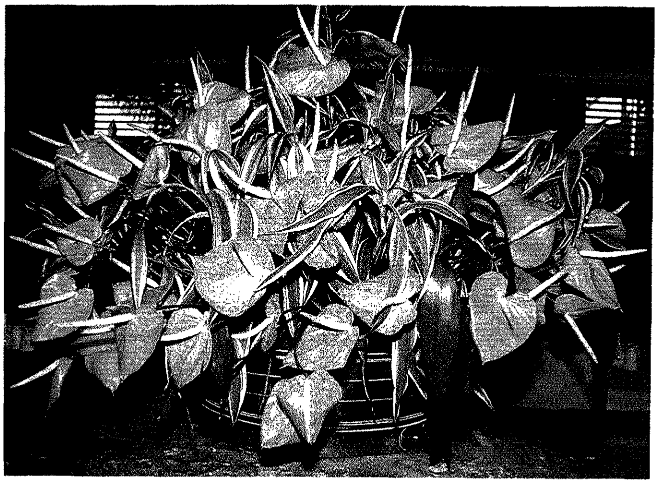


Figure 8–5.—*An important secondary crop of anthuriums marketed for export is produced beneath the wet lower montane forests of Dominica.*

The principal agroforestry systems in tropical America have been listed as follows (Anon. 1984c):

1. Sequential systems
   A. Shifting agriculture
   B. Taungya system

2. Simultaneous associated systems
   A. Trees/cultivated crops
      a. Coffee, cocoa, tea
      b. Trees over annual crops
      c. Trees supporting vine crops
      d. Orchards over kitchen gardens
      e. Mixed perennial crops
   B. Trees and forage crops
      a. Trees over pasture
      b. Grazed natural forests
      c. Forage trees

3. Adjacent tree systems
   A. Shelterbelts
   B. Live fences

Details of these systems in use in the region are presented in "Sistemas Agroforestales" (Anon. 1984e).

Possibilities Versus Limitations. Current farming practices in the Tropics vary, sometimes inexplicably, from place to place. This variation may be due to a lack of communication among farmers, but it is also often due to real differences in local environments, such as climate, soils, or markets. Thus, it cannot simply be assumed that differences in practices are based on ignorance and can, therefore, be eliminated merely by informing farmers of what seem to be better practices elsewhere. First, foresters must make sure that the differences are not a result of many lengthy trials and errors that have led to practices well adapted to each area. If so, any new practices must, at least for a time, coexist with, rather than replace, traditional practices.

Complex, traditional, farm-crop mixtures in tropical areas seem a tempting target for simplification, but the temptation should be resisted, at least until such cropping systems are well understood. Mixtures generally include plants found compatible through long experience. Their growth cycles or harvest times may be asynchronous and, thus, complementary. Their arrangement and representation in the cultivation scheme may be optimum. Their respective canopy heights and light-interception capabilities may minimize competition. Their individual water demands may dovetail temporally. They may also be complementary in their demand for harvesting labor. They may provide a needed balance between subsistence and marketable crops. Their foods may provide diversity needed for security or nutritive balance. The light weight of the crops may make them marketable in areas where trees are not. Any drastic change may thus upset some or all of these complementary features that may be vital to (or, at any rate, not initially negotiable by) the farmers.

As agroforestry applies to tree products and their benefits, it must be seen in light of the needs of an entire nation and usually as a potential supplement to concentrated timber production elsewhere that is unrelated to agriculture. The latter will normally be the primary source of industrial wood for urban populations or for export because centralized control and economies of scale are required for the sustained flow of forest products to support major processing industries and to compete in free markets. Agroforestry is by nature a widely dispersed activity on relatively small areas under individual ownerships. Thus, it is ill adapted to meeting the standards of uniformity in quality and flow required for major timber markets on a national scale. Rather, its potential is for supplying the wood needs of farming communities and possibly some specialty woods for crafts, roundwood, and fuel. Thus, agroforestry must focus first on supplying the needs of the rural communities.

The efficacy of secondary-forest succession in accumulating phytomass suggests that forest culture simulates this process (Holdridge 1959). Studies in Costa Rica showed that subsistence gardens around homes simulate the forest in being diverse and relatively permanent. Mixed-crop agriculture on a larger scale, believed capable of maintaining adequate nutrient recycling without fertilizers, may include an overstory of *Cordia* and pejibaye palm *(Guilielma gasipaes)* with an understory of cacao and a groundcover. During establishment, rice, corn, manioc, and bananas could be used. A complete cycle would be composed of 30 plots of 0.1 ha each, 1 established each year, plus 0.6 ha for a house site, garden, fruit trees, and pasture (Holdridge 1959).

A system in Brazil also focuses on nutrient retention through simulation of natural succession (Uhl and Murphy 1981). The system begins with forbs, grasses, successional woody species, lianas, and even forest trees, using only species of economic value. Practices that assist establishment may include dry mulching, introducing legumes (especially bred crops), and applying lime. The degree to which such a system can survive intensive cropping remains to be seen.

Burley (1980b) concluded that genetic tree improvement for agroforestry must begin now and that the effort must be international in scope. However, the diversity of tree uses in agroforestry is seen by geneticists as complicating attempts to improve tree quality, a process recognized as differing in four major ways from genetic improvement for industrial timber plantations. These are as follows:

- Genetic testing for agroforestry purposes must encompass a range of companion agricultural crops and managerial treatments.

- Character weighing must reflect the wide variety of tree uses.

- Genetic work will normally not be done by the growers; therefore, an extension effort will be required to put results to use.

- Sampling and testing will be complicated by the development of "races" that may already have occurred with many species.

Enthusiasm for what agroforestry appears to promise must not lead to blind efforts to repeat past attempts to develop agriculture everywhere (Sholto Douglas 1968). Many forest areas remain within agricultural regions where tree production alone, serving the rural population, is more appropriate than interplantings of trees and other crops. Examples are wastelands along roadways, canals, parks, and village woodlots (Randhawa 1946). Moreover, even where interplanting seems appropriate because agriculture has otherwise failed, variations in productivity will persist. Therefore, the most favorable areas should receive the most attention, those least favorable possibly being left in fallow or forest until the best areas have been well developed. In other words, there is still a need for separate management of most land that is best suited to either agriculture or forestry, rather than to assume a need everywhere to mix the two (Holdridge 1959).

Adding trees to farm crops unmistakably improves the stability of agriculture in tropical regions. However, the permanence of the combination as a source of adequate subsistence or cash crops without added nutrients remains to be proved. But even if the system does not supply all the nutrients needed, it may still approach self-sufficiency, so only minimum fertilizing would be required.

A review of the literature reveals that agroforestry's possibilities and limitations are really little known because of a lack of firm data (Alvim 1981). The scientific community still considers agroforestry not to be sufficiently documented for immediate and widespread technical application (Gleissman 1981a). This view is due in part to a lack of general acceptance that yields should be assessed on a long-term, diversified basis.

Further application of agroforestry in the Tropics apparently will call for much more than technical acceptability. Even in a society as highly educated and developed as Denmark's, the development of small, privately owned woodlots has required public subsidies (Frolund 1962). Apparently, such incentives will be necessary long into the future.

Prospective Benefits of Agroforestry. Successful agroforestry promises both social and economic benefits. In India (Sangal 1981), the prospect was seen for producing fuel and small timbers outside the closed forest areas, thus reducing rural population pressure on forests needed for industrial wood. Other potential benefits include reduced shifting cultivation, productive agriculture on land not presently tilled, and more employment.

A shift toward perennial crops in agroforestry may itself increase potential yields. For example, a 12-year planting of oil palms can produce 4 t of oil per hectare per year, a yield that cannot be achieved by any annual crop over any long period (Best 1962). Also, the deep-rooted trees serve as nutrient pumps whose litter benefits interplanted, shallow-rooted crops. *Erythrina glauca* roots in Suriname may go three times as deep as the roots of coffee or cacao (Stahel 1949).

Intercropping is beneficial for reasons other than mere crop diversification. Studies in what was formerly Zaire (Sparnaay 1957) indicated that intercropping enhances early development of oil palms. Nor is multiple cropping necessarily harmful to the shaded crop. In Bangladesh, 50 percent shade is considered ideal for tea (Skoupy and Vaclav 1976). In the Solomon Islands, the benefits of tree shade to crops are accepted as counterbalancing the space occupied and the susceptibility of trees to greater storm damage (Yen 1974). A test in what is now Malaysia over a period of 63 weeks showed yields of the grass *Axonopus compressus* of 21.3 t/ha/yr without shade versus 25.4 beneath *Samanea saman* (Jagoe 1949). Shaded sites produced grass with 9.6 to 11.7 percent protein, compared with 9.1 to 10.4 percent protein without shade.

Where fertilizer is not used, coffee yields are typically higher with shade than without it (Ostendorf 1962). The contention that the presence of shade trees always reduces soil moisture is questionable. In arid west Africa, several benefits of *Acacia albida* shading over crops have been noted, including increased relative humidity, reduction in temperature extremes, increased moisture absorption during rains, and better conservation of soil moisture thereafter (Dancette and Poulain 1969).

The benefits of tree litter to associated crops have been shown under many conditions. In west Africa, oil palm production was increased 8 percent by underplanting with coffee, the benefit being attributed to the litter (Sparnaay 1957). Within oil palm plantations, the soil is more productive close to rather than far from the palms (Kang and Moorman 1977). As distance from the palms increased from 0.25 to 4.00 m, the first 30 cm of soil declined in moisture content and increased in bulk density. Organic C, total N, and extractable P, K, Ca, and Mg all decreased at least 50 percent. Not even application of

NPK fertilizer masked the effect. After the palms were removed, a subsequent maize crop still showed significant benefits from the palms as determined by leaf analysis for N, P, K, Ca, Mg, and manganese (Mn).

Leguminous litter may be significantly richer in nutrients than nonleguminous litter, even when leaffall is natural rather than the result of pruning. In what is now Malaysia, leguminous shade produced grass with 13.8 to 14.8 percent protein, compared with 9.6 to 11.7 percent for nonleguminous shade (Jagoe 1949). Shade for tea in Bangladesh is generally provided by leguminous *Albizia* spp., *Gliricidia sepium,* and *Senna siamea* (Skoupy and Vaclav 1976); shade for coffee in tropical America, too, is typically provided by leguminous species.

Food cropping may be extended to 8 to 10 years under some conditions if a leguminous, green-manure crop is included once every 2 years (Newton 1960). Two crops of legumes can increase the yield of the subsequent food crop. This, however, does not alone prove that they are more economical than natural fallow. The value of legumes versus nonlegumes as fallow deserves testing.

Tests in India (Ranganathan and Ghatnekar 1984) illustrate the potential of agroforestry in a region receiving about 200 cm of rainfall per year, all of it from June through September but with supplemental irrigation of 1.5 to 2 L per tree once a month from October through May. *Leucaena* (the K8 variety) spaced at 1 by 1 m yielded 23 t/ha/yr at 33 months. At a spacing of 2 by 2 m, the yield was 12 t/ha/yr. Comparisons of mixed plantings with monocultures showed no clear superiority. In fact, a *Eucalyptus* monoculture yielded about 36-m^3/ha/yr after 33 months compared with 27 m^3/ha/yr for a mixed planting of five species.

Intensive culture in India also showed much promise. Rainfed plantations of K8 *Leucaena* spaced at 0.3 by 0.3 m and cropped eight to nine times in 12 months yielded 13 t/ha/yr, worth 2.9 times the cost. Foliar irrigation, adding 3.5 L of water per tree each week between October and May increased the yield to 23 t/ha/yr, still worth 2.9 times the cost.

According to some definitions, tree shelterbelts at the edge of crop areas may not strictly be agroforestry because their integration with crops is horizontal rather than vertical. Nevertheless, a few principles seem appropriate. In the Temperate Zone, optimum crop gains are most likely from narrow shelterbelts (Stoeckeler 1965). For maximum benefits, they should be oriented perpendicular to the most damaging winds. Single rows do not survive well in dry areas, so belts of up to five rows are recommended. The distance between belts may range from 5 to 25 times tree height, depending on topography and wind velocity. The tree species selected must be well adapted, effective as wind screens, windfirm, resistant to breakage, disease free, fast growing, long lived, and easy to establish (Stoeckeler 1965).

The potential employment value of agroforestry is significant. An experiment with a new oil-palm plantation in what is now Benin showed that intercropping with food crops for the first 4 years, compared with regularly maintained natural cover, could increase employment over the period from 390 to 1,455 days (Sparnaay 1957).

The employment value of some tree crops compares favorably with that of other agricultural crops. Rubber plantations in the Andaman Islands covering 7,400 ha have provided some 6,000 jobs, and oil palm plantations covering 2,400 ha have employed 1,200 workers (Singh, B. 1973).

Some Drawbacks to Mixed Cropping. Crop combinations may be beneficial under certain circumstances, but there are also important limitations. It is rarely possible to maintain optimum conditions for two different crops on the same land (Sparnaay 1957). A combination of rubber and *robusta* coffee lowered yields of both crops and cost more to manage, because neither crop was growing under optimum conditions. Rubber dominates economically and generally determines the suitability of a second crop. The following limitations for crop combinations are quoted from Allen (1955):

1. The second crop should not grow as tall as the main crop, and the root system should exploit different soil horizons.

2. The second crop should be tolerant of partial shade.

3. The second crop should not be more susceptible than the main crop to diseases they have in common.

4. Harvesting of the second crop must not damage the main crop or the soil.

5. The economic life of the second crop should not be longer than that of the main crop.

Most perennial crop combinations with oil palms present problems (Sparnaay 1957). Cacao, for instance, requires more and more light, yet palms steadily increase their shade. Tests in what was formerly Zaire with coffee at various spacings showed that no combinations were economically justified. It was necessary either to prune the palms or to eliminate the coffee too soon after planting.

Shade over cacao intercepts rainwater, reduces solar radiation, lowers temperature, raises humidity, and reduces wind velocity (Hardy 1962b). The net effect is to lower the rate of transpiration of the cacao, adversely affecting mineral nutrition and, hence, yields.

In dry climates, competition for water between crops may be deleterious. This is illustrated by the effects of selective girdling of widely spaced trees in miombo woodlands in Africa (Ward and Cleghorn 1964). Forage grass yields were increased from 355 to 1,460 kg/ha for the subsequent 4 years.

The reduction of yields beneath shade is characteristic of many crops. For example, although 50 percent shade is considered favorable for tea in Bangladesh (Skoupy and Vaclav 1976), tea yields in east Africa decreased 10 to 15 percent when grown beneath 20 to 90 percent shade and even when grown up to 12 m from the shade trees (McCulloch and Pereira 1965). A decline in cacao yields with proximity to *Terminalia ivorensis* shade was demonstrated in Ghana (table 8–10; Bonaparte 1967). The differences in numbers of cacao pods are attributable to distance from the shade trees and are highly significant. The probable explanation is the amount of light, because moisture was plentiful and may well have been greatest near the shade trees (Bonaparte 1967).

Crop Combinations. However incomplete the information may be, many examples of interplanting, even just technically, appear at least temporarily successful. One of the most successful combinations uses rubber as the main crop. In what is now Malaysia, trees planted in rows about 20 m apart and interplanted with well-manured food crops provided an environment that benefitted both crops (Allen 1955). This configuration increased the efficiency of labor, and replanting could overlap. Among the crops recommended were coffee, cocoa, bananas, tea, and oil palms as well as balsa on a 6-year rotation and *Gmelina arborea* on an 8-year coppice.

Table 8–10.—Shade effects of *Terminalia ivorensis* on cacao yields in Ghana

Distance from shade tree (m)	Sunlight (%)	No. of pods per tree	
		Total	Healthy
2.2	38	37	25
4.8	52	44	31
6.5	62	51	36

Source: Bonaparte 1967.

Coffee has been grown under shade for centuries. Although with more intensive management, greater production is generally possible without shade, the use of shade can be expected to continue. The shade crop is generally of less value than the coffee and is typically a leguminous tree such as *Erythrina, Inga,* or *Senna,* which are used chiefly for fuel. Selecting such trees for their spreading crowns indicates the lack of emphasis on wood production (Garcia Gutierrez 1976, Uribe Uribe 1945). Other indications that wood is unimportant compared with coffee have been found in Uganda, where farmers rejected deciduous species and "excessively competitive" genera such as *Casuarina, Cedrela, Eucalyptus,* and *Senna* (Thomas 1940).

The possibility of producing timber in combination with coffee is recognized in Costa Rica, where the recommended tree species are *Cordia alliodora, Enterolobium cyclocarpum,* and *Samanea saman* (Budowski 1959). In India, *Grevillea robusta* has been considered a good companion species, despite insect and disease problems and its reputation for drying out the soil (Rao 1961).

Cacao, like coffee, has generally been produced under tree shade. Species of *Erythrina* are commonly used and clearly benefit the cacao in Costa Rica (Zevallos and Alvim 1967). Cacao was found to be much more productive when growing near the *Erythrina* (2.5 m) than when growing farther from it (8.4 m). However, this improved performance is not caused by shade but rather by the fact that the soil near the *Erythrina* is richer in minerals than elsewhere and is more moist in the top 30 cm.

While forage perhaps does not constitute a "crop" in the usual sense, grazing is important in agroforestry. Combining trees with pasture may favor either the grass or both grass and trees. Spreading, leguminous trees favor the grass alone, whereas combinations of coconut or oil palms with forage grasses may favor both crops. In nonforested northern Argentina, 2.5 ha of tree plantations are needed for every 1,000 head of cattle to provide shelter from wind and storms (Flinta 1960).

Forage values under open stands of *C. alliodora, E. poeppigiana, Gliricidia sepium,* and *S. saman* were studied in Costa Rica (Daccarett and Blydenstein 1968). The 7-year-old trees did not reduce dry-matter production below that of unshaded pasture but did reduce the fiber percentage. Under the three legumes, N in the upper soil layers was slightly higher than under the *C. alliodora* or without tree shade. The protein content of the grasses was significantly higher under the legumes.

With stocking of one animal per hectare, animal-weight increases of 0.25 kg/d were possible even during a severe drought in Mexico under *Pinus caribaea.* The trees had been heavily thinned from 1,330 trees per hectare at age 6 to 740 per hectare and then 500 per hectare at age 9 (Gregor 1973). The grazing beneath the pines also reduced the fire hazard.

A combination of heavy thinning of *P. radiata* and sheep grazing in New Zealand created less conflict with traditional farm practices than did pure forest plantations (Knowles 1972). Animals were excluded until the trees were about 3 m tall; herbicides were used where necessary for weed control. At 4 years, the trees were thinned to 500 per hectare and pruned to 2 m. At a height of 10 m, trees received a final thinning, leaving a crop of 200 per hectare. When the heights reached 14 m, pruning to 8.5 m had been completed. The tree rotation was reduced from 35 to 25 years.

Leucaena leucocephala is one of the most promising agroforestry species because the more vigorous varieties combine rapid wood growth with valuable forage from their foliage. A study in India (Mohatkar and Relwani 1985) shows the combined effect of producing both forage and wood. During a 3-year period, the trees were pruned to 120 cm in height either once or twice per year (table 8–11). Apparently even the closest spacings did not diminish forage yields.

Table 8–11.—*Leucaena leucocephala* wood and forage production in India

Density (no./ha)	3-year yield (t/ha)	
	Dry firewood	Green forage
5,000	44.4	39.1
10,000	44.6	46.1
20,000	53.0	53.7

Source: Mohatkar and Relwani 1985.

An underdeveloped potential agricultural product from tropical trees is honey. In equatorial lowland rain forests, nectar is so continuously available that native bees have no storing instinct, but wherever the climate is seasonal, European bees do well (Smith 1960). Honeyflow is greatest during the cool or dry season. A few of the meliferous (honey-bearing) trees adapted for agroforestry are *Albizia* spp., *Anacardium* spp., *Azadirachta indica, Cocos nucifera, Coffea arabica, D. sissoo, Eucalyptus* spp., *Eugenia* spp., *Grevillea robusta, Mangifera indica, Melicocca bijuga, Moringa oleifera, Musa* spp., *Persea* spp., *Prosopis* spp., *Psidium* spp., *Roystonea* spp., *Syzygium jambos, Tamarindus indica,* and *Toona ciliata.*

Agroforestry plans have been proposed to incorporate apparently compatible crop plants so as to favor subsistence. In Brazil, three systems involving different land areas have been recommended (Bishop 1978). On an area of 2 ha, eight sections of 0.25 ha each were planted to garden crops for 2 to 3 years followed by a fallow of 5 to 6 years with poultry on grass and legume pastures under leguminous firewood trees. A second plan involved 8 ha, or eight plots of 1 ha each, also on about an 8-year cycle. The only difference was that swine were used on the fallow pastures instead of poultry (Bishop 1978). A third plan required 40 ha, with 20 divisions of 2 ha each, and a cycle of at least 20 years. Maize was produced during the period of tree establishment, after which cattle grazed beneath timber, fruit, and nut trees for 19 years.

A plan for combined pasture and tree production in the Brazilian Amazon is based on the assumption that a widely spaced tree plantation, starting with 750 trees per hectare and thinned to 150 to 200 by age 13 to 15, permits development of good pasture (Kirby 1976). The proposal assumes an early crop of beef and adequate control of grazing intensity to prevent site deterioration. The combination is more labor intensive than either crop alone. The need for added nutrients apparently has not yet been reported.

A 12-ha pattern of agroforestry was developed in Quintana Roo, Mexico (Chavelas Polito 1980). The design comprises four concentric rectangles (fig. 8–6). An outer

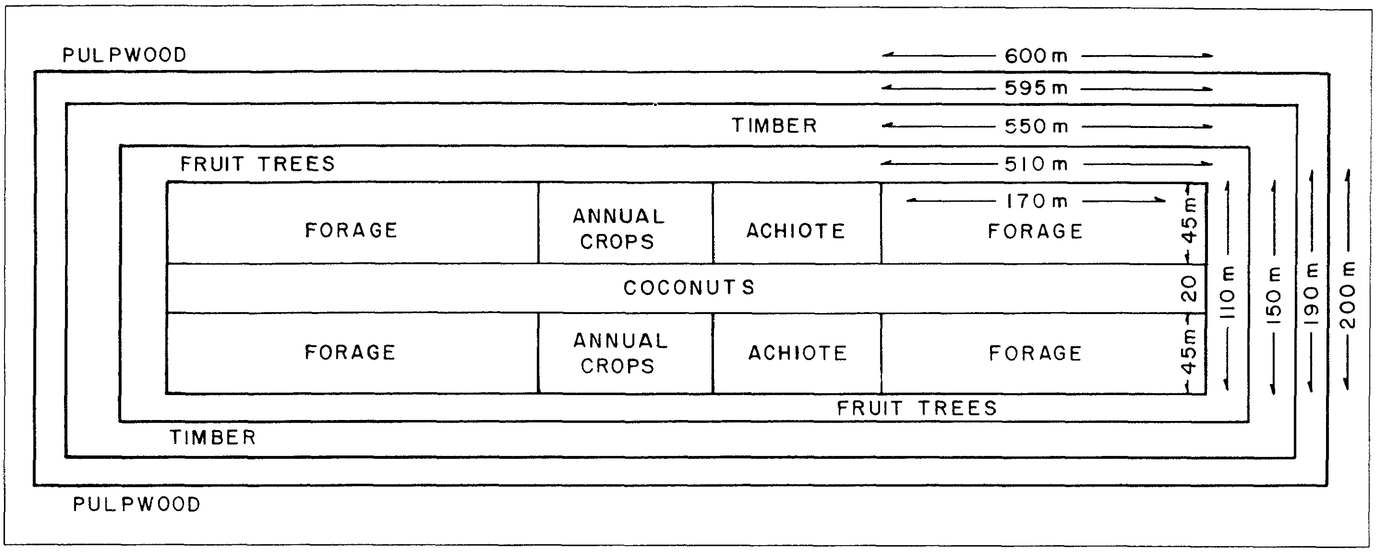


Figure 8–6.—*Multiple-use agroforestry plan for 12 ha in southern Mexico (Chavelas Polito 1980).*

strip, 5 m wide, contains about 0.8 ha of pulp- and veneer-wood trees (*Gmelina arborea* and *Pseudobombax ellipticum*) and a construction species *(Colubrina arborescens).* The next strip inward, 20 m wide and about 3 ha in area, has a mixture of nine timber trees. Inside that, another strip of 3 ha contains a variety of fruit trees and forage grasses. In the center is a rectangle 110 by 510 m that is divided by a central strip 10 m wide planted to coconut palms *(Cocos nucifera).* The remaining area is subdivided into six 0.85-ha plots. Of these, four are put to forage crops and two to a mixture of annual and biennial cultivated crops. The plan proved unpopular because of its testing close to an urban market for cash crops.

A plan for tree "biomass farms" in arid areas, using deep-rooted N fixers such as *Acacia, Leucaena,* and *Prosopis,* has also been proposed (Felker 1981). Intercropping with food staples such as millet, sorghum, and peanuts is contemplated, and irrigation will be required temporarily. On areas of at least 25 cm of annual rainfall, the system can thrive on ground water within 10 m of the surface. Phosphate fertilizer and micronutrients are required as well as rhizobial inoculation so that N can be provided by the plants.

Much of the data that is presented here is conceptual. Data showing the results of actual practices are scarce, and much has been written recently on this subject. Vergara (1985) described the information base of agroforestry as extremely weak and warns that inaccurate information could lead to rejection if results do not live up to farmers' expectations. A general inclination to overestimate the potential of agroforestry is seen by Groenendijk (1988). He points out that knowledge of interactions between trees and crops is still limited.

A lack of "hard data" on agroforestry is also noted by Scherr and others (1989), who point to the paucity of actual farm-survey studies or information on the economics of agroforestry.

These words of caution are not without foundation. Enthusiasm for agroforestry outgrew and still exceeds the available scientific basis. The danger is that decision makers may count on unfounded postulations for increasing pressures on marginal land. There is no doubt that the integration of trees into conventional agriculture in the Tropics holds much promise. This goal may be achieved, however, only with research to support all new proposals.

Chapter 9
Forestry Research

Research will probably always be an important need in tropical forestry. Not only are the forests and their environment complex but responses to interactions are not all readily visible or immediate. Research should not be looked upon by the forest manager as purely something for advanced specialists. The solution to many of the problems of forest management has resulted from the acute observations and resourceful interpretations of employees not considered "scientists." Supplementary to this, however, the manager must recognize that the greater the impact of forest operations on the forest the more profound should be concurrent study of the consequences as a guide to future improvement.

Research may be defined as systematic investigation of phenomena to determine facts. Knowledge critical to tropical forestry is elusive because of the complex and invisible nature of many of the forces involved. Also, in many tropical areas, forestry research has barely begun because only recently has the need to do more than merely reap the bounties of already existing forests become compellingly evident.

History of Tropical Forestry Research

In the broad sense, forestry research in the Tropics began with the practice of forestry itself, because observed trials of any new practices constitute rudimentary research. Some of the earliest work was essentially botanical and descriptive. Broad classes of forests were recognized, and tropical tree species were identified and classified according to traditional uses. An early stage of such collected knowledge is reflected in the monumental descriptive work of Schimper (1903) on plant geography, referred to throughout Chapter 2.

Studies of tropical woods were reported as early as 1901 in the Malay Peninsula (Ridley 1901) and were followed by other detailed reports (Foxworthy 1909, 1921). The timbers of India were first described extensively in 1902 (Gamble 1902).

Formalized institutional research did not develop until later. The Forest Research Institute at Dehra Dun, India, was established in 1906 (Hart 1922). Four years later, a program of sample-plot measurement was begun that by 1956 totaled 1,762 plots covering observations of more than 100 tree species (Mathauda 1956). By 1931, an "Experimental Manual" for India had been produced (Nair 1952). And by 1960, broad research programs were underway in several of the states of India. In Mysore, lines of investigation included nursery practice, planting, taungya, teak *(Tectona grandis)* seed origin comparisons, the application of manure, and termite controls (Krishnaswamy 1960). In Madhya Pradesh, research was dealing with rehabilitation of former proprietary forests, natural regeneration of teak, thinning, and rates of tree growth within the forests (Mujumdar 1960b).

In what is now Malaysia, formalized forest research began in 1918, 17 years after the appointment of its first forest officer (Menon 1976). The Forest Research Institute of Malaysia at Kepong has been in existence since 1929. The source of much of the advanced dipterocarp forest silviculture, this institution has become one of the largest of its kind in the world (Anon. 1988a). In 1987, the Institute had a professional and subprofessional staff of more than 100, the world's best dipterocarp arboretum, and an herbarium of more than 100,000 sheets. Branches of the Institute are concerned with natural forest silviculture, plantations, biology, forest protection, and forest products.

In the Philippines, evidence of early research can be found in a study of *Leucaena leucocephala* management published in 1914 that is still remarkably valid (Matthews 1914). In Nigeria, planting was first tested in 1907, and a Research Branch of the Forest Department was established in 1943 (Rosevear and Lancaster 1952). In what is now Sri Lanka, phenological records in the diaries of forest officers marked the beginning of research in 1937 (Holmes 1956). These records were later systematized to cover 2,000 trees of 125 species in 40 plots visited monthly for 5 years.

In the Western Hemisphere, systematic forestry research appears to have begun in southern Brazil with *Eucalyptus* introductions, dating from about 1906 (Navarro de Andrade 1941a). Interest in indigenous forest trees of Brazil was formalized by studies of nine species beginning in 1953 (Gurgel Filho 1975). A formal forestry research program began in the Amazon with the work of Pitt in 1960 (Pitt 1961a), which included studies of natural regeneration, post logging coppice, enrichment, and close plantings.

Research has accompanied forestry development in all countries of tropical America, although the intensity of the research effort varies widely. Research institutions with independent programs now at least exist in Argentina, Brazil, Colombia, Costa Rica, Mexico, Peru, Puerto Rico, and Venezuela (fig. 9–1). Research in tropical Mexico, more recent than research on the Temperate

Figure 9–1.—*Headquarters of the USDA Forest Service, International Institute of Tropical Forestry, in Puerto Rico, one of the most venerable research institutions.*

Zone forests in that country, has for some time included extensive studies of natural forests, plantations, and agroforestry (Cedeno Sanchez 1976, Chavelas Polito 1976).

A need for international collaboration among forestry research institutions and scientists was recognized by the Food and Agriculture Organization (FAO) Regional Office for Latin America in supporting the Instituto Forestal Latinoamericano de Investigacion y Capacitacion at Merida, Venezuela, in 1956. The FAO Latin American Forestry Commission established a Regional Committee on Forestry Research in 1958. A product of that committee's work was an analysis of 16 research institutions, showing a high degree of similarity in the goals of their respective research programs and administrative problems (Wadsworth 1969).

Actually, international collaboration on forestry research in the Tropics began among the countries of the various colonial empires. More recently, broader based collaboration was fostered by the Commonwealth Forestry Institute (now Oxford Forestry Institute) through the collection and distribution of seeds of popular plantation species from a variety of provenances. By 1990, the Institute had collected and distributed more than 22,000 separate seedlots of 108 tree species to 122 countries, including most of those of tropical America (Barnes and Burley 1990).

Tropical America must do more of its own research. The solution to the area's problems will be found within the area and must be integrated with the changes being brought about by development.

Regional Research Needs

Before research needs are listed, a fundamental condition in most of the Tropics needs to be emphasized. What is termed "modern" research is almost totally a product of wealthy societies (Mlinsek 1982). These countries have tended toward expensive methods that substitute elaborate instrumentation for cruder techniques of approximation. Such methods have their place in raising the precision and conclusiveness of results. Yet, under common conditions in the Tropics, where approximations may initially be adequate in the absence of any prior work, the very cost of such methods may be excessive if not prohibitive. The selection of technology that is appropriate to the Tropics is thus as important to research as it is to the practice of forestry.

Tropical America needs more information on myriad forestry topics. The first (and still incomplete) task of those responsible for tropical forestry research is identifying the most urgent problems. A number of efforts to that end have been reported. Those summarized here indicate the conclusions reached by many experts. Three broad stages of timber management research have been recognized as follows (Dawkins 1949):

1. Compositional—How to recognize, measure, and use forest constituents

2. Ecological—How desirable trees behave in relation to site

3. Silvicultural—Effects of cultural practices on forest behavior and productivity.

A broad view of research needs by the FAO (King 1979b) was prefaced by the comment that developing countries are aware of the significant role that forests, forestry, and forest industries can play in economic development. They know that forests can help save and earn foreign exchange, can stimulate many other economic activities both at the raw-material source and in the fabrication of products, and can create significant employment opportunities, particularly in rural areas. Factors viewed as needing attention are:

- Tree species in moist tropical forests
- Standing wood volumes by species
- Tree species distribution and growth rates
- Forest reactions to silviculture and management systems
- Techniques for regenerating commercial species
- Economically feasible techniques for pulping mixtures
- Long-term effects of intensive tree plantation culture on soil productivity
- Superior seed sources
- Genotypes adapted to difficult sites
- Vegetative propagation techniques for tree improvement

Research needs of the Amazon region have been outlined in general terms (Fearnside 1979b, Prance 1982):

- The biota (at least 20 percent of the plant species are as yet unnamed as are more than half of the insects)
- The carrying capacity of sites in terms of number of people that can be supported and how much timber can be extracted under sustained yields
- The extent, causes, effects, and methods of controlling deforestation
- The rational, planned use of the forests
- The role of mycorrhizae
- Germplasm breeding systems.

The Center for International Forestry Research under the auspices of the Consultative Group for International Agricultural Research has drafted a medium-term program (1993–98) with the following components:

Policy development
Policies and incentives to achieve sustainability of forests
Systems for equitable distribution of benefits and costs of forest goods and services
Adoption of policy change
Policies to increase employment and income from forests
Location and types of global forest resources to satisfy future demands for goods and services

Management and conservation of natural forests
Low-impact harvesting and management
Management for biodiversity and diverse products
Growth-and-yield prediction systems
Sustainable management of dry-zone woodlands
Reproductive biology and genetics

Reforestation of degraded lands
Nonindustrial techniques
Matching tree species and genotype to biophysical site conditions and management systems
Techniques for characterizing genetic variations and relating them to physiological and morphological adaptations
Physiology and biochemistry of plant material for improved vegetative propagation
Plantations of mixed tree species for multiple products
Yields in second and subsequent rotations of tree plantations

Products and markets
Management by local communities and user groups of resources for nonwood forest products
Market requirements and possibilities for underused, nonwood forest products
Expansion and harmonization of data bases on properties and uses of tropical timbers and nonwood forest products
Social and economic effects of new technology for adding value to products in or near the forests

Research support and information
Human resource development
Publication and information services
Data base harmonization, integration, and dissemination.

Bamboo (Gramineae) is one of the tropical plant groups of greatest present and potential use. Thus, a broad range of basic research priorities (many of which apply equally to many other forest species) has been recommended for this plant group (Lessard and Chouinard 1980) including: taxonomy, field identification, propagation, anatomical structure, mechanical strength, and preservative treatment.

It is not enough, however, to merely list subjects for study when the means for undertaking the research are inadequate everywhere. A review of 16 forestry research institutions in the region (Wadsworth 1969) led to the following conclusions:

- The most critical deficiency was in training of scientists.
- There was a danger of excessive duplication of effort, because technical problems are common to much of the area.
- Coordination of efforts should begin through regional problem analysis and priority setting.
- Meetings of institution leaders and scientists were either too infrequent or nonexistent, yet they are necessary to an effective regional research effort.
- Particularly neglected were the generally important technical fields of soils; hydrology; wildlife management; agroforestry; waste utilization; fire control; and the processing, grading, and marketing of products.

In 1970, the FAO Latin American Forestry Commission's Committee on Forest Research issued a comprehensive list of recommendations to national governments and international technical assistance agencies to strengthen forestry research in the region (Anon. 1970). Most observations detailed in that list are still valid, including the following:

- Forestry research must no longer be looked upon as merely a troubleshooting adjunct to forestry agencies or as an exercise in graduate teaching but rather as a technical spearhead for future forestry development.
- Forestry research responsibilities need to be clearly assigned and continuously supported within government organizations first, as a primary activity in a single national forestry authority, and second, as a supplementary activity at existing forestry colleges.
- Forestry scientists need salaries at least commensurate with those in other research fields and adequate to encourage career-oriented dedication.
- Research institutions concerned with forestry, agriculture, and wood technology need coordination, team effort, and frequent direct communication among scientific personnel.
- Forestry scientists need continuing training opportunities in special subjects, such as experimental design and techniques, research administration, and technical report writing.
- A centralized documentation service is of vital importance to the forestry scientists of the region.
- To ensure comparability, regionally standardized techniques are needed for the collection, analysis, and interpretation of forestry statistics and field data involving the measurement of forest trees and stands.
- An almost total lack of information concerning the economics of timber harvesting in the region calls for studies on the value of standing timber and the costs of logging and transportation to wood-processing facilities and consumption centers.
- There is a growing regional need for basic information on the role of forests in soil and water conservation and in flood control, calling for relevant investigations and a regional network of demonstration watersheds.
- There is need for a regionwide, up-to-date listing of centers of tropical forestry research able to supply or exchange quality forest tree seeds.
- There is a need to reserve natural areas in the unmodified forest ecosystems of the region for basic ecological research useful to forest management.

Worldwide concern with tropical forests has intensified the attention to research needs. Starting from a paper on forestry research needs in developing countries (Anon. 1981a), the second "Bellagio" meeting in 1988, working through a task force, led to a proposal for the following research thrusts (Anon. 1990a):

- The role of forests, woodlands, and on-farm trees in contributing to agricultural productivity and suitable land use (including soil fertility, microbiology, mycorrhizal organisms, the role of nitrogen (N)-fixing trees, pests, and diseases) tree-management systems, both intercropping and monoculture
- Conservation, selection, breeding, and improvement of multiple-purpose tree species, particularly N-fixing species for agroforestry, wasteland reclamation, fuelwood, fodder, cash crop-tree farming, and industrial planting
- Natural forest ecology, management, and conservation of biodiversity
- Utilization and forest products research: timber testing, forest products engineering, causes of deforestation, agricultural settlement, land tenure policies, economic linkages, incentives for reforestation, and equity and gender issues.

Research within tropical forests requires safeguards against outside interference. Representative forests (both primary and secondary stands) must be conserved until foreseen (or unforeseen) studies can be undertaken. Such preservation is vulnerable to pressures to modify or use the land for other purposes and may eventually fail unless an active forestry research program is undertaken and its findings publicized and utilized.

Research Components

Research must be approached with an open mind. One can neither complacently accept traditional knowledge nor summarily discard it. The scientist must constantly question, knowing full well that his or her questions may not always have simple answers. New studies will not always eliminate uncertainties, but they may provide a better basis for informed human judgment.

Orientation. Research is concerned with the nature, direction, and control of changes leading to a better future and with outcomes that represent long-term efforts. For these reasons, it is vital that scientists look far beyond current activities. For national research programs, this long-range view calls for analyzing forestry problems and setting priorities so that study selection may reflect the most critical needs, now and in the future.

One proven approach to research orientation is problem analysis, a detailed plan for problem solving in use in the United States (Anon. 1940–90). It contains pertinent literature and expert scientific thinking. Important points usually covered include the following:

- Precise problem definition
- Environmental considerations
- Problem components
- Predicted benefits of the solution of each component
- A proposed approach
- Indicated studies and priorities
- Plan for diffusion and implementation of results
- Personnel, facilities, and needed cooperation
- A time schedule for study initiation
- Anticipated completion time for each component
- Estimated cost of each component.

The development of clear questions to be answered is primary to research planning. The process of deriving research priorities for forestry oriented toward producing commodities is illustrated in figure 9–2.

Much has been written about how to conduct an experiment. Yet, most experiments do not accomplish all that is expected of them because they are imperfect in concept, execution, or interpretation. Some points to keep in mind about investigations are presented here.

Any serious study should begin with the preparation of a written plan, presenting sufficient detail so that it could

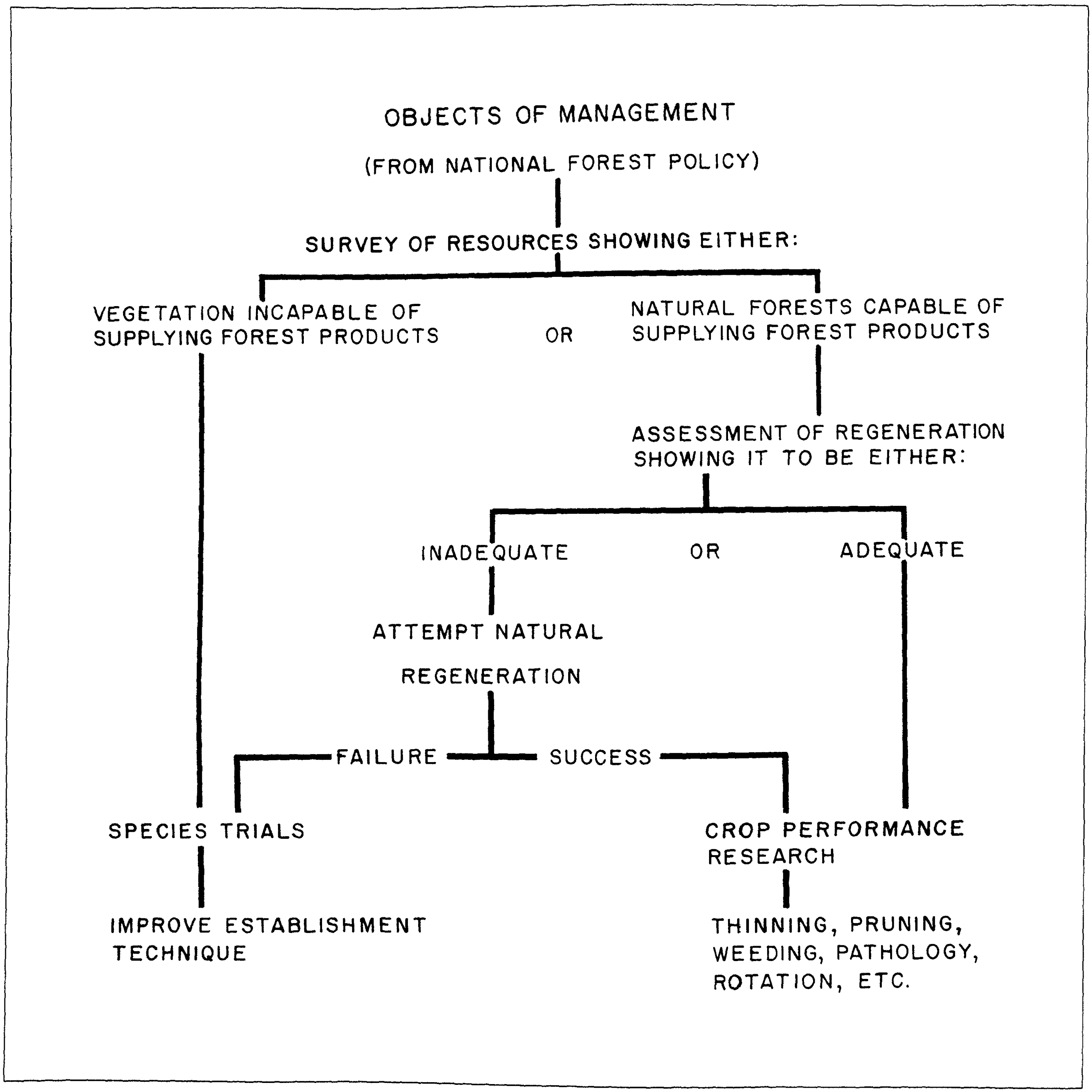


Figure 9–2.—*Derivation of research priorities oriented toward forest production (Philip 1964).*

continue if it were taken over by different scientists before being finished. Such a plan might include the following:

Title
The title should be brief yet distinct from other studies, and generally the plan is given a number.

Literature
The status of knowledge concerning the subject, techniques, related studies in progress, and literature sources should be described. Where literature is not readily available, it is still important to complete this step to the extent possible to avoid duplicating or overlooking recently developed methodology.

Objectives
The hypothesis and the specific question to be answered should be stated clearly, its importance and urgency explained, and potential applications and benefits of results described.

At the outset, the importance of the entire line of investigation must be assessed. This is a critical and often overlooked step. Not only must this investigative approach lead toward important conclusions or decisions, but it should be superior to alternative approaches.

Most research is undertaken to shed light on broad questions, such as, "Which is the best tree for site X?" Because of the multiplicity of interacting factors, seldom can a single experiment definitively answer such a question. Generally, a broad question must be reduced to a subset of more specific questions, such as, "Which of four promising tree species grows fastest in 3 years, untended, on site Q?" A single test may be designed to answer this question. Then, results from this and other tests concerned with ease of establishment, local site effects, wood quality, social acceptability, and so forth, can be synthesized into a hypothesis about species selection that can then be tested more comprehensively. An example could be that on the basis of a series of tests, species Y appears superior to W, X, and Z throughout the extent of site Q.

Forethought in selecting the question to be answered is of overriding importance. The question must be framed so that a clear response, either affirmative or negative, may be obtained, or if the answer raises the question "how much?," the amount must be decided in terms precise enough to distinguish important from unimportant differences.

Methods
The design of the experiment (size, replications, plot arrangement, derivation, and data to be collected) and corresponding analyses should be described. As appropriate, location should be assigned, time scheduled, and materials and equipment specified.

Use of Results
Methods of presentation to audiences, the review process, publications, and other means of using the results should be described.

Design and Analysis
The study objective should be stated in statistical terms, and an acceptable design (size, sites, replications, plot or sampling arrangement, data to be collected, and scheduling) should be derived. The proposed analytical use of the data should be described. As appropriate, locations, materials, and equipment should be prescribed.

Requirements
Human resources, scheduling, transportation, other facility needs, and funding should be taken into consideration.

Appendix
Location maps, plot arrangement, and recording instructions should be provided in appendices to the written study plan. An abstract should be prepared and placed at the beginning of the plan to attract the reader and summarize the problem, objectives, scope, design, and analysis.

Representativeness. Experiments are worthwhile only if they have predictive value. What has been observed on a small scale must be applicable to a larger area, or the study is of limited utility. It would seem obvious, therefore, that experiments must be done under conditions representing a large area of interest. However, this basic requirement is commonly either overlooked or given so little thought that many experiments are not truly representative. Results are then applied improperly to conditions that may in fact be very different from those of the study area. This discrepancy is commonly caused by bias toward locating experiments in areas that are accessible or convenient, a practice usually permissible only for exploratory tests to obtain crude information for more definitive, subsequent experiments.

The prospect that conditions in the area of application may not be uniform is also frequently overlooked. Wherever there is reason to suspect significant variation, this must be represented in the study design or in a series of trials to determine which of any recognizable "subconditions" may be significantly different. In testing new tree species, for example, trials should be carried out throughout the range of climates and soil conditions that characterizes the entire area for which results are needed. Should results differ significantly from place to place, independent conclusions will be needed for each, and the distinct sites must be studied separately.

Replication. Most conclusions in forest research are not finite but rather are based on probabilities, that is, the percentage of a total number of instances in which an observed phenomenon can be expected. These probabilities can be determined only by replicated (or repeated) observations. True replication occurs only when repeated tests are carried out in a similar manner and under conditions representing the full breadth of the question to be answered.

The number *(n)* of replicates (or samples) required for a desired degree of accuracy may be approximated in advance by the following steps (Burley and Wood 1976):

1. Determine from preliminary observations (or estimate) the mean value *(m)* to be expected.
2. Determine the standard deviation *(s)*. If preliminary observations are available, the square root of the sum of their individual departures from the mean is divided by their number less 1. If preliminary observations are not available, take one-quarter of the range from the predicted smallest and largest values to be expected.
3. Determine the coefficient of variation *(CV)* by dividing 100 times the standard deviation by the mean.
4. Select a degree of precision *(e)*, the number of units that constitutes an important difference.
5. Select a level of probability that is considered reliable, commonly 95 times out of 100.
6. Determine a proper value for "Students' t." As seen in tables (Wenger 1983), the "t" value depends on the number of replicates, which is what is being determined. So, the t value may have to be determined by trial and error. However, for all practical purposes, for any number of replicates over 30, the value t is 2 for 95 percent probability (table 9–1).
7. Determine the approximate sample size by squaring the product of t and *CV* divided by e^2.

For example, assume that the mean ratio of tree-crown diameters to stem diameters at breast height is to be determined. Measuring a few typical trees has indicated that the mean may be about 20 and the range may be from 10 to 30. The approximate standard deviation is then 30 minus 10 divided by 4. This means that the coefficient of variation is 100 times 5 divided by 25, or 20 percent. If the degree of precision desired for the ratio is within 2 points of the mean (20), then *e* equals 10 percent. The predicted value of t for a probability of 95 percent and an estimated number of replicates of 40 is 2.02. The first trial for the true number of replicates is then the square of 2.02 times 20, or 1,632.16, divided by the square of 10, giving the result of 16.3 replicates. Recalculation then with the t value corresponding to 16.3 replicates (2.12) gives the number of replicates as 18.0, or $(2.12 \times 20)^2/100$. Because of the approximations involved, a safe number of replicates apparently would be 20 or more.

Much of the guesswork in selecting sample sizes for research plots can be eliminated by using tables that give sample sizes as a function of an estimated coefficient of

Table 9–1.—Values of "Students' t" (95-percent probability level) for various numbers of replicates in research studies

Replicates	t	Replicates	t
2	12.71	10	2.23
3	4.30	15	2.13
4	3.18	20	2.09
5	2.78	30	2.04
6	2.57	40	2.02
7	2.45	60	2.00
8	2.36	120	1.98
9	2.31		

Source: Wenger 1983.

variation and a prescribed sampling error using various levels of confidence. A set of such tables has been published by Stauffer (1983). Many additional and more precise details on experimental design for various research inquiries are to be found in Burley and Wood (1976). Table 9–2 approximates numbers of replicates based on the coefficients of variation and the precision required.

Precision. Experimental differences that may have been slight on a small scale will be of similar proportion on the grander scale of application. The above process also tends to multiply any errors of experimentation and, thus, can easily lead to unacceptable results on a large scale.

The best safeguard against this problem is to ensure the precision with which observations are made and responses measured (fig. 9–3). At least three measurement levels merit attention. First, to the degree possible, the effects measured must be related directly and solely to causes. Eliminating extraneous influences or indirect responses is necessary to clarify true causes and effects.

Second, the instruments used in measuring responses should be selected for their reliability at the level of precision required. The fact that an instrument is new, complex, or sophisticated does not necessarily mean that it is appropriate to a particular study. Instruments may need prior testing or calibration under the precise conditions of the experiment.

Table 9–2.—Approximate number of observations required for a specified precision in experiments based on coefficients of variation

Coefficient of variation (%)	No. of observations for desired precision (95-percent probability) ±5 percent	±10 percent	±20 percent
10	16	4	1
30	144	36	9
50	400	100	25

Source: Burley and Wood 1976.

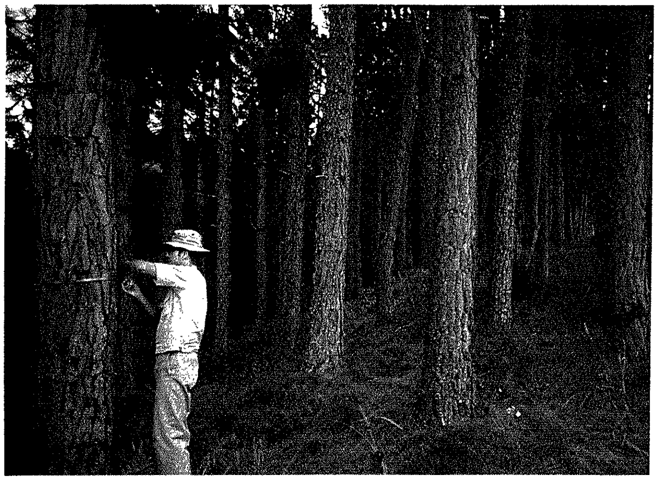


Figure 9–3.—*Accurate and repeated assessments of the forests are fundamental to the acquisition of new knowledge through research.*

Appropriate care must be used in obtaining measurements. The more precise are the readings required, the closer the supervision must be. Those who take readings not only must be trained for the task but also must be fully convinced of the need for the stated level of precision and of the determination of the supervisor to accept nothing less.

Third, the data, once collected, should be interpreted only to the degree that their precision warrants. Measurements geared to centimeters tell nothing about unit precision in millimeters. Even where readings may be taken to the millimeter there may be no validity in generalizing from them. An example is annual rainfall, summed for a year or averaged for several years and presented to the nearest millimeter. Individual storm readings or daily totals may be measured to the nearest millimeter for the gauge used at its precise location and for the precise period measured. However, anyone measuring annual rainfall knows that for different years, totals differ, not by millimeters, but usually by many centimeters. Likewise, a second rain gauge, even if placed near the first, will show differences over a year measured in centimeters. Accordingly, summed rainfall data expressed in centimeters are, for most purposes, as meaningful as those in millimeters.

Results of summaries of observations or comparisons commonly are expressed in terms of sample means with some measure of dispersion, such as the standard error (standard deviation/n). For some practical purposes, a more meaningful figure than the sample mean is the "reliable minimum estimate," a figure derived by subtracting from the sample mean the standard error multiplied by the value of t for a probability of 0.95 (Dawkins

1958d). The reliable minimum estimate so determined is to be expected with a probability of 97.5 percent.

Comparing research results throughout a region as large as tropical America calls for similar reliability in the studies undertaken. This should not limit ingenuity in designing studies for specific local conditions. However, a goal of similarity could provide a guide to plot sizes and definitions of tree height and diameter groups for summarizing tree performance, and so forth.

Interpretation of Results. The foundation of interpretation is observation. Mlinsek (1982) points to the tendency to use expensive research equipment in place of direct observation. He states that forestry research used to lean on observation and clever interpretation, yet good qualitative results appeared. He concludes that, even with sophisticated instruments, it is still essential that scientists maintain a permanent contact with the nature of forests. This may be intellectually demanding but is modest in terms of equipment needs and may produce results equal to those of laboratory research.

The interpretation of research results calls for a broad understanding of all values involved. Plantation productivity, for example, is usually expressed in terms of volume (or aboveground phytomass) per unit of area and time. However, under some circumstances, the maximum volume yield per unit of investment or per unit of employment may be most meaningful (Wood 1974).

Investigations are commonly undertaken more to prove something already suspected or believed than to search for a completely unsuspected truth. The motivation is often to demonstrate the benefits of applying some new finding to management. Even where this is not the case, the investigator, either at the outset or as the study progresses, may be tempted to prejudge and interpret what has not yet been shown conclusively. This impulse can lead to bias in the design, conduct, and interpretation of investigations. Any satisfaction thus derived may be short lived, because decisions based on biased conclusions will sooner or later prove deficient and will be exposed by costly mistakes or by other more objective investigators. Interpretation should be limited to the strength or scope of the observations, even if the results fall short of study objectives. Such limitations, openly recognized and reported, can stimulate an improved second attempt by the same or other investigators.

Another aspect of interpretation concerns "indications" not fully supported by measurements (such as differences less than probable at the 95-percent level of confidence) but nevertheless part of the investigator's impressions during the study. These may lead to hypotheses to explain phenomena observed and, thus, to new profitable lines of investigation. Descriptions of such impressions are an important by-product of research expertise and have a place in scientific reporting, the only proviso being that they be described only for what they are and not as scientifically established fact.

Presentation. The purpose of research is to provide new information. But to whom? The audience is a critical consideration in selecting research priorities and presenting research results. The most obvious audience for research in forest production is the practitioner: the forest manager, agroforester, or landowner who may apply new information in policy formulation and in the treatment of forests and forest lands. A second distinct audience is the general public, whose support underlies much research and yet is interested only casually in the details. A third audience is the scientific community that is interested in learning of study techniques and technical results as a foundation for further research.

Good research should have something to offer each of these audiences, but seldom are all three addressed at the same time. Scientists tend to address other scientists in terms that are not familiar to either practitioners or the general public. Much research is, therefore, undersold where it might be applied or could win further support. It is incumbent on the scientist to reach all of these audiences with the results of his or her work. This calls for clarity, simplicity, and purposeful presentations acceptable in a variety of media.

Research Focuses

A balanced research program is generally composed of several studies that collectively are focused on critical problems. This balance normally is between long-term, fundamental investigations and short-term studies for prompt solutions to immediate problems. Long-term studies may concern underlying causes for observed phenomena, such as variations in the productivity of different sites. Balance also is enhanced by recognizing the priority of research to determine the physical, biological, and technical possibilities over the priority to determine the limits or degree of economic feasibility.

Forest Classification and Inventories. Climatic and ecological classifications of tropical forests have been described in earlier chapters. They are useful in that they emphasize key characteristics that (1) may be common to forests separated by long distances or superficially different, or (2) may distinguish forests otherwise apparently similar. But such classifications are imperfect and are a continuing subject for research in the region. One of their limitations arises directly from their tendency to group forests solely on the basis of a few readily measurable parameters. Attempts to achieve universal forest classification systems have been challenged for obscuring as many differences as they reveal similarities (Grubb and others 1963). Whereas broad similarities should be recognized, attention must also be paid to changes in associations and individual species with differentiation of site factors such as elevation, slope, aspect, and physical soil properties. Better understanding of these relationships through research should bring to light both limitations and possibilities for wiser forest management in tropical countries.

Forest inventories in tropical America promise to be an ongoing focus of research attention. Much of the region has never been inventoried, and yet rational protection and productive management must be based on forest assessments that only some form of inventory can provide. At the very least, inventories must provide reliable information on the location and extent of existing forests, information now derived almost universally by remote sensing.

Valuable as this basic information may be, it suffices only for cursory forest policies, suggesting the overall importance of forests as a national form of land use and possibly indicating where to concentrate forestry efforts. To rationalize harvesting rates, identify the most productive sites, and determine sustainable yields, tropical forests must be inventoried in much more detail and repeatedly over time. Continuous inventories, showing changes over time, are generally based on repeated measurements of representative samples of the forests.

In planning for the conversion of Uganda's forests to a 70-year, monocyclic management program, foresters found it essential to have reliable inventories based on well-planned, comprehensive ground sampling of the forest composition, the silvicultural condition, and the productive potential of each area (Hughes and Brown 1962).

The percentage of the forest to be included in the sample, the parameters to be measured, and the nature of the analysis all depend on how much information is required and how precise it must be. For overall estimates of total standing timber volume, sampling of 2 to 5 percent may suffice, but a much larger sample will generally be required in mixed forests when the goal is to estimate the volume of trees of harvestable size or of only one (or a few) species. Gathering these data could require an almost complete inventory because of the irregular occurrence of each species in mixed forests. Where possible, grouping of species in inventories may greatly reduce such irregularity and, consequently, the sampling intensity required for any specified level of precision. The sampling intensity required can be based on the coefficient of variation, as previously described (table 9–3; Meyer and others 1961).

The sampling intensity needed for a given reliability can be reduced by subdividing a heterogeneous forest into more homogeneous subunits. The heterogeneity of mixed forests can be reduced for sampling purposes by stratifying according to environmental factors such as elevation, soil type, or past forest treatment. Such stand variants may be discernible through remote sensing. In general, any variation that can be so mapped is a promising source of potential savings in field sampling intensity, because each forest type (or class) tends to be more homogeneous than the aggregate mixture, and thus, each

Table 9–3.—Probable error from ground sampling in forest inventories (%)

Size of forest (ha)	Probable error for different samples		
	1 percent	5 percent	10 percent
	Coefficient of variation of 15 percent		
40	14.9	6.5	4.5
400	4.7	2.0	1.4
4,000	1.5	0.7	0.4
	Coefficient of variation of 60 percent		
40	59.8	26.2	18.0
400	18.9	8.3	5.7
4,000	6.0	2.6	1.8

Source: Meyer and others 1961.

might be sampled less intensively for a given level of probable error.

In any forest inventory, no matter how routine and repetitive, there is a continuous need to assess techniques as well as their results in a search for better and less expensive methods. For detailed information on forest inventories, their purposes, designs, sampling techniques, remote sensing, measurements, data recording and processing, and interpretation, the reader is referred to the FAO's manual on this subject (Lanly 1973). For tests of tree species, a good reference is that of Briscoe (1990).

Forest Ecosystems. Before rational decisions can be made about whether or how to modify tropical forests to stimulate production, one must be aware of how the natural functions of unmodified ecosystems operate (Assman 1970). For example, regeneration under undisturbed conditions must be understood as a guide for regeneration under conditions rendered unnatural by removal of timber (Richards 1957). Similarly, in secondary forests, the study of the natural succession of species can guide silviculture (Hall and Okali 1979).

Given the heterogeneity of tropical forest ecosystems, research may be less fruitful in the discovery of universals than in the search for causes of differences (Levins 1968). The challenge is to discover ways of treating natural systems for human benefit without losing the rich source of biological information they contain (Farnworth and Golley 1973). Research must be directed toward a sustainable yield of useful benefits or products, meaning that our actions must not diminish productivity, richness, or long-term stability.

An Institute of Ecology task force concluded that the following ecological research needs in tropical forests are of high priority (Farnworth and Golley 1973):

- Studies of the morphology, physiology, behavior, and population structure of forests
- Time and energy budgets of individual organisms and of populations, and rates and strategies of energy acquisition and expenditure
- Life histories of flora
- Potential organic yields, productivity, decomposition, and cycling
- Relation of diversity to stability
- Stress limits tolerable without loss of recovery potential
- Nutrient dynamics in forest treatment, destruction, and recovery
- Systems approach to pest management
- Research techniques

Other recommendations for strengthening ecological research on tropical forests (Brunig and others 1975) focused on: (1) the nature and quantity of flows and fluxes; (2) the structure, functions, and interactions of flora and fauna; (3) nutrient cycling and decomposition, and the role of mycorrhizae; (4) species-site relationships; (5) terrestrial and aquatic systems interrelationships; (6) reactions of the natural ecosystem structure and functions to environmental variation and human interference; and (7) the development of predictive models.

Basic data on forest structure and composition are considered essential to an understanding of the management of mixed Malaysian forests because of a tendency to increase the representation of commercial tree species and shift toward more even-aged crops (Wyatt-Smith 1966).

Tree Life Histories. Despite the need for studies of ecosystems as a whole, there is much to be gained by studying the life histories of individual component species. This is true partly because the culture of mixed forests for different management objectives usually favors some species at the expense of others. The selection process itself should be based partly on the relative performance of alternative species. Then, as a result of such selection, the performance of the system or stand as a whole tends to reflect the performance of the selected species that are gradually becoming more prominent within it.

For each species, various types of information are needed. The first to be considered is the species' "identity," including any racial variants, distinguishing taxonomic features, and species nomenclature, both scientific and vernacular. Second, the environmental factors that appear critical to its occurrence and welfare should be investigated. Among these are climate, including frost occurrence and drought severity; soils, particularly physical factors such as depth and porosity; and the supply of nutrients (Richards and others 1939).

Third, the nature of the forests where a species occurs (or is apparently well adapted) should also be determined. Information should be included on elements such as canopy closure, gap size, shade intensity, and any layer that may constitute the primary habitat of the species. Associated species are also significant, as is the species' relative occurrence in primary forests or forests in various successional stages.

Fourth, the habit of the species itself is also important, including form, size at maturity, bark peculiarities, buttresses, leaf type and size, deciduousness, flowering, pollination, fruiting, seed transport mechanisms, the mechanics of establishment and growth through life, and the relation of all these to the environment.

Under the category of "silvical information" would come the response of trees to silvicultural practice, data that may be derived in part from the behavior of the species in nature. Types of related information include adaptability to artificial regeneration, external dangers (such as pests and breakage), response to different silvicultural treatments, and rates of volume growth (Fanshawe 1947a, 1947b, 1948; Kadambi 1954; Soerianegara 1973). A compendium of silvical details on the trees of Trinidad and Tobago presented the following information categories (Marshall 1939): distribution and habitat, botanical description, germination, seedling development, silvicultural characteristics, and utilization. A presentation of tree information for Ghana (Taylor 1960) includes scientific, vernacular, and trade names, botanical description, uses, distribution, phenology, seeds and the seedling, and the abundance of and conditions for natural regeneration.

The Silvicultural Study Group of the North American Forestry Commission has developed from other sources a comprehensive outline for silvical information that should serve as a guide in the region and is presented in appendix M. Very nearly the same outline is being used by the Silvics Manual of Tropical American Trees, in preparation at the International Institute of Tropical Forestry in Puerto Rico (Francis 1984–present).

Field identification is generally based on more characters than are used for taxonomic classification. The identifying characters must be visible throughout the year. Some common examples (Allen 1956, Rosayro 1954) include crown form, bole form, buttresses, stilt roots, spines, dehiscence of bark, scaling bark, bark color, bark exudations (latex) of different colors, color change of inner bark on exposure, distinctive color of middle layer of bark, streaked inner bark, distinctive odor or taste of bark or wood, and presence of stinging ants. Such information for the preparation of field keys is basic to research in the region (Dubois 1971).

The study of natural regeneration of tropical trees is still in its infancy; generally, we know neither how most species reproduce in the absence of human intervention nor how the process might be stimulated. In India and what is now Malawi, natural regeneration became the accepted silvicultural practice decades before foresters recognized that little or nothing was really known about the reproductive process and that more research was needed (Hursh 1960, Nair 1960).

A case has been made for research on regeneration under undisturbed conditions as a source of basic information (Stern and Roche 1974), yet the study of regeneration (or the lack of it) under the modified conditions that typify exploited or secondary tropical forests may prove more useful. Furthermore, because the problems of natural regeneration are not solely those of recruitment, there is a need for concurrent developments of technology for regeneration inventories and for tending (Dubois 1971).

An understanding of the natural reproduction of key forest species is fundamental to silviculture and management of natural forests. An FAO Asia-Pacific Forestry Commission meeting in 1960 recommended that research first determine the ecology of the younger stages of economically significant tree species (Anon. 1960a). A need was seen for techniques to assess the abundance of regeneration present relative to what was deemed necessary for sound forest management.

Studies of natural regeneration logically begin with phenology—the timing of tree maturity and the season of flowering and fruiting. Because most tropical plants depend on animals for at least one phase of their reproductive cycle, it is particularly important that studies of pollination and seed dispersal be undertaken in natural environments, if possible before modifications (including those caused by invading honeybees) take place (Frankie and others 1974b).

Although the heterogeneous character of most tropical forests results from mechanisms that inhibit development of concentrated groups of the same species, the fact remains that many species successfully survive in pure or nearly pure stands. Some of these are fast-growing, long-lived pioneers, suggesting that they should be especially well adapted for intensive production (Whitmore 1981). Questions for research are how such species avoid diseases and epidemics, and what mechanisms are responsible for rapid growth.

The consolidation of information about a tree species necessary for its management is generally lacking. The components of such a life history have been outlined by Garcia Gutierrez (1976). Against a background of the description of the adult and its natural geographical range is presented information on the floral biology (including the period and duration of flowering), the flowering mechanism, the mechanisms and agents of pollination, the period of fruit maturation, the nature of the fruit, fruits per tree, and seeds per fruit. A natural sequence then includes details on seed durability and dispersion, the germination requirements, the germination process, the fate of seedlings, and the development of the tree to maturity.

Life histories have been published for few tropical tree species, including *Pentaclethra macroloba* and *Stryphnodendron excelsum* in Costa Rica (Hartshorn 1972), *Cecropia peltata* (Silander 1979), *Schefflera morototoni* (Nieves 1979), *Buchenavia capitata* (Sastre de Jesus 1979), and *Inga vera* (Muñiz-Melendez 1978) in Puerto Rico. All of these studies were made over a brief period and lack significant data on mortality rates and causes. The study of *P. macroloba,* based on 4 ha of forest, determined the rate of diminution of tree numbers per unit of forest area with increases in the tree height or diameter. From this was deduced the mortality rate relative to the time of passage from one tree size class to the next larger one.

Tree Growth. The assessment of forest ecosystems is not limited to determining current conditions. More elusive and yet more valuable in the long term is information on the character and rate of changes that may be taking place, particularly the volume growth of the potentially economic component of stands. Some of the earliest monitoring of tropical forests was undertaken in what is now Malaysia. Tree-growth data were derived from repeated measurements of selected specimens located along permanent transect lines (Watson 1934).

By 1958, measurement techniques had been developed in what is now Malaysia for determining the following (Wyatt-Smith 1958b):

- Volume of commercial-size timber for management purposes (commercial enumeration surveys)
- Composition and size-class distribution of trees and seedlings (research enumeration surveys and large botanical plots)
- Structure of the forest (profile transects)
- Frequency and distribution of the best seedling regeneration of economic species per unit of area (sampling for pre- and postexploitation seedling regeneration)
- Development (recurrent measurement in permanently marked botanical plots).

In harvested forests, linear sampling may be used to decide on a preliminary silvicultural treatment; sampling intensity generally varies from 2.5 to 10.0 percent, depending on tree size. When the treatment has been decided on, treatment plots are established to assess the effects. Units are 20 by 200 m in size, and within them, trees less than 10 cm in d.b.h. are subsampled. Units are grouped in a randomized block design in areas selected subjectively by any criterion independent of the treatment. Square arrangements are generally precluded by topography (Wyatt-Smith 1958b). In Malaysian rain forests, long, narrow samples are more efficient than square samples for obtaining a normal distribution of the basal area (Cousens 1958). Strips 20 m wide and 100 to 400 m long have proved satisfactory.

In Suriname, sampling for tree size and distribution of species has been done on quadrats 10 by 10 m, either located along lines or grouped in 1-ha squares (Schulz 1960). It was found that the 10 leading species could be assessed adequately on 50 to 100 quadrats. The most decisive parameter is the number of trees that reach 25 cm in d.b.h.

Uganda has had long experience in developing techniques for measuring high forest. It was concluded there that the only sound method of estimating growth is recurrent measurement of the whole stand (Dawkins 1958d). The second-best method is the use of permanent sample plots. Even within these plots, measuring all trees is difficult. Everything must be marked, including weeds, and both paint and nails have presented problems of durability. Ingrowth and mortality must be recorded currently, a task made less arduous by concentrating only on chosen trees. If the final crop of mature trees is to have no more than 50 stems per hectare, only two stems need be recorded per plot of 20 by 20 m. In practice in Uganda, yield plots are typically 100 m square and sited in random pairs, two per 250 ha. Each plot is subdivided into 25 quadrats within each of which the 4 best trees are measured. Each measured tree is tagged, even if no larger than a sapling or seedling. This system yields an adequate stand table.

A logical sequence of sampling techniques was developed in Uganda from a physical survey to a biological survey to a production survey (Dawkins 1958d). The physical survey, which was considered exploratory, estimates the tree population. This was followed by dynamic sampling, concerned with recruitment, growth, and mortality.

The simplest monitoring procedure in Uganda has focused on the tree-growth plot, designed to estimate the significance of the passage of time for desirable species. No more than 10 trees of any diameter class are needed on each site. The trees are selected for their potential soundness for sawtimber. A ring is painted at the point of measurement, and measurements to 0.1 cm in d.b.h. are repeated at 1- to 5-year intervals. Individual trees may then be classified as to crown position and form (Dawkins 1958d).

Production surveys in Uganda have called for classifying trees according to utilization (Dawkins 1958d). Those considered "desirables" include prime timbers, secondary timbers, and unknowns that are of potential value (considered harmless). "Undesirables" include proscripts (no known value), weeds, defectives, and impeders.

The absence of reliable growth rings in the wood of most tropical trees has left managers with a long-term task of determining growth rates. Efforts have been made to accelerate the development of this information, but the processes are complex and of uncertain reliability. Repeat measurements of the same areas or trees still produce the best results.

New, more precise methods for measuring diameter growth appeared with the introduction of the vernier d.b.h. tape and the use of fixed dendrometer (an instrument for measuring tree dimensions) bands. The latter, however, must be installed and reach stable tension a year before growth measurements are reliable (Bower and Blocker 1966). For special studies, the xylem of selected trees can be pricked through the bark with a needle, leaving a permanent mark against which later growth can be measured (Wolter 1968).

An attempt in Cuba to determine the age of planted trees by growth rings indicated that for at least a few species, the error need not be large (Gonzalez Rondon and Eremeev 1976). The mean number of years per growth ring (age coefficient) was found to be 0.8 for *Pinus caribaea,* 0.9 for *P. tropicalis,* 0.9 for *Cedrela odorata,* and 1.0 for *Eucalyptus saligna, Hibiscus elatus,* and *Swietenia* spp. Other studies have produced less certainty as to the number of clearly visible rings.

In the sharply seasonal climate of northern Australia, three species of *Eucalyptus* form clear annual rings (Mucha 1979). However, to determine tree ages, carefully selected material is needed. With increasing tree age, the width and distinctiveness of the outer rings diminish. These findings suggest a need for evaluating rings in other eucalypts in dry climates.

A sensitive indicator of forest condition and change is diversity, one measure of which is the number of tree species per unit of forest area. In unmodified forests, the more species there are, the more favorable conditions are presumed to be. The degree to which the species present are equally represented (rather than some common and some rare) is also recognized as a mark of diversity. A measure of this tendency is the Shannon-Weiner function, derived by multiplying the percentage of all trees that each species represents by the natural logarithm of the same percentage, changing the sign from minus to plus and summing for all species (Boyce and Cost 1978). The larger the result, the greater the number of species and the more uniform their respective degrees of representation, which is considered to be greater diversity.

Monitoring is especially useful in secondary forests as a guide to management during the early stages of recovery from disturbances (Richards 1955). The successional stages should indicate the stage of soil restoration.

An extension of the monitoring of past or current changes is the prediction of what to expect in the future. Inventory methods must not only measure the current composition and quantity of the growing stock but also indicate the prospective growth rate under alternative stand treatments (Bunn 1968).

Predictions of the consequences of human interventions in moist tropical forests are limited by the fact that tropical forest systems are imperfectly understood. Observational approaches may be based on assumed but unproved analogies with other ecosystems. Experimental predictive approaches are time consuming and costly. The preferred approach is computer simulation, which uses current measurements to compare the potentials of different strategies (Goodall 1975). The use of multiple regressions enables quantification of the relative effects on dependent variables of several levels of different independent variables, at least during periods of no extraneous interference (Dawkins 1964b). There is clearly a need to search for a stronger correlation between external tree measurements and product yields.

The effect of competition on individual trees would appear to be closely related to prospective growth rates. One expression of such competition is zone counting, a mathematical measurement of crown overlapping based on a basal area of about 10 m^2/ha (Opie 1968). Assuming that the zone of influence of each tree corresponds to a circle of a size that is a function of d.b.h., the theoretical areas of crown overlap can be determined. These techniques appear to be useful largely in research at present, but practical applications in the field may be developed later.

Another index of the competitive status has been tested in the Temperate Zone. The "area potentially available," as it is called, is the area of a polygon around each tree derived from points along lines to each of its neighbors, the location of the points being at a distance from each in proportion to their respective d.b.h. (Moore and others 1973). In one test, this index explained between 61 and 71 percent of growth variability.

It might seem most logical to monitor changes in forests by concentrating on individual components as indicators of constancy or change. However, the significance of such findings may be difficult to interpret. Extrapolating information about individual trees to a group effect for the ecosystem as a whole is a complex leap in logic that may be misleading. In fact, with vegetation of great diversity, the autecological or physiological approach may not be the best starting point for an investigation (Webb 1968). The physiological parameters of any community may not result from merely adding together those of its individual elements. It may well prove impossible to select significant indicators without wasting much time on unfruitful attempts. A more promising approach may be the study of plant communities, their succession and dynamic relationships (Webb 1968).

The difficulties of characterizing tropical forest stands through individual trees are further complicated by apparently irreducible differences in individual tree behavior due to the great variation in local environments and the stratification of complex forests (Mervart 1969). Each tree is subject to different probabilities of growth acceleration, deceleration, and death. To take all these factors into consideration, long-term observations of many trees are needed. Even then, the process of synthesizing to represent the stand as a whole may be problematic.

Difficulties in isolating cause and effect in complex ecosystems should come as no surprise. There is much evidence that the survival and welfare of the system as a whole are determined by subtle interactions among components. A corollary would seem to be that no single behavior is likely to be a response solely to one or maybe even a few causes.

Silviculture. So little is known about the effects of silvicultural treatments on mixed natural forests in the Tropics that the results of extensive silvicultural programs cannot be predicted. Three lines of research promise a broader scope for tropical silviculture (Synnott 1979). These are as follows:

- Markets for lesser used timber species and smaller products other than timber
- Felling and extraction practices that better conserve the productive potential of cutover forests
- Climber cutting, both before and after logging, to reduce logging damage and increase subsequent productivity.

Another assessment of silvicultural research needs for natural forests referred specifically to dipterocarp forests but is of general interest (Ashton 1978b). It was concluded that the research needed to ensure sustained yields from mixed dipterocarps has not yet been undertaken. Re-exploitation of natural forests in times of favorable markets is likely to preclude natural regeneration. Yet, plantations may prove profitable only on good sites where agriculture is a competitor. Research is needed to prove the dependence of rural communities on forests. Reserves must be set aside before modifications obscure ecological relationships that should guide management.

In the dipterocarp forests of Sabah, the following four lines of research have been considered most important (Fox 1967b):

- Study of the virgin forest to guide reservation of representative examples as controls and to locate and assess the volume available for removal
- Assessment of old regeneration in cutover forests
- Determination of seedling performance for a few of the more problematic species
- Management of competitive vegetative growth as a potential source of industrial cellulose.

Studies of natural regeneration and its response to silvicultural treatments can be relevant to much of the region. Of interest is the technique developed in Uganda to follow the fate of seeds and seedlings around seedtrees (Dawkins 1955a). Bands 2 m wide are cleared out from each tree in four directions just before seedfall. Quadrats are laid out to measure the quantity, time, and direction of seedfall, germination, and eventual survival. Hundreds of seeds per square meter may be monitored in this way.

Silvicultural research in the high forests of Uganda led to classifying studies by stand component and a corresponding set of plot sizes (Dawkins 1957). Studies of seedlings and small saplings record trees from 15 cm to 2 m tall by height class: the first class is 15 to 33 cm and subsequent classes increase by 33-cm increments to 2 m. In studies of shrub and lower understory species, saplings from 2 m tall to 5 cm in d.b.h. are counted, and poles from 5 to 20 cm in d.b.h are recorded in 2.5-cm d.b.h. classes. Studies of the overstory or canopy record trees larger than 20 cm in d.b.h. and measure their girth to the nearest 0.25 cm with a steel tape. The measured trees are permanently ringed with paint at the point of measurement to ensure precisely comparable remeasurements. The trees are classified by crown condition and quality.

The minimum plot size in Uganda has been the 20- by 20-m quadrat (Dawkins 1957). For studies of regeneration and survival of trees up to 20 cm in d.b.h., single quadrats are used. For studies of silvicultural effects on the understory or shrub layer, plots of 10 by 100 m or 60 by 80 m are used, and two quadrats are located randomly within each plot. For more extensive understory treatment, four quadrats may be located within an 80- by 80-m square. For studies of the overstory with no clear felling, nine quadrats are centrally located within a square hectare. For drastic canopy treatments, an area of 400 by 400 m is assessed along two transects 20 m wide, each with 20 quadrats.

For experiments that measure growth response following treatments, plot size should be based on the number of trees that are to remain at the end of the experiment, possibly after repeated thinnings or other treatments. In Europe, the recommended practice is to use replicate plots with not less than 100 measured trees in each (Assman 1970). In mixed tropical forests where a few species are being studied, such a requirement could dictate very large plots or long transects.

Priority research needs for bamboo recommended at a symposium in India in 1965 (Anon. 1965g) were as follows:

- Growth behavior and clump development, age of culm of maximum cellulose content, solidity and longevity of culms, root development and competition relative to trees, flowering and measures to delay or induce it
- Nutrient requirements, uptake, and recycling
- Ecology of gregarious flowering
- Analytical identification of bamboos
- Strength properties as related to age and locality
- Tree species suitable for mixtures with bamboos
- Inventory techniques
- Growth statistics and yields
- Genetic improvement
- Optimum felling cycles and cutting intensity

- Techniques for reducing clump congestion
- Effects of fertilizers.

Species Adaptability

The large number of tree species (both native and exotic) that grow well in tropical climates and the great variety of site conditions in the Tropics have led to widespread trial-and-error testing, producing conflicting results. Seeds have been exchanged with too little information about the species; as a result, plantings on unlikely sites have led to rejections of species based on inconclusive evidence. The results of large-scale planting based on such testing are apparent in Puerto Rico where, after 65 million trees were planted over a period of 37 years, only 3 percent were still alive in 1958 (Marrero and Wadsworth 1958).

A more systematic approach to species testing was used in a 1962 species trial in what is now Zambia (Cooling 1962b), involving the following steps: (1) screening of species on the basis of published information, (2) introduction and preliminary testing, (3) determination of growth and yield, and (4) response to edaphic variations.

Preliminary testing in this case was done in 0.4-ha plots, then replicated in two contiguous plots except where site variation was pronounced. Elsewhere, greater replication may be required. Replication in time was needed where seasonal changes were great. Spacing was usually 1.8 by 1.8 m or 1.8 by 2.7 m where mechanized weeding was practical. Plots of 35 to 64 trees were assessed for survival, vigor, health, and form; d.b.h. and tree height were measured annually for the first 5 years, at which time species could usually be selected. In some instances, it was necessary to continue observations to the 10th or even the 15th year (Cooling 1962b).

Growth-and-yield plots in this study, which were used only for the species selected from initial trials, were about 1 square hectare, with a 0.2-ha inner plot subject to measurement. These plots were not replicated but were sited as representatively as possible. Height, d.b.h., form, and vigor were measured. Thinning volume was measured to enable determination of yield. This information aided final species selection and shed light on the benefits and costs of thinning and pruning as well as on probable rotations (Cooling 1962b). Finally, uniformity trials were conducted over a range of site conditions to compare performances.

Experience with species testing in Kenya led to a different approach (Edwards and Howell 1962). The first step was to develop an "arboretum" where a few trees of each promising species were established to determine their suitability for further trials. Next, the promising species were established in "forest gardens" under favorable conditions where tree habit and performance could be observed further. Then, experiments with trees in randomly located plots in pairs or larger numbers were carried out. The final step was forest-scale plantations.

Kenya's experience showed the importance of clarifying planting objectives at the outset, classifying climates and soils, and obtaining all available information about new species. Where possible, seeds from at least three widely separated provenances were obtained. Seeds and nursery practices were not perfected until the species had proved satisfactory in the first trials (Edwards and Howell 1962).

In east Africa, the initial "arboretum stage" was thought to involve too many species for any helpful results and, thus, was not generally used (Leuchars 1962). The second step, using 0.04-ha plots, was thought to be simple and to avoid "high-flown statistical virtuosity for its own sake." Randomized blocks, either complete or incomplete, may be used. Thus, if the number of seedlings available is limiting, not all species need to be tested on all sites. Generally, more than one site was tested, and there may be several replications per site or in time. If the number of species is four to seven, the use of Latin squares is more precise than randomized blocks, because the numbers of species, rows, and columns may all be equal. Otherwise, an incomplete Latin square of lattice design may be appropriate. The use of split plots may provide for several years of planting in each square of a Latin square or block pattern. The final phase, concerned with spacing, pruning, and thinning, is on a larger scale and may require less replication (Leuchars 1962).

Practice in Uganda has included arboretum plots of 10 by 10 m, with 25 trees of each species. Height measurements are limited to two dominant trees per plot (Kriek 1967a through 1967h). For species trials, a series of 0.04-ha square plots was used, with 64 trees planted at a spacing of 2.4 by 2.4 m. The inner 16 trees of the sample were measured for d.b.h and height, beginning at 7.5 cm in d.b.h and repeated every 2 years. Mean annual increments are determined periodically.

In India, species elimination trials have been composed of two to four trees with six replications. Complete or incomplete blocks no larger than 0.5 ha (to avoid local site variation) were used (Ganguli 1967). In testing pines, the importance of provenance and the presence of mycorrhizal fungi have been recognized.

Others have tested species in three stages (Morandini 1968). The first stage, elimination trials, might involve many species with numerous repetitions on various sites. This phase is followed by establishment of a network of experimental plots of the most promising species on a scale that is sufficient to indicate their volume production. Finally, each chosen species is tested to find the best provenances.

The design of species trials has evolved independently in several tropical countries over the past 20 years. Five precepts appear to be universally applicable (Briscoe 1990): (1) define a range of conditions for testing, (2) restrict each study to no more than a few simple treatments, (3) randomize treatments located so as to minimize variation within blocks, (4) replicate each treatment (preferably four times), and (5) record everything planned and done.

Species trials with eucalypts have led to four generally recommended principles (Anon. 1963c): (1) the stands from which seeds are obtained should be carefully described, (2) nursery practices for each species should be comparable, (3) standards of rejection should be uniform for all species, and (4) species elimination trials should cover the widest possible range of sites. Fulfilling this last requirement may entail a detailed land survey, including climate, soil type, topography, and history of land use. Subsequent growth trials may be conducted on a more limited number of sites yet with as wide a range as possible.

With eucalypts, elimination trial plots of four, six, or nine trees have in some areas proved sufficient, and no guard rows have been required (Anon. 1963c). Blank rows have been left between plots. In contrast, subsequent growth trials have required plots of 16 to 100 trees, depending on the rotation of the study. Square plots have usually been acceptable, and they minimize intraplot competition for a given length of edge. Guard rows have been necessary. More than one plot of each species must occur on each site. The number of replicates needed has depended on the size of the differences regarded as important and the precision likely to be achieved. The number of replicates needed to detect different degrees of precision in experiments in terms of percentage of the mean is indicated in table 9–4 (Anon. 1963c). For example, in an experiment with an expected precision of 10 percent in which a difference of 12 percent is important, six replicates would be needed. This might be six blocks with eight species in each.

The precision likely to be attained may be estimated where experience has been adequate. If this experience is not available, it may be advisable to confine early work to pilot trials designed to assess precision for more formal subsequent work.

Randomization of species plots in each experiment is essential if valid estimates of experimental errors are to be obtained (Anon. 1963c). Randomization must be strict, not haphazard, or other objective devices should be used to assign location. Moreover, conditions on the ground may affect the experimental layout. Within the randomized plots, the design should minimize variations resulting from vegetation, soil, or past use. Plots should be grouped within blocks so that each block contains a complete set of comparisons (or species); these groups

Table 9–4.—Differences for significance (expressed as a percentage of the mean) that will be obtained in experiments for given precision and number of replications (%)

No. of replications	Estimated precision of the experiment (percentage of mean)				
	5	10	15	20	25
2	10[a]	20	30	40	50
3	8	16	24	33	41
4	7	14	21	28	35
5	6	13	19	25	32
6	6	12	17	23	29
8	5	10	15	20	25
10	4	9	13	18	22
15	4	7	11	15	18
20	3	6	9	13	16
25	3	6	8	11	14

Source: Anon. 1963c.

Note: Numbers are the percentage difference for significance.

are termed "randomized blocks." Where site variations are in two directions (slope and aspect), Latin-square arrangements with each species in each row and column may be indicated if there are equal numbers of species and treatments. Otherwise, incomplete Latin-square or lattice designs are indicated. Complete standardization of experimental designs, however, is considered neither necessary nor desirable.

During a meeting of the Latin American Forestry Commission in Trinidad in 1967, a technical subcommittee called for coordination and standardization of species trials in tropical America (Anon. 1968a). The following recommendations are still valid. The aim of selection is to choose species that: (1) are suited to the site and will remain healthy throughout the anticipated rotation; (2) will produce an acceptable growth rate and yield; and (3) will produce raw materials suitable for the objectives defined by the policymaker, with flexibility for changing market demands.

The administrative steps in developing a program of species trials are typically as follows:

- Precisely define the research objective so that it is well understood by the research staff.
- Prepare a written plan for the research.
- Review the plan to ensure that it reflects a clear grasp of the objective, specifies adequate resources, schedules operations according to urgency and resources, provides adequate background information for choosing sites and species, makes adequate provision for statistical design, provides for meticulous standards of cultural practice, and provides for subsidiary experiments on cultural techniques.
- Obtain official approval for the plan along with a commitment to support it.
- Regularly report progress with continuing reference to the original plan or to needed modifications.

The document cited earlier (Anon. 1968a) cites Leuchars (1965) to the effect that three general requirements are necessary for study layout. The design must be: (1) robust, meaning that the loss of some plots will not jeopardize the remainder of the experiment; (2) flexible, so that it can be fit to any irregularities of the site; and (3) simple, so that it can be carried out by untrained field staff. Except under unusual circumstances, completely randomized blocks are recommended.

The initial step for species trials is to collect basic information on the sites to be planted, including climate (especially total and seasonal rainfall), soil (especially physical conditions), topography, vegetation, and past use or abuse. The choice of species is then based on the extrapolation of data from one locality to another.

Intraspecific variation may qualify the results of species trials. One sample from a species cannot be said to represent that species as a whole until the range of variation between its populations has been established (Harper 1977).

Even where all needed comparative data may be at hand (which is extremely rare), it may be unwise to proceed immediately with large-scale planting. Small experimental plots can provide better information than a 1,000-ha block and at a fraction of the cost. There is a sound argument for continually testing additional species that may prove superior or for at least providing alternatives for diversity.

While providing increasing data on sites and species, species trials progress from many species to few and from small plots to large. Three sequential phases are: elimination, testing, and proving (Anon. 1968a).

The elimination phase deals with possible species, often 20 to 40 in tropical America. The object is to reduce the number of species for more critical testing. Survival and early growth rates are the principal criteria. The number of possible species selected will depend on the site quality, the breadth of prospective market demand, and the availability of seeds, staff, and funds. The trials consist of small plots with 1 to 25 trees per plot. With the single-tree plots, there is no isolation between species, a circumstance that economizes on area but may penalize a species that is not precocious if it is located adjacent to others that are. In the 25-tree plot, if only the 9 (3 x 3) central trees are measured, outside interference may be eliminated.

Land and fund constraints for research have led to the use of single-tree plots (Shiue and Pauley 1961). In Puerto Rico, a lattice design has been used with 16 rows and 1 tree of each species in each row, replicated on each site. Mortality in such experiments constitutes a loss of plots, making the analysis more complicated here than in plots with more trees, where the effect of mortality is only partial (Wollons 1980).

In the testing phase, only the promising species are used. The object is to relate performance closely to site differences. Plots of 25 to 144 trees range in size from 0.02 to 0.10 ha. A generally recommended plot contains 121 trees (11 × 11) with a 2-row isolation strip, leaving 49 trees (7 × 7) in the middle for measurement. Growth in diameter, height, and basal area is measured to the time of a first thinning.

In the proving phase, the object is to confirm (for normal planting conditions) the results shown by one to three superior probable species. The intent is to determine how to manage the species for timber production. Plot size will depend on the range of thinning treatments to be evaluated and may range from 0.4 to 5.0 ha with isolation strips of up to five rows.

For single-tree plot elimination trials, only one location should be used in each major climatic (not edaphic) province, such as a life zone. Within each location, there should be 12 replicates, or trees, per species. Each replicate can be a single row of trees with one of each species laid out on the contour. With 25-tree plots, the only difference is that the number of replicates (plots) within each zone need not be more than 4.

In the testing phase, different sites and types within each life zone are compared in two or more groups of plots. At each location, at least three replicate plots are recommended. For the final proving phase, locational comparisons have already been made, and because large plots are used, no further geographical replication is generally necessary.

Tree-measurement practices vary with the nature of the test. For single-tree elimination plots, the height of every tree is measured at 6 months, at 1 year, and annually thereafter until the mean d.b.h. reaches 5 cm, at which time annual d.b.h. measurements begin. For the 25-tree plots, heights of only 2 of the dominants in the inner 3- by 3-tree plot are measured annually before a mean d.b.h. of 5 cm is reached. Thereafter, heights of these two trees and diameters of all nine trees are measured annually.

Measurements in the testing phase (121-tree plots) are confined to the inner 7 by 7 rows. Heights of the 250 tallest trees per hectare (8 per plot) are measured annually until at least age 5. Diameters of all trees are measured annually after a mean of 5 cm has been reached. A similar scheme is also suitable for proving trials, with provisions for permanent tree numbering, pre- and post-thinning measurements, and the felling and complete measurement of sample trees for volume determinations.

The usefulness of these studies decreases after their chief purpose has been served. Elimination trials may have served their purpose in 3 to 5 years; testing trials, in 5 to 10 years; and proving trials, by the end of a practical rotation. Measurements taken after these ages may be of some value but usually not in the context of the original test objectives.

The FAO guide (Anon. 1968a) makes a further point in discussing the use of standard species for comparison. Most species trials are conducted to find new species superior to those already recognized. Thus, it is necessary to include the species already considered best in each test of new species.

Species trials inevitably require a long time. Repeat trials may be necessary to compare seasons and weather, particularly in relation to the dry season. Absolute certainty regarding the adaptability of a species may not be established until after one or more rotations. Even later, insect or disease problems may appear.

Experience in Australia has shown the need to adhere strictly to the statistical requirements of replication and randomization and to plot establishment and maintenance (Wollons 1980). Without replications, it is not possible to test hypotheses or obtain precision estimates. Unreplicated treatments are always liable to be biased by a single result that could lead to erroneous management decisions. With limited replications, large phenotypic variations between trees may limit the value of experiments. Where background data is not at hand, one approach is to establish a series of uniformity plots for 2 to 5 years to compare variations within species on a site. These data can then be used to predict further variations.

In the Tropics, many treatments are greatly affected by season and site, meaning that only with a series of trials can general responses be evaluated (Wollons 1980). Block comparisons, where the variations between blocks can be kept small, give a higher sensitivity to variations than may be obtained in a generally randomized arrangement. The need for careful plot maintenance over whole rotations is also emphasized (Wollons 1980). Unanticipated problems may include disease and insect attacks, grazing, fire, wildlife damage, weed competition, and management errors. Because of these problems, it is prudent to search for early indicators that may predict future performance. For example, for some Mexican pines, height growth at 1 year may be strongly correlated with that at 5 years (Barrett 1970). Such indicators are important for managers who are reluctant to wait for full results of species testing.

When a species has been tentatively selected, further research may be needed to develop the best establishment techniques. This may be done by a series of short-term studies. In east Africa, uniform spacing of 1 by 1 m has been used, with up to 100 trees per treatment (Stuart 1955). Good nursery stock is planted in well-prepared and fertilized soil (Griffith and Howland 1962). Roots are pruned both vertically and horizontally every 2 weeks. Planting is done as early in the wet season as is safe and at a depth somewhat greater than in the nursery. Root exposure is avoided, and weeding is intensive, removing deep-rooted grasses.

A comprehensive manual on tropical species and provenance research (Burley and Wood 1976, 1977) is available as a general guide for most work. This manual calls for trials of provenances contemporary with trials for species because intraspecific variation may prove significant to comparisons with other species. The manual emphasizes a need for thorough study of the base population; genetic variation; site assessments, both for seed sources and for test sites; experimental design; care in propagation; and assessment of results.

Tree Propagation, Artificial Regeneration

Much research is needed on tree propagation and artificial regeneration; many problems are universal, although different solutions may be better in different areas. A logical (but generally underestimated) first step is a thorough review of the performance of any existing plantations under conditions similar to those where regeneration is proposed (Hinds 1952).

With a wide array of problems in need of study, it is crucial to assign local priorities and schedule studies in sequence, beginning with the most urgent. Public research institutions may be guided by the process of problem analysis, in which all factors contributing to the relative importance of the different problems and the relative benefits to be gained from their solution are assessed.

The complexity of some of the research required in tropical forestry should not be underestimated. This can be illustrated by the nearly 40 years of research on the adaptability of *C. odorata* in Trinidad (Beard 1942). *Cedrela odorata* is abundant in Trinidad's semi-evergreen forest. Research on its regeneration began in 1905. Attempts to establish the species with wildings and direct seeding were abandoned after repeated losses to fire. Then, the species was planted with food crops and in gaps under shelterwood. By 1923, these efforts were also considered failures. The species started well but could not be maintained because of insect and disease problems. Beginning in 1924, tests were made with different light intensities, soil supplements, and mixtures with other species, but again, all failed. Transplanting during the dry season, when the trees are out of leaf, gave good results initially, but later, the trees all died. By 1929, clean weeding was discontinued because it was thought that *C. odorata* needed cover. The results were disappointing. By 1933, it was concluded that *C. odorata* grew vigorously in evergreen forests for 18 months and in semi-evergreen forests for 3 years. Soil investigations were inconclusive. Soil deterioration resulting from prior exposure during cultivation was found not to be responsible. Nutrient studies applying N, phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) showed that *C. odorata* grew no better with fertilizers than with tap water. It was concluded that the problem was chiefly one of soil moisture, because the trees frequently dropped their leaves during the rainy season. In 1945, it was further concluded that successful establishment of *C. odorata* may require several years of research by plant physiologists and soil chemists, yet the species is so valuable that success could repay such efforts (Cater 1945). Thus, the problems of production of *C. odorata,* an American species that is highly successful in parts of Africa, still remain unsolved in most of tropical America.

Fertilizer Use

The use of fertilizers in tropical nurseries and plantations has been generally accepted as desirable (Qureshi and Yadar 1967). In many areas, however, fertilizer applications have outrun any scientific basis for them. Frequently neglected is prior analysis of the fertility of the soil. Standard agricultural soil tests may be of some use, but they do not help in concerns important to forestry, such as growth period, rooting depth, and physiological requirements. Fertilizer tests generally needed (Qureshi and Yadar 1967) include: (1) dosage of NPK singly or in combination; (2) utility of inorganic fertilizers versus manure; (3) timing of applications and age of crop at which fertilizer applications should be discontinued; and (4) frequency and method of application.

The complexities of fertilizer research are illustrated by studies of *Pinus elliottii* in the Southern United States (Mead and Pritchett 1971). Studies on six soils showed a weak correlation between field and plot performance. No single measure of seedling response to treatment (height, diameter, or dry weight) consistently correlated with the average tree height in the field. The correlation of pot-experiment tree heights with those in the field was poor after 3 years and only slightly better after 7 years. Thus, although greenhouse experiments are useful for studying deficiency symptoms and for determining limiting nutrients, the results must be used cautiously for predicting fertilizer response in the field

Future research on fertilizers should involve studies of mycorrhizae because of their effect on nutrient assimilation. Deterioration of mycorrhizae in second-rotation plantations of *P. patula* in Swaziland (Robinson 1973) suggests the importance of these organisms.

Growing Space

Much silviculture is concerned with providing individual trees with adequate growing space. Experimental techniques for studying responses to spacing have been tested widely in the Tropics. Poor experimental design is common. Studies of natural stands require clearly understood objectives at the outset and a fixed number of surviving, measured trees over a wide range of spacings (Smith 1959). In plantations, the use of a constant number of trees for each spacing is more efficient than a uniform plot area with the number of trees variable. There should be an equal number of residuals after the final thinning for each treatment. A common final number has been 49 (7 x 7) with a 2-row buffer (Smith 1959).

The complications of thinning research have been pointed out by Vuokila (1965). Permanent plots, including extras, are necessary to determine responses to thinning. The precision of long-term studies suffers because of the subjective judgment of successive personnel. Field and calculation procedures change before studies terminate. Successive tree-volume estimates during short periods that are may be subject to too large an error to accurately measure growth. Thinning treatments that best show biological responses may be impractical for wider application. Different thinning intervals require growth comparisons between periods that are dissimilar in time and weather. Replicated plots greatly increase costs.

Two ingenious developments in thinning research techniques are O'Conner's correlated-curve-trend methods (1935) and the Pudden clinal-plot design of treatments (Borota and Procter 1967, Dawkins 1960, Vuokila 1965). O'Conner's correlated curve trend is based on the concept that the growth rates of different trees exposed to an array of spacings can be related before competition affects any of them; then, as competition starts to constrain the growth of those that are most closely spaced, the degree of constraint can be determined by comparing a tree's performance with that of widely spaced, unconstrained trees. Such spacing studies make it possible to develop regressions (1) predicting mean growth rates of any size trees at any spacing and (2) defining the spacings necessary to attain mature size within any period from any present tree size.

The Pudden clinal-plot design uses either narrow, rectangular plots or concentric circles in a sequence of spacings with differences between adjacent treatments that are so small that no isolation strips are needed (Dawkins 1960). A single row of trees is planted around the outside of the plot. The technique has been rightly criticized as nonrandom, but if it is replicated, the plot design should still be a reliable source of preliminary information on optimum spacings for different tree sizes. The Pudden rectangular layout may also be used for thinning, with progressively heavier treatments adjacent to one another. The heaviest thinning, which must leave 5 to 10 trees per plot, dictates minimum plot size (Dawkins 1960).

A layout for a clinal thinning study is illustrated in figure 9–4 (Borota and Procter 1967). The thinning schedule might then be set as in table 9–5.

Briscoe (1990), in an excellent research field manual, illustrated the circular-spacing study design of Nelder (1962) as shown in figure 9–5. As he describes it, the wheel is laid out with a fixed angle between the spokes, with distances between the trees increasing with distances from the hub.

Experience in Suriname led to systematic thinning and yield plots in plantations (Voorhoeve and Schulz 1968). These provide mean and periodic annual increments in diameter, height, and volume. They indicate site classes

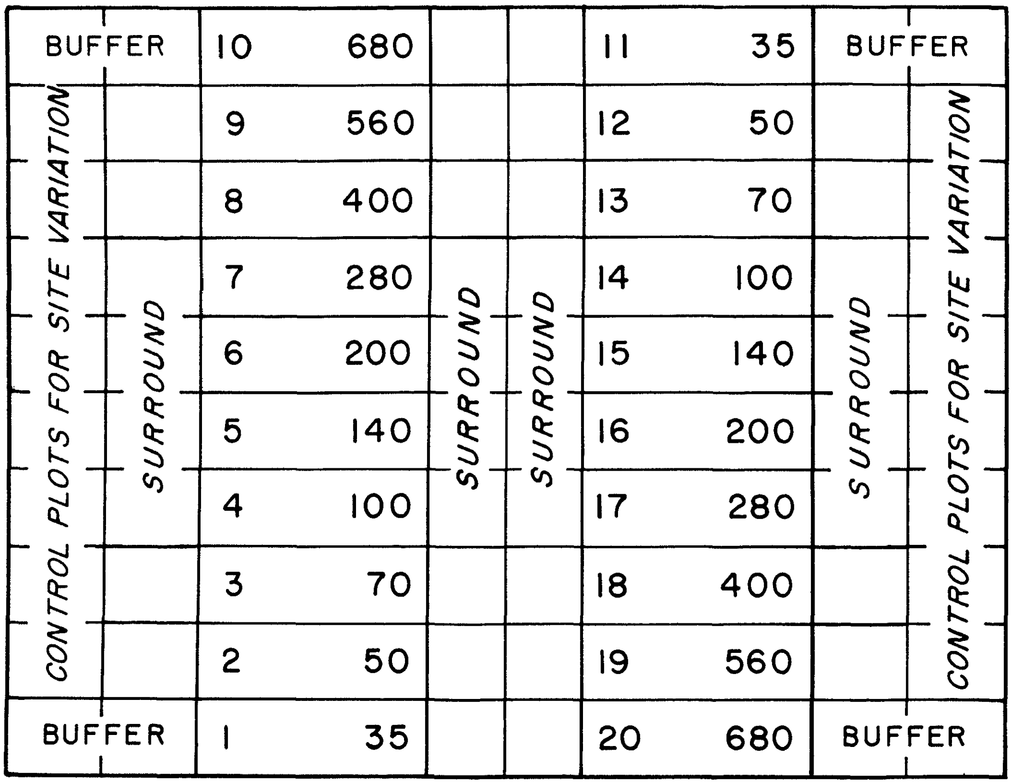


Figure 9–4.—*Clinal thinning study layout (Borota and Proctor 1967).*

Table 9–5.—Prescribed thinning schedule for the design in figure 9–2 (yr).

Final stocking (trees per ha)	Stems per hectare								
	1,380	990	690	490	345	245	170	125	85
1,680	Not thinned								
1,380	3[a]								
990		3							
690		3	4						
490		3	4	5					
345		3	4	5	6				
245		3	4	5	6	7			
170		3	4	5	6	7	8		
125		3	4	5	6	7	8	9	
85		3	4	5	6	7	8	9	10

Source: Borota and Procter 1967.

[a] Numbers are thinning age in years.

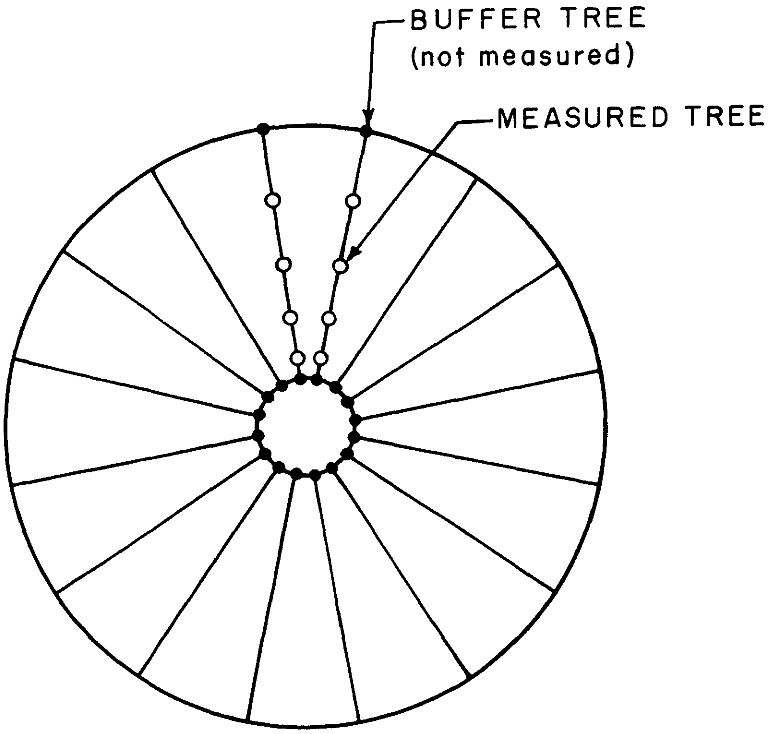


Figure 9–5.—*Nelder's (1962) design for spacing studies (Briscoe 1990).*

and are a source of volume and yield tables and thinning prescriptions. The data are collected from plots 10 by 10 m isolated by 10 m or eight rows of trees. Spacing is expressed in terms of the spacing index (S%), already described.

Tests in what is now Malaysia with widely spaced *Ochroma lagopus* (4.3 by 4.3 m) showed that a single boundary row was adequate to isolate the core planting (Wycherley and Mitchell 1962).

Pruning is much less common in the Tropics than is thinning, although it may be important in coniferous plantations. With many angiosperms, pruning may be done merely by control of spacing. Nevertheless, far too little is known about the effects, benefits, and economic returns of pruning. Research is needed to define the need for and response to pruning for different species, its effects on tree form, the timing of the first pruning, the best season for pruning, rapidity of healing, insect and decay problems, the effects of pruning on growth, and epicormic branching (Laurie 1941e).

Tree Improvement

Generally, timber harvesting in moist tropical forests is highly selective, removing only the best trees. Although the quality of trees in natural ecosystems is much more a reflection of environment than heredity, this could deteriorate the genetic quality of subsequent seed crops, an effect termed "dysgenic." Thus, genetic tree improvement is important, if only to counteract such deterioration (Jasso 1970).

General recommendations for tree-improvement research in the Tropics to counteract the negative impact of current forest treatment include the following (Jasso 1970):

- Explore and evaluate genera and species of worldwide economic importance.
- Evaluate the variability of species that have gone unnoticed and that may have economic importance.
- Increase research on vegetative propagation, with emphasis on species threatened with extinction of genotypes.
- Establish forest "gene banks" in countries where each important species is native to preserve trees of superior qualities.

A primary objective of tree-improvement research in tropical countries should be the conservation of germplasm in both natural populations and gene banks (Brune and Melchior 1976). To accomplish this, conservation of gene resources must become an integral part of forest-management planning and practice (Roche 1975). Conservation "in situ" is ideal, with protection extended to all distinct tropical ecosystems. Conserved gene sources should be used for research and for demonstration of their values.

Because the potential areas in the Tropics to be dedicated to forest production are large, even small genetic improvements may significantly increase social benefits, land values, and raw material production (fig. 9–6; Namkoong and others 1980).

A key feature of breeding is the recurrent and cumulative nature of genetic improvement (Namkoong and others 1980). Many generations of gain can be achieved and yields increased beyond the extremes of the present population. Gains in value as great as 30 percent have been made in the first generation of selection.

Genetic improvement of forest trees begins with the study of the external appearance of each individual (its phenotype) and seeks to enhance this appearance through manipulation of inherent (or genotypic) qualities. Because of the long life of trees and their repeated seed crops or regrowth of vegetative material, opportunities for multiplication of desirable characters are greater than for shorter lived plants. Also, genetic tree improvements, once achieved, are inexpensive to maintain (Larsen 1956).

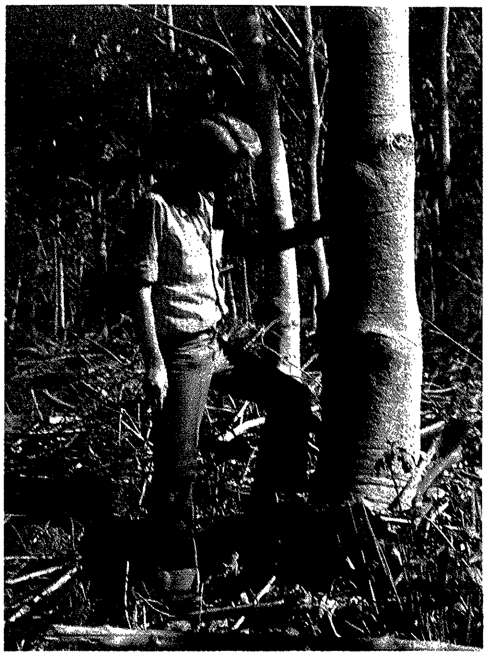


Figure 9–6.—*The exceptional growth of the 4-year-old* Gmelina arborea *at Jari, Brazil, is an example of the prospective sources of genetic improvement of tropical trees through modern research.*

The natural variation displayed by most tropical species over their geographic ranges indicates the genetic variation that can be released by breeding (Namkoong and others 1980). The problems lie in the limited ability to observe variation, difficulties in recognizing gene combinations that may become useful only as requirements change, and the dangers of loss of variation through forest destruction.

Expected genetic improvement depends on the "selection differential," or the difference between the mean of a trait in the selected individuals and the population mean. If more than one trait is selected, the differential is reduced greatly for each trait that may be added (Shelbourne 1973).

Ideally, tree improvement should be limited to species that have been evaluated over a full rotation, at least in trial plots with not less than 100 ha of stands of good provenance (Shelbourne 1973). Wherever possible, the selection index should combine information on the economic importance of each trait and the expected prospects for changing each trait by genetic selection. Usually, an educated guess must be made at the outset.

Provenance variations in *P. taeda* and *P. elliottii* have both adaptive and nonadaptive significance (Burley 1966). Some are random, but most are clinal, relative to latitude and longitude. However, conclusions based on early observations may be contradicted later; so, long-term observations are needed.

By itself, higher yield is not an adequate tree-improvement objective. Wood quality must be accepted as a criterion for selection as are form and branching (Hughes 1973). Selection must also be related to performance on specified sites. On soils of marginal or better suitability for agriculture, only high tree productivity can succeed. Elsewhere, tolerance of soil poverty is important. Genotypes must be developed that have acceptable productivity with minimum fertilizer and yet do not lead to soil deterioration (Bevege 1976). A wide genetic base must also be maintained for continuing selection.

Cost increases for petroleum have suggested that genetics research should be directed toward low-input, multiuse, extensive agroecosystems to supplant high-input, intensive agriculture (Duke 1981). This would call for a pooling of genes best adapted to marginal environments. The goal of such efforts would not be single-product yields in monocultural situations but multiple yields in multitiered, intercropped agroecosystems. Prospective practices include the use of tolerant germplasm, intercropping, return of residues, biological pest control, and full utilization of yields (Duke 1981).

Cost is critical in tree-improvement research. Despite the promise of higher yields and quality, the necessary research calls for highly specialized scientists and long-term experimentation. Efforts must be made to keep costs moderate and to produce early results. Some possible ways to save include the following (Carlisle and Teich 1975):

- Determining the minimum level of sampling needed to represent natural genetic variation
- Determining the minimum period that tests must be exposed to climatic variation
- Rationally weighting yield and timber quality
- Predicting adult performance from early observations
- Exploiting the full potential of vegetative propagation.

In the Tropics, most of the fundamental information about differentials is not available and must be presumed from experience with similar species in the Temperate Zone. Nevertheless, scientists must proceed with tree improvement on many important tropical species. A tally by a panel of FAO experts on forest gene resources indicated that, for tropical America, 43 tree species merited tree-improvement research, and of these, 14 species urgently needed work (Kemp 1974).

Research on tropical tree improvement cannot be expected to prosper purely on an individual or local basis. It can best proceed regionally, with international cooperation. Most tropical tree species occur naturally and are potentially significant in more than one country. Few countries have the resources to support the highly specialized research necessary for tree improvement. International efforts can provide the following (Burley and Kemp 1973):

- Information on the distribution, phenotype variation, and genotype variation throughout the natural range of each tropical species
- Sufficient seeds for all interested countries to establish adequately designed and replicated provenance trials
- Representative gene pools for preservation
- Regionally centralized breeding orchards

Despite the need for regional tree-improvement efforts, final performance assessments are strictly a local responsibility. A test of six teak provenances in India showed after 16 years that local seeds usually produced good results but not necessarily the best; therefore, each provenance had to be tried on each site (Mathauda 1954a). Seeds from moist-site provenances proved superior to seeds from dry areas.

The impact of the local site on tree performance is seen in tests of *P. caribaea hondurensis* from the same provenance but grown in seven countries (Palmer and Tabb 1973). Variation in pulping characteristics of the wood species was so great that quality could be reliably forecast only on the basis of samples from the actual site.

The development of a genetics program for tropical forests typically begins by assessing genetic variations within the most important commercial tree species (Stern and Roche 1974). In countries not well endowed with commercial species, provenances of exotics may be introduced and tested under a variety of conditions. As these trees mature, single-tree selection for desirable characteristics is begun, and progeny are produced either from seeds or vegetatively. However, before selecting from exotic populations, it is highly advantageous to know about the performance of stands approaching rotation age (Goddard 1973). Superior test material is then mass produced. Short-term objectives may be achieved through seed orchards. For longer term objectives, research orchards are needed to conserve a broad genetic base of genotypes that may eventually prove useful. The next phase is a breeding program, which requires a knowledge of reproductive biology of the species based on phenological observations (Bawa 1976).

In the early stages of tree improvement, it is desirable to plant blocks of about 2 ha with each likely candidate species and provenance as a potential early source of seeds (Shelbourne 1973). Once local seed-bearing stands of a good provenance are available, superior seeds may be collected, either from the best individuals throughout the plantations or from a smaller area of exceptional quality thinned to about one-tenth of its original stocking and managed as a seed-production area.

In an analysis of the status of genetics research on tropical pines, Burley (1976) outlined a required orderly sequence of research. The first step is to study variations throughout the natural range and assess provenances in exotic as well as native environments. This phase, for tropical pines as with many other species, calls for international cooperation and coordination. Next, the nature of the breeding systems of each species must be determined. Then, further information must be collected on gene distribution and population structure, usually through studies of pollen and seed dispersal and resultant geographical distributions of genotypes. Methods of evaluating gene pools include provenance and progeny comparisons, analyses of chemical properties, and analyses of genotype interactions with the environment.

Provenance trials go through the same phases as species trials (Burley 1969). The first elimination phase may deal with 50 or more provenances. It is a simple comparison completed at one-fourth to one-half rotation age. Square plots of 1 to 25 trees may be used. The chief criteria are survival and height growth. In the second phase, involving 5 to 10 provenances, plots of 49 to 169 trees are utilized with a 1- to 2-row isolation strip. The proving phase involves replicated plots of 0.5 to 1.0 ha on the major sites in each country. For all stages, the most favored design is the randomized complete block with one plot of each provenance in each replication. Evaluation may be done at 6 months, after each of the first 3 years, and at 3- to 5-year intervals thereafter. Recorded are survival, height, d.b.h., crown width and depth, branch number and angle, uniformity, straightness of stem, and bark thickness.

A major contribution to tropical tree improvement is the "Manual on Species and Provenance Research" compiled by Burley and Wood (1976) from contributions by various scientists. The description that follows is adapted from this source.

Three natural types of variations result in differences among individuals of the same species. One is genetic and heritable, such as the number of stamens. Another is environmentally induced and commonly includes local variations in leaf size. The third may be termed developmental and is illustrated by the differences between juvenile tree leaves and those of mature specimens.

Seeds are frequently collected to improve the population or compare provenances. Careful choice of select phenotypes can greatly benefit population improvement. For representative samples of provenances, however, intensive selection is not appropriate. Likewise, collections to conserve a broad representation of genes must come from a large number of trees.

Selecting stands for provenance testing calls for at least five or six collection sites so that both the limits and the center of the geographical range can be sampled. When the approximate location of collection sites has been determined, specific stands must be selected that are representative and large enough to provide good samples. Within each, collections should be made from not less than 25 trees. Taking additional trees is a small added cost after site selection, access, and all other costs are considered. Tree selection might well be random, except that this is usually inconvenient and does not exclude diseased or deformed individuals; therefore, some subjectivity is desirable. With widely scattered tree species, it may be possible to collect from most of the trees and even then have a small number of samples. To the degree possible, the same number of seeds should be collected from each tree. Absolute certainty as to the seeds' origins is essential; so, each lot must be tagged as to site and possibly also as to tree number.

In the design of experiments to compare provenances, five possible sources of variation must be recognized. These are as follows:

1. Controlled genetic differences between the populations being compared
2. Controlled environmental differences within a site or between two or more experimental sites
3. Uncontrolled genetic variation among the experimental plants and between those plants and the population they represent
4. Uncontrolled environmental variations from plot to plot or tree to tree as a result of differences in soil, microclimate, aspect, etc., including some differences that cannot be assessed
5. Experimental error resulting from random variations within plants, errors in locating provenances within the plots, and inaccuracies in assessing and recording data.

Some pros and cons of common provenance test designs are summarized in table 9–6 (Wright and Andrew 1976).

If the trees selected for seed collection are too young, their characteristics may not indicate their later performance or quality. For pines in the Southern United States, trees that would have superior height and diameter at age 30 could not be identified with much certainty before age 20 or at the very least age 15 (Wakeley 1971).

Agroforestry

A strong appeal for mixed cropping and its social as well as physical benefits in the Tropics has been made by Igbozurique (1971): "Yield is not the only index of agricultural efficiency, but it is hardly debatable that a system which fares so well without the astounding technological material of Anglo-American agriculture, the vast manpower inputs of Oriental agriculture or the coercive sociology of Soviet agriculture is worthy of intensive study. The call is for unstinted research into mixed cropping." Research is needed on the synergistic and antagonistic interactions of crop species in mixtures and their sustainable yields (Duke 1981).

By one estimate (Bene and others 1976), more than half of all the land of the Tropics, although too dry, too steep, or too rocky to be classified as arable, was considered suitable for agroforestry. Although there are few hard data to support this contention, the field is a promising avenue for research (Alvim 1981).

Research in agroforestry requires an integrated approach and is much more complex than conventional field experimentation (Alvim 1981). Interactions between different species are usually site specific, making it difficult to generalize conclusions from isolated studies.

A better balance is needed between research on tree plantations and farm crops in the Tropics (Pelzer 1958). Most of the effort so far has concerned intensifying practice in plantations. Hill cropping has received little scientific attention. If agroforestry is to progress, there must be more research collaboration between foresters and agronomists.

Because agroforestry is commonly expected to replace (or mitigate) the problems of shifting cultivation in the Tropics, Kellogg (1963) suggested that research should begin with quantitative studies of existing systems of shifting cultivation. Many such studies have been done since his recommendation, but their significance is mostly local, and there undoubtedly remain many practices based on long experience that are still little known or understood by the scientific community. An early outline of such studies includes literally hundreds of avenues for research (Conklin 1963). Some of special interest include the following (Newton 1960; Watters 1968a, 1968b, 1968c):

- General considerations—climate, soils, biotic factors, cultural setting, trends
- Burning practices—timing

Table 9–6.—Pros and cons of tree provenance test designs in forestry research

Feature of the experiment	Fully random design	Randomized	
		Complete block	Latin square
Number of replications	Need not be the same for all species	The same for all species	The same for all species
Number of treatments (species and provenances) possible	Unlimited, except that a very large number may lead to much variability	If too many, the advantage of blocks may be lost	Effectively limited to 5 and 10; if less, the layout is intensive; if more, unwieldy
Laying out the trial	Easy	Fairly easy but the blocks are of fixed size and must be carefully made out according to the size	Design is fixed and little flexibility is possible
High variability between plots	No account can be taken of this	Can take care of variation in one or more directions, depending on layout of the blocks	Particularly good if variation is in two directions
Missing plots	No difficulty in analysis	Little difficulty but some loss of efficiency	May entail much loss of efficiency and complex analysis
Residual degrees of freedom	Maximum number available	Number reduced by number of blocks	Number reduced both for rows and columns
Differences in treatment	Whole area must be treated uniformly	Blocks may be treated differently	Whole area must be treated uniformly if two-way effectiveness is not to be reduced

Source: Wright and Andrew 1976.

- Cropping practices—timing, soil preparation, seed preparation, fencing, guarding, weeding, protection from animals, thinning, mulching, manuring, harvesting, storing of crops, secondary cropping
- Fallowing—necessity, preferred vegetation, time ratios, procedures, use of legumes, soil relationships
- Supplementary inorganic fertilizer potentials.

A shift in focus in genetics research is foreseen as a result of increasing attention to agroforestry (Burley 1980b). Contrasts with research on industrial plantations are apparent in the following new considerations:

- The need for a range of agricultural crops and managerial treatments in combination with the tree crop
- Comparisons of a wide range of tree products and uses
- Active communication between scientists and growers
- Testing and conservation of the local adaptation and race development that many agroforestry tree species have already achieved
- Recognition that interactions of tree genotypes with agricultural crops are equally important to those of tree provenances, but more difficult to identify.

Research priorities identified in a workshop in Sri Lanka (Shea and Carlsom 1986) are directed specifically at multipurpose tree species but are of much broader import. Their research objectives and high priority goals and activities are outlined below:

1. Selection, genetic improvement, and conservation of species
   A. Choice of species
   B. Tree breeding and vegetative propagation

2. Nursery, establishment, and tending techniques
   A. Seed collection methods
   B. Site selection methods
   C. Site preparation techniques
   D. Establishment techniques

3. Management systems
   A. Spacing, thinning, and rotation
   B. Water consumption
   C. Tree/crop interface
   D. Shelterbelts
   E. Irrigation systems
   F. Production economics

4. Pest management

5. Maintenance and improvement of soil productivity
   A. Culture and inoculation with N-fixing organisms
   B. Assessment of N-fixing species
   C. Field trials concerning the N cycle and organic matter
   D. Fertilizer experiments

6. Determination of social, economic, and environmental aspects

As scientific information concerning agroforestry possibilities accumulates, there should be a trend toward the testing of systems rather than merely practices.

Chapter 9 has brought together the thinking on tropical forestry research from a large number of sources under different circumstances. Many of the practices described differ for reasons not fully clarified. No intention exists to decide for the reader which of the alternatives described best suits any local need. The variety of experience is presented. It will be up to practitioners to retest and improve on the judgments to date.

Chapter 10
Implementation

The question "Can we manage tropical forests to sustain them?" is frequently asked. Some respondents, either unfamiliar with (or unimpressed by) a century of tropical forestry experience throughout the world, consider our technical knowledge to be grossly inadequate. What is needed, they say, is more research to ascertain objectives, policies, strategies, and the effect of prospective forest management practices on the environment, the people, and the economy of the Tropics before anything is done. While experts may procrastinate, it is fortunate that protection alone can sustain the forests and that it poses no technical challenge. Nevertheless, procrastination may not ensure even protection and certainly will not provide the forest products increasingly needed in the region.

There are also those who believe that an adequate technical basis exists for making the region's forest lands sustainably productive, at least where conditions are favorable. In their view, the task appears to be one of merely getting on with the job, starting with the information already available from experience. The main obstacle they see is a lack of the means or will to proceed.

Whatever the merits of these extreme viewpoints, some aspects of the situation are clear. In 1980 some 21,881,000 ha of the forests of tropical America were already being managed at what may be a sustainable level (Anon. 1985e). These included 14,066,000 ha of forests apparently legally protected from use, 522,000 ha of natural forests so managed that yields can be expected to be sustained, and 7,293,000 ha of forest plantations, also managed as to be sustainable. This total, however, is only 3.2 percent of the total forested land of tropical America, indicating that forests being sustained are few. Furthermore, the forests are diminishing and deteriorating, primarily as a result not of mismanagement, but of no management.

Steps to restore or enrich forests on vast areas where their former protective or productive functions have deteriorated or ceased would seem warranted without fear of irreversible environmental damage. On the contrary, such a course should go a long way toward restoring at least some of the attributes and biota of the tropical environment, even if the structure and composition of the resulting forests differ from the originals.

Closing the wide gap between present practice and full application of forest production technology is one of the most beneficial steps that could be taken in this region. Tree cover on much of tropical America is essential to the water resources upon which the agriculture and the very habitability of the land depend. Improving forest productivity will help fulfill the most pressing need of the region, the supplying of food.

Most of the literature concerning forestry in the Tropics deals with the consequences of technological practices. Little reference is made to the challenge of promoting social acceptance and support for implementing those practices. Lack of widespread support is understandable; in the past, forest products have been available simply for the taking. Sustainability, on the other hand, calls for refraining from depleting the forests that remain and investing in what is seen as a distant future. Difficulties in mobilizing support from communities either distant from or perceived to be only indirectly dependent on forests indicate that implementing technical knowledge can be harder than acquiring it. Yet, depletion of forest resources has continued along past the time when distance and scarcity began to increase the costs of forest products.

Implementing what is known would in itself generate a need to acquire more knowledge, to perfect practices, and to develop new or improved practices. Therefore, emphasis on implementation must not be in lieu of continued research directed toward better management.

Pierre Gourou concluded that the problems of the Tropics are due more to a lag in organizational techniques than to economics (Frisk 1979). By that reasoning, the key to progress is administrative improvement.

Inexperienced administrators tend to mistake planning and decision making for action and achievement (Phillips 1961). Commonly encountered throughout the Tropics is great enthusiasm for industrial development for its own sake. Too few government leaders in the region seem to realize that development in agriculture, forestry, and the related industries is a gradual and intricate undertaking, liable to fail unless based on experience, vision, sound technology, consistent financial support, and of course, full integrity.

The success of forest production depends partly on preventing human activities that threaten forest lands. These threats cannot be met opportunistically; they must be anticipated. Experience suggests a number of circumstances that foster such perils, including: (1) impotent national land-use planning, (2) misguided agrarian reform, (3) unenforced legislation and regulations, (4) underevaluation of indirect forest environmental values, (5) inadequate concern for soil limitations, (6) agronomically neglected small farming, (7) the taking for granted of water supplies, and (8) the perception that forests, once cut over, are worthless.

Eliminating such threats requires the combined efforts of planners, agronomists, foresters, soil experts, hydrologists, government leaders, and the general public. There can be breakthroughs. The Lands Advisory Committee of Trinidad and Tobago, which was composed of cabinet members, at the urging of the head of the Forestry Department, ordered acquisition of the Northern Range as a forest reserve and protection of all reserves from the threat of takeover by powerful petroleum interests (Brooks 1941a). As a consequence, the department has been compensated for petroleum extraction, and productive forestry was intensified on most of the land so reserved.

The sequence of forest policies and practice in the Tropics is similar for most countries and consists of some or all of the following steps (Sartorius and Henle 1968, Wyatt-Smith 1959):

- Exploitation of the best timber from accessible forest areas
- Uncontrolled hunting of game animals in the forests
- Permitting of widespread deforestation for shifting agriculture
- Creation of a forest department governing parks, water, and wildlife
- Initiation of legislation defining national conservation policies and protecting forests and fauna
- Inventorying of forests on a national scale
- Reservation of public forests as a national commitment
- Protection of reserved forests, including control of wood cutters, consumers, and forest cultivators
- Development of incentives for wood production on privately owned land and for wood-processing industries
- Preparation of management (working) plans for regulation of production and orderly disposal of public timber
- Surveying of soils on a national scale and the mapping of land capability
- Biological studies of the forests
- Reservation of forest lands to be left unmodified (some may be national parks)
- Research in ecology, silviculture, and wood utilization
- Intensification of wood production to sustain yields from public forests
- Improvement of wood utilization technology and markets
- Establishment of public outreach programs, administering public recreation and education on public forest lands
- Strengthening of national planning for land use and rural development, fully recognizing uses and benefits derived from forests and related industries.

These steps are only in approximate order and many overlap. Placing public outreach programs near the end does not indicate low priority but rather recognizes that normally the earlier steps so completely occupy the available staff that this important function is delayed until the program matures. Actually, this delay may also postpone some of the earlier steps. Specialists must not presume public privilege based on the importance of their managerial role over extensive public land areas (Ovington 1974). Public acceptance and support of their programs must be actively sought and earned.

These developmental steps emphasize public lands because private forest owners are generally interested only in immediate returns. Moreover, many of the indirect forest benefits are vital to national welfare. Throughout the region, there is little protection of privately owned forests except those clearly bearing a potentially valuable crop.

The first and, historically, probably the most effective forest department in the Tropics was in India (Parker

1923, Qureshi 1968a). As early as 1800, a study of the availability of teak *(Tectona grandis)* was completed. The first conservator of forests was appointed in 1847. A simple but effective national forest policy was enunciated in 1855. By 1871, working plans for the publicly owned forests were in preparation. In 1875, the oldest extant forestry journal of the Tropics, the *Indian Forester,* began publication. Throughout the last half of the century, informal studies in forest botany and wood anatomy were underway. The Forest Research Institute began in 1906, working largely on volume tables, growth, and yield. The first of some 10 All-India Silvicultural Conferences was held in 1918. A survey of the forest types of India and what is now Myanmar was published in 1936, and a section of Forest Ecology was added to the Research Institute in 1948. For decades, the Indian Forest Department generated more revenue than it spent.

In tropical America, early evidence of concern for forests was to be found in the laws of the Spanish Crown, applied to Puerto Rico and the rest of the Spanish West Indies. In the "Ley Primera" of 1513, Ferdinand V offered land with the proviso that part of it be planted to trees (Peyton and Peters 1912). In 1824, the government of Puerto Rico required the leaving of trees growing along streams (Ramos 1866). A forest law was issued by the Crown in 1843 (Rodriguez San Pedro 1865). In 1860, a Forest Department was created, and in 1876, public forests were reserved (Anon. 1907). Between then and the end of the century, the disposal of timber from public lands was by permit, and royalties were collected according to tree species and volume.

The appreciation of forests by the city of Veracruz, Mexico, led, as early as 1890, to the plantations of *Casuarina* that have stabilized the sand dunes north of the city (Quevedo 1945). Forest, water, wildlife, or park departments concerned with the forest goods and services now exist in nearly every independent political unit within the region. Some of the first departments established are still in existence, including those begun in Trinidad in 1901 (Swabey 1932), Puerto Rico in 1917 (Wadsworth 1949), British Honduras (now Belize) in 1922 (Oliphant 1925), and Jamaica in 1937 (Swabey 1945). Advancements in the region have been made in all 18 of the developmental stages described earlier.

The Forces Behind Implementation

Implementation of forest technology requires the support of both people living near the forests and people living in distant population centers. Unfortunately, decision making tends to be concentrated at a great distance from the forests, where people are least likely to see a critical link between technology, forests, and their lives.

Those most obviously involved are the "forest people" who live within or adjacent to the forests and who directly depend on them for shelter, fuel, food, implements, and transportation. An attempt to convince these people that they need forests is a redundancy that could occur only to a rank outsider. Not only are forest people intensely aware of the role of the forests in their lives, but they also may be better aware than anyone else of the degree to which the resource is deteriorating and why. These are outdoor people who know the forests and their uses well.

Forest people are capable of undertaking the work needed to make the forests produce in perpetuity (and could use the employment), and their proximity makes them ideal candidates for such work. Where outside leadership and support have been available, these people have implemented nearly all the forest-management practices of the region.

Another distinct group, also rural, lives in farming centers concerned with processing and distributing other products of the land. These people may farm coastal or irrigated lands distant from forests. However, the presence of upland forests may protect their lands from floods or sedimentation even though they are less dependent on the forests for fuel or food than the forest people. Some of these farming communities have cooperated in common resource needs, such as the allocation and distribution of irrigation water, the construction of reservoirs, and the provision of community services.

City dwellers are generally oblivious to the importance of forests to their welfare, except in areas where a large volume of forest products is processed or exported, where tourism in forest areas is important, or where domestic water must be brought a long distance. Nevertheless, these people should be concerned about the fate of the forests and may have the financial resources to do something about it. City residents have the income, leisure, and work-related stress that makes them look to forests for respite and enjoyment. They also have the purchasing power to pay the highest domestic prices for the more prized forest products. These people are also conditioned to paying taxes for such long-term social benefits as libraries, municipal reservoirs, and parks. Forests could also benefit from such enlightened support.

The Government's Role. Democratic national governments theoretically represent all of these diverse populations and are concerned with aspects of national welfare that are not better provided at local levels. These include the widespread distribution and benefits of forests within each country, the need to forego maximum short-term benefits for greater long-term benefits, and the difficulty of amassing adequate financial and personal resources at local or regional levels for highly specialized activities. For these reasons, forestry leadership for most tropical countries must rest at the national level.

At the national level, goals, policies, plans, and programs are formulated, funds or assistance is allotted to regions where the need is beyond local capability, incentives to forest landowners and processors of forest products are offered, specialized training may be available, and forestry contributions from international donors are received and administered. All forestry practices need not emanate from the national government, but other agencies of implementation are clearly impaired without an effective forestry program at the national level. The strengthening of national institutions is thus a key to the continuity of effort that attracts outside assistance.

Government has an interest in implementing forestry, because its indirect and noncommodity values are of major importance to the public. One of these values is sustained timber yields. Another is water quality for the population's domestic needs. In some countries, such as Mexico, legally formalized rural communities (ejidos) have proved receptive to management practices that both perpetuate timber supplies and preserve other forest benefits. Governments more remote from the forest areas also have much to gain from stabilized or increased employment, water resources, and tourism.

National governments are now all somewhat sensitive to forest problems and needs. Some are responsible for major water storage and transportation projects, and they discern potential international benefits from forests, such as tourism, export products, and the substitution of local forest products for more costly imports.

The Public's Role. The average citizen is largely concerned with maintaining or bettering his or her standard of living. Any ideas about forests (if indeed they exist) are concerned only with how the forests directly affect one's own way of life. Such a narrow perception suggests the most effective approach to implementation: convince the citizens that their way of life depends in part on forests that must be conserved. This tie is equally valid for every group: farmers, landowners, community leaders, industrialists, and educators.

Primary responsibility for focusing public attention on the needs of forest production lies with professionals who understand and can explain human dependence upon forest resources and the actions needed to conserve them. Such talent is better developed in some forestry curricula than in others. Nevertheless, weaknesses in both technical knowledge and persuasiveness on the part of foresters have been major obstacles to progress.

It is increasingly apparent that other disciplines must be involved in implementing good stewardship of tropical forest resources. A multidisciplinary approach is needed largely because forest benefits are manifested in diverse ways. An example is water conservation as a component of agriculture. In the past, agronomists have been largely responsible for developing forestry in many countries of the region. Others who must participate include ecologists, hydrologists, and social scientists, who could develop more effective ways to demonstrate interdependencies and improve persuasiveness.

Private individuals and organizations, especially forest landowners and forest products processers, have played a dominant role in the deterioration of forest resources in the region and so must be vital participants in implementing good management. Therefore, they are prime targets for persuasion. They are most responsive to economic incentives, a key therefore to the success or failure of forest conservation in much of the region.

Outside Assistance. Local resources to be used in implementing forest conservation and management tend to be least available where the consequences of the mistreatment of the forests are most tragic. This fact has led to more than a century of efforts by extratropical governments and multinational organizations to assist in implementing forestry in the Tropics. Such outside donors have frequently increased initial investments for forestry manyfold, and they are in a nonpartisan position to influence priorities. Their financial resources solve a great local problem: the shortage of investment capital. However, many forestry projects undertaken with outside assistance have fallen short of expectations. The reasons, more social than technical, are complex.

A summary of investments by multinational and unilateral donors in projects involving forestry between the late 1960s and 1985 totaled $US 400 million (Spears 1985). Although only about 1 percent of this amount was assigned directly to forestry, the contributions of outside donors, including nongovernmental organizations, are a major supplement to the investments of developing countries for this purpose. The "nonforest" portion of this investment has gone largely into land-use planning, watershed rehabilitation, rural development, and integrated agriculture.

International assistance is fraught with pitfalls. Despite good intentions by both donors and recipients, there are several obstacles to achieving what both parties may intend. Uncompromising policies by the donor may ultimately lead to the accusation of outside interference in the affairs of a sovereign nation. External concepts that usually do not fully reflect the situation on the ground may prove inapplicable even where accepted.

Outside assistance is frequently implemented through one or more counterpart agencies of the recipient government. This can produce horizontal imbalance and interagency rivalries that obstruct coordinated utilization of what is offered. Then there is the prospect of vertical imbalance, the ratio of expenditures for administration versus those that reach the forest.

Local governments often differ from donors in their degree of emphasis on assisting the rural poor. Lack of synergy between outside "experts" of the donor and local professionals is another potential problem. Finally, and perhaps most important, is the lack almost everywhere of coordination among donors.

Donors have been aware of these problems, and a mechanism was developed to foster voluntary coordination (Harcharik 1986). At a meeting of 20 donating governments and agencies in 1985, agreement was reached to cooperate in implementing the Tropical Forestry Action Plan under the aegis of the Food and Agriculture Organization (FAO) in cooperation with each government. Subsequent meetings have been productive, and moves have been taken to include nongovernment organizations, where a lack of coordination has also been evident. Recent critical assessments suggest that much improvement is still possible, particularly in increased local participation in the generation of plans and in more comprehensive consideration of environmental problems as a whole.

Roche described some of the problems of international assistance as experienced in Africa (Roche 1986). As he saw it, developing nations draw up a list of projects and sell what they can to donors. Outside support tends to flow into an elitist structure rather than to the mass of the people. Roche concludes that until agricultural production by the masses is seen to be as important as mass agricultural production, and until western nations are prepared to forego some of their selfish interests, there can be no major improvement in the present system despite the incidence of famine and the generosity of donors.

Similar conclusions regarding tropical America were reached by Mery (1987). He concluded that most of the constraints affecting the forest sector have their roots in the socioeconomic structural problems of Latin American societies. A significant change in the contribution made by forestry to the general welfare cannot take place without a more general change in these societies. Structural changes that secure long-term interests must prevail over those that favor short-term interests. Such changes must aim at reducing present inequalities, allow the spread of benefits obtained from economic growth, overcome dependence on transnational corporations with goals that are often distinct from those of the nations, and permit the implementation of policies aimed at stopping uncontrolled deforestation and promoting sustained use of forest resources.

The mounting criticism of international assistance programs as causes of forest destruction led the United States Congress to legally sharpen the focus of assistance to developing countries by resolving to do the following (Anon. 1986f):

- Support and cooperate with others in identifying, establishing, and maintaining a network of protected tropical forest ecosystems.

- Conserve remaining forests by supporting forest production on lands already cleared.

- Support training, education, and institutions that increase the local capacity to formulate policies, plan land use, and develop and apply environmentally sound forest management.

- Support stable farming in areas that are already cleared or that will inevitably be settled, using locally suited technologies, including agroforestry.

As an example of the adaption of donor interests to international assistance, the Canadian International Development Research Centre, in channeling funds to institutions in developing countries for the development of research, has applied the following criteria, among others, in assessing projects (Anon. 1986h):

- Are the research findings likely to apply in most developing countries or only in the one in which the research takes place?
- Will the research help close gaps in living standards or lessen the imbalance in development between rural and urban areas?
- Will the project make full use of local resources and research workers from the region?
- Will the project result in better trained and more experienced local scientists and more effective research institutions?

The Brundland Report of 1987, addressing world environmental problems, called for more effective international efforts to support national conservation strategies, biosphere reserves, and the Tropical Forestry Action Plan (Anon. 1987b). The report singled out the need for national forestry planning, enhanced cooperation among development agencies in forestry, and an increased flow of technical and financial resources into forestry and such related fields as small-holder agriculture.

Some Long-Term Goals

Global efforts to prioritize problems of tropical forestry and goals and strategies for their solution have been reported in documents from multinational agencies. In 1980, the United Nations Environmental Program and the International Union for Conservation of Nature and Natural Resources, with assistance from the World Wildlife Fund (Anon. 1980h), released "World Conservation Strategy," a document that went a long way toward closing a previous rift between environmental concerns and forest-management agencies. It defined conservation as the management of human use of the biosphere to yield the greatest sustainable benefit to present generations while maintaining its potential to meet the needs and aspirations of future generations. The level of sustained yield is considered an index of its achievement. Integration of multiple forest uses is supported, and the potential for making some uses compatible under good management is recognized. The International Union for Conservation of Nature (IUCN) recommendations that are essential to forestry in the Tropics include the following:

- Nations should form conservation strategies, meet their requirements, and raise public consciousness concerning them.
- Such strategies should be formulated for the protection of watersheds and mangroves, and for the restoration of degraded environments, including reforestation.
- Government agencies should be given clear conservation mandates and the power and funds for implementation.
- Nations should ensure that laws are both economically and socially feasible to provide for protection and sustainable utilization of resources.
- Conservation education should be intensified at all levels.
- Conservation efforts should be prioritized to make the best use of available funds.
- Conservation measures that require deferral of consumption should be complemented by measures to maintain or improve living standards.
- More subtropical rain forests should be placed in biosphere reserves.
- Resource uses should be compatible with ecosystem capacities and in harmony with each other.
- Lands most suitable for food crops should be reserved for agricultural use.
- Existing information about resource management should be put to use and more information gathered.
- Rural communities should adapt new production systems that are known to work.
- More research should be dedicated to sustainable production systems.

- The economic (and other) benefits of the well-planned, multipurpose use of rain forests should be demonstrated.

- Tropical forests should be managed to yield increased goods and services if production can be sustained without damage to the resource.

- The productive capacities of forests should be determined as a prerequisite to determining sustainable yields.

- The utilization of forest goods and services should be efficient and ecologically sound.

- Governments should control logging operations and assist settlers to develop land that is suitable for planting trees and other crops.

- Diverse gene pools should be preserved to sustain improved forest production.

- Plantations should be established to produce fuelwood and industrial timber.

More specifically directed at forests of the Tropics is the Tropical Forestry Action Plan of the FAO's Committee on Forest Development in the Tropics (Anon. 1985e). The committee, representing 45 countries, convened a meeting of specialists who recommended action in five priority areas: ecosystem conservation, land use, energy development, industrial development, and institutions. The proposed goals are summarized here.

- *Ecosystem conservation*
  - —Select and establish a series of protected areas covering the whole range of tropical ecosystems and the genetic resources of species of actual or potential socioeconomic value.
  - —Guarantee the permanence of existing and future protected areas by improving legislation and administrative policy to that end.
  - —Expand the concepts of conservation policy and management to include maintenance of the intraspecific variation of species of actual or potential socioeconomic importance; conserve, where possible, the variation of other species whose qualities are not known.
  - —Develop closer links between policies for the conservation of ecosystems and genetic resources and policies for the recovery of natural vegetation to provide protection for soil and catchment areas.
  - —Treat protected areas as part of the land-use pattern that surrounds them; design and operate these areas in such a way that they are acceptable to local people and benefit them.
  - —Adapt silvicultural methods for unmanaged forests to enable them to produce wood, food, and other nonwood products in a sustainable manner.

- *Land Use*
  - —Create political and public awareness of the contribution of forestry to the sustained use of the resource and to minimizing damage and degradation to food security and rural development caused by desertification, floods, droughts, torrents, cyclones, and high tides.
  - —Ensure that forestry is made a vital part of national plans involving food security, conservation, and prevention of desertification.
  - —Enhance the role of forests and woody vegetation within sound land husbandry to ensure that the whole system will contribute effectively to the production of goods and services and to the wider aim of food security.
  - —Enhance public benefits from appropriate use of the forest resources by involving the community in their expansion, diversification, management, conservation, and rehabilitation.

- *Energy Development*
  - —Raise political awareness, encourage sustained commitment and support of wood energy programs, and adapt and strengthen the responsible institutions.
  - —Promote coordinated policies and programs defining priorities for wood energy in national forestry planning, and encourage the collection of information required for sound planning for resources and for the production and use of wood for energy.
  - —Develop and disseminate approaches that integrate environmental, social, economic, and technical aspects of energy development, and promote more efficient technologies and cost-effective solutions to energy problems.
  - —Mobilize national and international technical and financial assistance to build up capabilities and meet the requirements of large-scale wood energy programs.

  - —Encourage the active participation of rural communities and local organizations in the design, implementation, and distribution of benefits of fuelwood/wood-energy programs and strengthen the communities' capabilities to undertake and sustain self-help initiatives.
  - —Promote international and regional cooperation in research, development, demonstration, and training in new developments and successful approaches to energy problems.

- *Industrial Development*
  - —Create awareness of the need for holistic forest industries, integrated from the resource development and management stage through harvesting, transport, and processing to marketing.
  - —Create awareness of the social, legal, and institutional aspects of planning and implementing forest-industry projects.
  - —Improve managerial capability for resource management, for planning, construction, and operation of forest industries, and for raw-material harvesting operations.
  - —Provide vocational training in raw-material procurement and forest industries.
  - —Establish forest industries that are appropriate for tropical conditions and developmental objectives.

- *Institutions*
  - —Integrate forestry development into national development.
  - —Increase human capabilities in forestry and promote support for forestry development.
  - —Improve the administration of tropical forest lands through appropriate utilization of institutional support.
  - —Ensure active participation of all institutions and social sectors with a view to making forestry development technically efficient, productive, and socially effective.

Most of these goals are social in nature and call for effective communication as much as they do the development and application of management practices to make forest resources contribute more goods and services.

The task of augmenting forest productivity in tropical America so exceeds the funding to be expected that misdirected efforts are tragic. A starting point for minimizing such losses is to focus efforts on long-term goals subject to general agreement. Examples of goals that might apply at national levels are:

- *Keep tree-covered rural lands that are incapable of sustained production of food or forage crops but capable of producing forests.*

This goal calls for classifying lands according to slope, soil erodibility, and potential productivity. It does not dictate land ownership, although the land-use constraints implicitly call for controls that must be attained through government action.

The use of the term "rural" recognizes the traditionally dominant importance attached to urban, industrial, and commercial development, and the need for forested areas to be accommodated thereto. However, in rural areas, this goal calls for more forests than result from merely abandoning submarginal farmlands. Provision must be made, however, for shifting cultivation if it can be sustained by forest fallows and if adequate fallows are ensured.

- *Utilize forests concurrently for a broad range of purposes, both social and economic.*

This objective recognizes the diverse benefits and products of tropical forests, including water, recreation, and wildlife, as well as timber. The requirement of a "broad range" implies that conflicting uses must be governed by constraints on one or all as to location or intensity of use. Fragile resource values, such as primary ecosystems or habitats for unique fauna, must be sheltered from uses that could damage them.

- *Reserve a public forest estate, composed of representative forests, to preserve national diversity, demonstrate progressive forest management, and, through research, develop better techniques to protect, restore, and manage forests and their resources.*

Implicit in this goal may be a program of public land acquisition and protection, followed by investments in management, investigation of better techniques, and an extension program for other forest landowners and forest products processors. Despite the importance of this goal, governments generally retain but a small proportion of the forest lands dedicated to commercial production.

- *Promote rational, private, forest enterprises to meet the needs for forest products—local, national, and international.*

Fundamental to this goal is the assumption that forest enterprises should be largely private rather than public. The government role here is to offer incentives and, where necessary, establish controls. Specific goals include sustainable raw material supplies, improved utilization and processing, better marketing, trade promotion, and effective labor-management relations.

- *Develop public appreciation of forests and forestry.*

This is a prerequisite to good management by private enterprises but, more importantly, to public support for the conservation of tropical forest land resources. The task is largely one for the government, working with appropriate informational and educational institutions. Local school and university curricula to these ends are being expanded.

- *Base forestry policies and practices on scientific research.*

This goal implies development and maintenance of one or more scientific institutions focused on solving a nation's forestry problems. Research institutions need not all be within the national territory, because regional research programs may adequately address some of the priority problems. Training of professional forestry scientists and providing for adequate and stable support for their work are prerequisites to effective research but are absent in many tropical countries. Government support is generally vital.

These goals are general and applicable to most countries of the region. For local adoption, however, more specific language is needed, and a timetable should accompany each goal. These goals could well be adopted in preambles to legislation or in a government proclamation, against which future forestry proposals, support, and progress could be assessed.

Strategies

Identifying long-term goals is an important first step toward implementing forest practices, but it is only that. Many studies to foster implementation of these goals have been made throughout the region, but results have been so general that little that appears concrete, feasible, or attractive to decision makers has resulted. So the next step is to develop strategies to prepare the way for realistic progress toward the goals.

Before strategy for better forest management is actually planned, opinions should be sought from the different sectors of the public that will be affected or must support what may be proposed. Forestry often calls for limitations on present forest use that may conflict with the interests of either those accustomed to using the forests at will or those who profit from forest exploitation. Moreover, the social rewards of forestry are not immediate and appear only gradually, so public attitudes may range from lack of interest to hostility. In India, for example, where strong forest policies and a well-organized forest department have existed for a century and the more remote forests have been maintained in fairly good condition despite severe population pressure, foresters have been blamed for the deterioration of 24.5 million ha of village forests over which they have had no authority (Tiwari 1983).

Public attitudes such as these may be partly a matter of ignorance, but usually the causes go much deeper and require a thorough analysis in planning future public support for forestry. A favorable corollary to such situations is that soil and water resource deterioration is recognized as serious and its relationship to forests has become common knowledge. If the forest department is blamed, the reasons must be understood clearly. Part of the blame may be properly placed, but more often many other factors are involved, such as overall governmental weakness, bickering among government agencies, or grievances of individuals. Unless the underlying causes are identified and fully understood, efforts to sustain forests may be frustrated. The analysis and interpretation of such situations call for the application of sociological disciplines that in the past have incorrectly been considered remote from forestry.

A fundamental argument underlying the strategy for the preservation of tropical forests is presented by Westoby (1983a). He believes that local pressures on the forests by landless people can be reduced only with greater equity in access to land and other resources. He concludes that technologies adapted to the sustained use of tropical forests are unlikely either to be developed or to find widespread application until the rural poor have won both a stake in the land and a share of political power. So the key to saving the tropical forests is political. Catinot (1984) reached the same conclusion regarding tropical Africa, recommending using the very rural dwellers who have been the principal agents of destruction to reforest and giving them a majority ownership in the new stands.

Several such strategies are appropriate generally within the region.

- *For Further Planning*
  - Determine the most pressing needs of specific groups, particularly in rural areas and near forest lands.
  - Integrate forest resource conservation into national land-use planning and agrarian reform.
  - Identify and quantify local nonmarket and offsite benefits, present and potential, of forest land resources.
- *For Rural Development*
  - Quantify forestry benefits to rural development, including watershed protection, food security, and employment.
  - Stabilize rural land tenure.
  - Stimulate rural investment in tree growing.
  - Promote tree production with multiple benefits.
  - Develop alternative sources of off-farm income.
- *For Forest Land Resources*
  - Assess the relative potential of different forest areas to produce products and benefits as guidance for location priorities.
  - Prevent deterioration of remaining forests.
  - Intensify the management and development of existing forest land resources.
- *For Wood Supply*
  - Reduce wastes in the forests and during processing, including the development of new uses for forests and processing residues.
  - Concentrate wood production in plantations to ease current wood demand on remaining native forests.
  - Increase processing near the forests to raise living standards in and near the forests.

Principles for Achieving Success

There are different approaches to all these strategies. Many have failed miserably, usually at least partly because of faulty approaches or execution. A few have been successful. Listed here are some approaches that have proven merit:

- Strengthen and link the national institutions responsible for leadership, whether their function is stewardship, information dissemination, or research.

- Identify and consider local circumstances that may not be obvious before a course of action is prescribed.

- Involve affected local groups, be they small communities or isolated rural people, in forestry matters from the outset.

- Strengthen local expertise at the professional, managerial, and technical levels before attempting to implement plans.

- Do not propose departures from tradition beyond that proven acceptable in other activities.

- Do not begin programs on a scale that will overtax the local system, calling for more trained personnel or other scarce resources than can be promptly provided without more than compensatory costs to other important community needs.

- Develop a link between research, demonstration, extension, training, and education. Without such links, programs generally fall far short of their potential.

- Maintain open communication and continuing publicity directed toward key audiences, such as decision makers or youth, focusing on themes designed to mold opinion and persuade rather than merely inform.

- Make sure that rewards to forestry personnel are attractive and closely linked with responsibilities and accomplishments on the job.

- Establish working conditions that are sufficiently favorable and stable to develop deep career involvement in employees.

- Establish an ongoing training program, conducted by experts, and timed to precede promotion opportunities.

The crucial role of national institutions is illustrated by the experience of the World Bank (Spears 1985). Such external agencies can, at best, contribute only minimally to the solutions of long-term deforestation problems. Outside aid may create an infrastructure and institutions to begin forestry programs, but such investment decreases as soon as a combination of government effort, political commitment, and private investment has elicited favorable responses from farmers, communities, and private enterprises for self-sustaining programs. Moreover, the notion that forestry yields low rates of return (because of the long time needed for trees to mature) is contrary to experience (Spears 1985). In fact, some agroforestry and environmental protection projects have yielded higher rates of return than those of industrial forestry projects (15 to 30 percent versus 10 to 15 percent).

The record in Latin America strongly supports such governmental incentives as shared payments, tax relief, or credit for forest planting (Romero Pastor 1983). In Peru, without such incentives forest planting from 1964 to 1981 averaged only 62 km^2 annually, whereas in Brazil, with such incentives, the corresponding average was 305 km^2.

Overcoming Resistance

Resistance to intensified forest production is motivated by diverse circumstances. Some objections may be purely emotional and cannot be allayed simply by presentation of the facts. In such cases, it is crucial to understand the underlying reasons and search for an acceptable middleground until the benefits of the proposed practice (which may have to be curtailed or postponed for purposes of agreement) become so evident (if they do!) that emotional opposition becomes patently untenable.

One pervasive opposing viewpoint on timber production (and especially harvesting) nowadays is founded on what is perceived as "environmental damage." Presumably, however, timber production can be environmentally sound. But if proposed forest practices can be shown to be ecologically unsound, they should be modified forthrightly by their proponents, not as a defensive action under duress of heated controversy.

Usually, such controversies are not rapidly and peacefully settled, because opponents (and proponents!) may have a distorted perception of the proposal's consequences, greatly exaggerating its environmental effects, all in the absence of conclusive evidence. Here, the soundest course may involve one or more of the following actions:

- Incorporate in advance as many suggestions as possible (such as these) into any proposal that appears potentially controversial.
- Use a diverse team to review proposals to seek a balanced consensus rather than an individual judgment.
- Bring in genuine experts to advise on the validity of opposing viewpoints and accept their counsel.
- Sharpen evidence of intangible values or financial returns to answer critics who begrudge the use of funds for the proposal.
- Readily omit controversial aspects of a proposal that do not jeopardize its overall result. An example here might be to accept less land for timber production or lower yields to accommodate integration of other values into management.
- Reduce the proposal's scope so that any controversial consequences can be assessed on a small scale.
- Reduce the proposal's time period, so fewer steps are contemplated before early consequences can be assessed.
- Incorporate monitoring features in the proposal to allay fears of undetected, irreversible, environmental damage.
- Incorporate concurrent or prior research precisely to clarify controversial issues in advance of large-scale application.
- Appoint a diverse team to oversee the proposal as the work is undertaken, to sense unforeseen problems, and to counsel on the issues of concern; plan to publish both good and bad reports, and take guidance therefrom.

Effective Organization

Institutions concerned with implementing forestry technology, be they governmental or private, must have the following characteristics to endure and be effective:

- A clearly defined mission with a widely supported purpose
- The legal authority to make decisions and the resources to take action
- Continuing counsel from those served and responsiveness to needed changes
- Program orientation defined by long-range planning goals and short-range strategies
- Differentiation of line authority (directing programs and personnel) and staff authority (evaluating and recommending policies, programs, and procedures)
- Staff performance that presents solutions, rather than problems, to those with line authority
- Clear and prompt internal transmittal of policies, information, instructions, and feedback between management and those who execute the plan
- Systematic coordination of the functions required to achieve objectives and organization for efficient work performance
- Sharing of authority and responsibility for decisions and accomplishment through delegation to the lowest level consistent with effective managerial control
- Capability to ensure timely accomplishment of objectives
- No more than eight subordinates per supervisor
- Employees with but a single supervisor and supervision directed solely at immediate subordinates.

Personal Commitment

Conservation of the tropical forests is of overriding importance. The fate of society itself may depend on it. It is a difficult task calling for long-term dedication. The values at stake, when fully understood, should inspire great personal commitment on the part of those who may become responsible. This strong incentive for involvement, diligence, and extra effort can best be instilled in public employees at the time of (and shortly after) their recruitment.

Forestry work in tropical areas will continue to be directed largely by employees of institutions such as governments and large nongovernment agencies. Such employment, to be effective, carries certain responsibilities involving ethics, laws, loyalty, and knowledge of the governing regulations and an intent to execute them.

Some Successes

Industrial Production in Brazil. *Eucalyptus* plantations were established in Brazil on a large scale in 1910, and in 1966, a successful forestry incentive program was instituted that allowed a generous portion of Federal income taxes to be used for certain forestry activities. This program is chiefly responsible for 2.2 million ha of industrial and fuelwood plantations in the southern part of the country. More than a quarter of the national industrial wood requirement has now been met from plantations, nearly all in private ownership (Anon. 1981f).

One of the most spectacular planting enterprises in Brazil is at Aracruz near Victoria in the states of Espiritu Santo and Bahia (Spears 1985). Planting of 60,000 ha of *Eucalyptus* was undertaken and supported by a strong companion research program (12 percent of the recent budget), emphasizing tree improvement, pathology, entomology, soils, and nutrition. Success in vegetative propagation led to commercial clonal plantations in 1979. Average yields have been increased from 33 to 70 cubic meters per hectare per year with an increase of 25 percent in wood density and 23 percent in cellulose content.

Fuelwood in Haiti. A reforestation project in Haiti, sponsored primarily by the United States Agency for International Development and conducted by numerous independent agencies, has focused on alleviating soil erosion and fuelwood shortages caused by excessive tree cutting, while enabling farmers to earn an income growing trees (Anon. 1986e). The trees used are fast growing, producing fuelwood or poles in 2 to 3 years. Regeneration is by coppice, so replanting is not necessary. In the first 5 years, some 20 million seedlings were planted by 110,000 farmers. The key to the project's success was the motivation of farmers to accept and care for seedlings on their own property. Some 73 Haitian voluntary organizations and missions participated in the operation of 22 local nurseries.

Multipurpose Trees in Costa Rica. The Centro Agronomico Tropical de Investigaciones y Ensenanza (CATIE) in Costa Rica has been testing innovative ways to introduce trees into small-holder production systems (Spears 1985). At Pedades Norte, the organization persuaded 900 farmers to plant some 50,000 trees as "live fences," as windbreaks, and for shade. Farmers proved quick to introduce trees into their farming systems, mainly for their own use but also for the market.

Pilot Project in Mexico. Sixteen rural communities (18,000 people) in southeastern Mexico were conceded 360,000 ha, of which they selected 150,000 ha of fairly good natural forest to remain permanently forested (Bruenig and Poker 1989, Santos 1991). The area was inventoried and a management system implemented with a specific rotation and an annual cutting area of 5,000 to 6,000 ha. Enrichment planting was tested. Participants used technical assistance and government credit to acquire logging equipment. Both the most valuable species, such as mahogany *(S. macrophylla)* and cedar *(Cedrela odorata),* and secondary species are being harvested. The communities have constructed two carpentry shops and train carpenters to increase wood utilization. Several of the communities formed a joint council as an authority for collective decision making. Technical support for research and training has been provided by the government and the German Agency for Technical Development. Nearly 600 people are employed.

Within the American Tropics there are other examples of successful rural betterment as well as forest conservation and production. Some are so local that they are not widely known. The importance of applying more generally what has succeeded under different conditions presents one of the world's most important messages for the coming revolution in human communications.

There is every reason to approach forest conservation and production within the region with optimism. We now live in a world where forest mismanagement is rapidly becoming a general concern. Growing social enlightenment is calling for protection and production of forests. Technically, so much is known that the costs of inaction far surpass those to be expected from moving ahead cautiously using fully existing knowledge. Past experience has taught many lessons. Causes of former deficiencies, being generally known, can, with judgment, conviction, and patience, be overcome. A coming public demand for a shift from forest exploitation to productive management provides for those for whom this book is directed, the forestry students of tropical America, challenges but also unprecedented opportunities to perform a service fundamental to the future of the entire world.

Appendix A
Regional Weather Features

Mexico

Mexico south of the Tropic of Cancer and east of the Sierra Madre Oriental is continuously exposed to the Atlantic easterlies, which bring orographic precipitation and occasionally tropical disturbances. Interior Mexico normally receives 90 percent of its rainfall between June and October. During the winter, this subregion is reached by cool winds and storms from the north that may continue to the Isthmus of Tehuantepec on both coasts. In late summer, southern Mexico is occasionally invaded by intertropical fronts from the south that bring moist air and frontal waves.

Central America

The entire Central American isthmus is exposed to the easterlies throughout the year and to occasional northerlies in winter. The Caribbean Coast is subject to a large amount of orographic precipitation accompanied by thunderstorms. At Bluefields, Nicaragua, the mean annual precipitation exceeds 400 cm. The Pacific Coast, in the shadow of the Cordillera, receives far less rainfall. At Managua, for example, which is geographically opposite Bluefields, the mean annual precipitation is only 115 cm. This contrast is greatest from January to March, locally termed the "verano" (dry season). During this period, Bluefields normally receives 50 cm of precipitation, whereas Managua receives only about 1 cm. However, during the "invierno" (wet season), from April to December, the intertropical convergence zone enters these areas and brings disturbances that produce copious precipitation over both coasts. Managua receives 98 percent of its rain from May through November.

The Isthmus of Panama is subject to easterlies almost constantly from December to April, a period during which only about 11 percent of the annual rainfall occurs. The intertropical front normally crosses the isthmus from south to north in May and produces rainy weather until a short dry period in July. This is followed by the return of the intertropical front and unsettled weather from the southwest from August to November. Despite this general pattern, there is a marked contrast in rainfall between Colon on the Atlantic Coast, which has a mean annual precipitation of 340 cm, and Balboa on the Pacific, which receives 170 cm (Portig 1976).

West Indies

Weather in the West Indies is dominated by airflow from the Atlantic. At Bridgetown, Barbados, for example, the variation in mean monthly wind direction is only 21°; the annual mean is 90° (due east) (Portig 1976). From Hispaniola and Jamaica to Trinidad, the heaviest precipitation is from May to November, interrupted by a dry period in July. There is a marked difference in precipitation on windward and leeward exposures because of orographic lifting. At Guanica, on the leeward coast of Puerto Rico, for example, precipitation is only 52 percent of the precipitation received at Fajardo on the windward coast, only 130 km distant. From May to October, intense rain squalls may develop in this subregion under enormous cumulonimbus clouds.

Cyclonic storms (with winds of 62 km/hr or more) and hurricanes (with winds of 117 km/hr or more) are characteristic of the West Indies (Alaka 1976). These storms originate in the Atlantic between latitudes 10° and 30° N., often as far east as the Cape Verde Islands. Most frequently, they enter the Caribbean Sea in the latitude of the Lesser Antilles. Generally, these storms pass westward to the south of Cuba and enter the Gulf of Mexico, dissipating their energy over northeastern Mexico or southeastern United States; or they pass northwestward to the north of Cuba, thereupon leaving the Tropics and veering to the northeast. Based on observations from 1901 to 1972, the probability of at least one hurricane occurring each year ranges from 0.22 in June to a high of 0.88 in September and a low of 0.17 in November. Wind gusts of 250 km/hr or more and total rainfall of 240 cm over 4 days have been recorded.

The southern Windward Islands, Trinidad, and the adjacent Venezuelan coast are subject to northeasterly winds from January to May without frontal weather. At Bridgetown, Barbados, for example, only 20 percent of the annual rainfall is received during these months (Portig 1976). Between June and December, moist equatorial air masses produce continual tropical fronts with thunderstorms from north of Trinidad to the estuary of the Orinoco River. Farther west, along the Caribbean coasts of Venezuela and the Netherlands Antilles, easterlies prevail, resulting in a dry region. At San Pedro de Coche, Venezuela, for example, only about 300 km west of Trinidad, the mean annual precipitation is only 27 cm (Walter and others 1975).

South America

The Caribbean coast of Colombia is predominantly under the influence of the intertropical front. From January to April, northwest winds produce little precipitation. Cartagena normally receives only 2 percent of its annual rainfall during these 4 months. In May, the arrival of the front from the south brings southwest winds and heavy cumulonimbus clouds and thunderstorms that subside in July. A second period of intense storms occurs in November. The extreme northeastern Guajira Peninsula escapes this influence, receiving a mean annual precipitation of only about 30 cm (Snow 1976).

The Pacific slope of the Colombian and Ecuadorian Andes south to the Gulf of Guayaquil is permanently under the influence of moist and unstable equatorial maritime air. Andagoya, Colombia, for example, receives at least 50 cm of precipitation every month. Just south of the Gulf of Guayaquil, a heavy stratus cloud layer hangs almost continuously over the entire coast southward beyond the Tropic of Capricorn. The weakness of onshore winds and the tendency of the clouds to dissipate over the heated land prevent the coast from receiving any precipitation. At Molienda, Peru, for example, the wettest month of the year averages less than 1 cm of precipitation. Between June and September, a thin drizzle may fall along the immediate coastline, but inland areas remain cloudless and arid.

In the Orinoco-Guiana subregion, there is a sharp contrast in precipitation from east to west. Cayenne, French Guiana, receives precipitation averaging 370 cm annually, whereas San Fernando de Apure in the Venezuelan Llanos receives 150 cm (Snow 1976). This contrast is particularly pronounced during December, when the Guianas receive great quantities of precipitation from equatorial maritime air, as well as January (75 cm versus 1 cm). During the northern solstice, the intertropical front lies over this region and brings heavy showers, particularly between May and August when the Venezuelan Llanos receive about 70 percent of their annual precipitation (Snow 1976).

Extreme eastern Brazil experiences stable air during the spring, while a drying effect is felt throughout the lower and middle Amazon Basin. Recife, for example, normally receives less than 10 percent of its annual rainfall from September through December. During the southern solstice, this subregion may experience heavy showers with the convergence of the intertropical front. However, in years when the front does not advance far enough to the southeast, disastrous droughts are inflicted on the region of Fortaleza and Bahia.

The climate of the Amazon Basin is affected throughout the year by the convergence of the easterly air mass as it approaches the Eastern Cordillera of the Andes. Mean annual precipitation decreases upriver from Belem (270 cm) to Santarem and Manaus (200 cm), and then rises to 280 cm at Fonte Boa and Iquitos in Peru. Large convective clouds and heavy showers of increasing intensity approaching the Cordillera are characteristic. The mountain crest itself is almost permanently cloud covered. Cloudiness is the reason the mean temperature at Iquitos (24.8 °C) is lower than at Manaus (27.2 °C).

The interior highlands that extend from Brazil south to Paraguay, eastern Bolivia, and northern Argentina are virtually without precipitation during the northern solstice. Cuiaba, Brazil, for example, normally receives less than 20 percent of its annual precipitation between April and September. La Quiaca, Argentina, receives less than 5 percent during this time. During these months, the valleys of the Paraguay and Parana Rivers and the Gran Chaco are relatively cold. The mean July temperature at Corumba, Brazil, at latitude 19° S. and at an altitude of only 138 m, is 21 °C; an extreme low temperature in July was 4 °C (Ratisbona 1976).

Some representative climatic means from throughout the latitudinal range of the American Tropics appear in table A–1.

Table A–1.—Representative climatic means in tropical America

Latitude	Altitude (m)	Mean annual precipitation (cm)	Mean temperature (°C)	Climatic station
23° N.	20	120	25	Havana, Cuba
22° N.	20	120	24	Tampico, Mexico
21° N.	130	140	25	Camaguey, Cuba
20° N.	2,000	180	15	Terquitlan, Mexico
19° N.	50	160	25	Veracruz, Mexico
18° N.	0	190	26	Belize City, Belize
17° N.	2,130	120	14	San Cristobal de las Casas, Mexico
16° N.	0	260	26	Tela, Honduras
15° N.	140	180	25	Fort-de-France, Martinique
14° N.	820	440	25	San Andreas, Osuna, Guatemala
13° N.	60	130	26	Bridgetown, Barbados
12° N.	10	420	26	Bluefields, Nicaragua
11° N.	40	160	25	Port of Spain, Trinidad and Tobago
10° N.	1,120	190	20	San Jose, Costa Rica
9° N.	1,500	180	19	Merida, Venezuela
8° N.	0	430	26	Jaque, Panama
7° N.	0	240	27	Georgetown, Guyana
6° N.	100	220	27	Puerto Ayacucho, Venezuela
5° N.	60	690	27	Andagoya, Colombia
4° N.	420	410	26	Villaviciencio, Colombia
3° N.	100	160	28	St. Ignatius, Guyana
2° N.	110	350	26	San Carlos de Rio Negro, Venezuela
1° N.	10	270	27	San Lorenzo, Ecuador
0°	80	290	25	Uaupes, Brazil
1° S.	950	430	26	Belem, Brazil
2° S.	950	430	26	Puyo, Ecuador
3° S.	50	200	27	Manaus, Brazil
4° S.	100	280	26	Iquitos, Peru
5° S.	80	110	26	Barraldo Gorda, Brazil
6° S.	20	270	26	Manicore, Brazil
7° S.	140	270	25	Alto Tapajos, Brazil
8° S.	60	150	26	Recife, Brazil
9° S.	660	310	25	Tingo Maria, Peru
10° S.	240	180	26	Porto Nacional, Brazil
12° S.	3,380	70	19	Huancayo, Peru
13° S.	260	190	25	Puerto Maldonado, Peru
14° S.	1,380	130	20	Apolo, Bolivia
15° S.	910	160	21	Formosa, Brazil
16° S.	520	180	24	Goias, Brazil
17° S.	20	130	24	Pirapora, Brazil
18° S.	440	100	24	Santa Cruz, Brazil
19° S.	140	110	25	Corumba, Brazil
20° S.	920	160	21	Belo Horizonte, Brazil
21° S.	560	140	22	Riberao Preto, Brazil
22° S.	160	130	23	Bela Vista, Brazil

Source: Walter and others 1975, Wernstedt 1961

Appendix B
Climatic Classifications

Koeppen's System

In 1900, Wladimir Koeppen published a climatic classification that with modifications (Koeppen 1936), is still used by geographers today. He conceived the idea that plants integrate climatic elements, and their distribution defines climatic regions. His main climatic classes for tropical America are as follows:

A. Tropical: coolest month has average temperatures above 18 °C
  Ar = Wet: driest month has at least 6 cm of rainfall
  Am = Monsoon: short dry season, but ground continually wet
  Aw = Wet and dry: distinct dry season of at least 1 month with less than 6 cm rainfall

B. Dry: evaporation exceeds precipitation
  Bs = Steppe: rainfall above the mean for the group
  Bw = Desert: rainfall below the mean for the group

The tropical wet climate (Ar) covers eastern Central America, parts of the Caribbean Islands, western Colombia, the Guianas, the Amazon Basin, and the Atlantic margins of Brazil (fig. B–1). Mean monthly temperatures are seldom higher than 27 °C because of cloudiness, which ranges up to 60 percent. Nevertheless, because of slight air movement, the atmosphere has low cooling power. Annual precipitation is generally more than 180 cm.

The Amazon Basin is the world's largest area of tropical wet climate. However, only the area upstream from Manaus is without 1 or 2 dry months. Along Brazil's Atlantic coast, from south of Cape St. Roque to about 13° S. latitude, late spring and summer are relatively dry. The heavy precipitation in the Pacific lowlands of Colombia results from unstable equatorial air that enters from the west and southwest and is blocked by high mountains. In this region, rains are most common between midnight and 4 a.m. On the Caribbean slopes of Central America and the West Indies, summer rains decrease briefly during July and August.

The tropical wet-and-dry climate (Aw) has less precipitation and a longer dry season than the tropical wet climate (Ar). It generally occurs between 5° and 20° S. latitude. The rain forests of the Aw areas give way to less dense, more deciduous forests and tree-studded grasslands called "savannas." The change in vegetation gradually intensifies as the latitude increases. The warmest season generally precedes a heavy rainy period. Annual precipitation is commonly 100 to 150 cm. The wet season (Koeppen's Aw) resembles the Ar climate, and the rest of the year resembles desert or arid (Bw) climate.

The campos of interior Brazil south of the rain forest areas are Earth's most extensive region of Aw climate. Rainfall is strongly concentrated in the high-sun season. The llanos of Venezuela and Colombia are a counterpart to the Brazilian campos. Other Aw areas in tropical America include a small section on the Pacific side of Ecuador near the Equator, the Pacific side of Central America, the Yucatan Peninsula, and the low-elevation islands of the West Indies.

Thornthwaite's System

Thornthwaite (1948) endorsed Koeppen's system of defining climatic regions according to the distribution of vegetation. Nevertheless, he concluded (Thornthwaite and Hare 1955) that the system was futile as a method for classifying forest climates, pointing out that simple temperature and precipitation values are not parameters of actual vegetation control by climate. However, he extended the climatic classification to include estimates of water loss as a balance against precipitation by estimating potential evapotranspiration; that is, evapotranspiration that would ensue if adequate water were continually available. Thornthwaite and Hare (1955) list four factors responsible for evapotranspiration:

- Supply of external energy to the evaporating surface (principally by solar radiation)
- Capacity of the air to remove the vapor (dependent on wind speed, turbulent structure, and the decrease of vapor concentration with height)
- Nature of vegetation (especially its capacity to reflect incident radiation, how extensively it occupies the soil, and the depth of its root system)
- Nature of the soil (especially the amount of water in the root zone).

The capacity of vegetation to reflect radiation (albedo), expressed as a percentage of the radiation received, was measured in the Temperate Zone in the 1920's (Angstrom 1925). For grasslands, the albedo was about

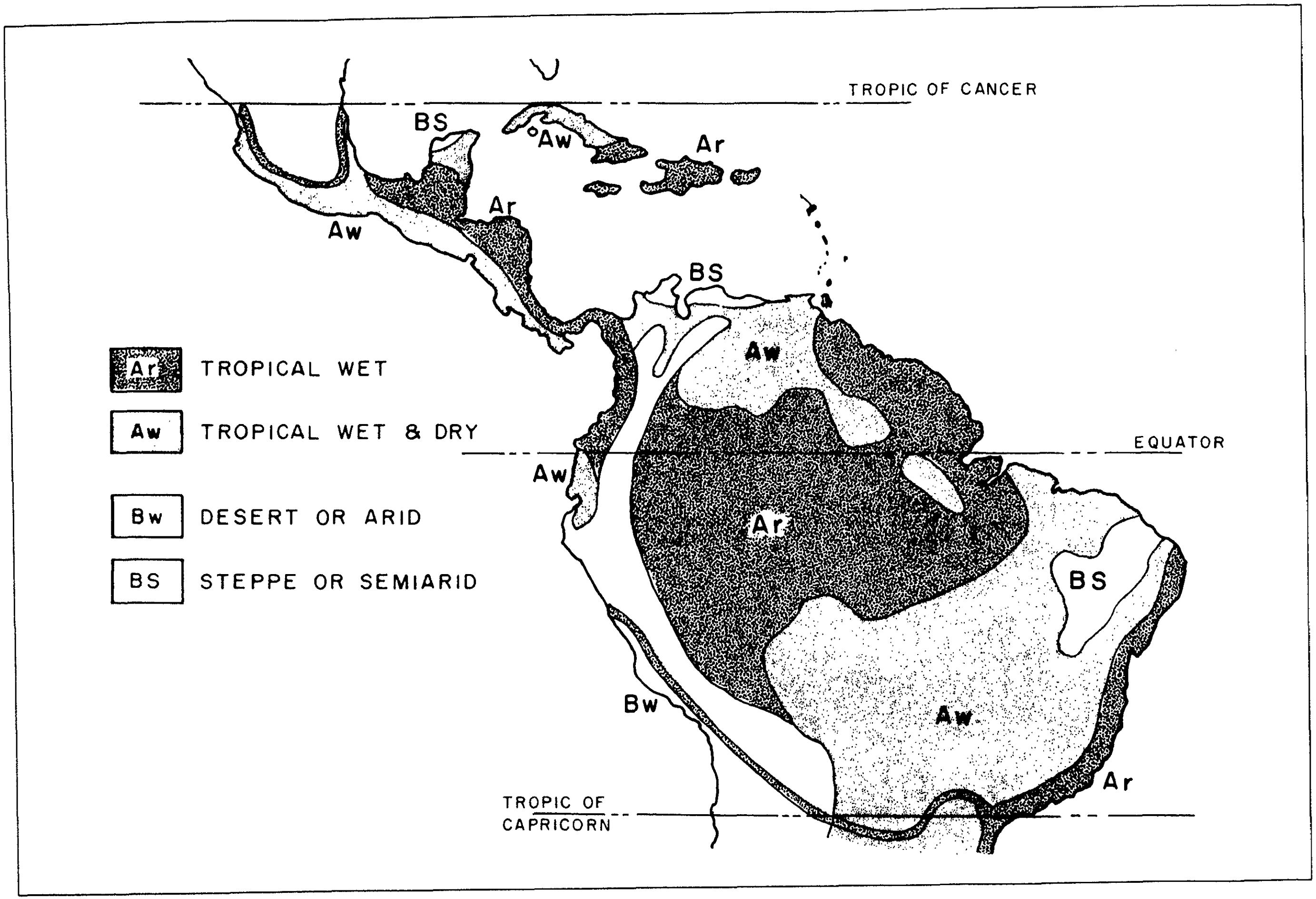


Figure B–1.—*Koeppen's climatic zones, as modified by Trewartha (1968) for tropical America.*

0.26 (26 percent), for oak woodlands, 0.175, and for pine forests, 0.14.

Potential evapotranspiration is an index of thermal efficiency. The relationship between the logarithm of potential evapotranspiration and the logarithm of temperature is linear; therefore, temperature, adjusted for day length, is a measure of thermal efficiency.

The first step in determining potential evapotranspiration by Thornthwaite's scheme is to determine the "heat index" by adding values derived for the mean temperature for each month (table B–1). Once the aggregate heat index is deduced, the potential evapotranspiration rate (unadjusted for day length) is derived from a chart for each monthly mean temperature. Each unadjusted monthly potential evapotranspiration value is then multiplied by a factor for day length (Thornthwaite 1948). From these relationships, also assuming 30-cm water storage in the soil, Thornthwaite and Hare (1955) developed a water budget that includes actual monthly

Table B–1.—Heat index values for monthly mean temperatures between 10 °C and 30 °C

°C	Index	°C	Index
10	2.9	22	9.4
12	3.8	24	10.8
14	4.8	26	12.1
16	5.8	28	13.6
18	7.0	30	15.1
20	8.2		

Source: Thornthwaite 1948.

evapotranspiration and months of water deficit and surplus. The end result is illustrated in figure B–2 (Golfari 1968b). During any month of the year, water may be either deficient or excessive. Part of the excess may go to replenish soil-water storage before a surplus recurs.

A moisture index was derived by Thornthwaite as follows (1948):

$$Im = \frac{(100\,s - 60\,d)}{n}$$

where s = annual water surplus
d = annual water deficiency
n = annual potential evapotranspiration, or water need.

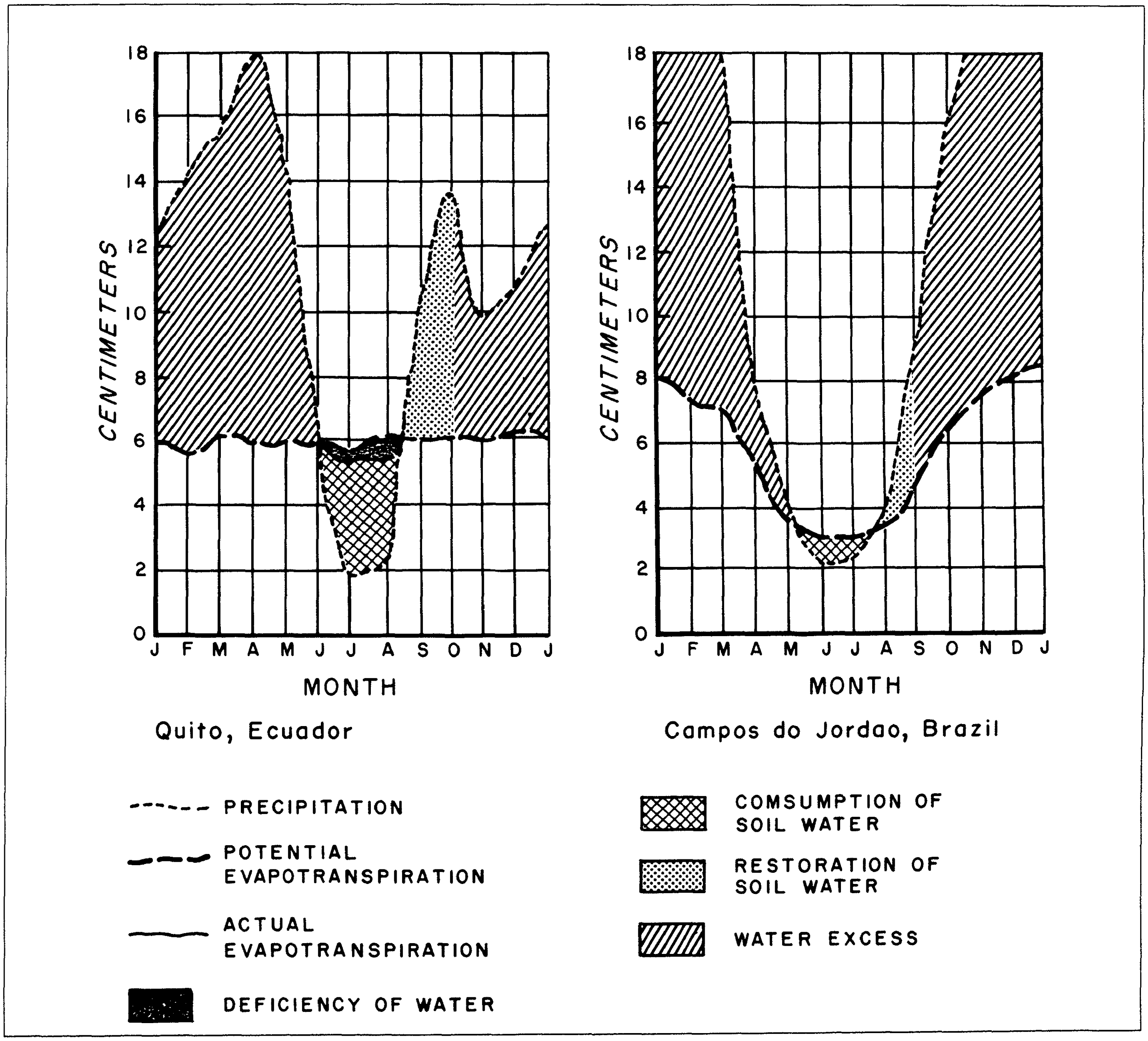


Figure B–2.—*Results of application of Thornthwaite procedures to two climates (Golfari 1968b).*

He classified climates with an index of +100 or more as "perhumid"; those +20 to +100 as "humid"; those -20 to +20 as "subhumid"; those -20 to -40 "semiarid"; and those below -40 "arid." A weakness of the system is the derivation of potential evapotranspiration from temperature data alone. The results are not always reliable, but the system permits an estimate where more accurate formulas cannot be applied (Cochrane and Sanchez 1981).

The Holdridge System

Holdridge (1947) published a diagrammatic classification of life zones worldwide, which, with subsequent modifications (Holdridge 1967), has been applied in many countries of tropical America. The zones are defined by geometrically progressive limits of mean annual precipitation and mean biotemperature. The latter is derived for an average year by adding all hourly temperatures between 0 and 30 °C (the presumed limits for plant growth) and dividing by the total number of hours in the year. Figure B-3 illustrates the system for the region.

Holdridge's tropical zones all have mean biotemperature in excess of 24 °C; his subtropical zones average 18 to 24 °C and are generally frost free. At low (basal) elevations, these two zones correspond roughly to the equatorial and outer Tropics defined elsewhere. The basal Tropics is at elevations corresponding to biotemperatures of about 24 to 18 °C (about 500 to 1,500 m). A premontane altitudinal belt is found at 18 °C or 1,500 m. Above it, from about 18 to 12 °C (1,500 to 2,500 m) is the lower montane zone, and so on. At latitudes classed subtropical at sea level (24 to 18 °C), the first altitudinal belt (18 to 12 °C) is called lower montane (500 to 2,500 m), and that from 12 to 6 °C (about 1,500 to 2,500 m) is termed montane, and so on. Land areas in each of Holdridge's life zones of Central America (excluding Belize) are summarized in table B-2 (Budowski 1964b).

One of the main advantages of Holdridge's system is that it is based on climatic parameters that may be already available: mean annual precipitation and biotemperature. The latter, however, requires a record of hourly temperatures. Where this is not at hand, Holdridge

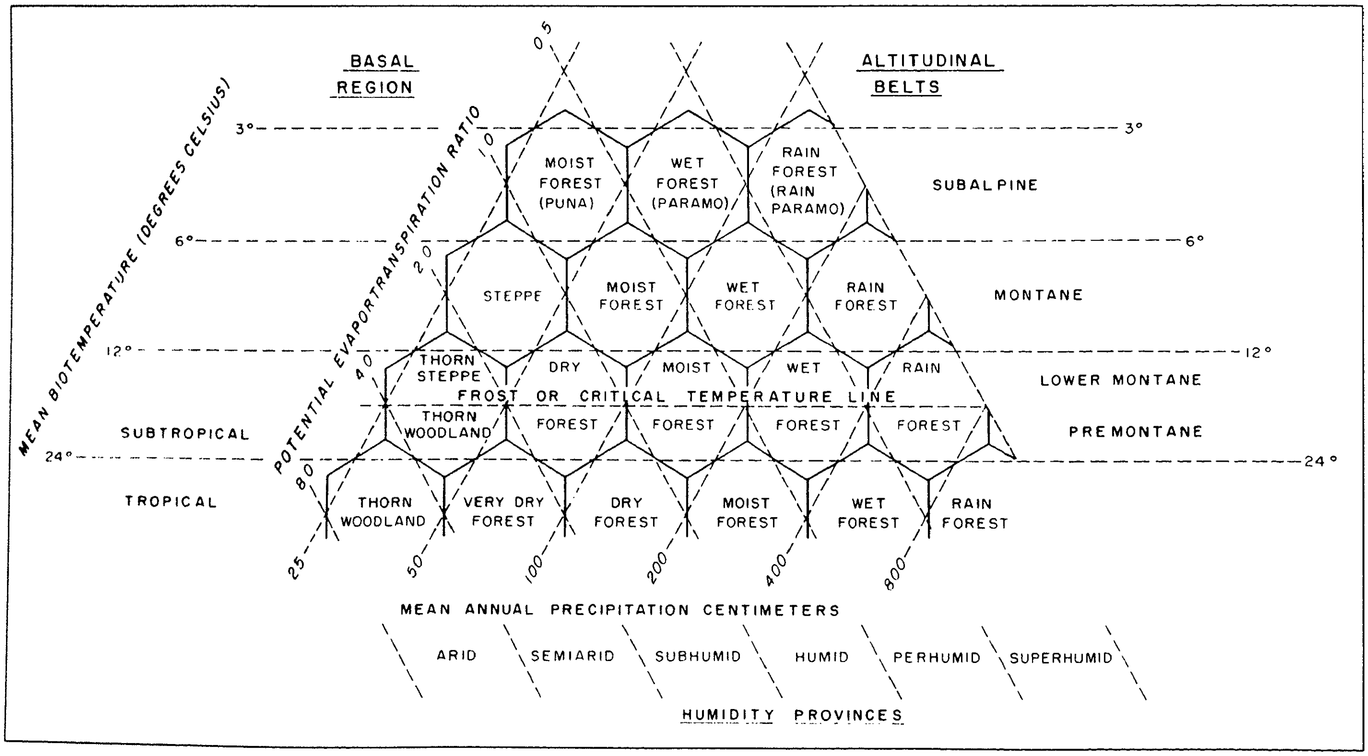


Figure B-3.—*The Holdridge life zone system, slightly modified.*

Table B-2.—Land area in life zones in Central America (thousand km²)

Altitudinal belt	Total area by precipitation zones					
	Very dry	Dry	Moist	Wet	Rain	Percent
Tropical	6.2	98.5	171.8	9.5	0.0	60
Subtropical	0.0	16.6	64.5	72.9	0.8	32
Lower montane	0.0	0.3	19.8	12.7	0.7	7
Montane	0.0	0.0	0.8	1.3	trace	1
Subalpine	0.0	0.0	0.1	1.3	trace	1
Percent	1	25	54	20	trace	100

Source: Budowski 1964b.

approximates biotemperature for the outer Tropics by the following formula (Holdridge 1978):

$$\text{Biotemperature} = \frac{\text{Mean t °C} - (0.3)\,(\text{° latitude})\,(\text{mean t °C} - 24)^2}{100}$$

where t °C = temperature in degrees Celsius.

Holdridge's system differs from others in its geometrically progressive scales, primary reliance on annual means (for describing seasonal climate), and altitudinal belts. Its large number of zones complicates mapping on a global scale. Nevertheless, a series of large-scale (1:250,000 to 1:1,000,000) maps for individual countries in Central America, the Caribbean, and northern South America has been completed. Figure B–4 is a much-reduced map of Puerto Rico from this series (Ewel and Whitmore 1973).

Walter's System

In 1964, Walter (1971) diagrammed world climates by superimposing monthly temperature and precipitation on vertical scales in which 10 °C equaled 20 cm of precipitation (fig. B–5). In these diagrams, the station is identified at the top, followed by its elevation in meters. To the right are mean temperature in degrees Celsius and annual rainfall in millimeters. The number of years of record is indicated below the station name. At the lower left corner are the mean temperature of the coldest month and, below it, the extreme minimum temperature. The horizontal scale is the months of the year, with the warm season placed centrally (opposite in the southern and northern hemispheres). The vertical scales are temperatures with 10 cm intervals on the left and 20 mm monthly rainfall intervals on the right, the scale reduced to one tenth above 100 cm. The dotted area is defined as "relatively droughty," and the area with the vertical lines "relatively humid." The solid black area indicates rainfall in excess of 100 mm monthly. This system shows the seasonal pattern of moisture availability without estimating potential evaporation or soil-moisture storage. World maps with charts for most regions, accompanied by data on elevation, mean temperature, and annual precipitation, facilitate broad comparisons of climate. This system recognizes nine climatic zones, two of which are clearly tropical (fig. B–6):

I. Equatorial zone—10° N. and 10° S. latitude, two rainy seasons, rainfall and humidity very high and little temperature variability.

II. Tropical zone—10° to 30° N. and 10° to 30° S. latitude, moist summer season, coinciding with or lagging behind the latitude of the Sun, rainfall decreasing with distance from the Equator; generally frost free.

Other zones shown on Walter's map (fig. B–6) include subtropical arid (III) and warm temperate (V). He notes that the mean temperatures decrease outward from the Equator more rapidly in the Southern Hemisphere than in the Northern, although the seasonal differences increase less rapidly, because of the buffering effect of the smaller land mass in the Southern Hemisphere. For the same reason, temperature differences increase with distance inland from the coast.

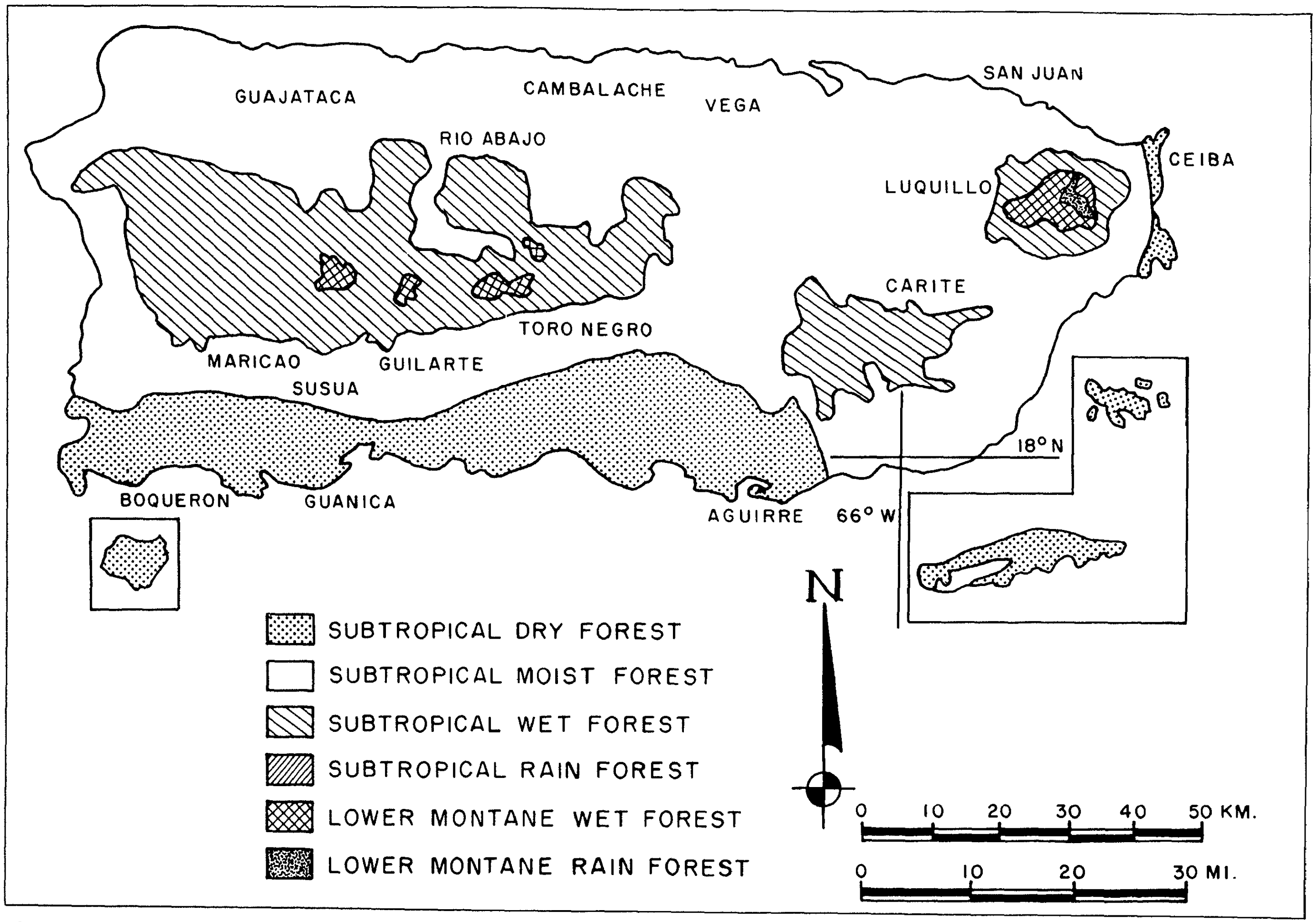


Figure B–4.—*Application of the Holdridge life zone system to Puerto Rico (Ewel and Whitmore 1973).*

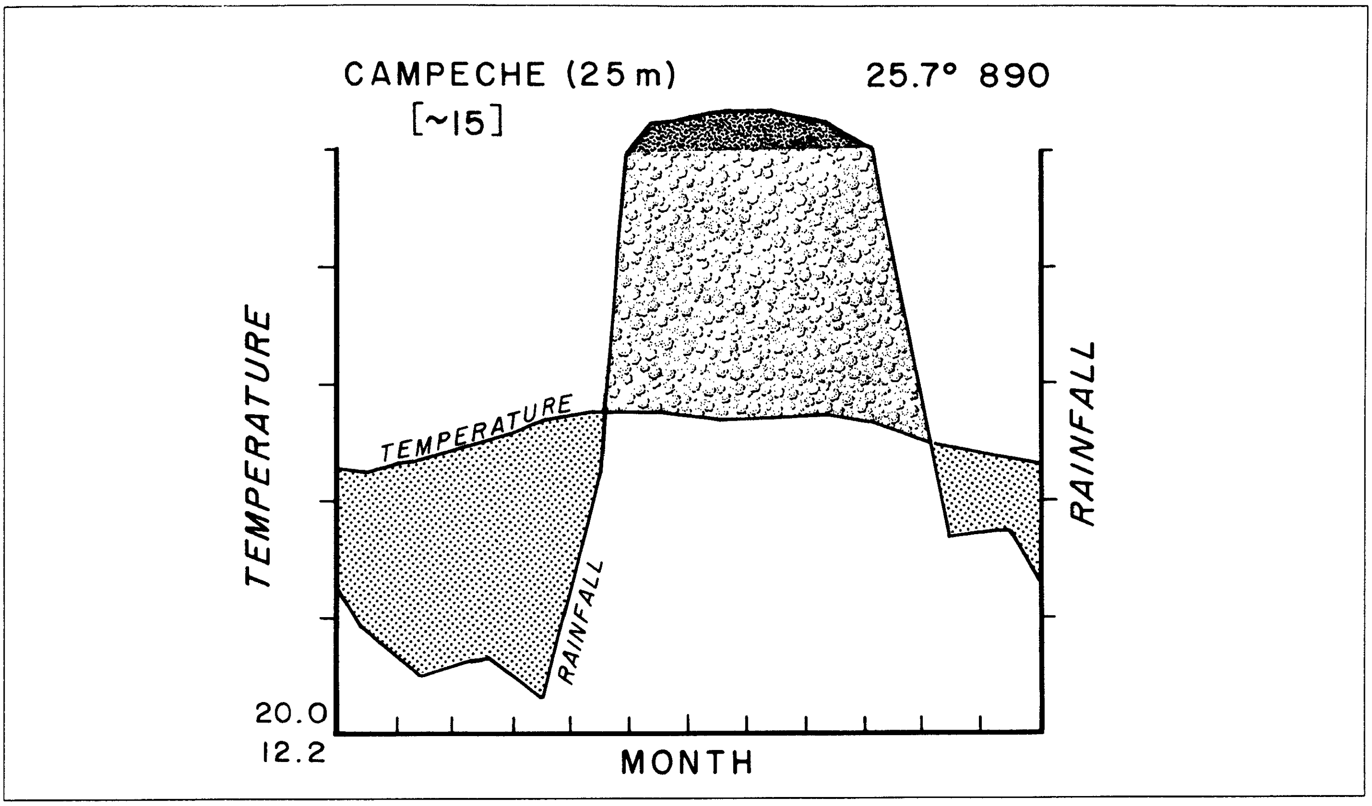


Figure B–5.—*Example of Walter's diagram of world climates (Walter 1971). Campeche = station being monitored; 25.7 = mean temperature in degrees Celsius; 890 = annual rainfall in millimeters; [~15] = number of years of record; 25.0 = mean temperature of coldest month; and 12.2 = extreme minimum temperature.*

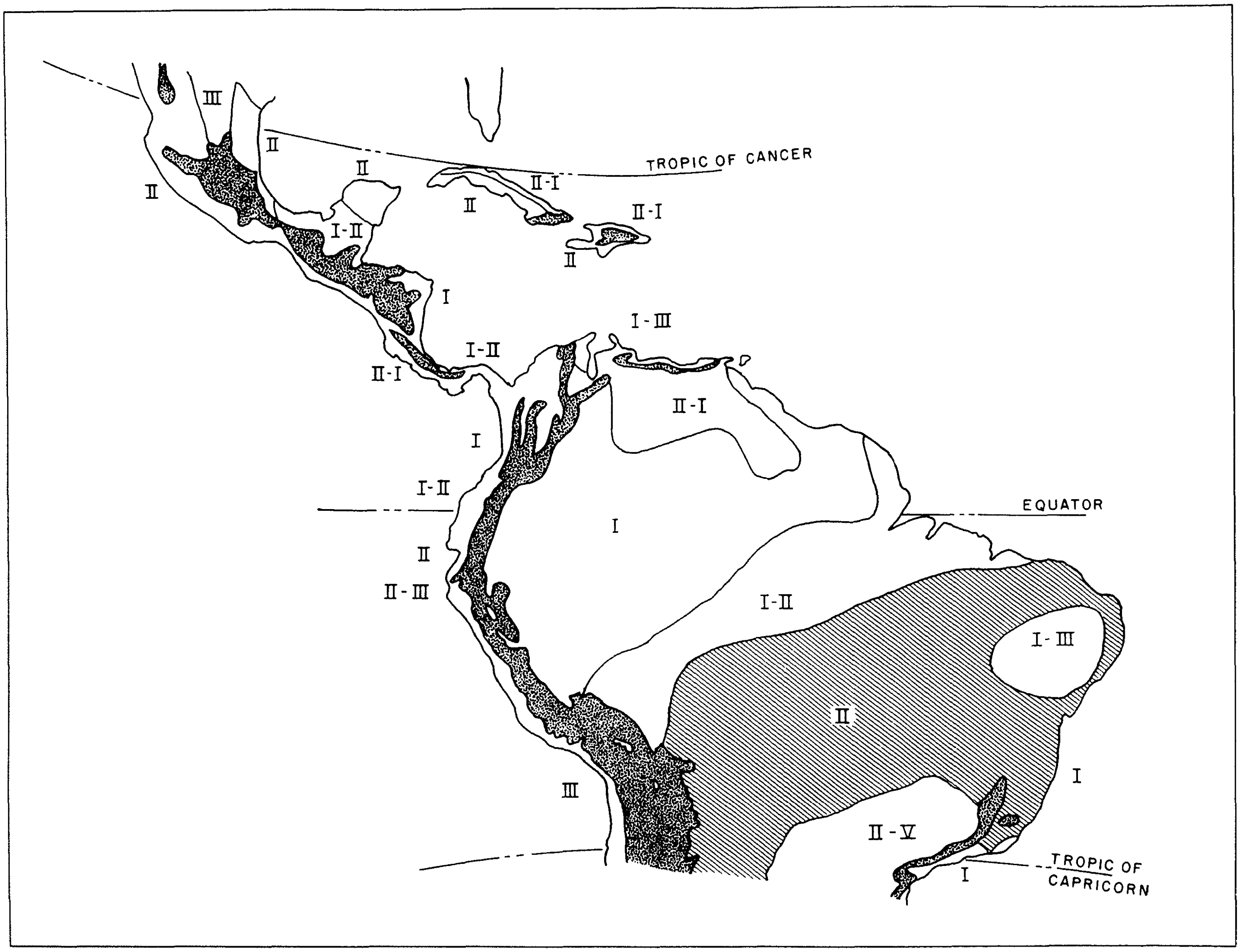


Figure B–6.—*Of the nine recognized climatic zones, four are in Central and South America: I = equatorial; II = tropical; III = subtropical arid; and V = warm temperate (Walter 1971).*

Appendix C
Past Development of Forests

The information that follows is summarized from a study by Unesco (United Nations Educational, Scientific, and Cultural Organization), UNEP (United Nations Environment Programme), and the Food and Agriculture Organization (FAO) (Anon. 1978b).

After the Paleozoic Era, some 230 million years ago, Earth's only continent separated into northern and southern land masses. Subsequently, plant and animal life evolved divergently, adapting to distinct and changing conditions. Thus, the flora of Central and South America are different.

Until the late Cretaceous Period, possibly 100 million years ago, what are now South America and Africa were joined and had similar flora (Herngreen 1974). At that time, the southern land mass separated into two continents, which drifted apart. However, until the Cenozoic Era, which began 65 million years ago, they were separated by only 600 km; intermediate islands linked the species of the two areas until the Eocene Epoch, about 38 million years ago (Prance 1978). At that time, western North America was still joined to Asia, and floral and faunal migration continued into what is now Central America. Since then, the climate of northern South America has been tropical.

During the Cenozoic Era, about 10 million years ago, the uplift of the Cordillera, which had begun long before, continued. By the mid-Pliocene Epoch, some 6 million years ago, North and South America were rejoined (Prance 1978). However, even while the two continents approached one another, there was an intermingling of plants and animals that may have begun as early as 16 million years ago. The severe topography of the upland environment of the Central American isthmus slowed this process. The Cordillera reached its present height about a million years ago.

Changes during the last half million years of the Pleistocene Epoch produced glaciation in the cooler regions of the Earth but also affected the Tropics. However, glaciers did not eliminate many species at low elevations (Vuilleumier 1971). Nevertheless, the advancing and retreating glaciers caused the sea level to fluctuate in the vast lowlands of the Amazon Basin, periodically flooding much of the area. This left only isolated refugia (areas of unaltered climate during periods of continental climatic change) of former terrestrial ecosystems (Prance 1978). When floods subsided, the terrestrial systems advanced from these refugia. That this process may still be in progress is evident in the high endemism (restriction of species to a particular locality) of two large refugia, the Brazilian and Guyana shields (continental nucleii covered by sedimentary rocks), even though these refugia are not far apart.

Rainfall has also fluctuated since the Amazon Basin was formed (Prance 1978). The area was wet and forested 9 to 10 million years ago, subsequently dried, and then returned to forests during the past 2 million years.

More detailed evidence of development of the biota of tropical America is as yet fragmentary and comes largely from plant remains (chiefly pollen grains) and animal remains found in lake sediments that have resisted decay in anoxic, acid environments.

Modern tree taxa began to make their appearance in the region some 70 million years ago. Certain Bombacaceae appeared in the Paleocene Epoch (55 to 65 million years ago), *Rhizophora* in the Oligocene Epoch (25 to 35 million years ago), and *Symphonia* in the Miocene Epoch (10 to 25 million years ago). Most extant mammalian families arose during the Tertiary Period (1 to 65 million years ago). The present South American mammalian fauna include forms of both northern and southern origin.

The present tree flora of tropical America reflect both north-south and east-west migration. Included are families with subtropical affinities as well as many genera that are pantropical. Juglandaceae *(Juglans)* relates to the north, whereas Cunoniaceae *(Weinmannia),* Magnoliaceae *(Talauma),* and Myrtaceae *(Eugenia* and *Psidium)* relate to the south. Pantropical tree genera in tropical America include the following (Anon. 1978b):

Genus (Family)	Genus (Family)
Beilschmiedia, Persea (Lauraceae)	*Dendropanax* (Araliaceae)
Calophyllum, Clusia (Guttiferae)	*Diospyros* (Ebenaceae)
Casearia, Homalium (Flacourtaceae)	*Erythroxylon* (Erythroxylaceae)
Cassia, Cynometra (Caesalpiniaceae)	*Eschweilera* (Lecythidaceae)
Celtis (Ulmaceae)	*Fagara* (Rutaceae)
Cordia (Boraginaceae)	*Guarea, Trichilia* (Meliaceae)
Dacryodes, Protium (Burseraceae)	*Ixora, Psychotria* (Rubiaceae)

Genus (Family)	Genus (Family)
Licania (Chrysobalanaceae)	*Simarouba* (Simaroubaceae)
Manilkara (Sapotaceae)	*Sloanea* (Eleocarpaceae)
Pentaclethra (Mimosaceae)	*Sterculia* (Sterculiaceae)
Pterocarpus (Papilioaceae)	*Terminalia* (Combretaceae)
Rauwolfia (Apocynaceae)	*Vitex* (Verbenaceae)
Sapium (Euphorbiaceae)	

Studies of the eastern Cordillera of Colombia (van Geel and van der Hammen 1973, van der Hammen 1974, van der Hammen and Gonzalez 1960, van der Hammen and Wijmstra 1964, van der Hammen and others 1973) show early lowland tropical forests containing the family Bombacaceae and the genera *Alchornia, Hieronyma, Humiria, Ilex, Iriartia,* and *Mauritia.* Elevation controlled the distribution of these species. The present flora appeared some 3 million years ago. From the north, *Alnus* reached the area about 2 million years ago and *Quercus* less than 1 million years ago.

Forest development during the Quaternary Period, the past 600,000 years, and particularly during late Pleistocene ice ages of the past 50,000 years greatly influenced the location and character of the present forests. The sequence of climatic changes that characterized glacial and interglacial periods in the Northern Hemisphere was mirrored in the Tropics.

Appendix D
Classifications of Forests

The task of describing and attempting to explain the wide diversity in forest ecosystems of the Tropics has occupied biologists, ecologists, and foresters for well over a century.

Temperate Zone scientists, comparing tropical with temperate ecosystems, have concluded that the differences are generally only of degree. De Laubenfels (1975, p. 38) states that "it cannot be fairly said that there is any kind of vegetative formation in the middle latitudes that can be successfully segregated from corresponding tropical types. It is only possible to identify floristic divisions and the unique features that separate any given plant or set of plants from any other." As two examples, tropical plants are frost sensitive, and temperate plants need variations in day length or temperature to complete their life cycles.

De Laubenfels (1975) listed a number of physiognomic characteristics that distinguish four major plant formations: rain forest, seasonal forest, woodland, and desert. He considered a continuous understory to be a characteristic of rain forests. Seasonal forests are not structurally distinct, but have only scattered trees beneath their canopies; they also include trees that may become defoliated for several weeks. Forests differ from woodlands in that they have continuous canopies, gaps between the tree crowns and the ground, and juvenile trees either at random or concentrated in forest openings. De Laubenfels also concluded that prolonged drought eliminates the delicate, shade-enduring plants.

Attempts to characterize and differentiate tropical forest ecosystems have generally involved grouping observations into classes, the members of which share common characteristics (Havel 1980). This grouping may be followed by attempts to relate classes to underlying environmental conditions. Classification implies an assumption that differences among members of each class are less than differences between classes.

Generally acceptable classifications of tropical forests have proved elusive. When external factors (such as climate and soil) are used as criteria, the resulting categories have mostly lacked validity (De Laubenfels 1975). Where vegetation characteristics reflect external factors, it is more logical to use the vegetation characteristics as classifiers. Species do not generally serve to classify plant formations, and little can be made of individual plant forms because of aggregations of different plant forms. Grubb and others (1963) even find using the number of vegetative stories to be questionable in separating types of tropical forests. They conclude that any attempt at a universal system of classification obscures as many truths as it reveals. Havel (1980) agrees that because of the great variety of physiognomic and environmental characteristics used to classify forests for various purposes, no one classification is best in all circumstances. He points out that the description and classification of forest types are still unsettled despite the recent surge of interest in ordination, which, in contrast to classification, is primarily concerned with continuities and gradients, whether physiognomic or environmental.

Schimper's System

In 1898, Schimper assembled what was then known about the general significance to plants of water, heat, light, air, soil, and animal life. Schimper considered woodland, grassland, and desert to be climatic, depending primarily on the amount and distribution of rainfall and on the desiccating influence of atmospheric moisture-saturation deficits and air movement. He concluded that flora are primarily distributed according to temperature. Schimper also concluded that abrupt transitions among woodland, grassland, and desert are determined chiefly by soil. He termed plant communities reflecting general moisture and temperature regimes and local soil conditions as climatic or edaphic "formations."

Schimper defined woodland as vegetation dominated by woody plants, and included "forest" (if closed), "bushwood" (if shrubs were more abundant than trees), and "shrubwood" (if entirely of shrubs). He concluded that woodlands grow where rainfall is generally more plentiful than in grassland areas. However, it is not continuous rainfall but rather continuous moisture availability within reach of tree roots that produces woodlands. Schimper's edaphic woodlands included "fringing forests" along rivers and lakes with moving water and swamp forests near stagnant water. Among the latter are mangroves.

Schimper used the term "rain forests" for the natural vegetation of tropical regions that are constantly moist. He concluded that rain forests typically receive more than 200 cm of precipitation annually, although in some areas, 150 cm produces vegetation with rain forest attributes. In the Amazon, where annual rainfall of more than 200 cm is the exception, luxuriant forests are confined to the riverbanks.

Schimper described the rain forests as presenting a variety of green colors, few visible flowers, a tangle of lianas, straight-trunked trees, and abundant undergrowth. Terrestrial herbaceous vegetation is developed only in the lighter portions of the forests, and grasses are insignificant. The tree stems are covered with diverse epiphytes. The struggle of the plants for light is evident everywhere.

Schimper concluded that the forests of the interior of Brazil south of the Amazon should be classed as "monsoon forests," his term for the type of forest nearest to rain forests in moisture availability. This type of forest trends into savanna and thorn forest over large areas. He considered the thorn woodland (the caatinga with thorny Cactaceae and Mimosaceae) to be intermediate between the Amazon forests and the savannas (campos) to the south.

He also referred to the significant effect that mountains have on vegetation, not only on the slopes themselves but also in the flatter areas that surround them. There, rainfall exceeds that of lowlands and may produce rain forests of exceptional luxuriance. The vegetation on lower mountain slopes in the equatorial Tropics contrasts with vegetation of the lowlands chiefly in composition. Generally, the trees in tropical montane rain forests are evergreen and lack plank buttresses. Their appearance is more massive, their branching is more pronounced, and their leaves are smaller and thicker than those of the lowlands trees. Lianas are fewer and thinner; epiphytes may be more luxuriant, but they are smaller and tend to be mosses or ferns rather than phanerogams. Equatorial mountains and outer tropical lowlands are ecologically closely allied. In the outer Tropics at upper elevations, the montane forests become temperate (deciduous).

On tropical mountains above the montane forests, Schimper describes a transition through an elfin wood of short, branchy trees with xerophilous foliage to an alpine region. The successive elevational belts produce xerophilous shrub, alpine grassland or steppe, and finally alpine desert. In dry regions, only the montane belt may be forested.

In summary, Schimper recognized the following formations of woodland vegetation in the Tropics:

Climatic	Edaphic
Lowland rain forest	Swamp forest
Montane rain forest	Littoral woodland above high tide
Monsoon forest	Littoral woodland below high tide
Savanna forest	Forest of limestone soil
Thorn woodland	Forest of humus soil
	Forest of silicaceous soil

Schimper provided much groundwork for more recent attempts to characterize tropical forests. Burtt-Davy (1938) concluded that Schimper's primary reliance on climate for vegetation classification and the subdivision of climatic zones on the basis of the habit or physiognomy of plant life made it especially useful to foresters, who have "multifarious duties, both administrative and executive that preclude them from being ecologists pure and simple." P. W. Richards (1961) concluded that Schimper underestimated edaphic influences on vegetation types in the wet Tropics, where they are less evident than in the seasonal Tropics but equally important.

Chipp's System

A classification combining vegetative physiognomy with edaphic and climatic bases was proposed by Chipp (Tansley and Chipp 1926). Chipp's tropical woodland categories were as follows:

Closed forest—grass generally absent

1. Rain forest—lower altitudes, temperature high, dry season short, if any; where confined to belts along water courses, termed "fringing forest"
2. Mountain forest—higher altitudes, temperature moderate, generally subject to mist and clouds
3. Mangrove—groundwater salty or brackish

Parkland—trees in groups or isolated, herbaceous cover partial or continuous, lianas generally absent

1. Transition—belts or islands of closed forest surrounded by grass areas with trees
2. High grass, low tree savanna—trees in groups or occurring singly, short and gnarled stems; grass 2 to 4 m tall
3. Open woodland—no closed canopy, groundcover herbaceous with grass predominating
4. Orchard country—trees occurring singly, scattered through grass; often with palms
5. Thorn country, low thorn—heavy trees with spiny shrubs, grass cover rarely continuous.

Burtt-Davy (1938) considered this system imperfect because it did not cover all existing types, such as deciduous forest, it had overlap, and it was vague as to the boundaries of some types.

Champion's System

An extension of the use of physiognomy in classifying tropical forests was offered in 1936 by a forester stationed in India (Champion 1936a). He proposed the following classification:

Wet forest (24 m tall or more)

1. Wet evergreen (rain forest)—dense, entirely or almost entirely evergreen
2. Semi-evergreen—dominants include deciduous trees, but evergreens predominate
3. Moist deciduous—dominants mainly deciduous, but subdominants and lower stories largely evergreen; top canopy rarely dense.

In addition, Champion recognized 10 wet edaphic types (such as bamboo brake) and 8 seral types (such as beach, tidal, freshwater, swamp, and river rain forest).

Dry forest

1. Dry deciduous—canopy rarely more than 24 m high, entirely deciduous
2. Thorn forest—canopy more or less broken, deciduous
3. Dry evergreen—usually less than 18 m high, often dense, hard-leaved evergreen trees predominant.

Champion also recognized 12 dry edaphic types (such as inland dune), 4 primary seral types (such as dry riverain), and 3 secondary seral types (deciduous, deciduous scrubby, and savanna).

Montane subtropical forest

1. Wet—broadleaved, largely evergreen
2. Moist—pine associations predominant
3. Dry evergreen—low xerophytic forest and scrubs.

Burtt-Davy's System

Struck by the similarities in the classifications Chipp and Champion derived in distant regions, Burtt-Davy (1938) concluded that separate classifications should not be necessary. Using the life form of dominant trees in mature associations, Burtt-Davy proposed a composite classification of formations and distinguished three hierarchical plant communities:

1. Association—the fundamental floristic unit of vegetation, based on Tansley and Chipp's (1926, p. 9–10) definition: "The largest unit which consists of a definite assemblage of species (usually with definite dominants) and adequate habitat. Named by the dominant or dominant and codominant species."
2. Formation type—woodland, grassland, or desert, distinguished by the physiognomy of their dominants
3. Formation—a group of associations that resemble each other in general physiognomy and in climatic or edaphic habitat more closely than they resemble any other association; usually named on the basis of physiognomy or climatic or edaphic habitat (evergreen forest).

Burtt-Davy's classification of tropical forest formations follows:

A. Moist woodland
  1. Moist climatic formations
    a. Woodland evergreen rain forest, including lower montane evergreen rain forest
    b. Semi-evergreen rain forest
    c. Moist deciduous forest
    d. Upper montane rain forest
    e. High montane conifer forest
    f. Montane bamboo forest
    g. Alpine elfin woodland
  2. Moist edaphic formations
    a. Riparian woodland
    b. Freshwater swamp forest
    c. Palm swamp
    d. Mangrove woodland
    e. Littoral woodland
B. Dry woodland
  1. Dry evergreen forest
  2. Savanna woodland
  3. Thornland

For each formation, Burtt-Davy gave synonyms, definitions, general descriptions, habitat, climate, and subformations. His moist woodlands are separated from dry woodlands on the basis of available water, not just rainfall. Nevertheless, his moist formations generally receive more than 120 cm of rainfall per year, and the dry formations less. Upper montane refers to elevations 1,500 m or higher in the equatorial Tropics. Alpine elfin woodland is generally 2,900 m or higher.

Beard's System

Beard (1944b) considered Burtt-Davy's work an attempt to correlate nomenclature and harmonize classification systems, and he was strongly influenced by its physiognomic approach, which was based on the study of community structure as determined by the occurrence of major types of plants (Beard 1973). He concluded that the physiognomic basis of classification meets all the essential requirements for the treatment of climax tropical formations. Structure and life form can be reduced to exact measurements in the field, and for types so recorded, the structure and life form of any desired formation may be mathematically defined. Structure is diagrammed from actual measurements. Life form can be expressed mathematically in percentages in various ways, such as stating that 56 percent of the trees forming the topmost story of the forest have compound leaves. Once this has been done, he points out, a worker elsewhere in the Tropics can determine the structure and life form of any forest community in the area and can readily tell how it compares with the "norm." An essential feature of the assessment is the profile diagram shown in figure D–1 (Beard 1949). Beard used a strip about 8 m wide by 60 m long.

Beard's formation series are defined by habitat. His classification includes one rain forest formation, six seasonal forests, two dry evergreen forests, nine montane forests, four swamps, and four marsh or seasonal swamps. He describes each formation in detail and then presents the following key to arborescent vegetation for use in the field (Beard 1944b):

1. Palms dominant or present in large numbers
 2. Tall palms, up to 20 m or more, emergent over lower woody or herbaceous growth
  3. Fan palms over a dense thicket of bushes and small trees 5 to 10 m high .... palm marsh
  3'. Fan or pinnate palms over low and irregular herbaceous or woody undergrowth with scattered small trees .... palm swamp
 2'. Palms not emergent
  3. Palm brake—low forest about 10 m high composed mainly of palms with no large trees, very luxuriant herbaceous ground vegetation, abundant moss and epiphytes .... mountain community
  3'. Marsh forest—forest with two tree strata, the upper consisting of scattered trees up to 25 to 30 m, the lower consisting mainly of palms and forming the canopy at 10 to 15 m .... lowland community
1'. Thicket of bamboo .... bamboo brake

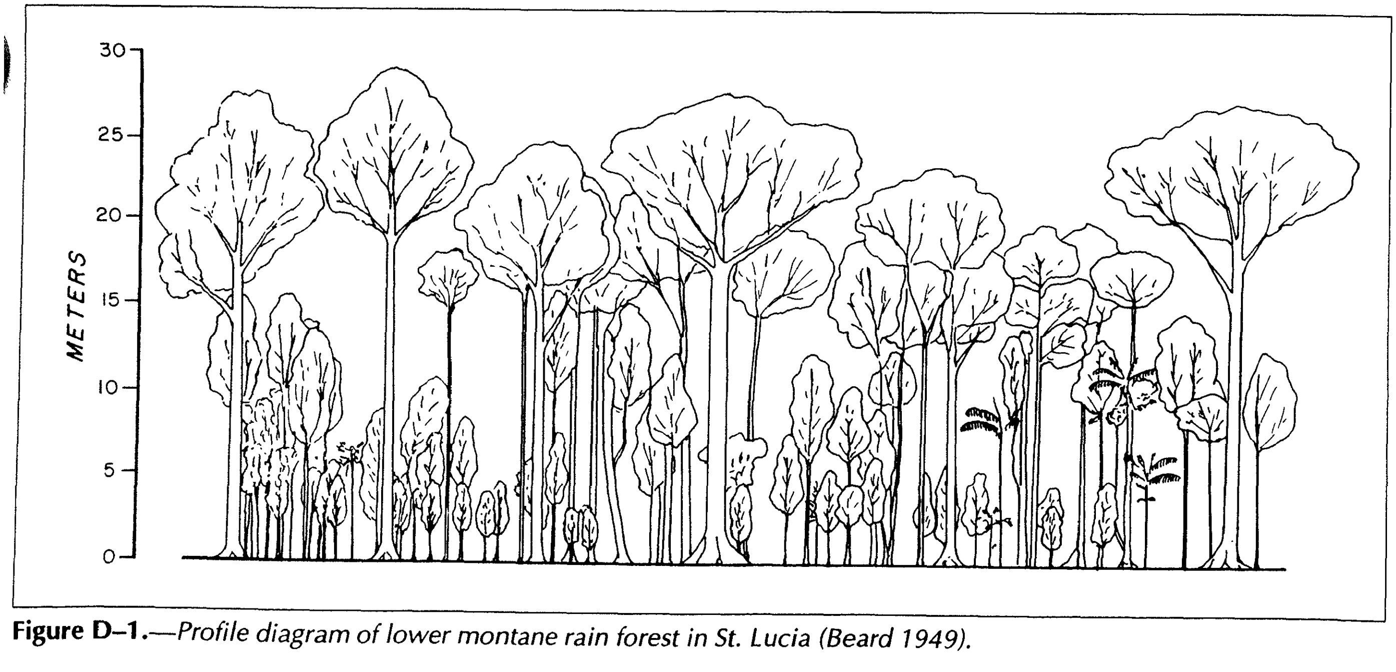


Figure D–1.—*Profile diagram of lower montane rain forest in St. Lucia (Beard 1949).*

1".Woody growth dominant, palms and bamboos not abundant
2. Tree growth over 10 m high
3. Deciduous species present........... seasonal forest
4. Tree strata 3, less than half of the individuals in the topmost story deciduous .... evergreen seasonal forest
4'. Tree strata 2, the upper open and with over two-thirds of individuals deciduous .... deciduous seasonal forest
3'. Forest entirely evergreen (or nearly so)
4. Tall forest with large trees forming a continuous canopy at 20 m or more above ground
5. Tree strata 3 or 4, dominants 40 m or more tall, leaves predominantly compound .... rain forest
5'. Tree strata 2, dominants about 30 m tall, leaves predominantly simple .... lower montane rain forest
5". Tree strata 2, dominants about 20 m tall, leaves simple, abundant moss, tree ferns present .... montane rain forest
4'. Lower forest without continuous canopy or with a canopy formed below 20 m from the ground
5. Pine forest .... mountain pine forest
5'. Broadleaved trees
6. Tree strata 2, the upper formed of scattered trees up to 30 m, the lower closed and forming the canopy at about 15 m .... xerophytic rain forest
6'. Tree strata 1, sometimes 20 m high, usually lower
7. Stilt roots or erect pneumatophores present; inundated tidally with brackish water .... mangrove woodland
7'. Sinuous plank buttresses or stilt roots and knee-shaped pneumatophores present; inundated with fresh water .... swamp forest

2'. Tree growth less than 10 m high
3. Species predominantly spinescent or thorny
4. More or less closed woodland of microphyllous, thorny trees 3 to 19 m high .... thorn woodland
4'. Open vegetation with abundant column cacti and prickly pears .... cactus scrub
4". Exceedingly sparse growth with large bare patches of soil .... desert
3'. Armed species few or absent
4. Vegetation markedly windswept
5. Trees covered thickly with moss and epiphylls; abundant epiphytes and climbers; a high mountain community ..... elfin woodland
5'. Moss scarce, no epiphylls, epiphytes and climbers very rare; a seashore community .... littoral woodland
4'. Vegetation not markedly windswept
5. A fairly open woodland containing some stout temperate genera present; high mountains .... frost woodland
5'. A dense woodland or thicket of small, branchy tree tropical genera .... lowland marsh woodland

Beard's system is easiest to apply in the areas where his familiarity with the vegetation was greatest, the Antilles and northern South America. One feature that has appeal is his listing of prominent species for each formation; this facilitates approximation where no climax vegetation remains. Fanshawe (1954) used the scheme to identify eight types of forests in Guyana.

Limitations exist in using Beard's classification system. It requires a knowledge of the climax forest, a disappearing resource. Therefore, there is already a need to key it into secondary forests, possibly using related physiognomic criteria. Another criticism comes from Grubb and others (1963), who consider it too reliant on stratification. Nevertheless, the principle of a system based on physiognomy, depending on natural rather than contrived representations of the features of each habitat, has much in its favor.

Beard (1953, 1967) made an intensive study of savanna vegetation, defining tropical American savannas as "communities comprising a virtually continuous, ecologically dominant stratum of more or less xeromorphic herbaceous plants, of which grasses and sedges are the principal components, and with scattered shrubs, trees or palms sometimes present." He concluded that in tropical America all climates, given suitable soil conditions, can and do support woody vegetation of some kind. The driest climates in tropical America support woodlands, never savannas. Savanna life forms indicate a response to soil rather than climate. He concluded that there is no such thing as a grassland climate in tropical America.

Beard contrasts tropical Africa and Australia with tropical America. In tropical Africa and Australia, annual rainfall of less than 100 cm is the rule rather than the exception. The grassy woodlands, savannas, and steppes of those regions are entirely absent in tropical America. Grasses are inconspicuous in American deciduous seasonal forests, thorn woodlands, and cactus scrubs. There are, nevertheless, large areas of grasslands in tropical America and, indeed, the word "savanna" is of Amerindian origin (Beard 1967). Savanna vegetation is fire hardy. Savannas are often swept by fires, but they do not depend on fire, being an edaphic climax vegetation type. They occur in areas of 100 to 300 cm of rainfall annually. They are, however, subject to impeded drainage and have intermittent perched water tables with alternate periods of waterlogging and desiccation, the latter too severe for tree growth. Sombroek (1966), who studied Amazon soils, agrees as to the essentially edaphic origin of the vegetation.

The term "derived savanna" refers to savannas generated by clearing or burning, practices that lead to increased drying of upper soil layers (Young 1969).

The Holdridge System

Holdridge's (1978) classification of world climates into life zones designates each with the name of a vegetative formation. The system, applied throughout Central America, northern South America, and some of the Greater Antilles, is useful in relating homoclimes (climatically similar environments). The system assumes that two annual average phenomena, rainfall and biotemperature define vegetative formations and relegates to a lower order seasonal and edaphic effects, considering them responsible for associations. Beard (1973) concluded that this approach puts some disparate types of vegetation in the same compartments and separates some similar types into different compartments. There is no doubt that in many areas zone limits cross continua at points not sharply reflected in the vegetation. Budowski (1964a) notes the possibility of providing for associations reflecting edaphic, hydric, or atmospheric phenomena within life zones. He also concludes that lack of fit may be due to human disturbances in the vegetation. Holdridge (1967) has proceeded to define associations within his life zones that are physiognomic. He set different limits of elevation for his altitudinal belts, depending on whether the basal zone is tropical or subtropical (table D–1).

In a similar effort, van Steenis (1972), concerned with the islands of Melanesia (latitude 5° S. to 20° S.), designated areas below 1,000 m in elevation, "tropical"; those from 1,000 to 1,500 m, "subtropical"; those from 1,600 to 2,400 m, "montane"; and those from 2,500 to 4,000 m, "subalpine."

In contrast to Holdridge, Troll (1958) emphasized climatic seasonality in his classification scheme, using the number of what he terms "humid months" as the sole criterion for separating wet from dry formations (table D–2).

The Unesco System

An attempt to standardize the classification of vegetation worldwide was made by a Unesco committee (Anon. 1978b). The international aegis of the organization and early favorable reactions to its approach (Kuchler and Montoya-Maquin 1971) suggest that it may become widely used. The tropical and subtropical formations recognized are as follows:

I. Closed forest (at least 5 m tall and tree crowns interlocking)
  IA. Mainly evergreen (canopy never without green foliage)
    IA1. Tropical ombrophyllous forest (rain forest) (neither cold nor drought resistant)
      IA1a. Evergreen lowland forest
      IA1b. Submontane forest
      IA1c. Montane forest (broadleaved, needle-leaved, microphyllous trees and bamboo)
      IA1d. Subalpine forest
      IA1e. Cloud forest (epiphytes; gnarled, broadleaved, needle-leaved, microphyllous trees)
      IA1f. Alluvial forest (riparian, occasionally flooded, seasonally waterlogged soil)
      IA1g. Swamp forest (broadleaved trees and palms)
      IA1h. Bog forest
    IA2. Tropical and subtropical evergreen seasonal forest
      IA2a. Lowland
      IA2b. Submontane (broadleaved, needle-leaved trees)
      IA2c. Montane (no tree ferns)
      IA2d. Dry subalpine

Table D–1.—Life zones within the Tropics

	Mean biotemperature (°C)				
	>24°C Tropical	18–24°C Premontane and subtropical	12–18°C Lower montane	6–12°C Montane	3–6°C Subalpine
Mean annual precipitation (cm)					
>800	Rain forest				
400–800	Wet forest	Rain forest	Rain forest		
200–400	Moist forest	Wet forest	Wet forest	Rain forest	
100–200	Dry forest	Moist forest	Moist forest	Wet forest	Rain forest
50–100	Very dry forest	Dry forest	Dry forest	Moist forest	Wet forest
25–50	Thorn woodland	Thorn steppe		Steppe	Moist forest
12.5–25	Desert Scrub	Desert scrub		Dry scrub	
Potential evapotranspiration/year (cm)	>141	106–140	71–105	36–70	18–35
Elevation range (10^3 m)					
Tropical at sea level	0–1	0–2	1–3	2–4	3–4.5
Subtropical at sea level		0–1	0–2	1–3	

Source: Holdridge 1967.

- IA3. Tropical and subtropical semideciduous forest
  - IA3a. Lowland
  - IA3b. Montane or cloud
- IA4. Subtropical ombrophyllous forest (very local)
- IA5. Mangrove
- IA9. Tropical and subtropical, evergreen, needle-leaved forest
  - IA9a. Lowland and submontane
  - IA9b. Montane and subalpine

IB. Mainly deciduous forest
- IB1. Tropical and subtropical drought-deciduous forest
  - IB1a. Lowland and submontane
  - IB1b. Montane and cloud

IC. Extremely xeromorphic forest
- IC1. Sclerophyllous (leather leaved trees) dominated by extremely xerophytic forest
- IC2. Thorn forest
- IC3. Mainly succulent forest

II. Woodland
- IIA. Mainly evergreen woodland
  - IIA1. Broadleaved
  - IIA2. Needle-leaved
    - IIA2a. With rounded crowns *(Pinus)*
    - IIA2b. With evergreen sclerophyllous understory
    - IIA2c. Without evergreen sclerophyllous understory
- IIB. Mainly deciduous woodland
- IIC. Extremely xeromorphic woodland

III. Scrub (mainly composed of caespitose (clumped) woody phanerophytes 0.5 to 5.0 m tall)

IV. Dwarf scrub.

Table D-2.—Drought influence on forest types

No. of humid months	Lowland type	Lower montane type
11–12	Evergreen	Montane
10	Semi-evergreen	Montane
7–9	Moist deciduous	Moist (valleys)
5–6	Dry deciduous	Dry (valleys)
2–4	Thorn	Thorn
1	Desert scrub	Desert scrub
0	Desert	Desert

Source: Troll 1958.

Regional and Subregional Vegetation Types

As the classification of forests is gradually based on more intimate knowledge of their character from place to place, an important subsequent step is the description of regional vegetation types. For tropical America, the outstanding example is Hueck's (1957) description of the natural vegetation of 33 tropical regions of South America (table D–3, fig. D–2). He gives a general description of the climate, structure, and the composition of the vegetation, and lists the species of economic importance in each region. Such works strengthen or correct broader systems of classification and are a necessary preliminary to land-use planning and management.

On a subregional scale, some of the forests of tropical America have been classified in great detail. An example is in the Amazon Basin (Aubreville 1961; Dubois 1971; Ducke and Black 1953; Pires 1974; Prance 1978, 1982; Veloso 1962). The Amazon valley supports perhaps a million plant and animal species, more than 50,000 of which are higher plants, about one-fifth of the world's total. The following classification system and volume of the forests vary more with soil than with climate; volume is highest near Caxuana, Brazil, with 200 cm of mean annual rainfall:

Terra firme—Forests are not subject to flooding covering some 85 percent of Amazonia. Their composition varies greatly. On loamy soils, the trees are tall, canopy is dense, lianas are large, and groundcover is sparse. Wood volume ranges from 160 to 270 cubic meters per hectare. On sandy soils, the forest is significantly poorer with mostly large trees. Wood volume is 100 to 150 m³/ha.

Table D-3.—Regions of tropical South America according to type of vegetation

1. The delta of the Amazon
2. The forests northeast of the Amazon (Paru-Jari)
3. The Tocantins and Gurupi regions
4. The middle and lower Xingu and the Tapajos
5. Rios Madeira and Purus
6. The western hyleia
7. The northwest hyleia (Rio Negro)
8. Flooded forests of the Amazon and lower Madeira
9. Acre, Beni, Mamore, and Griapore
10. The hyleia near the Andes
11. Caqueta, Vaupes, and Guainia
12. Tributaries of the right margin of the Orinoco
13. The Guianas
14. The delta of the Orinoco
15. The Tucuman-Bolivian forest
16. Forests of the eastern slope of the central Andes
17. High-altitude forests of the northern Andes
18. Rain forests of the Pacific and the Caribbean
19. The Colombian-Venezuelan tradewind forests
20. The coastal forests of Brazil
21. Subtropical forests of eastern and southern Brazil
22. Araucaria forests of southern Brazil
23. Dry forests of the true Chaco
24. The eastern Chaco
25. The Santa Cruz-Trinidad savanna region
26. Forests of the Velasco mountain region
27. Typical campos Cerrados
28. Moist and wet forests of the Cerrados
29. Typical caatinga
30. Moist forests of the caatinga region
31. The Babassu palm region
32. Dry forests of the Caribbean coasts of Colombia and Venezuela
33. The interior valleys of the Andes

Source: Hueck 1957.

Varzea—Forests are subject to periodic flooding, except blackwater (see "igapo" below) covering about 55,000 km². They tend to be denser than the terra firme forests but less rich in species. Buttresses and respiratory roots are common.

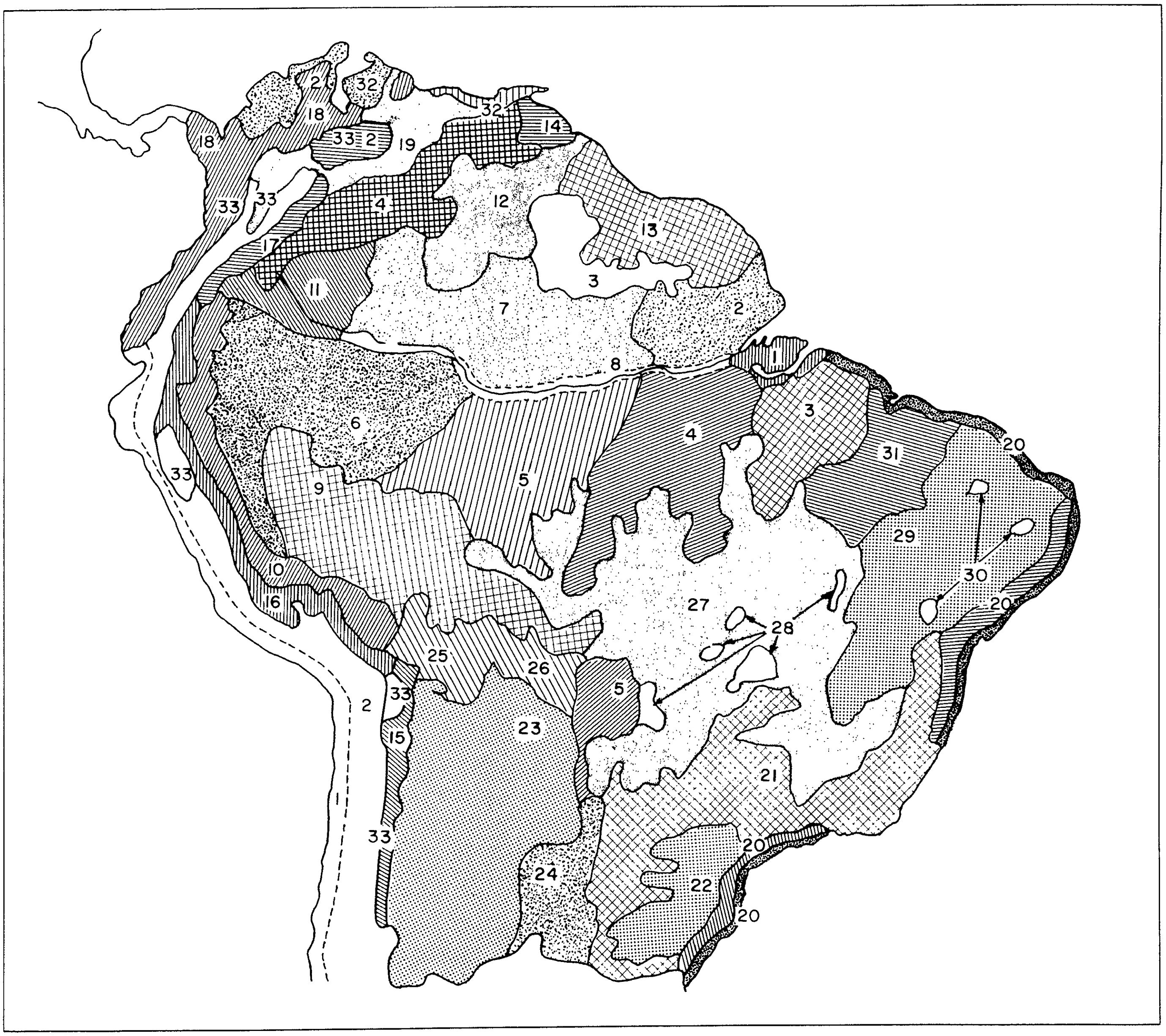


Figure D-2.—*Hueck's 33 vegetation regions of tropical South America; table D-3 defines the circled numerals (Hueck and Seibert 1988).*

Tidal varzea—Forests are flooded twice daily with fresh water; similar to seasonal varzeas. They contain palms, *Guazuma, Hevea, Symphonia,* and *Virola.*

Seasonal varzea—Forests are along clearwater rivers that flood annually for weeks. They contain *Carapa, Ceiba,* and *Hura.* Along blackwater rivers, they may contain *Virola.*

Rain varzea—Forests are flooded because of heavy rains, not by rivers. They contain *Carapa, Ceiba,* and *Virola.*

Igapo—Swamp forests are flooded annually by blackwater rivers and permanently waterlogged covering about 15,000 km^2. Blackwater rivers in the Amazon Basin generally drain areas of white sand. The color is caused by humic acids originating from incomplete decomposition of organic matter. This water is highly acid and, in stagnant areas, low in oxygen (Carter 1934, Medina 1978). Trees of few species tend to be short, twisted, and sclerophyllous. These areas contain *Bombax, Cecropia,* and *Hevea.*

Savanna—Trees are low and sparse covering about 30,000 km^2.

Campina—Trees are low and much branched growing on leached, white sands and covering about 115,000 km^2.

Montane vegetation—These are forests of the basin fringe, with high endemism.

Coastal vegetation—Forests are on sand dunes, covering about 10,000 km^2 composed mostly of *Chrysobalanus.*

Mangrove—Forests are subject to marine tidal influence near mouths of rivers. They have few species, short trees, low volumes, and cover about 1,000 km^2.

For general descriptions of tropical forests, broad classifications with little detail have been used. For example, Haig and others (1958b), in a worldwide treatment of the subject, used the following simple scheme:

- Wet evergreen—dominants entirely or mainly evergreen; typically 200 cm or more of rainfall annually, with little or no water deficiency
- Moist deciduous—dominants mainly deciduous; 125 to 200 cm of rainfall annually, 4 to 6 months dry
- Dry deciduous—dominants entirely deciduous or almost so, less than 125 cm of rainfall per year
- Mangrove
- Bamboo
- Conifers

Mangroves

The total area of mangroves in the world is estimated to be about 2,500,000 ha, at least 75 percent of which is in the Eastern Hemisphere (Molski 1970). Mangroves grow along protected seashores and saline estuaries to latitudes as high as 30°, withstanding brief frosts at the extremes (Cintron 1982). The seven mangrove species of the Western Hemisphere are not obligate halophytes but escape vegetative competition by tolerating a saline environment. Mangroves fed by inland waters are among the most productive ecosystems on the planet. They contribute to the stability of rapidly accreting shorelines, but the extent to which they promote accretion itself is unclear.

There are three general types of mangroves: riverine (estuaries with continuous waterflow and low salinity), fringe (areas with a pronounced gradient in topography or tidal amplitude), and basin (areas with a low gradient and sluggish water). Riverine mangroves produce about 24 g of organic matter per square meter per day, whereas fringe mangroves produce about 13 g, and basins about 18 g (Cintron 1982). Litterfall ranges from 2 to 4 grams per square meter per day.

Cerrado Vegetation

Cerrado vegetation is so extensive and distinctive that it deserves further description. It is semideciduous, xeromorphic vegetation covering some 1.5 million km^2 in central Brazil (Ferri 1961). It gives way to mesic (medium moisture conditions) forests on the west and southeast, to caatinga on the northeast, and to chaco on the southwest (Eiten 1972). The soils are usually deep, rainfall ranges from 130 to 200 cm annually, and 3 to 5 months are almost without rain. The rainfall in the driest month may be 1 to 3 cm, compared with 4 to 20 cm along the Amazon, where the effective dry season averages only 2 weeks (Eiten 1972). The tree roots in cerrado may go down 10 m. Evidence of adequate groundwater is seen in the high rate of transpiration.

Eiten (1972) describes cerrado as having tall, woody plants characterized by thick bark, leaning and twisted trunks, twisted boughs, thick twigs, open crowns, and large leaves (table D–4). The cerrado region ranges from arboreal woodlands to open savannas and pure grasslands and has soils with low nutrient contents and high available aluminum (Latosols). There is no evidence that large areas formerly in forest have become cerrado. Conversely, cerrado protected from fire shows no tendency to succeed to forest. It occurs solely on certain geological formations and soils (Eiten 1972).

The Instituto Brasileiro de Geografia e Estadistica recognizes the following types of cerrado (Eiten 1972):

1. *Cerradao*—arborescent woodland
2. *Cerrado*—low forest, closed or slightly open scrub
3. *Campo cerrado*—tree and scrub savanna
4. *Campo sujo* or *limpo*—grassland, pure or with dwarf shrubs.

Table D–4.—Stand characteristics of cerrado forests

Type of cerrado	Trees (no./ha)	Basal area (m^2/ha)	Stem height (m)
Cerrado	1,092	16.5	5.9
Tipico	819	10.2	5.2
Ralo	616	6.1	4.4
Campo	273	2.1	3.8

Source: Eiten 1972.

Ferri (1961) contrasts caatinga with cerrado. Caatinga may be either deciduous or evergreen. Deciduous caatinga has low transpiration; evergreen caatinga is more like cerrado, with high rates of transpiration. Deciduous caatinga receives about 50 cm of rainfall annually; while evergreen may receive 200 cm. Ferri explains the poverty of these formations as being due to limited nutrients in evergreen caatinga, limited water in deciduous caatinga, or combinations of both.

Appendix E
Chronological Development of Forest Refinement

Date	Event	Reference
1880–1900	Very large forest areas in Southeast Asia subjected to improvement fellings	Dawkins 1916a
1892–1922	Improvement fellings in what is now Myanmar brought on teak *(Tectona grandis)* reproduction and doubled growing stock	U Kyaw 1953
1900–1910	Young gutta percha trees liberated in natural forests of what is now Malaysia	Barnard 1954
1906	Silvicultural practices in rain forests begun in Andaman Islands	Baur 1964a
1906	Thinnings applied in management of natural forests of the Sundarbans in India	Sen Gupta 1952
1907	First improvement fellings undertaken in what is now Sri Lanka	Holmes 1956
1910	First natural forest treatment in what is now Malaysia (applied to 20,000 ha by 1920)	Baur 1964a
1926	Liberation and inducement of mahogany *(Swietenia macrophylla)* seedlings in cutover forests tested in what is now Belize on 1,800 ha	Anon. 1927
1935–41	Poison use initiated in improvement fellings in what is now Malaysia	Barnard 1954
1937	Improvement fellings begun in Puerto Rico	Author, personal communication
1945–54	Tending technique perfected in what is now Malaysia	Barnard 1954
1954	Improvement fellings applied throughout many of the forests of India and what is now Sri Lanka	Stracey 1959
1955	Improvement fellings became standard practice in naturally regenerated teak forests in what is now Myanmar	Long 1955
1957–60	Testing of liberation of understory before and after exploitation in Brazil	Pitt 1961a
1957	Improvement fellings recommended for Costa Rica to reduce density and eliminate nontimber species	Holdridge 1957
1980	A variant known as liberation thinning, in which crop trees are identified and liberated to a degree defined mathematically, became central to silviculture of residual hill dipterocarps in Sarawak	Hutchinson 1980

Appendix F
Selecting Tropical Tree Species for Planting

The process of selecting tree species for planting will concern foresters into the distant future. With time, the objectives of planting may change, new or modified sites will become available, and attributes of more tree species, varieties, provenances, and genotypes will become known or be developed.

The selection of a species for a specific site and purpose depends on a growing fund of information about each option. Some of this information is so specific or so subject to change or to primarily local variables that generalization can be no more than a preliminary guide. All that is attempted here is to present a succinct compendium of information of a universal, probably durable, nature to remind foresters concerned with any sets of conditions under which species might be categorized as probables, possibles, or improbables. This information is incomplete, evidenced by the absence of some data. Much of this information may exist but was not found in the sources reviewed.

Once a species has been selected, the next step is more detailed and specific. A large amount of additional information should be obtained on subjects such as silvicultural practices; seed weight, sources, and handling; propagation; and pests and diseases.

The information included here was collected from a number of sources. Conflicting information was screened to favor the source that is apparently most representative of plantations growing under reasonably favorable circumstances.

Name. The most commonly accepted scientific name, with author, is followed by commonly used vernacular names.

Elevation. Two ranges of elevation are given in meters, the first corresponding to latitude 24° N. and the second (in parentheses) corresponding to latitude 10° S. These data, based on the study by Webb and others (1984), indicate where prospects of success seem greatest. Nevertheless, with unusual conditions of moisture, temperature, or soil, testing may show greater adaptation.

Rainfall. The range of annual rainfall is indicated in centimeters; the number of dry months and their season (W = cool and S = warm) are given in parentheses.

Soil. The soils corresponding to best development are described first; known tolerances of inferior conditions are then listed.

Resistance. References to resistance to frost (Fr), fire (F), and wind (W) are given. Where appropriate, low-temperature limits are shown. Slashes indicate evidence of a lack of resistance. Frost resistance of large trees is greater than that of small trees, and temperature tolerance varies with duration of the cold, moisture, and other factors. Wind resistance does not necessarily imply resistance to hurricanes, only to lesser winds.

Synonym. Only currently and widely used scientific names other than the accepted name are noted.

Utility. The first line shows the upper limit of diameter at breast height (d.b.h.) in nature; this is given in meters, to the nearest decimeter, and is followed by a slash and the corresponding height in meters (1.2d.b.h./20–30ht). These upper limits are usually much larger than minimal commercial maturity, but this indicates the degree to which commercial sizes might be attained by trees that are still young. This information is followed on the first line by a whole number or range of whole numbers corresponding to the reported specific gravity of the wood times 10 (4.5g). This is usually, but not always, based on oven-dry weight and green volume. The second line concerns traditional or prospective wood uses:

F = One or more of the following: furniture, cabinet work, interiors, millwork, moldings, novelties, musical instruments, or carving

V = Veneer or pulpwood, utility plywood, or core stock

T = Turnery, novelties, or carving

C = One or more of the following: light construction, heavy construction, boat building, flooring, carpentry, boxes, tools, handles, pallets, crossties, or decking

Pu = Pulpwood or particle board

Po = Poles or posts

Fu = Fuel (including charcoal)

R = Soil reclamation, erosion control, or dune stabilization

A = Agroforestry, including taungya and other forms of integral production with food or fodder crops

MAI. Mean annual increment to maturity for the most logical product is expressed in cubic meters per hectare (m^3/ha) or in some instances in tonnes per hectare (t/ha). There is no consistency with regard to outside or inside bark, or top diameter, because these are not always stated in source documents. Branchwood and bark are usually excluded. Where widely various levels are shown, such as in yield tables for different site qualities, data for slightly better than medium sites were used, rather than extremes. These figures are generally derived from living stands and are generally somewhat larger than actual yields to be expected from harvested crops. The letter "c" shown after the MAI figures indicates that the species reportedly coppices well enough for one or more coppice crops. These commonly exceed in yield the seedling crops cited in the MAI figures.

Growth. This factor is included primarily to give some idea of the rapidity of early height growth on sites to which the species is well adapted, reflecting the length of the period of weeding or vulnerability to fire, browsing, or frost prior to canopy closure. The height in meters precedes the slash, and the number of years follows it. The heights are not maxima but are commonly "top height," meaning the average height of the 10 percent of the trees with the largest diameters on sites to which the species is well adapted.

Planting. The complexity of plantation establishment is indicated, including the prospects for direct sowing or mechanized planting of bare-root stock or cuttings.

S = Direct sowing, may dominate weeds without attention; aerial, broadcasting, or spot-seeding

B = Bare-root stock, including possibly wildings

Str = Striplings, bare-root with leaves partially removed

Stu = Stumps, bare-root with stem removed

C = Containerized stock, baskets, pots, bags, and tubes

Cu = Stem or root cuttings

u = Sufficiently tolerant to be suitable for underplanting with direct overhead light

Source. The extremes of the native range of the species (not necessarily the source of seeds) are given, along with the range in latitude.

References. The most important general sources follow:

fuelwood yields	Burley (1980c)
timbers	Chudnoff (1984)
Australia	Fenton and others (1977)
Latin America	Flinta (1960)
dry forest species	Goor (1955)
	Goor and Barney (1968)
Central America	Loock (1950)
Trinidad	Marshall (1939)
tropical Africa	Parry (1954a, 1954b, 1954c)
what was formerly Zaire	Pierlot (1958)
the British Commonwealth	Streets (1962)
the Tropics generally	Webb and others (1984)

In addition, the following references listed chronologically by individual species, were consulted:

Acacia spp.	Giffard (1975)
	Anon. (1983b)
Acrocarpus fraxinifolius	Burns and Mosquera (1988)
Agathis spp.	Anon. (1961a)
	Whitmore (1977)
	Bowen and Whitmore (1980)
	Francis (1984–present)
Albizia lebbek	Parrotta ([n.d.]a)
A. procera	Parrotta ([n.d.]b)
Anacardium occidentale	Bascope and others (1958)
	Lefebvre (1966)
	Goujon and others (1973)
Andira inermis	Weaver (1989)
Anthocephalus chinensis	Grijpma (1967)
	Lugo and Figueroa (1984, 1985)
Araucaria spp.	Anon. (1960a)
	Ntima (1968)
	Golfari (1970a)
Aucoumea klaineana	Biraud and Catinot (1960)
	Deval (1976)
Avicennia germinans	Jimenez and Lugo (n.d.)

Azadirachta indica	Anon. (1963a)
	Parrotta and Chaturvedi (1994)
Bambusa vulgaris	Anon. (1962a)
	Groulez (1966)
	Francis (1984–present)
Brosimum alicastrum	Burns and Mosquera (1988)
Bucida buceras	Francis (1984–present)
Bursera simaruba	Francis (1984–present)
Calophyllum calaba	Burns and Mosquera (1988)
	Weaver (1990a)
Casuarina equisetifolia	Anon. (1961c)
	Burns and Mosquera (1988)
	Parrotta (1993)
Cedrela odorata	Bascope and others (1957b)
	Anon. (1962b)
	Burns and Mosquera (1988)
	Lamb (1968d)
Ceiba pentandra	Anon. (1975d)
	Chinea-Rivera (1990)
Chlorophora excelsa	Anon. (1973c)
Cordia alliodora	Johnson and Morales (1972)
	Burns and Mosquera (1988)
	Liegel and Stead (1990)
Cunninghamia lanceolata	Anon. (1961d)
Cupressus spp.	Anon. (1960d)
Dalbergia sissoo	Anon. (1962c)
	Parrotta (1989)
Entandrophragma cylindricum	Anon. (1974e)
E. utile	Anon. (1973d)
Entrolobium cyclocarpum	Francis (1984–present)
Eucalyptus spp.	de la Lama Gutierrez (1976–77)
	Jacobs (1981)
E. camaldulensis	Anon. (1963b)
	Eldridge (1975)
E. deglupta	Grijpma (1969)
	Francis (1984–present)
E. grandis	Anon. (1959a)
	Burns and Mosquera (1988)
E. robusta	Gueneau (1969)
	Burns and Mosquera (1988)
E. saligna	Anon. (1959a)
	Burns and Mosquera (1988)
E. tereticornis	Anon. (1963b)
Gliricidia sepium	Parrotta (1992a)
Gmelina arborea	Lamb (1968c)
	Boulet-Gercourt (1977)
	Greaves (1981a)
	Burns and Mosquera (1988)

Grevillea robusta	Nelson (1960)
	Burns and Mosquera (1988)
	Bokkestijn and Francis (n.d.)
Guaiacum officinale	Francis (1984–present)
Guazuma ulmifolia	Francis (1984–present)
Hibiscus elatus	Swabey (1940)
	Weaver and Francis (n.d.)
Hura crepitans	Francis (1984–present)
Hymenaea courbaril	Francis (1984–present)
Khaya spp.	Anon. (1959g)
	Burns and Mosquera (1988)
	Bokkestijn and Francis (n.d.)
Laguncularia racemosa	Jimenez (n.d.)
Leucaena leucocephala	Anon. (1977c)
	Parrotta (1992b)
Lophira procera	Anon. (1976c)
Maesopsis eminii	Francis (1984–present)
Manilkara bidentata	Weaver (1990b)
Mitragyna ciliata	Anon. (1976d)
Musanga cecropioides	Doat (1971)
Nauclea diderichii	Anon. (1975a)
Ochroma pyramidale	Anon. (1961f)
	Francis (1984–present)
Paulownia spp.	Moraes Victor and others (1974)
	Anon. (1974d)
Pinus spp.	Critchfield and Little (1966)
	Mirov (1967)
	Palmer (1977)
P. caribaea	Anon. (1958f)
	Lamb (1973)
	Francis (1984–present)
P. kesiya	Anon. (1960f)
	Armitage and Burley (1980)
	Gueneau (1970)
P. merkusii	Anon. (1959i)
	Cooling (1968)
P. oocarpa	Burns and Mosquera (1988)
P. patula	Anon. (1959j)
	Gueneau (1970)
	Wormald (1975)
	Gillespie (1992)
Pithecolobium saman	Burns and Mosquera (1988)
Podocarpus respligliosii	Lamprecht (1954)
Prosopis juliflora	Anon. (1962f)
	Burns and Mosquera (1988)
Rhizophora mangle	Jimenez (1985)
Schefflera morototoni	Liegel (1990)
Senna siamea	Anon. (1960b)
	Parrotta and Francis (1990)

Swietenia spp.	Bascope and others (1957a) Anon. (1959) Lamb, F. B., (1966) Francis (1984–present)
Tabebuia donnell-smithii	Lamb (1951) Francis (1984–present)
Tectona grandis	Horne (1966) Wood (1968) Weaver (1993)
Terminalia catappa	Francis (1984–present)
T. ivorensis	Lamb and Ntima (1971) Anon. (1974b) Francis (1984–present)
T. superba	Anon. (1974c) Tariel and Groulez (1958)
Toona ciliata	Anon. (1962b)
Triplochiton scleroxylon	Anon. (1976i)
Vochysia spp.	Normand (1966–67)

Species Information

Abies guatemalensis Rehd.
Common Name: Guatemala fir
Elevation: 1,800–3,200 (1,300–2,700)
Rainfall:
Soil:
Resistance:
Synonym:
Utility: .9dbh/35ht
MAI:
Growth: 2/6
Planting:
Source: Mexico to Guatemala, 20° to 14° N.

Acacia auriculiformis A Cunn. ex Benth
Common Name: Tan wattle
Elevation: 0–500
Rainfall: 130–170 (3–6 W)
Soil: Heavy—tolerates shallow, calcareous, sandy soils; acidity; alkalinity; and impeded drainage
Resistance: W
Synonym:
Utility: .6dbh/30ht/5–8g
Pu, Po, Fu, R
MAI: 6–20 c
Growth: 6/2, 14/5, 17/8
Planting: S, C, U
Source: Papua New Guinea to Queensland, Australia, 7° to 20° S.

Acacia mangium Willd.
Common Name:
Elevation: 500–1,200 (0–700)
Rainfall: >160
Soil: Sandy loam—tolerates poor acid soils and impeded drainage
Resistance:
Synonym:
Utility: 30ht/4–6g
F, C, Pu, Po, Fu
MAI: 20–46 c
Growth: 18/4, 23/9
Planting: S, B, C, Stu
Source: Queensland, Australia, 11° to 19° S.

Acacia mearnsii de wild.
Common Name: Acacia negra, black wattle
Elevation: 1,500–2,500 (1,000–2,000)
Rainfall: 90–160 (2–3 W)
Soil: Deep, free-draining—tolerates poor or heavy soil but not calcareous ones
Resistance: Fr (moderate), W
Synonym: *A. decurrens* var. *mallis* Lindl.
Utility: 7–20ht/5–8g
Pu, Po, Fu, tanning, R, A
MAI: 14–25
Growth: 10/5, 15/9, 20/12
Planting: S, B
Source: Queensland to Tasmania, Australia, 25° to 43° S.

Acacia melanoxylon R. Br.
Common Name: Blackwood
Elevation: 1,500–2,500 (1,000–2,500)
Rainfall: 90–270 (0–2)
Soil: Deep, free-draining—tolerates sand and acidity
Resistance: Fr (–10 °C)
Synonym :
Utility: 1.2dbh/18–30ht/6–7g
FC, Po, Fu
MAI: 5–12 c
Growth: 12/6, 22/16
Planting: Stu, C
Source: Queensland to Tasmania, Australia, 34° to 43° S.

Acacia senegal Willd.
Common Name: Goma, gum arabic
Elevation: 0–500
Rainfall: 20–50 (6–11 W)
Soil: Free-draining—tolerates acidity and poor, heavy, and sandy soils
Resistance: Fr, W
Synonym: *A. verek* Guill. and Perr.
Utility: .6dbh/2–10ht
Fu, A, Po, R, gum
MAI: 4–7 c
Growth: 1/3
Planting: S, C
Source: Senegal to the Red Sea, 11° to 18° N.

Acrocarpus fraxinifolius Wight
Common Name: Indian ash, pink cedar
Elevation: 0–1,500 (0–1,000)
Rainfall: 110–160 (0–4 W)
Soil: Deep, free-draining—tolerates acidity but not impeded drainage
Resistance:
Synonym:
Utility: 3.0dbh/30–50ht
F, C, Fu, A
MAI: 10
Growth: 8/3, 11/4
Planting: C
Source: Myanmar to India, 17° to 23° N.

Agathis dammara L. C. Richard
Common Name: Damar
Elevation: 100–1,600 (0–1,100)
Rainfall: 200–400 (0–2)
Soil: Free-draining—tolerates heavy soil and acidity but not impeded drainage
Resistance: W
Synonym: *A. loranthifolia* R.A. Salisbury
Utility: .6dbh/45–60ht/4–5g
C, Pu
MAI: 20–30 (20 t)
Growth: 8/6
Planting: C, Cu, u
Source: Southeast Asia and the Pacific, 11° to 20° N.

Species Information

Agathis robusta (C. Moore ex F. Muell) F.M. Bailey
Common Name: Queensland kauri
Elevation: 100–900 (0–1,100)
Rainfall: 110–500 (0–2)
Soil: Free-draining—tolerates heavy soil and acidity but not impeded drainage
Resistance: W (old trees only), Fr
Synonym:
Utility: .4dbh/45–60ht/4–5g F, C, V, Pu
MAI: 20–35 (20 t)
Growth: 8/6, 14/20, 27/50
Planting: C, Cu - u
Source: Papua New Guinea to Australia, 5° to 28° S.

Albizia lebbek (L.) Benth
Common Name: Acacia amarilla, siris
Elevation: 0–1,400 (0–900)
Rainfall: 50–250 (2–6 W)
Soil: Free-draining—tolerates acidity, alkalinity, and heavy and eroded soils
Resistance: Fr (slight)
Synonym: *Mimosa lebbek* L.
Utility: 1.5dbh/25–30ht/4–6g F, Fu, Po, A
MAI: 5–18
Growth: 2/1, 5/3, 18/10
Planting: S, B, Stu, Cu
Source: India to Myanmar, 27° to 11° N.

Albizia procera (Roxb) Benth
Common Name: Albizia, white siris
Elevation: 0–1,000 (0–500)
Rainfall: 100–500 (0–3 W)
Soil: Deep, free-draining—tolerates shallow soils and acidity
Resistance: W
Synonym:
Utility: .6dbh/25ht/6–9g F, Pu, Fu, A, R
MAI: 10 c
Growth: 12/6, 23/13
Planting: B, Stu
Source: India to Papua New Guinea, 15° N. to 10° S.

Alnus acuminata O. Ktze
Common Name: Jaul, aliso
Elevation: 1,200–3,200 (700–2,700)
Rainfall: >100
Soil: Deep, sandy, free-draining
Resistance: Fr (slight)
Synonym: *A. jorullensis* H.B.K.
Utility: .4dbh/25ht/5–6g F, C, Fu, R, A
MAI: 10–15
Growth: 16/11
Planting: B, Cu
Source: Mexico to Argentina, 18° N. to 23° S.

Anacardium excelsum (Bert. & Balb.) Skels
Common Name: Espave, cajú assú
Elevation:
Rainfall: 150–200 (W)
Soil:
Resistance:
Synonym:
Utility: 1.5dbh/45ht/4–6g F, V, C, Pu
MAI:
Growth:
Planting:
Source: Honduras to Ecuador, 16° N. to 5° S.

Anacardium occidentale L.
Common Name: Maranon, cajú pajuil, cashew
Elevation: 0–900 (0–400)
Rainfall: 160–400 (3–6 W)
Soil: Free-draining—tolerates shallow, poor, or sandy soils
Resistance: Fi
Synonym:
Utility: .3dbh/8ht/5g A, nuts, fruit, resin
MAI: 250 kg/ha fruits c
Growth:
Planting: S
Source: The West Indies to Brazil, 24° N. to 10° S.

Andira inermis (W. Wright) D.C.
Common Name: Moca, maquilla, acapúrana
Elevation: 0–900
Rainfall: 100–400
Soil: From sandy soils to poorly drained clays
Resistance: W
Synonym: *A. jamaicensis* (W. Wright)
Utility: 1.5dbh/35ht/6g F, T, C
MAI:
Growth: 2/9
Planting: S
Source: Mexico and the West Indies to Brazil, 23° N. to 20° S.

Aniba spp.
Common Name: Silvervalli, pao rosa
Elevation:
Rainfall:
Soil:
Resistance:
Synonym:
Utility: .8dbh/30ht/5–6g F, T, C
MAI:
Growth: 7/8
Planting:
Source: Amazonia-Colombia to Guyana, 10° N. to 5° S.

Anogeissus latifolia Wall.
Common Name: Damas
Elevation: 0–800 (0–300)
Rainfall: 25–60 (6–8 W)
Soil: Sandy, alkaline—tolerates salinity and impeded drainage
Resistance: Fi
Synonym: *Conocarpus latifolius* Engler
Utility: 1.0dbh/20ht/8–9g C, Po, Fu, Po
MAI: 5–10 c
Growth: 6/11
Planting: Str, Stu, C
Source: Somalia, 10° to 11° N.

Anthocephalus chinensis (Lamk) Rich.
Common Name: Kadamba, bengkal, kadam, laran
Elevation: 0–1,000 (0–500)
Rainfall: >160 (0–3)
Soil: Light, free-draining—tolerates acidity and impeded drainage but not degraded soils
Resistance: Fr (slight), W
Synonym: *A. cadamba* (Roxb) Miq. *Neolamarckia cadamba* Bosser
Utility: 1.0dbh/45ht/3–7g V, C, Pu, R, matches
MAI: 10–30 c (young)
Growth: 3/1, 7/4, 10–25/9
Planting: S, B, C, layering, u
Source: India to Papua New Guinea, 17° N. to 9° S.

Araucaria angustifolia (Bert.) O. Kuntze
Common Name: Pino brasileiro, pino paraná, parana pine
Elevation: 1,500–2,200 (1,000–1,700)
Rainfall: 125–220 (0–2 W)
Soil: Deep, fertile, free-draining acid clays—does not tolerate salinity
Resistance: Fr (-7 °C), Fi, W
Synonym: *A. brasiliana* A. Rich.
Utility: 2.0dbh/60ht/5–6g F, C, Pu, Po, seeds
MAI: 8–24
Growth: 4–7/5, 9–16/10, 11–21/15
Planting: S, C, u
Source: Brazil to Argentina, 10° to 30° S.

Araucaria cunninghamii Sweet
Common Name: Hoop pine
Elevation: 0–2,000 (0–1,500)
Rainfall: 100–180 (2–4 W)
Soil: Deep, fertile, free-draining—tolerates acidity, heavy soils, and gravelly sands
Resistance: Fr (slight), W
Synonym:
Utility: 1.2dbh/35–45ht/5–6g F, V, C, Pu, Po
MAI: 10–18
Growth: 5–12/6, 19/9, 26/12
Planting: C, Cu, u
Source: Papua New Guinea to Australia, 8° to 32° S.

Appendix F

Species Information

Araucaria hunsteinii K. Schumann
Common Name: Klinki pine
Elevation: 200–2,900 (0–2,400)
Rainfall: 160–400 (0–2 W)
Soil: Deep, free-draining, fertile—tolerates heavy soils but not impeded drainage
Resistance:
Synonym: *A. klinkii* Lauterbach
Utility: 1.0dbh/40–80ht/4–5g F, V, C, Pu, Po
MAI: 20–30
Growth: 3/2, 9/6
Planting: C, u
Source: Papua New Guinea, 8° to 9° S.

Aucoumea klaineana Peirre
Common Name: Gaboon, okoumé
Elevation: 0–500
Rainfall: 160–300 (0–2)
Soil: Free-draining—tolerates acidity and heavy soils but not impeded drainage
Resistance:
Synonym:
Utility: 2.4dbh/30–40ht/4–5g F, V, C, Pu
MAI: 15–30 (5–10)
Growth: 3/2
Planting: S, Str, u
Source: Gabon to Zaire, 2° N to 2° S.

Avicennia germinans L.
Common Name: Mangle negro, black mangrove
Elevation: 0
Rainfall: >100
Soil: Tidal muck—tolerates flooding and high salinity
Resistance:
Synonym: *A. nitida* Jacq.
Utility: .3dbh/30ht/9–10g Pu, Po, Fu, tannin
MAI: c
Growth: 5/5
Planting: S, B
Source: Tropical America and Africa, 30° N to 30° S.

Azadirachta indica A. Juss
Common Name: Neem, lilaila, paraíso
Elevation: 0–500
Rainfall: 25–100 (5–7)
Soil: Deep, free-draining—tolerates shallow, infertile, or heavy soils, and alkalinity; pH 5.0 to 8.5; species increases alkalinity
Resistance: Fr (old trees)
Synonym: *Melia azadirachta* L., *M. indica* Braud
Utility: .6dbh/20–25ht/5.8g F, V, C, Po, Fu, R, A
MAI: 5–18 (13 t) c
Growth: 3/1, 8/8, 12/20
Planting: S, B, C, cuttings, Stu
Source: India to Myanmar and Sri Lanka, 34° to 6° N.

Bagassa guianensis Aubl.
Common Name: Bagasse, bagaceira, kauhoedoe
Elevation: 0–500
Rainfall: >160 (0–3)
Soil: Fertile, free-draining—tolerates sandy soils and Latosols
Resistance:
Synonym:
Utility: 1.2dbh/30ht/7–8g F, C
MAI:
Growth: 2/3, 15/5
Planting: Stu, Cs
Source: The Guianas to Brazil, 9° N. to 5° S.

Bambusa vulgaris Schrad.
Common Name: Bambu, bamboo
Elevation: 0–1,000 (0–500)
Rainfall: >100 (0–3)
Soil: Deep, fertile, and free-draining
Resistance:
Synonym:
Utility: .2dbh/20ht/7g Pu, Fu, A, R
MAI: 2–9 t/ha c
Growth: 20/1
Planting: Cu, offsets
Source: Tropical Asia, latitude range unknown

Bertholletia excelsa Bompl.
Common Name: Castanha do Para, Brazil nut
Elevation: 0–600
Rainfall: 150–250 (0–2)
Soil: Deep, free-draining
Resistance:
Synonym:
Utility: 3dbh/50ht/6g F, C, nuts
MAI:
Growth: 8/8
Planting:
Source: Venezuela to Brazil, 10° N. to 12° S.

Bombacopsis quinatum (Jacq.) Dugand
Common Name: Pochote, amapá doce
Elevation: 0–800 (0–300)
Rainfall: 80–120 (3–5 W)
Soil: Free-draining—tolerates heavy soils, acidity, and impeded drainage
Resistance:
Synonym:
Utility: 1.8dbh/30–40ht/4–5g F, V, C, Pu
MAI:
Growth: 4/3
Planting: Stu, Cu
Source: Nicaragua to Venezuela, 14° to 6° N.

Brosimum alicastrum
Common Name: Ramón, capomo
Elevation: 0–1,000
Rainfall: 60–400
Soil: Tolerates shallow karst
Resistance: W
Synonym:
Utility: 1.5dbh/40ht/5–7g F, V, C, Pu, Po, A
MAI: 3
Growth: 8/10
Planting: C
Source: Southern Mexico to the Peruvian Amazon, 20° to 12° N.

Bucida buceras L.
Common Name: Gregre, úcar
Elevation: 0–200
Rainfall: 80–140 (0–2) W
Soil: Grows best on deep, well-drained soils; tolerates temporary flooding and rocky hills
Resistance: W
Synonym:
Utility: 1.0dbh/20ht/9g C, Po, tanning
MAI: C
Growth: 13/40
Planting: B, u
Source: Mexico, the West Indies, and the Guianas, 25° to 5° N.

Bursera simaruba (L.) Sarq.
Common Name: Gumbo limbo, almácigo
Elevation: 0–1,800
Rainfall: 50–140 (1–6 W)
Soil: Usually calcareous
Resistance: Salinity, Fr (old trees)
Synonym: *Elaphrium simaruba* (L.) Rose
Utility: 1.0dbh/30ht/3–4g C, V, fencing, Fu
MAI: C
Growth:
Planting: C
Source: Florida to northern South America, 27° to 7° N.

Calliandra calothyrsus Meissn.
Common Name: Calliandra
Elevation: 0–1,500 (0–1,000)
Rainfall: >100 (0–3 W)
Soil: Tolerates infertile heavy clays
Resistance: Fi
Synonym: *C. confusa* Spraque and Riley
Utility: .2dbh/10ht/5–8g Fu, Po, A, R
MAI: 5–65 c
Growth: 3/1
Planting: S, B
Source: Central America, 18° to 8° N.

Species Information

Callitris glauca R. Br x R.T. Bak et H.G. Sim.
Common Name: Cypress-pine
Elevation: 500–1,500 (0–1,000)
Rainfall: 25–80 (4–6 W)
Soil: Light, free-draining—tolerates poor, acid sands
Resistance: Fr (slight)
Synonym: *C. columellaris* F.V.M.
Utility: .9dbh/18–30ht/5–7g
F, C, Po
MAI: 2–10 c
Growth: 1/1, 5/9
Planting: S, C
Source: Australia, 20° to 35° S.

Calophyllum calaba L.
Common Name: Santa María, jacareuba
Elevation: 0–500
Rainfall: 125–500
Soil: Deep alluvium—tolerates poor soils and impeded drainage
Resistance: W
Synonym: *C. brasiliense* Camb.
Utility: 1.5dbh/45ht/5–7g
F, C, Po, R
MAI: 1–7 c
Growth: 6/5, 8/8
Planting: S, C
Source: Mexico to Brazil, 20° N. to 10° S.

Carapa guianensis Aubl.
Common Name: Andiroba, carapa
Elevation: 0–500
Rainfall: 16–300
Soil: Deep alluvium or sand—tolerates impeded drainage
Resistance: W
Synonym:
Utility: 1.0dbh/30ht/5–7g
F, V, C, T
MAI: c
Growth: 3/2, 8/5, 7–11/7
Planting: B, Str, C, u
Source: Honduras and Cuba to Brazil, 15° N. to 5° S.

Cariniana pyriformis Miers
Common Name: Abarco, jequitibá amarilla
Elevation: 0–600 (0–100)
Rainfall: 200–400 (0–2)
Soil: Free-draining—tolerates acidity
Resistance:
Synonym:
Utility: 1.8dbh/40–50ht/4–6g
F, V, T, C
MAI: 10–20
Growth:
Planting: B, Str, C, u
Source: Venezuela to Colombia 9° to 1° N.

Caryocar villosum Pers.
Common Name: Almendrillo, piquiá
Elevation:
Rainfall:
Soil:
Resistance:
Synonym:
Utility: 2.1dbh/45ht/6–9g
C
MAI:
Growth: 12/11
Planting:
Source: Costa Rica to Suriname to Brazil, 10° N. to 5° S.

Casuarina equisetifolia L. ex J.R. & G. Forst.
Common Name: Casuarina, she-oak
Elevation: 0–1,750 (0–900)
Rainfall: 70–500 (3–6)
Soil: Sandy, free-draining—tolerates poor, calcareous, alkaline, or saline soils and impeded drainage
Resistance: W, Fr
Synonym: *C. littoralis* Salisb.
Utility: .5dbh/20–40ht/6–12g
C, Pu, Fu, R, tannin
MAI: 6–20 (6–20 t)
Growth: 5/2, 15/6, 20–32/12
Planting: B, C
Source: Southeast Asia and Pacific Islands, 22° N. to 32° S.

Cecropia schreberiana (Miq.)
Common Name: Yagrumo, trumpet-wood, bois canon
Elevation: 0–1,500 (0–1,000)
Rainfall: >160 (0–3 W)
Soil: Fertile, free-draining—tolerates impeded drainage but not extremely infertile soils
Resistance: W
Synonym: *C. peltata* L.
Utility: .7dbh/20ht/3g
V, C, Pu, R, matches
MAI: c
Growth: 7/3
Planting: B
Source: Mexico to the Guianas, 20° to 5° N.

Cedrela odorata L.
Common Name: Cedro, Spanish cedar
Elevation: 0–1,200 (0–700)
Rainfall: 160–250 (2–4 W)
Soil: Fertile, free-draining, calcareous, not strongly acid—tolerates heavy soils
Resistance:
Synonym: *C. mexicana* M.J. Roem
Utility: 2.0dbh/30–40ht/3–6g
F, V, A
MAI: 5–10 c
Growth: 6/3, 15/5, 22/10, 27/20
Planting: Str, C, u
Source: Mexico to Argentina, 24 to 27 S.

Cedrelinga catenaeformis Ducke
Common Name: Tornillo, cedrorana, iaciaca
Elevation: 0–1,000 (0–500)
Rainfall: 160–350
Soil: Free-draining
Resistance:
Synonym:
Utility: 3.0dbh/50ht/4–6g
F, C
MAI:
Growth: 9/8
Planting:
Source: Brazil to Peru, 0° to 10° S.

Ceiba pentandra (L.) Gaertn.
Common Name: Ceiba, sumaumá
Elevation: 0–1,200 (0–700)
Rainfall: 75–570 (3–6)
Soil: Deep, free-draining—tolerates shallow soils and alkalinity
Resistance: Fr (-7 °C)
Synonym: *Bombax pentandrum* L.
Utility: 2.0dbh/50ht/2–4g
F, V, C, Pu, Fu, kapok
MAI: 7–10 t/ha pods c
Growth: 5/5
Planting: S, Cu, grafts
Source: Turkey to Syria, 40° to 32° S.

Chlorophora excelsa (Welw.) Benth & Hook
Common Name: Iroko, mvule
Elevation: 0–1,200 (0–700)
Rainfall: 100–180 (0–3)
Soil: Deep, free-draining—tolerates acidity
Resistance: W
Synonym:
Utility: 35–40ht/5–6g
F, V, C, A
MAI: 5–8 c
Growth: 3/3, 9/10, 12/12
Planting: Str, Stu
Source: Tropical Africa, 10° N. to 5° S.

Cordia alliodora Cham.
Common Name: Laurel, cypre, capá prieto
Elevation: 0–1,500 (0–1,000)
Rainfall: 100–500 (0–4 W)
Soil: Free-draining—tolerates shallow soils, heavy clays, alkalinity
Resistance: W
Synonym: *Cerdana alliodora* R. & P.
Utility: .9dbh/25–30ht/4–6g
F, V, C, A
MAI: 10–20 c
Growth: 6/3, 17/10, 21/15, 29/24
Planting: S, Stu, u
Source: Mexico to Argentina, 20° N. to 25° S.

Species Information

Cryptomeria japonica Don.
Common Name: Sugi
Elevation: 1,500–2,400 (1,000–1,900)
Rainfall: 150–250 (0–2)
Soil: Deep, fertile, free-draining—tolerates heavy clays and acidity
Resistance: Fr, W
Synonym:
Utility: 2.4dbh/30–50ht/2–4g V, C
MAI: 10–33 c
Growth: 5–9/5, 9–17/10, 12–22/15
Planting: C, Cu
Source: China to Japan, 40° to 30° N.

Cunninghamia lanceolata (Lamb) Hooker
Common Name: Chinese fir, cuningamia
Elevation: 800–1,300 (300–800)
Rainfall: 125–190
Soil: Sandy
Resistance: Fr (slight)
Synonym: *C. sinensis* Rich.
Utility: 1.7dbh/50ht C
MAI: 14–36
Growth: 3–6/5, 8–15/10, 11–21/15
Planting: C, Cu
Source: Central and South China, 27° to 22° N.

Cupressus arizonica Greene
Common Name: Arizona cypress
Elevation: 1,500–2,800 (1,000–2,300)
Rainfall: 25–75 (4–7 S)
Soil: Light, free-draining—tolerates alkalinity
Resistance: Fr (W)
Synonym:
Utility: 1.0dbh/10–20ht/4–6g C, Po, windbreaks
MAI: 3–5
Growth: 2/2
Planting: B, C
Source: Southwestern United States to Mexico, 35° to 25° N.

Cupressus lusitanica Mill.
Common Name: Ciprés, Mexican cypress
Elevation: 1,300–3,300 (800–2,800)
Rainfall: 100–150 (2–3 W)
Soil: Deep, fertile, free-draining—tolerates acidity
Resistance: Fr, W
Synonym: *C. benthami* Endl.
Utility: 1.1dbh/25–30ht/4–5g V, C, Pu, Po, R
MAI: 8–40
Growth: 8/5, 12/10, 23/16, 27/25
Planting: B, C
Source: Mexico to Honduras, 27° to 13° N.

Cupressus macrocarpa Hartweg
Common Name: Monterey cypress
Elevation: 1,200–3,500 (700–3,000)
Rainfall: 70–160 (2–4 S)
Soil: Fertile, free-draining, loams—tolerates alkalinity and moderate salinity
Resistance: Fr (-3 °C), W
Synonym: *C. hartwegii* Carriere
Utility: 2.0dbh/15–25ht/5g C, Po, R
MAI: 11–25
Growth: 8/7, 12/14, 17/35
Planting: B, C
Source: California, 36° N.

Cupressus tolurosa Don.
Common Name: Bhutan cypress
Elevation: 1,500–2,800 (1,000–2,300)
Rainfall: 65–240 (3–4 W)
Soil: Light, free-draining, calcareous—tolerates acidity
Resistance: Fr (–10 °C), W
Synonym:
Utility: .8dbh/30–45ht/5g C, Po
MAI: 12–17
Growth: 13/22, 20/27
Planting: B, C
Source: The Himalayas, 32° to 28° N

Cybistax donnell-smithii Rose
Common Name: Primavera, san juan
Elevation: 0–1,000 (0–300)
Rainfall: 100–300 (2–3 W)
Soil: Deep, light, free-draining—tolerates acidity
Resistance:
Synonym: *Tabebuia donnell-smithii* Rose
Utility: 1.0dbh/25–35ht/3–5g F, V
MAI: 20–30 c
Growth: 9/4, 14/10, 31/36
Planting: B, Stu, C
Source: Mexico to Honduras, 21° to 13° N.

Dacrydium cupressinum Solander
Common Name: Rimu
Elevation: 500–1,200 (0–700)
Rainfall: 150–330
Soil:
Resistance:
Synonym:
Utility: 1.4dbh/40ht/4–5g F, V, C, tannin
MAI:
Growth:
Planting:
Source: Malaysia to New Zealand, 3° N. to 45° S.

Dalbergia sissoo Roxb.
Common Name: Shisham, sissoo, Indian rosewood
Elevation: 0–1,000 (0–500)
Rainfall: 50–400 (3–6 W)
Soil: Deep, free-draining—tolerates sandy soils and salinity but not shallow soils
Resistance: Fr, W
Synonym:
Utility: 1.6dbh/30ht/7–8g F, V, C, Fu, R, A
MAI: 5–8 (c9–12)
Growth: 5/3, 11/5, 15/10
Planting: S, Str, Stu, Cu
Source: Himalayas to Bangladesh, 33° to 24° N.

Entandrophragma utile (Dawe & Sprague)
Common Name: Utile, sipo
Elevation: 0–900 (0–400)
Rainfall: 150–250
Soil:
Resistance: W
Synonym:
Utility: 2.6dbh/60ht/5g F, V, C, A
MAI:
Growth: 2/3, 10/10, 15/15
Planting: Str, u
Source: Ivory Coast to Uganda, 10° N. to 2° S.

Enterolobium cyclocarpum (Jacq.) Gris
Common Name: Guanacaste, dormilón, carocaro
Elevation: 0–900 (0–100)
Rainfall: 75–250 (1–6 W)
Soil: Deep, free-draining—tolerates alkalinity and calcareous soils
Resistance: Fr
Synonym:
Utility: 3.0dbh/20–40ht/3–6g F, V, C, Po, Fu, tannin, A
MAI: 20–28 c
Growth: 13/8, 25/12
Planting: B, u
Source: Mexico to Brazil, 23° N. to 10° S.

Eucalyptus camaldulensis Dehn.
Common Name: Red river gum (northern provenances)
Elevation: 0–1,400 (0–900)
Rainfall: 25–125 (4–8 W)
Soil: Tolerates poor, heavy soils, acidity, alkalinity, moderate salinity, impeded drainage, but not calcareous soils
Resistance:
Synonym: *E. rostrata* Schlecht
Utility: 2dbh/30–50ht/6–9g C, Pu, Po, Fu, R
MAI: 15–30 c
Growth: 3/1, 9/10, 36/28
Planting: C, Cu
Source: Tropical and subtropical Australia, 15° to 32° S.

Species Information

Eucalyptus camaldulensis Dehn.
Common Name: Red river gum (southern provenances)
Elevation: 500–2,000 (0–1,500)
Rainfall: 20–100 (4–6 S)
Soil: Free-draining—tolerates shallow soils, heavy soils, alkalinity, and impeded drainage
Resistance: Fr (–8 C)
Synonym: *E. rostrata* Schlect
Utility: 2.0dbh/35–45ht/7–10g
C, Pu, Po, F, R
MAI: 5–35 (20 t) c
Growth: 5/2, 16/10
Planting: C
Source: Temperate Australia, 32° to 38° S.

Eucalyptus citriodora Hook
Common Name: Spotted gum
Elevation: 0–1,800 (0–1,300)
Rainfall: 65–160 (5–7 W)
Soil: Deep, light, free-draining—tolerates poor soils and acidity
Resistance: Fr (–2 °C)
Synonym: *E. maculatas* var. *citriodora* F. Muell.
Utility: 1.3dbh/30–45ht/7–11g
F, V, C, Pu, Po, Fu, oil
MAI: 5–20 c (weak)
Growth: 3/1, 15/8
Planting: C
Source: Queensland, Australia, 17° to 26° S.

Eucalyptus deglupta Blume
Common Name: Mindanao gum, bagras, kamarere
Elevation: 0–1,800
Rainfall: 200–500 (0–1 W)
Soil: Light, fertile, free-draining—tolerates acidity and impeded drainage
Resistance:
Synonym: *E. naudiniana* F. Muell.
Utility: 2.4dbh/35–80ht/3–7g
F, C, Pu, Fu
MAI: 14–50 (23 t)
Growth: 6/3, 15–24/5, 30–37/10, 34–45/15
Planting: C, u
Source: Mindanao, Philippines, to New Britain, Papua New Guinea, 4° N. to 11° S.

Eucalyptus globulus Labill
Common Name: Tasmanian blue gum
Elevation: 1,500–3,000 (1,000–2,500)
Rainfall: 50–180 (2–3 S)
Soil: Deep, sandy, free-draining—tolerates heavy soils and acidity but not salinity
Resistance: Fr (–8 °C) W
Synonym: *E. cordata* Miq.
Utility: 2.0dbh/40–65ht/6–8g
C, Pu, Po, Fu, R
MAI: 10–40 c
Growth: 6–15/3, 14–18/8, 18–24/12
Planting: S, B, C
Source: Tasmania, Australia, 37° to 44° S.

Eucalyptus grandis Hill ex Maiden
Common Name: Flooded gum
Elevation: 0–2,100 (0–1,600)
Rainfall: 100–400 (0–3 W)
Soil: Deep, free-draining—tolerates sandy soils and acidity
Resistance: Fr (–5 °C)
Synonym: *E. saligna* Sm var. *pallidivalvis* Baker & Smith
Utility: 2.0dbh/40–60ht/4–7g
F, V, C, Pu, Po, Fu
MAI: 15–50 (20–40 t) c
Growth: 4/2, 14/6, 24/10
Planting: C, Cu
Source: Queensland to New South Wales, Australia, 17° to 32° S.

Eucalyptus paniculata Sm.
Common Name: Grey ironbark
Elevation: 500–1,500 (0–1,000)
Rainfall: 75–130 (2–3 W)
Soil: Light, free-draining—tolerates shallow soils and acidity
Resistance: Fr (–2 °C)
Synonym: *E. terminalis* Sieb. ex Benth.
Utility: 1.2dbh/30–35ht/9–12g
C, Po
MAI: 9–18 c
Growth: 5/2, 15/9, 29/22
Planting: C
Source: New South Wales, Australia, 30° to 37° S.

Eucalyptus pilularis Sm.
Common Name: Blackbutt
Elevation: 500–2,000 (0–1,500)
Rainfall: 60–120 (3–4 W)
Soil: Sandy or clay, tolerates poor soils
Resistance: Fr (–15 °C)
Synonym: *E. semicorticata* F. Muell.
Utility: 2.0dbh/60–70ht/6–10g
C, Po, Fu
MAI: 10–20 c
Growth: 6/2, 14/9, 27/13
Planting: C, u
Source: Queensland to New South Wales, Australia, 25° to 38° S.

Eucalyptus resinifera Sm.
Common Name: Red mahogany
Elevation: 900–2,000 (400–1,500)
Rainfall: 100–300 (4 W)
Soil: Light, free-draining
Resistance: Fr (–9 °C)
Synonym: *E. hemilampra* F. Muell
Utility: 1.5dbh/30–45ht/6–10g
F, C, Po, Fu
MAI: 15–25 c
Growth: 3/1, 10/2, 23/15
Planting: C
Source: Australia, 17° to 34° S.

Eucalyptus robusta Sm.
Common Name: Swamp mahogany, robusta
Elevation: 0–1,500 (0–1,000)
Rainfall: 100–170 (1–4 W)
Soil: Deep, acidic—tolerates poor, heavy soils and impeded drainage
Resistance: Fr (–3 °C) W
Synonym: *E. multiflora* Poir.
Utility: 2.5dbh/25–50ht/6–9g
C, Pu, Po, R, A
MAI: 10–40 c
Growth: 4/2, 17/6, 22/13
Planting: B, C
Source: Queensland to New South Wales, Australia, 23° to 36° S.

Eucalyptus saligna Sm.
Common Name: Sydney blue gum, saligna
Elevation: 0–1,000
Rainfall: 100–400 (0–4 W)
Soil: Light, free-draining—tolerates acidity
Resistance: Fr (–7 °C) Fi W
Synonym:
Utility: 1.8dbh/35–55ht/5–10g
F, V, C, Pu, Po, Fu
MAI: 10–55 (25–40 t) c
Growth: 3–6/2, 12–18/5, 20–28/10
Planting: C, Cu
Source: Queensland to New South Wales, Australia, 26° to 36° S.

Species Information

Eucalyptus tereticornis Sm.
Common Name: Mysore gum, Zanzibar C, forest reel gum (northern provenances)
Elevation: 0–1,800 (0–1,300)
Rainfall: 50–100 (4–7 W)
Soil: Deep, free-draining, sandy loam—tolerates heavy acids, impeded drainage, but not high acidity
Resistance: Fr (–5 °C)

Synonym: *E. umbellata* (Gaertn) Domin.
Utility: 2.0dbh/35–45ht/4–10g C, Pu, Po, R
MAI: 12–25 (20 t) c
Growth: 6/2, 8/5, 13–19/7
Planting: C
Source: Papua New Guinea to Queensland, Australia, 15° to 38° S.

Eucalyptus urophylla S.T. Blake
Common Name: Timor white gum
Elevation: 200–1,500 (0–1,000)
Rainfall: 110–200 (2–6 W)
Soil: Free-draining—tolerates heavy soils and acidity
Resistance: Fi

Synonym: *E. decaisneana* Bl.
Utility: 1.2dbh/35–50ht
MAI: 20–60 c
Growth: 8/2, 15/5, 27/7
Planting: C, Cu
Source: Timor and nearby islands, 8° to 10° S.

Eucalyptus viminalis Labill.
Common Name: Manna gum
Elevation: 2,000–3,000 (1,500–2,500)
Rainfall: 75–250 (0–4)
Soil: Deep, fertile, free-draining—tolerates poor, heavy acids and acidity
Resistance: Fr (–12 °C) W

Synonym: *E. saccharifera* F. Muell ex Miq.
Utility: 1.6dbh/25–45ht/6–9g C, Pu, Po
MAI: 10–40 c
Growth: 7/5, 35/22
Planting: C
Source: Chiefly New South Wales, Australia, 28° to 44° S.

Flindersia brayleana F.v.M.
Common Name: Queensland maple
Elevation: 500–1,000
Rainfall: 130–200
Soil: Deep, free-draining loams—tolerates gravelly ridges
Resistance: W

Synonym:
Utility: 1.2dbh/30ht/4–5g F, V,
MAI: 10–14
Growth: 2/1, 10/5, 14/10, 21/10
Planting:
Source: Papua New Guinea to north Queensland, Australia, 15° to 18° S.

Gliricidia sepium (Jacq.) Stend
Common Name: Madre de cacao, mata ratón
Elevation: 0–1,200 F, C,
Rainfall: 150–230 (2–5 W)
Soil: Deep, free-draining—tolerates calcereous soils but not waterlogging
Resistance:

Synonym: *G. maculata* Kunth.
Utility: .4dbh/20ht Fu, Po, A, fences
MAI: 20–40 c 45–55t/ha
Growth: 8/2
Planting: S, Cu
Source: Mexico to the Guianas, 25° to 5° N.

Gmelina arborea L.
Common Name: Yemane, melina
Elevation: 0–800 (0–300)
Rainfall: 100–250 (2–7 W)
Soil: Deep, fertile, free-draining—tolerates shallow, sandy, or heavy soils and acidity but not impeded drainage
Resistance: Fi

Synonym:
Utility: 1.5dbh/30ht/4–6g F, V, C, Pu, Po, A, matches
MAI: 12–50 (5–14 t) c
Growth: 3–6/3, 7–14/6, 25/20
Planting: S, Stu, C, Cu
Source: India to Vietnam, 36° N. to 5° N.

Goupia glabra Aubl.
Common Name: Kopie, cupiuba, kabukalli
Elevation:
Rainfall:
Soil: Sandy
Resistance:

Synonym:
Utility: 1.0dbh/40ht/6–9g F, C
MAI:
Growth: 7/8
Planting: u
Source: Colombia, the Guianas, and Brazil, 8° N. to 5° S.

Grevillia robusta A. Cunn.
Common Name: Grevilia, roble de seda, silky oak
Elevation: 800–2,100 (300–1,600)
Rainfall: 70–150 (2–8 W)
Soil: Sandy, free-draining loam—tolerates acidity
Resistance: Fr (–10 °C), Fi

Synonym: *Grevillea umbricata* A. Cunn.
Utility: 1.2dbh/25–50ht/5–7g F, V, T, C, A
MAI: 5–17
Growth: 5/3, 19/14
Planting: B, C, Cu
Source: Australia, 25° to 30° S.

Guaiacum officinale
Common Names: Guayacan, lignum vitae
Elevation: 0–400
Rainfall: 30–100
Soil: Prefers deep alluvium but tolerates rocky limestone with pH range from 5.0 to 8.5; does not tolerate salinity
Resistance:

Synonym:
Utility: .8dbh/10ht/10–13g bearings, ornamental
MAI:
Growth: 3/7, 4.5/15
Planting: C, u
Source: Bahamas to Guyana, 24° to 6° N.

Guazuma ulmifolia Lam.
Common Name: Guácimo, West Indies elm
Elevation: 0–1,000 (0–500)
Rainfall: 65–160 (4–7 W)
Soil: Tolerates sands to clays, including poor drainage but not salinity
Resistance: Fr (slight)

Synonym: *G. guazuma* (L.) Cockerell
Utility: .8dbh/20ht/5–6g F, C, Po, Fu, Fo, A
MAI: c
Growth: 2/1, 7/3, 6 t/ha/yr
Planting: Stu, c
Source: Mexico to Argentina, 25° N. to 27° S.

Hibiscus elatus Sw
Common Name: Majo, mahoe, majagua
Elevation: 0–1,200 (0–700)
Rainfall: 100–380 (2–3 W)
Soil: Deep, free-draining—does not tolerate ridges but tolerates acid clays
Resistance:

Synonym: *Paritium elatum* (Sw.) G. Don.
Utility: .5dbh/25ht/5–8g F, C, T
MAI: 14–36 c
Growth: 8/5, 14/10, 21/17, 25/27
Planting: B, C, u
Source: Cuba and Jamaica, 22° to 18° N.

Hura crepitans L.
Common Name: Hura, sandbox, molinillo
Elevation: 0–100
Rainfall: >150
Soil: Best on sandy loams—tolerates poor drainage
Resistance:

Synonym:
Utility: 2–3 dbh/40–60ht/3–4g F, V, C, Po
MAI:
Growth:
Planting: C, Cu
Source: Costa Rica to Brazil, 24° N. to 19° S.

Species Information

Hymenaea courbaril (L.)
Common Name: Courbaril, locust, jatahy
Elevation: 0–900
Rainfall: 120–240 (2–4 W)
Soil: Best on deep sandy soil with a pH from 4.8 to 6.8; does not tolerate poor drainage
Resistance:
Synonym:
Utility: 2.0 dbh/40ht/7–8g C, T, fruit
MAI: C
Growth: 4/8, 11/13, 20/44
Planting: S, C
Source: Mexico, the Caribbean Islands to Brazil, 23° N. to 25° S.

Jacaranda copaia (Aubl.) D. Don
Common Name: Copaia, abey, pará pará
Elevation: 0–1,000
Rainfall: 60–200 (4–6 W)
Soil: Light to heavy, alkaline to neutral—tolerates poor soils, poor drainage, and salinity
Resistance:
Synonym: *Bignonia copaia* Aubl.
Utility: .8dbh/30ht/3–4g F, C, Pu, matches
MAI: c
Growth: 22/11
Planting: C, Cu
Source: Belize to Brazil, 18° N. to 25° S.

Khaya grandifoliola C. DC.
Common Name: Big-leaf mahogany
Elevation: 0–1,400 (0–900)
Rainfall: 100–180 (0–2)
Soil:
Resistance:
Synonym:
Utility: 1.5dbh/40ht/5–7g F, C, T, A
MAI: 2
Growth: 2/1, 7/5
Planting: B, Str, Stu
Source: The Guinean coast of Africa to Sudan, 5° S. to 13° N.

Khaya ivorensis A. Chev.
Common Name: Nigerian mahogany
Elevation: 0–500
Rainfall: >180 (0)
Soil: Deep alluvium near watercourses
Resistance:
Synonym:
Utility: 2.0dbh/60ht/3–5g F, V, C, T
MAI:
Growth: 8/6, 15/16
Planting: Str, Stu, u
Source: Sierra Leone to Uganda, 8° to 3° N.

Khaya nyasica Stapfex Baker
Common Name: East African mahogany
Elevation:
Rainfall: 60–160 (3–6 W)
Soil: Moist, well-drained alluvium; margins of flood plains
Resistance:
Synonym:
Utility: 4.5dbh/60ht/4–6g F, V, C, T, A
MAI: 14 c
Growth: 5/4, 15/16, 20/27, 31/50
Planting: B, C
Source: Tanzania to Mozambique, 5° N. to 23° S.

Khaya senegalensis (Desv.) A. Juss.
Common Name: Dry-zone mahogany, African mahogany
Elevation: 900–1,800 (400–1,000)
Rainfall: 75–175 (3–6)
Soil: Riverain—tolerates poorly drained, acid soils
Resistance:
Synonym:
Utility: 1.5dbh/40ht/6–8g F, V, C, A, Pu
MAI:
Growth: 5/3, 25/25
Planting: B, C, Str, Stu, u
Source: Senegal to Sudan, 14° N. to 10° S.

Laguncularia racemosa (L.) Gaertn.
Common Name: White mangrove, mangle blanco
Elevation: 0
Rainfall: 80–700
Soil: Saline silt and clay deposits—tolerates frequent waterlogging, prefers salinities below 50 parts per thousand
Resistance:
Synonym:
Utility: .7dbh/25ht/6–8g Po, Fu, tannin
MAI:
Growth: 19/22
Planting: B, Str
Source: Mexico to Brazil, 28° N. to 29° S.

Leucaena leucocephala (Lam.) de Wit
Common Name: Laucaena, tamarandillo, ipil ipil, tan tan
Elevation: 0–800 (0–300)
Rainfall: 60–100 (2–6 W)
Soil: Free-draining, neutral to alkaline—tolerates shallow and heavy soils
Resistance: Fr (slight), Fi (after 2 years)
Synonym: *L. glauca* (L.) Benth.
Utility: .2dbh/5ht/5–6g Po, Fu, R, A
MAI: 20–25 c
Growth: 3/2, 17/6
Planting: C, Cu, grafts, u
Source: Mexico to Guatemala and the Antilles, 27° to 12° N.

Leucaena leucocephala (Syn.)
Common Name: Giant leucaena
Elevation: 0–1,500 (0–500)
Rainfall: 60–200 (2–6 W)
Soil: Free-draining, neutral to alkaline—tolerates heavy soils and moderate salinity but not high acidity (pH of 6.0 or more)
Resistance: Fr (slight)
Synonym:
Utility: .6dbh/20ht/4–6g C, Pu, Po, Fu, R, A
MAI: 30–55 c
Growth: 9/2, 13/4, 18 t/ha/yr
Planting: S, B, C, Cu, Stu
Source: Mexico to Guatemala, 17° to 15° N.

Lovoa trichilioides
Common Name: Nkoba, Uganda walnut
Elevation: (0–500)
Rainfall: >180 (0)
Soil: Deep, fertile
Resistance:
Synonym: *L. klaineana* Pierre et Spraque.
Utility: 1.2dbh/45ht/3–5g F, V, C, T, Pu
MAI:
Growth: 3/5
Planting: Str, Stu, u
Source: Uganda to Tanzania, 4° N. to 3° S.

Maesopsis eminii Engl.
Common Name: Musizi
Elevation: 100–1,500 (0–200)
Rainfall: 120–300 (0–2 W)
Soil: Deep, fertile, free-draining—tolerates infertile, sandy soils and acidity
Resistance: W (moderate)
Synonym:
Utility: 1.2dbh/15–35ht/4–5g C, Pu, Po
MAI: 8–35 (5–10 t) c
Growth: 3/1, 8/5, 11/10
Planting: S, Str, Stu, C, u
Source: Liberia to Tanzania, 8° N. to 2° S.

Manilkara bidentata (A. DC.) Chev
Common Name: Balata, ausubo, bullet
Elevation: 0–600
Rainfall: 150–400
Soil: Acid clays over igneus or calcarious rocks on lower slopes
Resistance:
Synonym: *M. nitida* (Sesse & Moc) Dubard
Utility: 1.3dbh/50ht/8–9g C, T, latex
MAI: 3
Growth: 4.5/5
Planting: S, C, u
Source: Mexico to northern Brazil, 20° N. to 15° S.

Species Information

Melaleuca leucodendron (L.) L.
Common Name: Cajeput, malaleuca, paperbark
Elevation: 0–800 (0–300)
Rainfall: 80–160 (0–4 W)
Soil: Tolerates heavy, poor soils, impeded drainage, alkalinity, and salinity
Resistance: Fi, W
Synonym: *M. leucodendron* (Cav.) S. T. Blake
Utility: .6dbh/10–30ht/6–7g
V, C, Po, R
MAI: 10–16 c
Growth: 3/2 10/15
Planting: c
Source: Myanmar to east Australia, 24° N. to 25° S.

Melia azedarach L.
Common Name: Aleliala, chinaberry
Elevation: 700–1,400 (200–900)
Rainfall: <75
Soil: Well-drained sandy loams
Resistance: Fr (slight)
Synonym:
Utility: .6dbh/30/5–7g
F, T, Po, Fu, A
MAI: 25–40
Growth: 1/1, 8/5, 18/10
Planting: S, B, Cu
Source: Middle East to India, 35° to 25° N.

Mimosa scabrella Benth.
Common Name: Bracatinga
Elevation:
Rainfall:
Soil: Free-draining
Resistance:
Synonym: *M. bracatinga* Hoehne.
Utility: .4dbh/15ht
Fu
MAI: c
Growth: 5/1, 9/2, 15/3
Planting: S
Source: Southern Brazil, 15° to 25° S.

Mitragyna stipulosa O. Kuntze
Common Name: Abura
Elevation: 0–900 (0–400)
Rainfall: 100–180 (0–2)
Soil: Requires subsoil moisture throughout year, tolerates impeded drainage
Resistance:
Synonym: *M. ciliata* Andrew & Pellgr.
Utility: 1.5dbh/30ht/3–5g
F, C
MAI:
Growth:
Planting: B, Stu, Cu
Source: Uganda to Sierra Leone to Zambia, 10° N. to 15° S.

Nauclea diderichii Merrill
Common Name: Opepe, bilinga
Elevation: 0–900 (0–400)
Rainfall: 200–450 (0–2)
Soil: Free-draining—tolerates light soils but not impeded drainage
Resistance:
Synonym: *Sarcocephalus trillesii* A. Chev.
Utility: 1.8dbh/30–40ht/6–8g
F, C, T, Po
MAI: 3–10 (3–8 t)
Growth: 2/3, 4/4
Planting: Str, Stu, C
Source: Sierra Leone to Uganda, 10° N. to 5° S.

Ochroma pyramidale Cav.
Common Name: Balsa, guano
Elevation: 0–1,800 (0–800)
Rainfall: 150–300 (0–2)
Soil: Deep, fertile, free-draining loam—tolerates alkalinity
Resistance:
Synonym: *O. lagopus* Sw.
Utility: 1.2dbh/20–25ht/1–4g
Insulation, rafts, toys, specialities
MAI: 17–65 (11 t)
Growth: 2–8/1, 7–20/3, 32/6
Planting: S, C
Source: Mexico and the West Indies to Bolivia, 23° N. to 15° S.

Paraserianthes falcataria (L.) Nielsen
Common Name: Batai, white albizia
Elevation: 0–1,200 (0–700)
Rainfall: 200–400 (0–2)
Soil: Deep, free-draining—tolerates acidity and heavy soils
Resistance: W
Synonym: *Albizia falcata* (L) Back
Utility: .6dbh/25–45ht/3–5g
V, Pu, matches
MAI: 20–50 (29 t/ha) c
Growth: 13/2, 15–27/6, 30/11
Planting: S, Stu, C, u
Source: Malaysia to Indonesia, 3° N. to 20° S.

Parkinsonia aculeata L.
Common Name: Palo de rayo, horsebean
Elevation: 0–1,400 (0–900)
Rainfall: 25–40 (6–9)
Soil: Free-draining—tolerates poor soils, alkalinity, salinity, but not impeded drainage
Resistance: Fr (slight)
Synonym:
Utility: .4dbh/10ht/6g
Fu, Po, A, R
MAI:
Growth: 1/1
Planting: C, Cu
Source: Texas and Arizona to Mexico, 30° to 15° N.

Paulownia tomentosa Stend
Common Name: Kiri, piropó
Elevation: 500–1,200 (0–700)
Rainfall: 120–180 (0–2 W)
Soil: Deep, fertile, free-draining—tolerates acidity
Resistance: Fr (slight), W
Synonym:
Utility: 12–16ht/2–5g
F, C
MAI: 25–35 c
Growth: 6/5
Planting: Cu
Source: Japan, 40° to 32° N.

Pinus ayacahuite Ehrenb.
Common Name: Pino ayacahuite, Mexican white pine
Elevation: 1,800–3,200 (1,300–2,700)
Rainfall: 120–250 (0–2 W)
Soil: Deep, fertile, free-draining—tolerates light soils, acidity
Resistance: Fr
Synonym:
Utility: 1.5dbh/30–40ht/4–5g
F, V, C, Pu, resin
MAI: 8–15
Growth: 20/19
Planting: C
Source: Mexico to El Salvador, 19° to 14° N.

Pinus canariensis C. Smith
Common Name: Canary Island pine
Elevation: 1,000–2,500 (500–2,000)
Rainfall: 65–175 (2–8 S)
Soil: Deep, free-draining—tolerates light soils
Resistance: Fr (–8 C), Fi
Synonym:
Utility: 1.0dbh/20–30ht/–6g
C, Po, resin
MAI: 8–18 c (poorly)
Growth: 7/5, 12/10
Planting: S, C
Source: Canary Islands, 29° to 28° N.

Pinus caribaea Morelet var. *bahamensis* Barr. & Golf.
Common Name: Caribbean pine, pichipen
Elevation: 0–1,000 (0–500)
Rainfall: 75–150 (6–7 W)
Soil: Light, free-draining—tolerates coral limestone and alkalinity (pH 7.5 to 8.5)
Resistance: Fr (–8 °C), Fi (when old), W
Synonym: *P. bahamensis* Griseb.
Utility: .5dbh/15–20ht/3–5g
C, Pu, Po, resin
MAI: 10–28
Growth: 3/5, 20/23
Planting: C
Source: Grand Bahama to Caicos Islands, 27° to 21° N.

Species Information

Pinus caribaea Morelet var. *caribaea* Barr & Golf.
Common Name: Pino macho, pino caribaea
Elevation: 50–360
Rainfall: 110–180 (4–6 W)
Soil: Light, free-draining—tolerates acidity (pH 4.6) and shallow or serpentine soils
Resistance: Fr (–8 °C), W
Synonym: *P. caribaea* Morelet
Utility: .7dbh/20–27ht/3–5g
C, Pu, Po, resin
MAI: 10–28
Growth: 6/6, 22/26
Planting: B, C
Source: Pinar del Rio and Isla Pinos, Cuba, 23° to 21° N.

Pinus caribaea Morelet var. *hondurensis* Barr & Golf.
Common Name: Pino hondureno, pitch pine
Elevation: 0–850 (0–500)
Rainfall: 100–350 (2–6 W)
Soil: Deep, moderately fertile, free-draining—tolerates sandy soils, acidity (pH 4.0 to 6.5), and impeded drainage
Resistance: Fr (–8 °C), Fi (moderate), W
Synonym: *P. hondurensis* Loock.
Utility: 1.0dbh/35–45ht/3–7g
C, Pu, Po, resin
MAI: 20–50 (8–14 t)
Growth: 7/4, 12/9, 22/15, 30/30
Planting: B, C
Source: Belize to Nicaragua, 18° to 12° N.

Pinus chiapensis (Martinez) Andersen
Common Name: Chiapas pine, Mexican white pine
Elevation: 500–200 (0–1,500)
Rainfall: 100–160 (2–3 S)
Soil: Deep, free-draining—tolerates sand and acidity
Resistance:
Synonym: *P. strobus* var. *chiapensis* (Martinez)
Utility: 1.0dbh/25–30ht/4–5g
F, C, PU, resin
MAI: 10–30
Growth: 9/7
Planting: C, u
Source: Mexico to Guatemala, 21° to 15° N.

Pinus douglasiana Martinez
Common Name: Douglas pine
Elevation: 1,500–2,400 (1,000–1,900)
Rainfall: 90–120
Soil: Deep, sandy
Resistance: Fr (young)
Synonym:
Utility: 1.0dbh/30ht
C
MAI:
Growth: 9/8, 27/32
Planting: C
Source: Sinaloa to Guerrero, Mexico, 27° to 17° N.

Pinus durangensis Martínez
Common Name: Durango pine
Elevation: 2,500–2,800 (1,800–2,100)
Rainfall: 75–100
Soil: Moist, sandy, well-drained
Resistance: Fr
Synonym:
Utility: 1.0dbh/40ht
c, Fu, resin
MAI:
Growth: 5/11, 11/25, 21/41
Planting: C
Source: Chihuahua to Durango, Mexico, 31° to 22° N.

Pinus elliottii Engelm. var. *elliottii* Little & Dorman
Common Name: Slash pine
Elevation: 500–2,500 (0–2,000)
Rainfall: 65–250 (2–4 W)
Soil: Free-draining, with calcium and magnesium—tolerates heavy or shallow soils, acidity, and impeded drainage
Resistance: Fr, Fi (old)
Synonym:
Utility: 1.0dbh/30ht/5–7g
C, Pu, Po, resin
MAI: 10–22
Growth: 3/3, 6/6, 14/10, 19/16
Planting: C
Source: South Carolina to Louisiana, 35° to 27° N.

Pinus engelmannii Carr.
Common Name: Apache pine
Elevation: 1,600–2,500 (1,100–2,000)
Rainfall: 50–75
Soil: Light—tolerates poor soils
Resistance: Fr
Synonym:
Utility: 1.0dbh/30ht
C
MAI:
Growth: 7/16, 11/20, 7/16
Planting: C
Source: Southwest United States to Zacatecas, Mexico, 33° to 22° N.

Pinus greggii Engelm.
Common Name: Gregg's pine
Elevation: 1,500–3,100 (1,000–2,600)
Rainfall: 65–80 (3–5 W)
Soil: Deep, free-draining—tolerates heavy acidity
Resistance:
Synonym: *P. pseudopatula* (Bois.) Hort.
Utility: .5dbh/15–20ht/4g
C, Pu, Po
MAI: 5–13
Growth: 18/13, 23/19
Planting: C
Source: Coahuila to San Luis Polisi, Mexico, 26° to 20° N.

Pinus halepensis Mill.
Common Name: Aleppo pine, pino carrasco
Elevation: 1,500–2,500 (1,000–2,000)
Rainfall: 40–80 (5–8 S)
Soil: Free-draining—tolerates sands and shallow, calcareous soils
Resistance: Fr (–14 °C), Fi (moderate)
Synonym:
Utility: 2.0dbh/15–25ht/5g
MAI: 3–12
Growth: 5/5, 8/10
Planting: C
Source: Morocco to Israel to southern France, 31° to 45° N.

Pinus kesiya Royle ex Gordon
Common Name: Khasya pine, Benguet pine
Elevation: 1,000–2,000 (500–1,500)
Rainfall: 70–180 (2–7 W)
Soil: Deep, high, free-draining—tolerates heavy clays but not impeded drainage
Resistance: Fr (slight)
Synonym: *P. insularis* Endl.
Utility: 1.0dbh/45ht/4–6g
F, V, C, T, Pu, Po, resin
MAI: 14–28
Growth: 3/3, 8/6, 10–11/10, 16/20, 24/30
Planting: C
Source: India to Philippines, 29° to 12° N.

Species Information

Pinus leiophylla Schiede & Dieppe
Common Name: Smooth-leaved pine
Elevation: 1,500–2,400 (1,000–1,900)
Rainfall: 100–120
Soil: Deep, sandy loams
Resistance: Fr (moderate)
Synonym:
Utility: 1.0dbh/15–30ht/4g C, Fu, resin
MAI: C
Growth: 6/5, 11/10, 17/15, 27/29
Planting: C
Source: Arizona, U.S., to Oaxaca, Mexico, 34° to 17° N.

Pinus merkusiana Jungh & de Vriese
Common Name: Tenasserim pine
Elevation: 0–900 (0–400)
Rainfall: 100–280 (2–5 W)
Soil: Free-draining—tolerates heavy acidity
Resistance: Fi, W
Synonym: *P. merkusii* Cooling
Utility: .9dbh/30–40ht/4–6g V, C, Pu, Po, resin
MAI: 8–18
Growth:
Planting: C
Source: India to Cambodia, 23° to 12° N.

Pinus merkusii Jungh & de Vriese
Common Name: Merkus pine
Elevation: 800–1,600 (300–1,100)
Rainfall: 200–300 (0–2 W)
Soil: Free-draining—tolerates sand and acidity
Resistance:
Synonym:
Utility: 50–60ht/5g V, C, Pu, Po, resin
MAI: 12–30 (12–20 t)
Growth: 3/4, 11/7, 16/30, 16/20, 24–40/30
Planting: C
Source: Sumatra, 6° N. to 3° S.

Pinus michoacana Martinez
Common Name: Michoacan pine
Elevation: 1,800–2,400 (1,300–1,900)
Rainfall: 90–170 (2–3 W)
Soil: Deep, sandy, free-draining— tolerates poor, heavy soils and acidity
Resistance: Fr (moderate), Fi (moderate)
Synonym:
Utility: .9dbh/20–25ht/5g V, C, Pu, Po, resin
MAI: 6–12
Growth: 10/7, 18/21, 21/32, grass stage
Planting: C
Source: Nayarit to Chiapas, Mexico, 23° to 14° N.

Pinus montezumae Lamb.
Common Name: Montezuma pine
Elevation: 1,400–3,000 (900–2,500)
Rainfall: 90–160 (2–3 W)
Soil: Deep, fertile, free-draining—tolerates sands, acidity
Resistance: Fr (moderate), Fi (moderate)
Synonym:
Utility: .9dbh/20–40ht/4–5g C
MAI: 6–12
Growth: 6/5, 10/9, 20/15, 33/41, grass stage
Planting: C
Source: Coahuila, Mexico, to Guatemala, 27° to 14° N.

Pinus occidentalis Sw.
Common Name: Pino de Sierra Madre, bois pin, West Indies pine
Elevation: 0–1,500 (0–1,000)
Rainfall: 130–150 (2–4 W)
Soil: Free-draining—tolerates acidity and poor, heavy, and serpentine soils
Resistance: Fr (slight), Fi (old)
Synonym: *P. cubensis* Griseb.
Utility: 1.2dbh/25–35ht C, Pu, Po, resin
MAI: 5–10
Growth: 6/5, 12/10, 15/16
Planting: C
Source: Cuba and Hispaniola, 19° to 18° N.

Pinus oocarpa Schiede
Common Name: Pino ocote, pino colorado
Elevation: 900–2,400 (400–1,900)
Rainfall: 75–150 (2–6 W)
Soil: Free-draining—tolerates shallow, poor, or heavy soils and acidity
Resistance:
Synonym:
Utility: .9dbh/20–30ht/4–6g C, Pu, Po, resin
MAI: 10–40 (var. *ochoterenii*)
Growth: 7/4, 9/10, 12/13
Planting: C
Source: Sonora, Mexico, to Nicaragua, 28° to 13° N.

Pinus palustris Mill.
Common Name: Longleaf pine
Elevation: 0–1,500 (0–1,000)
Rainfall: 100–200 (2–3 W)
Soil: Deep, free-draining—tolerates sands and acidity
Resistance: Fr, Fi, W
Synonym: *P. australis* Michx.
Utility: 3.0dbh/25–40ht/5–6g C, Pu, Po, resin
MAI: 6–12
Growth: 3/2, 6/5, 17/13, grass stage
Planting: C
Source: Virginia to Texas, 37° to 26° N.

Pinus patula Schiede and Dieppe (includes var. *tecunumanii* (Schwerdt) Mittak & Styles)
Common Name: Pino patula
Elevation: 1,000–3,200 (700–2,700)
Rainfall: 50–240 (0–6 W) 100–300 (2–4 S) var. *tecunumanii*
Soil: Deep, free-draining—tolerates light soils and acidity, but not alkalinity
Resistance: Fr (−10 °C) frost tender (var. *tecunumanii*)
Synonym: *P. oocarpa* var. *ochoternai* Martinez
Utility: 1.2dbh/20–40ht/4–6g C, Pu, Po
MAI: 8–40 (14 t)
Growth: 6/5, 12/8, 15/10, 21/15
Planting: B, C
Source: Tamaulipas, Mexico, to Nicaragua, 24° to 16° N.

Pinus ponderosa Dougl. var *arizonica* Shaw
Common Name: Arizona pine
Elevation: 2,000–3,000 (1,500–2,500)
Rainfall: 65–90 (1–4 W)
Soil: Free-draining—tolerates sand, shallow soils, and alkalinity
Resistance: Fr, Fi, W
Synonym: *P. arizonica* Engelm.
Utility: 1.0dbh/25–30ht/5g V, C, Pu, Po, resin
MAI: 5–20
Growth:
Planting: B, C
Source: Southwestern U.S.to Mexico, 35° to 23° N.

Species Information

Pinus pseudostrobus Lindl.
Common Name: Pino blanco
Elevation: 2,100–3,000 (1,600–2,500)
Rainfall: 100–150 (0–3 W)
Soil: Deep, free-draining—tolerates heavy soils and acidity
Resistance: Fr (moderate)
Synonym:
Utility: 1.5dbh/5–40ht/4–5g C, Pu, resin
MAI: 15–30
Growth: 9/7, 15/10, 27/20
Planting: C
Source: Chihuahua, Mexico to Nicaragua, 27° to 12° N.

Pinus radiata D. Don
Common Name: Pino radiata, pino insignis, Monterey pine
Elevation: 1,500–3,000 (1,000–2,500)
Rainfall: 65–160 (2–3 S)
Soil: Free-draining—tolerates sandy soils and acidity
Resistance: Fr (−10 °C)
Synonym: *P. insignis* Dougl.
Utility: 1.9dbh/25–35ht/4–5g V, C, Pu, Po
MAI: 12–35 (20–30 t)
Growth: 7–8/5, 14/10, 22/17
Planting: C
Source: California, U.S., and Guadeloupe Islands, Mexico, 37° to 29° N.

Pinus roxburghii Sarg.
Common Name: Chir pine
Elevation: 1,200–2,500 (700–2,000)
Rainfall: 75–110 (2–4 W)
Soil: Free-draining—tolerates shallow or heavy soils and acidity
Resistance: Fr, Fi
Synonym: *P. longifolia* Roxb.
Utility: 3.0dbh/30–35ht/4–5g C, Pu, Po, resin
MAI: 7–14
Growth: 4/5, 12/17
Planting: C
Source: Pakistan to Bhutan, 27° to 35° N.

Pinus taeda L.
Common Name: Loblolly pine
Elevation: 1,300–2,400 (800–1,900)
Rainfall: 90–220 (0–2)
Soil: Tolerates heavy soils, acidity, and impeded drainage
Resistance: Fr, Fi
Synonym:
Utility: 1.0dbh/40–50ht/5g V, C, Pu, Po, resin
MAI: 12–30
Growth: 4/3, 6/5, 9/7, 13/10, 16/16
Planting: B, C
Source: New Jersey to Texas, U.S., 40° to 28° N.

Pinus tenuifolia Benth
Common Name:
Elevation: 1,500–2,400 (1,000–1,900)
Rainfall: 90–120
Soil: Deep alluvial—does not tolerate poor soils
Resistance:
Synonym:
Utility: .9dbh/30ht/4–5g C, resin
MAI:
Growth: 3/2, 10 & 6
Planting:
Source: Sinaloa, Mexico, to Guatemala, 24° to 14° N.

Pinus teocote Scheide & Dieppe
Common Name: Pino albacarotte, Aztec pine
Elevation: 1,500–3,000 (1,000–2,500)
Rainfall: 90–100
Soil: Sandy—tolerates poor, rocky soils
Resistance:
Synonym:
Utility: .9dbh/35ht C, Fu, resin
MAI:
Growth: 4/4
Planting:
Source: Chihuahua, Mexico, to Guatemala, 28° to 15° N.

Pinus tropicalis Morelet
Common Name: Tropical pine
Elevation: 0–100
Rainfall: (2–3 W)
Soil:
Resistance:
Synonym:
Utility: 1.3dbh/20ht C, Fo
MAI:
Growth: 1/1, 15/15, grass stage
Planting:
Source: Pinar del Río and Isla Pinos, Cuba, 23° to 21° N.

Pithecolobium saman Benth
Common Name: Saman, raintree, dormilón
Elevation: 0–700 (0–200)
Rainfall: 60–300 (2–4 W)
Soil: Free-draining—tolerates heavy, soils, acidity, and impeded drainage
Resistance: W
Synonym: *Samanea saman* (Jacq Merrill)
Utility: 2.5dbh/35ht/4–6g F, V, C, Fo, A
MAI: 25–35 c
Growth: 3/1
Planting: B, Stu, Cu
Source: Mexico to Brazil, 11° N. to 5° S.

Podocarpus respligiosos Pilger
Common Name: Pino laso
Elevation: 2,000–3,000 (1,500–2,500)
Rainfall: 200–260
Soil: Fertile, acidic
Resistance:
Synonym:
Utility: 1.2dbh/35–40ht/4–6g F, V, C, Pu
MAI:
Growth:
Planting: B
Source: Venezuela to Peru, 8° N. to 10° S.

Prosopis alba Griseb
Common Name: Algarrobo blanco, ibopé
Elevation: 0–1,000 (0–500)
Rainfall: 10–50
Soil: Tolerates acidity
Resistance:
Synonym:
Utility: 1.0dbh/15ht C, Fu, Fo, food
MAI: 7
Growth:
Planting: S, B
Source: Bolivia to Argentina, 17° to 27° S.

Prosopis juliflora (Swartz) DC
Common Name: Mesquite, algarrobo
Elevation: 0–1,500 (0–1,000)
Rainfall: 15–75 (6–8 W)
Soil: Free-draining—tolerates poor, sandy, or heavy soils, alkalinity and salinity
Resistance: Fr (varieties), W
Synonym: *P. glandulosa* Torr.
Utility: .8dbh/5–10ht/7–8g Po, Fu, R, A, honey
MAI: 3–5 c
Growth: 4/4
Planting: S, C, root suckers
Source: Southern U.S. to Ecuador, 35° N. to 20° S.

Prosopis tamarugo F. Phil
Common Name: Tamarugo, albarrobo de Chile
Elevation: 0–1,900 (0–2,400)
Rainfall: 20–40 (6–8)
Soil: Sandy, rocky—tolerates alkalinity and salinity
Resistance: Fr (−12 C)
Synonym: P. chilensis (Mol.) Stuntz
Utility: .8dbh/15ht/8–9g Fo, Fu, Fo
MAI: 2–4
Growth: 10/15 C
Planting: S, C, root suckers
Source: Peru to Argentina, 18° to 27° S.

Species Information

Pterocarpus indicus Willd
Common Name: Narra, Burma rosewood
Elevation: 0–900 (0–400)
Rainfall: 100–180 (0–2)
Soil: Deep, free-draining
Resistance:
Synonym:
Utility: 1.5dbh/40ht/5g
F, V, C, Fu, R
MAI:
Growth: 8/5
Planting: B, C, u
Source: Andaman Islands and Philippines, 18° to 10° N.

Pterocarpus macrocarpus Kurz
Common Name: Burma padauk
Elevation: 0–760
Rainfall: 100–200
Soil: Deep loams to dry shallow outcrops, not poorly drained soils
Resistance:
Synonym:
Utility: 1.7dbh/40ht/7–8g
F, C, T
MAI: c
Growth: 22/27
Planting: B, C, u
Source: Myanmar to Vietnam, 24° to 12° N.

Rhizophora mangle L.
Common Name: Mangle colorado, mangue vermelho
Elevation: 0
Rainfall: >100 (0–6)
Soil: Protected tidal muck—tolerates high salinity and impeded drainage
Resistance: W
Synonym:
Utility: 1.6dbh/50ht/9–12g
C, Fu, R, tannin
MAI: 8 t
Growth: 6/5
Planting: S, layering
Source: Tropical American, west African, and Pacific shores, 30° N. to 30° S.

Schefflera morototoni (Aubl.) Decne. Maguire, Steyermark, & Froden
Common Name: Morototo, yagrumo macho, jereton
Elevation: 500–1,500 (0–1,000)
Rainfall: 150–400 (0–3 W)
Soil: Deep, free-draining—tolerates both sand and clay
Resistance:
Synonym: *Didymopanax m.* (Aubl.) Decne.
Utility: .7dbh/25ht/4–5g
C, matches
MAI: 10–25 (5–10) c
Growth:
Planting: B, C, u, Cu
Source: Mexico to Argentina, 25° N. to 25° S.

Schinus molle L.
Common Name: Molle, terebinto, pepper tree
Elevation: 1,000–3,500 (500–3,000)
Rainfall: 30–60 (4–8 W)
Soil: Sandy, free-draining—tolerates alkalinity and salinity
Resistance: Fr (–10 °C)
Synonym:
Utility: 1.0dbh/20ht
Po, Fu, A
MAI: 3–5 C
Growth: 3/1
Planting: C
Source: Peru to northern Argentina, 7° to 33° S.

Senna siamea Irwin and Barnaby
Common Name: Yellow cassia, minjri
Elevation: 0–900 (0–500)
Rainfall: 50–150 (4–8 W)
Soil: Light, deep, free-draining—tolerates acidity, salinity, calcareous soil, and impeded drainage
Resistance:
Synonym: *Cassia siamea* Lam.
Utility: .8dbh/20ht/6–8g
F, Po, Fu, A, R
MAI: 11–30 c 21 t/ha
Growth: 5/3, 15/10, 20/25
Planting: S, B, U
Source: Sri Lanka to Indonesia, 20° to 1° N.

Sesbania grandiflora (L.) Pers.
Common Name: báculo, agate, gallito
Elevation: 0–800 (0–300)
Rainfall: >100 (0–4)
Soil: Tolerates poor, heavy clays and impeded drainage
Resistance:
Synonym: *Agati grandiflora* (L.) Desv.
Utility: 13dbh/10ht/4g
Pu, Fu, Fo, R, A, food
MAI: 20–25
Growth: 4/1, 8/3
Planting: S, B, Cu
Source: India to Philippines, 20° N. to 10° S.

Shorea robusta Gaertn.
Common Name: Sal
Elevation: 100–1,500
Rainfall: 100–250
Soil: Deep, fertile soils—tolerates poor but not impeded drainage
Resistance: Fr (slight)
Synonym:
Utility: 1.2dbh/35ht/8–9g
C
MAI: 5–9 (3–5 t)
Growth:
Planting: S
Source: Orissa to Assam, India, 27° to 17° N.

Simarouba amara Aubl.
Common Name: Marupa, bois blanc, pan parahyba
Elevation: 0–500
Rainfall: 200–280 (0–2 W)
Soil: Sandy, free-draining—tolerates poor drainage, acidity
Resistance:
Synonym:
Utility: 1.0dbh/40ht/3–4g
F, V, C, matches
MAI: 9
Growth: 3/2, 18/11
Planting: C
Source: Grenada to Brazil, 12° N. to 5° S.

Swietenia macrophylla King
Common Name: Caoba, mogno, big-leaf mahogany
Elevation: 50–1,400 (0–900)
Rainfall: 160–400 (0–4 W)
Soil: Free-draining—tolerates heavy clays and alkalinity
Resistance:
Synonym:
Utility: 1.9dbh/30–40ht/4–7g
F, V, C
MAI: 5–19 (10–15 t) c
Growth: 2/3, 11/11, 18–24/14, 25/33
Planting: B, Str, C, u
Source: Mexico to Brazil, 20° N. to 18° S.

Swietenia mahagoni Jacq.
Common Name: Caoba, West Indies mahogany
Elevation: 0–500
Rainfall: 125–200 (2–4 W)
Soil: Deep, free-draining, neutral of alkaline
Resistance: W
Synonym:
Utility: 1.4dbh/25ht/7g
F, V, C
MAI: 8 C
Growth: 5/3, 10–16/12
Planting: C
Source: Florida, U.S., to Dominican Republic, 25° to 18° N.

Tabebuia pentaphylla (L.) Hemsl.
Common Name: Apamate, roble, pink poui
Elevation: 100–1,000 (0–500)
Rainfall: 125–250 (0–3 W)
Soil: Free-draining—tolerates impeded drainage
Resistance: W
Synonym:
Utility: .9dbh/25–30ht/5–6g
F, V, C
MAI: 10–20 C
Growth: 3/1, 8/5
Planting: S, B, Str, C, Cu
Source: Mexico to Ecuador, 20° N. to 2° S.

Species Information

Tamarix aphylla (L.) Karst.
Common Name: Tamarisk
Elevation: 0–1,400 (0–900)
Rainfall: 20–50 (6–8)
Soil: Light, free-draining—tolerates alkalinity and salinity
Resistance: Fr (−10 °C), Fi
Synonym: *T. articulata* Vahl.
Utility: .6dbh/10–15ht/6–8g
F, C, T, Fu, R
MAI: 3–5 c
Growth:
Planting: C, Cu
Source: Saudi Arabia to Afghanistan, 25° to 40° N.

Tarrietia utilis Sprague
Common Name: Niagon
Elevation: 0–500
Rainfall: >180 (0)
Soil: Deep, free-draining—tolerates impeded drainage
Resistance:
Synonym:
Utility: .9dbh/40ht/5–6g
F, C
MAI:
Growth: 5/4, 21/20
Planting: Str, u
Source: Sierra Leone to Ghana, 10° to 5° N.

Tectona grandis L.
Common Name: Teak, teca
Elevation: 0–900 (0–400)
Rainfall: 125–250 (3–5 W)
Soil: Deep, fertile, free-draining, neutral—tolerates heavy soils
Resistance: Fi (moderately), W
Synonym:
Utility: 2.4dbh/30–40ht/6–7g
F, V, C, Po, A
MAI: 5–18 (5–16 t) c
Growth: 2–3/3, 8/5, 15/10, 19/15, 20–30/30
Planting: Stu, C, Cu, u
Source: India to Thailand, 25° to 12° N.

Terminalia amazonica (J.F. Gmel.) Exell
Common Name: Nargusta amarillo, cochun, white olivier
Elevation: 700–1,200
Rainfall: 100–400
Soil: Poor sandy soils or clay, not limestone
Resistance:
Synonym:
Utility: 1.5dbh/40ht/5–8g
F, C, T, tannin
MAI: c
Growth: 4/3, 12/7
Planting: B
Source: Mexico to Brazil, 20° N. to 5° S.

Terminalia arjuna Wight & Arn.
Common Name: Arjun, koha
Elevation: 0–500
Rainfall: 75–190
Soil: River banks—tolerates alkalinity
Resistance: Fr (tender)
Synonym: *T. glabra* W. and A.
Utility: 3dbh
C, tannin, R
MAI: 5 c
Growth: 3/3, 12/16
Planting: C, u
Source: Peninsular India, 20° to 12° N.

Terminalia catappa L.
Common Name: Almendro, chapeu de sol, Malabar almond
Elevation: 0–300
Rainfall: 75–200 (0–2)
Soil: Sandy, deep—tolerates calcareous soil, salinity, and acidity
Resistance: Fr
Synonym: *T. procera* Roxb.
Utility: 1.2dbh/30ht/4–7g
F, V, C, Fu, R, A, food
MAI: 4–6 c
Growth: 6/3, 16/9
Planting: S, B, u
Source: India to Philippines, 23° N. to 20° S.

Terminalia ivorensis A Chev.
Common Name: Idigbo, framire, black afara
Elevation: 0–900 (0–400)
Rainfall: 130–300 (0–2)
Soil: Free-draining—tolerates sand, acidity, and impeded drainage
Resistance: W
Synonym:
Utility: .9dbh/35–45ht/4–6g
F, V, C, Pu, A
MAI: 8–17
Growth: 7/3, 19/10, 30/15
Planting: Str, Stu, C
Source: Guinea to Cameroon, 11° to 4° N.

Terminalia myriocarpa Henrek
Common Name: Hollock
Elevation: 1,600
Rainfall: 200–500
Soil: Sandy, neutral
Resistance:
Synonym:
Utility: 5dbh
V, C
MAI: 5–15
Growth: 5/4, 26/25
Planting: C
Source: Nepal to Myanmar, 27° to 20° N.

Terminalia superba Engl. & Diels
Common Name: White afara, limba
Elevation: 0–900 (0–400)
Rainfall: 130–190 (1–3 W)
Soil: Deep, free-draining—tolerates alkalinity
Resistance:
Synonym:
Utility: 2.4dbh/4–60ht/4–7g
F, V, C, A
MAI: 10–14 c
Growth: 5/2, 9/3, 19/9
Planting: Str, Stu, C, u
Source: Sierra Leone to Zaire, 10° N. to 6° S.

Toona ciliata M.J. Roem var. *australis* F.v.M.
Common Name: Toon, burma cedar
Elevation: 0–1,200 (0–700)
Rainfall: 85–180 (2–6 W)
Soil: Deep, free-draining—tolerates acidity
Resistance: Fr (slight), W
Synonym: *Cedrela toona* Roxb.
Utility: 1.5dbh/30–45ht/4–6g
F, V, C
MAI: 7–18 c
Growth: 5/2, 8/5, 20/12
Planting: Str, C, root suckers, u
Source: Australia, 17° to 36° S.

Trema micrantha (L.) Blume
Common Name: Guacimilla, capulín
Elevation:
Rainfall:
Soil: Tolerates poor soils—a natural pioneer
Resistance:
Synonym:
Utility: .2dbh/15ht/4g
Pu, Po, Fu, R, A
MAI: c
Growth:
Planting: Stu, Cu
Source: Florida, U.S. to Argentina, 26° N. to 25° S.

Triplochiton scleroxylon K. Schum.
Common Name: Obeche, wawa
Elevation: 0–900 (0–400)
Rainfall: 160–300 (0–2)
Soil: Deep, free-draining
Resistance:
Synonym:
Utility: 1.5dbh/40–50ht/4g
F, V, C, Pu
MAI: 5–20 (5–10 t)
Growth: 4/2, 9/5
Planting: Stu, C, Cu
Source: Sierra Leone to Zaire, 10° N. to 0°

Species Information

Tristania conferta R. Br.
Common Name: Brush box
Elevation: 500–3,500 (0–300)
Rainfall: 90–160 (W)
Soil: Deep, heavy, fertile—tolerates poor, light soils
Resistance: Fr (tender)
Synonym:
Utility: 1.8dbh/40ht/7–9g
C, Po
MAI:
Growth: 5/8, 17/10
Planting: C
Source: Malaysia to Philippines, 15° N. to 32° S.

Virola surinamensis (Rol.) Warb.
Common Name: Baboen banak, dalli
Elevation:
Rainfall: >150
Soil: Deep, free-draining—tolerates poor drainage
Resistance:
Synonym:
Utility: 1.5dbh/45ht/4–5g
F, V, C
MAI: 10–15
Growth: 15/8, 18/10
Planting: u
Source: Guadeloupe to Brazil, 16° N. to 2° S.

Zizyphus mauritania Lam.
Common Name: Jujube, aprin
Elevation: 0–1,300 (0–800)
Rainfall: 30–50
Soil: Sandy—tolerates moderate salinity
Resistance: Fr (–6 °C)
Synonym: *Z. jujuba* Lam.
Utility: .3dbh/10ht/9g
Fu, Fo, A, food
MAI: c
Growth:
Planting: S, root suckers
Source: South Asia, 30° to 25° N.

Appendix G
Conifers for the Tropics

The table below lists the number of coniferous tree species for various genera found in the Tropics.

	Lowland Tropics			Montane Tropics			Species native to tropical America
Genus	Rain forest	Wet	Dry	Rain forest	Seasonal	Dry	
Abies	0	0	0	3	2	0	5
Agathis	14	1	1	8	1	0	0
Araucaria	2	1	0	9	1	0	1
Callitris	1	0	7	0	1	0	0
Calotropis	1	0	0	0	0	0	1
Caphalotaxus	0	0	0	0	5	0	0
Chamaecyparis	0	0	0	2	0	0	0
Cunninghamia	0	0	0	0	3	0	0
Cupressus	0	0	1	3	0	0	4
Dacrydium	1	0	0	5	0	1	0
Juniperus	0	1	0	0	3	1	5
Libocedrus	0	0	0	2	3	0	0
Phyllocladus	0	0	0	1	0	0	1
Pinus	2	2	0	4	15	2	25
Podocarpus	3	0	0	13	18	1	28
Tsuga	0	0	0	1	0	0	0
Taxus	0	0	0	1	0	0	1

Source: Weck 1963.

Appendix H
A Chronology of Tropical Forest Planting

Southern Asia

During the 18th and 19th centuries, the British Empire's dependence on teak *(Tectona grandis)* for naval timbers led early to concern for future supplies and attempts to plant teak in India (Laurie 1937). Teak became scarce about 1830, and planting was attempted on sites with 300 cm of rainfall annually. It was then that the difficulty with teak seed germination was first reported. A technique finally worked out after 20 years (by an accountant) was used for nearly a full century thereafter. The earliest plantings were harvested at about 75 years of age.

Most tree planting in India is concentrated in dry zones, and fuelwood is an important product. An annotated list of shrub and tree species for dry and desert areas appeared in 1946 (Badhwar and Griffith 1946). Also included were 33 species for binding sand, 54 for arid zones, 12 for irrigated plantations, and 28 for canal banks.

Casuarina equisetifolia became popular as a fuelwood tree for beach areas in India more than a century ago (Kesarcodi 1951a, Sharma 1951). By the 1950s, 1,400 ha of this species had been planted in Orissa and 440 ha in Bombay. *Eucalyptus,* introduced into India some two centuries ago, developed a hybrid there referred to as "Mysore gum." By 1978, this and several other species had been planted on 394,000 ha (Lohani 1978).

Tree plantings began in what is now Bangladesh in 1873, and planting has been increasing ever since (Rahman and others 1982). In Chittagong alone, where planting began in 1921, some 17,300 ha had been planted by 1978. By 1982, there were 6,500 ha of plantations 30 years old or older and 47,500 ha older than 15 years.

While Pakistan was still part of India, an extensive irrigated fuelwood plantation was established at Changa Manga (Khan, M.I.R. 1961), mostly with *Dalbergia sissoo.* Located in a region of widespread fuelwood famines, the plantation has produced an income that compares favorably with that of irrigated farming. By 1961, 50,000 ha of a total planned area of 218,000 ha had been planted. By 1980, the planted area had reached 160,000 ha (Anon. 1981g).

Africa

The introduction of teak in west Africa marks the beginning of reforestation efforts. Table H–1 summarizes progress to 1956.

Table H–1.—Teak *(Tectona grandis)* introduction and early planting in Africa

Country	Yr. of teak introduction	Hectares planted to 1956
Nigeria	1889	450
Togo	1905	4,500
Dahomey, now Benin	1916	950
Ivory Coast	1926	2,275
Senegal	1933	72
Guinea	1937	410

Source: Lanier 1959.

Tests of underplanting in francophone Africa, begun before 1940, showed promising results with *Swietenia macrophylla* and *Terminalia superba* (Aubreville 1953). By 1954, 3.6 million trees had been underplanted in the Ivory Coast, mostly *Tarrietia utilis* and several Meliaceae (Mensbruge 1962). In Nigeria, in contrast, emphasis was on plantations of teak, using the taungya system. By 1955, a total of 480 ha of teak had been established (Ross and Moss 1957). Seventeen other exotic tree species had been introduced and were being tested. In Uganda, about 10,000 ha of plantations for construction materials, boxes, poles, and fuelwood had been established on grassland (Anon. 1957c).

In Nigeria, during the early 1960s, with the abandonment of shelterwood, the shift was toward agroforestry, but there remained 150,000 ha of planted pines and eucalypts in the savanna reserves (Lowe 1984). In total, the planted area of Nigeria in 1990 was 216,000 ha (Anon. 1993a).

In South Africa, 15 years of testing indigenous species began in 1912 and included large-scale *Juniperus procera* plantings (Pudden 1957b). Growth was slow, so exotics were substituted. By 1955, there were 18,000 ha of three species of *Cupressus,* 4,400 ha of *Pinus patula,* and 3,500 ha of *P. radiata.* Also under test were 22 other pine species, 6 *Araucaria,* 3 *Callitris,* 12 other conifers, 70 *Eucalyptus,* and 80 other broadleaf species.

In francophone Africa, plantings had been undertaken in all the colonies by 1960. Soil-conservation plantings in the French Cameroons used *Albizia lebbek, D. sissoo, Khaya senegalensis,* and *Senna siamea* (Guiscafre 1961).

On the coastal sands of what is now Benin, more than 700 ha of *Casuarina* had been planted for poles and firewood. In addition, 3,500 ha of teak had been planted by taungya farmers (Buffe 1961b). In Togo, there were 3,400 ha of teak and 400 of *Anacardium occidentale* (Sarlin 1961). In what is now Burkina Faso, *Azadirachta indica, S. siamea,* and *Tectona grandis* had been planted on 850 ha of savanna (Mulard 1961). Teak had been planted on 3,500 ha, using the taungya system (Buffe 1961b). In Chad, 400 ha of fuelwood plantations had been established, using the same species as in the Cameroons (Goudet 1961).

By 1963, eucalypt planting in Africa south of the Sahara was proceeding at an annual rate of 13,700 ha (Begue 1963). The areas planted annually were 9,000 ha in South Africa, 1,800 ha in what is now Zimbabwe, 1,200 ha in Mozambique, 600 ha in Angola, 400 ha in Uganda, and lesser areas in six other territories. By 1990, the total planted area in this region had reached 1.057 million ha (Anon. 1993a).

Between 1949 and 1965, the Benguela Railroad in Angola planted 94 million *Eucalyptus* trees, mostly *E. rostrata* and *E. saligna,* all for fuelwood (Sampaio and Carita Frade 1965).

In the region as a whole, a wave of industrial plantings took place following the Second World War (Lanly 1982). Between 1960 and 1980, another 1.35 million ha of industrial plantations were established, nearly all by national governments. By 1980, the total of all plantations in 37 countries was 1.78 million ha, of which 31 percent was softwoods and 36 percent, fast-growing hardwoods. By 1990, the total had reached 3 million ha and the planting rate was 129,500 ha/yr for the 1980–90 period (Anon. 1993a).

Southeast Asia and the Pacific

In Peninsular Malaysia, tree planting was tested beginning in 1927 and rejected because of good natural regeneration on most areas (Watson 1935). However, by 1990 the planted area in Malaysia had reached 116,000 ha, and the annual planting rate was 9,000 ha (Anon. 1993a).

In Java, teak planting began in the 1880s and had covered about 850,000 ha by 1940 (Sieverts 1958). By that time these plantations produced an abundance of excellent and rather cheap material for furniture, shipyards, railroads, and even fuelwood. The entire yield was marketable. By 1975, the planted area was 1.193 million ha in Indonesia, 430,000 ha in the Philippines, and 394,000 ha in Taiwan (Skoupy 1976). Planting rates in 1975 for the Philippines were 18,000 ha/yr. By 1990, the total area planted in Indonesia was 8.75 million ha and in the Philippines, 290,000 ha. The annual planting rates were 474,000 ha for Indonesia and none for the Philippines (Anon. 1993a).

Recent concern about sources for electrical energy have led to a wood fuel energy program in the Philippines. In 1985, this program operated four electric generation plants and expected to have five more that year, each requiring about 90,000 m^3 of stacked wood per year (Durst 1985). More than 8,000 ha have been planted, mostly to *Leucaena.* The trees are owned by farmers who expect to profit when the wood is sold. Average yield is nearly 50 cubic meters per hectare per year, but plantation-produced wood falls short of demand, and further planting trials are in progress.

In Queensland, Australia, planting included 15,000 ha of *Araucaria cunninghamii* by 1937 and 12,000 ha of exotic pines, principally *P. elliottii* (Grenning 1957). By 1967, there were 25,000 ha of *A. cunninghamii* and 25,000 ha of exotic pines (Hawkins and Muir 1968).

In Fiji, there were more than 10,000 ha of *S. macrophylla* plantations by 1967 (Busby 1967). Between 1908 and 1960, nearly 1,100 tree species were introduced into the Hawaiian Islands, with as many as 10,000 trees of some species being planted (Nelson 1965).

Two countries, India and Indonesia, currently boast 93 percent of all the plantations in tropical Asia and the Pacific (Lanly 1982). The total planted area in 16 countries in 1980 was 5.111 million ha, of which 16 percent was softwoods and 45 percent fast-growing hardwoods. From 1975 to 1980, some 2.1 million ha were planted in this region. The planting rate is about one-fourth of the deforestation rate.

Tropical America

Tests of 83 Brazilian timber species in the early 1900s showed that most of them grew more slowly than eucalypts that had been introduced much earlier; therefore, by 1906, 72 species of eucalypts were under test in Brazil (Navarro de Andrade 1941). Planting progressed rapidly in the State of Sao Paulo with the appointment in 1903 of Edmundo Navarro de Andrade as director of forest planting for the Companhia Paulista de Estradas de

Ferro at Jundiai (Navarro de Andrade 1939). Another 120 species of eucalypts were introduced in 1913. By 1941, when Navarro died, nearly 100 million trees of 75 different species were growing in 17 plantations along the railroad despite vigorous public condemnation of eucalypts for alleged soil effects.

By 1951, Brazil's Companhia Siderurgica Belgo Mineira had planted 3.8 million *Eucalyptus* trees to be used in charcoal for steel production (Anon. 1951b). By 1970, charcoal production ranked in value just below rice and corn and far above coffee and sugar (Ayling and Martins 1981). By 1966, there were 450,000 ha of *Eucalyptus* plantations in the State of Sao Paulo alone and, by 1972, some 580,000 ha (Victor and others 1972). By 1970, the paper industry of the State of Sao Paulo consumed the production of 90,000 ha of plantations (Golfari 1970b). By 1976, there were also 40,000 ha of *Eucalyptus* plantations in the State of Parana (Stohr and de Hoogh 1980).

By 1983, the annual reforestation rate in Brazil had reached about 350,000 ha, and the total area planted was almost 4.5 million ha (Nock 1982), most of it by private enterprises. Rates of reforestation as high as 600,000 ha annually were being planned, with a goal of 8 million ha in total.

A large Brazilian *Eucalyptus* timber-plantation enterprise is Aracruz, in the State of Espiritu Santo (Carbonnier and Lanner 1979). The project began in 1967 on 75,000 ha in response to Brazilian tax incentives. Experts were sent to acquire *Eucalyptus* seed in Australia, Papua New Guinea, Timor, and South Africa. Seed orchards of *E. grandis* and *E. urophylla* were established, to be followed by vegetative propagation. The plantations were laid out before the processing facilities were built. Yields on a 7-year rotation average 36 m^3/ha/yr and total about 1.64 million m^3/yr. In 1978, Aracruz inaugurated the world's largest single-line bleached-pulp operation, with an annual capacity of 460,000 t. By 1979, a total of 59,000 ha had been planted, using 1,044 provenances of 37 species of *Eucalyptus* and also 1.5 million trees of native species, mostly jacaranda *(Dalbergia nigra)* and pau Brasil *(Guilandina echinata)* (Kalish 1979a). By 1985, the genetic base included 54 species, 1,254 provenances, and some 5,000 selected clones from established plantations (Anon. 1985a).

The opposition to *Eucalyptus* as a cause for deserts and changing climate has been effectively answered by exposing such myths (Golfari 1975a); still, there has been a trend toward *Pinus* in Brazil because of the greater versatility of wood, particularly for cellulose products. A native conifer, *A. angustifolia,* once covered 3 percent of Brazil's land area, but its regeneration has proved complex and its growth slower than that of exotic pines (Krug 1968). By 1970, some 90 percent of the native *A. angustifolia* forests had been exploited and were not regenerating (Stohr and de Hoogh 1980).

By 1948, Brazil's Instituto Nacional do Pinho had started pine reforestation projects with 3,500 ha planted in Sao Paulo, 990 ha in Parana, 680 in Santa Catarina, 650 in Rio Grande do Sul, and 80 in Minas Gerais (Anon. 1949b). Planting began with *P. radiata,* which failed (Krug 1968). By 1964, 106 million *P. elliottii* had been planted, nearly half of them by private landowners (Krug 1968). By 1968, many other gymnosperms were showing promise, including *Agathis, Cunninghamia, Cupressus, P. caribaea, P. kesiya, P. merkusii, P. oocarpa,* and *Podocarpus.* The annual planting rate exceeded 200 million trees.

By 1972, Sao Paulo had 176,000 ha of conifer plantations (Victor and others 1972). Of the conifers, 30,000 ha were *Pinus caribaea, P. oocarpa,* and *P. patula;* the rest were *A. angustifolia, P. elliottii,* and *P. taeda* (Golfari 1972). The area proving to be suitable for *P. caribaea* was vast, from Parana to the Amazon.

Brazil's 1966 legal reforestation incentive permitted an income tax reduction of up to 50 percent by an offsetting investment in reforestation (tax relief was reduced to 25 percent in 1972). This led to 38,000 ha of plantations in the first year (1967), 2.908 million ha by the end of 10 years (1977), and 5.189 million ha by 1983 (Romero Pastor 1983). From 1960 to 1970, Brazil's annual production of pulpwood rose from 300,000 to 800,000 t, and of paper from 470,000 to 1.08 million t.

In the Brazilian State of Parana, 295,000 ha of *P. elliottii* and *P. taeda* and 46,000 ha of *Araucaria angustifolia* plantations had been established by 1976 (Stohr and de Hoogh 1980). A typical successful pine-plantation enterprise in southern Brazil is that of Olinkraft, at Lages, Santa Catarina. By 1980, this company was producing kraft paper entirely for domestic markets from 400,000 ha of *P. elliottii* (Blackman 1980).

In 1968, the acquisition of 15,000 km^2 along the Rio Jari in Amapa began what was then Brazil's largest forestry venture (Anon. 1979c). By 1979, some 90,000 ha of

Gmelina arborea and *P. caribaea* had been planted, and 260,000 t of bleached kraft pulp were being produced per year. Some 3,000 km of plantation roads had been built, and employment had reached 10,000 workers at Monte Dourado. The wood residues from 4,000 ha of virgin forest have been used each year for energy for wood processing and for the adjacent isolated community (Kalish 1979b). This project now uses only a hybrid of eucalypts.

The study of native tree species in Brazil has not been abandoned. Silvical information on 64 species native to Sao Paulo can be found in Nogueira (1977). Standards for selecting superior trees for breeding have also been developed (Pires 1979). An excellent analysis of planting sites throughout northeastern Brazil was completed using Thornthwaite's water-balance studies (Golfari and Caser 1977). Tests of underplanting with both native and exotic species have been in progress in the Amazon Valley (Carvalho Filho and Marques 1979).

From 1965 to 1980, Brazil planted enough trees—some 4 million ha—to meet nearly 60 percent of its domestic requirement for industrial wood (Spears 1983). Within the foreseeable future, it could produce all of its industrial wood needs from plantations close to the population centers of the southern and eastern half of the country. Less than 10 percent of current production comes from the Amazon region. The expansion of plantations in Brazil has already taken pressure off the natural forests and increased prospects for setting aside large areas of natural forests as nature reserves, parks, and catchments. By 1983, the rates of return on 35 World Bank reforestation projects covering 1 million ha were all more than 10 percent and some were 25 to 30 percent (Spears 1983).

A landmark in the development of forestry in Trinidad was the introduction of teak from what is now Myanmar in 1913 (Brooks 1938). The teak was originally intended to provide boiler fuel for the sugar estates and for burning clay for road surfacing, among other uses. Only about 40 ha were planted in the following 10 years, but by 1956, plantations covered 4,100 ha (Ross 1959) and by 1979, 9,700 ha. *Pinus caribaea* was introduced in 1952.

In Suriname, the Gongrypp plantations were established at Zanderij from 1904 to 1924 (Swabey 1950). They covered 1,800 ha. Planted species included *Eperua falcata, Hymenaea courbaril, Goupia glabra, Manilkara bidentata, Mora excelsa, Vochysia* spp., and many others. In 1947, these plantations, long abandoned, were partly restored, and a more extensive planting program ensued using both native species and exotics (Schulz and Rodriguez 1966).

Plantings of *Eucalyptus globulus* in the Peruvian Andes were, by 1947, producing more than half that country's wood (Moulds 1947).

In Central America, planting was first undertaken in 1927 near Lancetilla, Honduras, by the United Fruit Company; the emphasis was on teak (Chable 1967). By 1953, the total area planted was 4,250 ha.

In Cuba, forest planting between 1940 and 1959 totaled 1,900 ha, mostly in Pinar del Rio Province (Gomez Ricano 1966). Between 1960 and 1964, an additional 60,000 ha were planted, nearly half of which was in Pinar del Rio. About 40 percent of the trees were eucalypts; another 12 percent were pines.

In the French Antilles, the introduction of *S. macrophylla* led to an active planting program beginning in 1924 (Chapuis 1955). By 1955, there were about 12,000 ha of plantations on Martinique, of which 5,000 ha were productive. Underplanting has been done extensively on Guadeloupe.

In Puerto Rico, timber-tree planting began in 1922, and more than 80 million trees have been produced since then. The current plantation area is about 6,000 ha.

In Venezuela, large-scale government forest planting of *P. caribaea* began in 1968 in the lower Orinoco Valley. By 1976, more than 50,000 ha of savannas had been planted (Lama Gutierrez 1976).

In 1979, Keogh listed the then-known teak plantation areas for tropical America; they included 9,700 ha in Trinidad, 800 ha in Puerto Rico, 560 ha in Colombia, 560 ha in Venezuela, 300 ha in Costa Rica, 230 ha in El Salvador, 200 ha in Cuba, 60 ha in Nicaragua, and 30 ha in Belize, or a total of 12,440 ha.

Appendix I
Examples of Rotation Selection

In Trinidad, provisional yield tables for teak *(Tectona grandis)* were developed based on 80 plots on two sites corresponding to mean heights of about 26 and 23 m at age 50 (Miller 1969b). The mean annual increment (MAI) decreased with age over 10 years (table I–1). *Pinus caribaea hondurensis* in Trinidad illustrates well the trends of current and mean annual increment (table I–2; Miller 1969a). The MAI rises continuously to 24 to 25 years of age.

The trend of MAI after age 20 has been documented for *P. merkusii* in Java (Alphen de Veer 1954). On good sites, it drops from 30 to 27 cubic meters per hectare per year between age 20 and 30. On mediocre sites, MAI continues to rise, from 20 to 21 m^3/ha/yr. On poor sites, the rise is more rapid, from 10 to 16 m^3/ha/yr. The implication is that on good sites growth is not only greater but also culminates earlier than on poor sites.

Yield trends of *Araucaria angustifolia* have been clarified by the development of yield tables based on numerous plantations in Brazil (Heinsdijk 1972). The effect of age on volume in plantations of 1,000 trees per hectare is shown in table I–3. The MAI occurs at about year 20 regardless of site. However, the peak is steepest on the best sites and relatively flat on the poor sites. Interestingly, Brazilian data indicate that MAI culminates at about the same age in plantations on the best sites stocked with either 600 trees per hectare (14.6 m^3) or 1,600 trees per hectare (928.6 m^3).

The wood-production potential of *A. angustifolia* was then derived from plantations where the number of trees ranged from 3,150 per hectare at age 8 to 730 per hectare at age 35 for site 3 (tree height at age 25: 10–14 m) (table I–4; Heinsdijk 1972). This table indicates that maximum annual production would be obtained with a

Table I–1.—Relation of age to growth and mean annual increment (MAI) for teak *(Tectona grandis)* in Trinidad

Age (yr)	No. of trees per hectare	Mean d.b.h. (cm)	Mean height (m)	MAI (m^3/ha/yr)
		Site I		
10	370	21	18	14
20	160	34	22	12
30	100	43	24	11
40	80	51	25	10
		Site II		
10	480	18	15	10
20	240	27	18	9
30	160	35	21	8
40	120	41	22	7

Source: Miller 1969b.

Table I–2.—Mean annual increment (MAI) of *Pinus caribaea hondurensis* in Trinidad as related to age and site quality

Age (yr)	No. of trees per hectare	Mean d.b.h. (cm)	Mean height (m)	MAI (m^3/ha/yr)
		Site I		
0	1,330			
10	490	23	18	14
15	370	31	23	17
20	300	37	26	19
25	230	44	28	20
		Site II		
0	1,330			
12	540	23	17	12
18	410	29	21	14
24	320	33	25	16

Source: Miller 1969a.

Table I–3.—Age/volume trends in *Araucaria angustifolia* plantations of 1,000 trees per hectare in Brazil (m^3/ha/yr)

Age (yr)	Site index[a] 18–22	14–18	10–14
10	14.1	4.9	3.3
15	19.3	9.4	4.5
20	20.7	10.0	4.8
25	20.5	10.0	4.8
30	19.7	9.6	4.6
35	18.7	9.1	4.4

Source: Heinsdijk 1972.

[a] Tree height in meters at age 25.

Table I–4.—Wood production potential of *Araucaria angustifolia* in Brazil

Age (yr)	No. of trees per hectare	Mean d.b.h. (cm)	Mean annual production per hectare: Pulpwood (steres[a])	Mean annual production per hectare: Timber (m³)
8	3,150	8	10.3	0
11	1,880	11	13.5	0
14	1,400	15	14.7	0
17	1,160	17	14.9	0
20	1,010	19	14.6	0
23	920	20	6.5	5.7
27	830	22	6.0	5.5
31	770	23	5.6	5.3
35	730	24	5.2	5.0

Source: Heinsdijk 1972.

[a] 1 stere equals 1 stacked cubic meter.

rotation of about 17 years for pulpwood and about 23 years for timber. However, if larger diameters were wanted, a longer rotation apparently would not mean a large decline in yield.

Similar yield tables were derived for *Cunninghamia lanceolata* in Brazil (Heinsdijk 1972). Age/volume relations for plantations of 1,000 trees per hectare appear in table I–5. Again, the peaking of MAI occurs at about the same age regardless of site quality. Plantations of 1,600 trees per hectare on the best sites also culminate at age 15 (30.1 m³). The decline in the means with longer rotations appears small, but the current annual growth from 15 to 20 years averages about 15 percent less than the mean up to that period.

Table I–5.—Age/yield trends with *Cunninghamia lanceolata* plantations of 1,000 trees per hectare in Brazil (m³/ha/yr)

Age (yr)	Site index[a] 22–26	18–22	14–18
10	20.6	14.9	9.0
15	22.9	16.6	10.0
20	22.2	16.1	9.7
25	20.7	15.0	9.0
30	19.1	13.9	8.3
35	17.6	12.8	7.7

Source: Heinsdijk 1972.

[a] Tree height in meters at age 25.

The wood productivity potential of *C. lanceolata,* based on actual plantation densities, is shown for site indices 10 to 14 in table I–6 (Heinsdijk 1972). The yields of *C. lanceolata* are higher than those of *A. angustifolia* (table I–4) because of the greater tree density tolerated by *C. lanceolata,* resulting in more than twice as many trees at maturity.

Yield tables were also made for *Cryptomeria japonica* in Brazil (Heinsdijk 1972). Age/volume trends for plantations of 1,000 trees per hectare are summarized in table I–7. As with *Cunninghamia lanceolata,* the mean annual volume growth of *Cryptomeria japonica* may culminate at about age 15, or possibly even earlier. In plantations on the best sites with 1,600 trees per hectare, growth also culminates at about age 15 (25.7 m³).

The wood-production potential of plantations of *C. japonica,* with the number of trees actually found on site indices 10 to 14 at each age, appears in table I–8 (Heinsdijk 1972). Great similarity between *C. japonica* in table I–8 and *Cunninghamia lanceolata* in table I–6 is apparent. A rational decision for a rotation for each would depend on these yield data as well as on information on the economics of tree size and carrying charges.

Yield tables for *Cupressus lusitanica* have been prepared from plantations in Piedras Blancas, Colombia (Falla 1968). Summarized in table I–9, they suggest a rotation

Table I–6.—Wood production potential of *Cunninghamia lanceolata* in Brazil

Age (yr)	No. of trees per hectare	Mean d.b.h. (cm)	Mean annual production per hectare	
			Pulpwood (steres[a])	Timber (m³/ha)
8	2,430	11	15.1	0
11	2,160	14	18.3	0
14	2,020	15	19.1	0
17	1,930	17	18.9	0
20	1,870	17	18.3	0
23	1,830	18	6.6	8.1
27	1,790	18	6.1	7.6
31	1,760	19	5.6	7.1
35	1,740	19	5.2	6.7

Source: Heinsdijk 1972.

[a] 1 stere equals 1 stacked cubic meter.

of about 20 years for maximum usable wood volume per unit of time.

Similar information has been developed for *Eucalyptus*. Yield data for *E. saligna* in Transvaal, South Africa, including stemwood under bark to a 7.6-cm limit, appear in table I–10 (Kotze 1961). These data suggest that the rotation for pulpwood might be longer than 10 years, unless trees then exceed the maximum diameter for chipping.

A record of a remarkably old *E. globulus* plantation in the Nilgiris Hills of India shows the capacity of old trees to sustain growth (Borota 1965). The data in table I–11 are based on a plot of 1.26 ha, which at age 91 had 58 trees per hectare, a basal area of 52 m²/ha, and a volume of 992 m³/ha. From age 91 to 99, the periodic annual basal-area growth was still as rapid as in the past, and the volume growth was 26 m³/ha. At age 99, 10 trees selected at random averaged 72.1 m in height.

Table I–7.—Age/volume trends with *Cryptomeria japonica* plantations with 1,000 trees per hectare in Brazil (m³/ha/yr)

Age (yr)	Site index[a]			
	22–26	18–22	14–18	10–14
15	19.7	13.8	9.1	5.3
20	19.1	13.4	8.8	5.0
25	17.8	12.5	8.2	4.8
30	16.4	11.5	7.6	4.4
35	15.2	10.7	7.0	4.1

Source: Heinsdijk 1972.

[a] Mean tree height in meters at age 25.

Early studies of nine species of *Eucalyptus* in Brazil spaced at 2.5 by 2.5 m showed that fuelwood production culminates early (table I–12). More recent yield tables for *Eucalyptus* in Brazil show prospective growth relative to age in much more detail (table I–13; Heinsdijk 1972). The MAI on all sites culminates at about age 12. This is also true for plantations with 1,800 trees per hectare on site index 20-24 (48.2 m³).

A study of the growth of *E. deglupta* in Papua New Guinea suggests possible rotation lengths (Davidson 1968). Trees spaced at 4.6 by 4.6 m grew to a mean d.b.h. of 54 cm and a mean height of 44 m at age 15 (table I–14). From these data, it is predicted that at age 40 there would be 49 trees per hectare averaging 84 cm in d.b.h.

The use of multiple regressions to predict volumes and growth has greatly increased with the advent of electronic data processing. Examples are seen in the following regression derived for *Eucalyptus* in India (Chaturvedi 1973, 1976). The term *r* is the coefficient of correlation, *d* is the diameter, and *ba* is the basal area.

1. Tree volume (under bark) in cubic meters = 0.0201 d^2 (in centimeters) x top height (in meters) – 0.0015 ($r = 0.99$).

Table I-8.—Wood production potential of *Cryptomeria japonica* in Brazil

Age (yr)	No. of trees per hectare	Mean d.b.h. (cm)	Mean annual production per hectare	
			Pulpwood (steres[a])	Timber (m^3/ha)
8	2,680	9	14.6	0
11	2,290	12	17.5	0
14	2,090	13	18.1	0
17	1,960	15	17.8	0
20	1,890	16	17.1	0
23	1,830	17	6.5	7.4
27	1,780	17	6.0	6.9
31	1,740	18	5.6	6.4
35	1,710	18	5.2	6.0

Source: Heinsdijk 1972.

[a] 1 stere equals 1 stacked cubic meter.

Table I-9.—Age/increment relations for *Cupressus lusitanica* in Colombia

Age (yr)	No. of trees per hectare	Mean d.b.h. (cm)	Volume (m^3/ha)	Mean annual increment (m^3/ha/yr)
10	3,350	9.3	119	11.9
20	1,415	22.3	401	20.1
30	610	36.3	496	16.5

Source: Falla 1968.

Table I-10.—Age/increment trends for *Eucalyptus saligna* in Transvaal, South Africa (m^3/ha)

Age (yr)	Mean annual increment	Next year's increment
2	12	40
4	27	90
6	53	120
8	71	120
10	81	

Source: Kotze 1961.

Table I-11.—Basal-area growth of old *Eucalyptus globulus* in India

Mean d.b.h. (cm) in 1954 at age 91	No. of trees per hectare	Annual basal area growth (cm^2)	
		Mean 1863–1954 Age 0–91	Periodic 1954–62 Age 91–99
70–94	17.5	61	65
94–117	27.0	94	86
117–144	10.3	146	166
144–180	3.2	216	305
Totals/means	**58.0**	**100**	**106**

Source: Borota 1965.

Table I–12.—Fuelwood production of *Eucalyptus* in Brazil

Age (yr)	Growth (m^3/ha/yr) Mean	Periodic
6	26.8	
		41
8	30.4	
		8
10	26.0	
		8
12	23.0	
		10
15	19.8	

Source: Guimaraes 1957.

2. Plantation volume (under bark to 5 cm in diameter) in cubic meters = 0.2869 × (*ba* [in m^2/ha] × top height [in meters]) – 2.5101 ($r = 0.98$).

3. Logarithm_n mean annual increment (in m^3/ha/yr) = 0.628 Log_n *ba* (in m^2/ha) + 2.467 Log_n top height (in meters) – 0.997 Log_n age (in years) – 4.580 ($r = 0.97$).

Volume-growth data on *Gmelina arborea* from Cebu, Philippines, from an unthinned, 0.2-ha plot planted at 2 by 2 m with an annual rainfall of 220 cm appear in table I–15 (Nanagas and Serna 1970). They suggest that, under these conditions, the MAI in basal area and volume hold up well to 8 years. Early practice at Monte Dourado, Brazil, was to clearcut *G. arborea* for pulpwood at 6 to 7 years or for sawlogs at 10 years (Anon. 1979e).

Table I–13.—Age/volume trends in *Eucalyptus* plantations of 1,000 trees per hectare in Brazil

Age (yr)	Mean annual volume increment by site index[a] (m^3/ha/yr) 24–28	20–24	16–20	12–16
4	26.0	17.8	11.8	7.2
6	43.7	29.7	19.7	12.2
8	52.0	35.4	23.4	14.5
10	54.8	37.4	24.7	15.3
12	55.0	37.5	24.8	15.4
14	53.8	36.7	24.2	15.1
16	52.0	35.4	23.4	14.6
18	49.9	32.6	21.6	13.4
20	47.8	32.6	21.5	13.4

[a] Mean tree height in meters at age 8.

Table I–14.—Age/increment relations for *Eucalyptus deglupta* in Papua New Guinea

Age (yr)	Mean d.b.h. (cm)	Mean height (m) Total	Clear bole
5	22	24	14
10	39	37	23
15	54	44	30

Source: Davidson 1968.

Yield tables for *Anthocephalus chinensis* in West Bengal, India, indicate the effect of rotation length on tree diameter and MAI on the best sites (table I–16; Singh 1981).

Growth of *Casuarina equisetifolia* on sandy hills along the Bay of Bengal in India has been projected in terms of both volume and green weight, assuming no mortality (table I–17; Ray 1971). Actual yields were lower than predicted in the table because of mortality. Records indicate a yield of 9.2 m^3/ha/yr at 12 years, of which 8.3 m^3 was stemwood of 20 cm or larger in diameter at the small end. By the 15th year, the MAI had dropped to 4.2 m^3.

The influence of age on usable wood volume per tree, and thus on the cost of handling prescribed timber volumes, is illustrated by data from a plantation of *P. elliottii* in Misiones, Argentina (table I–18; Molino 1972).

Table I–15.—Age/increment relations for *Gmelina arborea* in the Philippines

Age (yr)	Total height (m)	Mean annual increment D.b.h. (cm)	Basal area (m^2/ha)	Volume (m^3/ha)
4	2.4	2.5	5.0	21.5
6	2.0	2.2	5.7	29.2
8	1.6	1.9	5.6	34.2

Source: Nanagas and Serna 1970.

Table I–16.—Age/increment relations for *Anthocephalus chinensis* in India

Age (yr)	No. of trees per hectare	Mean d.b.h.[a] (cm)	Basal area (m^2/ha)	Mean annual increment[b] (m^3/ha)
5	551	16.7	7.2	8.1
10	464	23.7	13.4	13.4
15	355	28.5	15.8	13.6
20	279	31.8	16.6	12.7
25	228	34.0	16.9	10.8

Source: Singh 1981.

[a] Mean for 125 trees per hectare of those with the largest diameters.

[b] Including branchwood and thinnings.

Table I–17.—Age/increment relations of *Casuarina equisetifolia* in India

Age (yr)	Mean d.b.h. (cm)	Mean height (m)	Mean annual increment of volume under bark[a] (m^3/ha)
2	4.3	5.8	
4	8.1	10.7	3.1
6	10.3	14.8	13.3
8	11.2	17.0	16.9
10	12.0	18.4	17.5
12	12.7	19.8	17.5

Source: Ray 1971.

[a] Presuming a 2- by 2-m spacing, unthinned

Table I–18.—Relation of age to tree volume for *Pinus elliottii* in Argentina

Age (yr)	Mean d.b.h. (cm)	Total height (m)	Stemwood volume per tree (m^3)
5	10.6	5.5	0.02
10	17.2	14.3	0.20
15	26.1	20.0	0.64
19	30.0	23.0	0.98

Source: Molino 1972.

Appendix J
Selected Results of Thinning

Thinning of *Tectona grandis* plantations in Puerto Rico resulted in a much greater growth response than was possible through fertilizer application (Briscoe and Ybarra-Coronado 1972). The application of nitrogen (N), calcium (Ca), and magnesium (Mg) to 3- to 16-year-old plantations had no significant effect on height or diameter growth. Although minor increases in height growth were attributed to added phosphorus (P) and potassium (K), concurrent thinning increased growth much more than even the best fertilizer treatment.

Thinning intensity does not always produce a sharply defined response. Subsequent overall growth may be about the same over a wide range of residual stand densities. This is illustrated by a thinning in a 16-year-old plantation of *Araucaria angustifolia* in Brazil (Soares 1970). The basal area per hectare was reduced in four treatments from 35 m^2 to 29, 18, 11, and 7 m^2. During the next 3 years, the basal area growth was 6 m^2/ha for the unthinned plots, and 7, 6, 4, and 3 m^2/ha for the thinned plantations. The treatment that reduced basal area from 35 to 18 m^2/ha reduced the number of trees from 2,500 to 800 per hectare, yet did not reduce volume growth. In percentage, however, volume growth rose from 34 to 62 percent.

One explanation for this nearly uniform response regardless of the intensity of thinning is that diameter growth of the dominant trees is not much affected by the removal of subordinates, be they few or many. This suggests the desirability of complete utilization of these subordinates where pulpwood or pole markets exist.

Light thinnings may not stimulate tree growth unless done very early in the life of the plantation. A thinning of 20-year-old *Calophyllum calaba* on an adverse site in Puerto Rico reduced the basal area from 26 to 18 m^2/ha but produced no evident growth response 2 years later (Anon. 1952o). The crowns of the released trees were still essentially as narrow as when thinned. However, the crowns did fill out gradually over many years, possibly indicating slow recovery after having been constrained by long stagnation before thinning.

The effects of different thinning intensities and policies are apparent in a study of an 8-year-old teak *(Tectona grandis)* plantation in Nigeria (Nwoboshi 1971). The results are presented in terms of remaining tree quality (table J–1). Samples were taken from six plots of each treatment, for an aggregate of 0.24 ha per treatment.

The trend in basal-area growth of three *A. angustifolia* trees in Brazil is of interest (Buch 1971). From age 10 to 20 (before thinning), their average basal-area growth was 140 cm^2/yr. From age 20 to 30, still before thinning, it was 144 cm^2/yr. From age 30 to 40, with the thinning in the 33rd year, it rose to 473 cm^2/yr, more than triple the previous average.

A detailed study of thinning effects on *Pinus elliottii* in the southern United States clarifies a number of relations that appear to have broad applicability (Mann and Enghardt 1972). Different parts of the plantation were thinned to 16 m^2/ha of basal area at ages 10, 13, and 16; 13 and 16; and 16 only. Although overall volume growth was reduced by the thinnings, as shown in table J–2, the diameter growth of the large trees rose above that of the unthinned plots, as seen in table J–3. This indicates some benefits from removal of subordinate trees.

In Brazil, thinning has been shown to extend the rise in the mean annual increment (MAI) of *Eucalyptus* plantations (Heinsdijk 1972). In unthinned first plantings, the MAI culminates in about the 8th year. In thinned plantations, the MAI continues to rise to year 11 and, with complete utilization of small poles, may not culminate until year 14.

Thinning of *A. angustifolia* in Misiones, Argentina, strongly influenced overall yield and mean tree diameter (Cozzo 1958). Trees planted at 1 by 1 m were thinned at year 5 to 2 by 2 m or 4 by 4 m. By year 11, the most intensely thinned plots had about three times the mean d.b.h. of unthinned controls but only about a third the basal area and MAI (table J–4).

In another *A. angustifolia* plantation in Misiones, thinning at 10 years reduced basal area per hectare from 24 to 20 m^2, and thinning at 17 years reduced it from 34 to 12 m^2 (Cozzo 1970). Net growth of the thinned plantation from age 10 to 20 was 26.1 cubic meters per hectare per year compared to 35.7 m^3/ha/yr for the unthinned control. Thinning paid off well in tree size; however, at age 20 all the trees in the thinned plantation were 26 cm in d.b.h. or larger, whereas, in the unthinned plantation, only 19 percent were this large.

In Nigeria, variation in tree growth in teak plantations was found to be strongly related (about 70 percent) to tree size at the beginning of the measurement period rather than to competition, as indicated by summed

Table J-1.—Effects of various intensities of thinning on an 8-year-old teak (*Tectona grandis*) plantation in Nigeria

Treatment	No. of trees left per hectare	Percentage of trees by quality class[a] 1	2	3
Unthinned	921	46	39	15
One-third of rows removed	659	48	32	20
One-half of rows removed	479	38	40	22
Basal area reduced to 16 m^2/ha[b]	598	53	38	10
Eclectic (quintet)[c]	440	61	33	6
Eclectic (quartet)[d]	427	59	35	6

Source: Nwoboshi 1971.

[a] 1 = straight, sound dominants and codominants;
2 = dominants or codominants likely to be removed in subsequent thinnings;
3 = inferior trees.

[b] Low and crown thinning to yield fuelwood.

[c] Best of five in progression in each row.

[d] Best of four in progression in each row.

basal areas of surrounding trees (Lowe 1966). Thinning significantly reduces this variation, increasing the uniformity of growth rates among the trees.

An early analysis of sample plots in 11- to 21-year-old teak plantations in Java showed that conventionally thinned teak can even outproduce unthinned plantations (Hellinga 1939). Unthinned plantations had up to 250 percent as many trees as thinned plantations. They also had up to 200 percent as much basal area and up to 180 percent as much volume. The mean d.b.h. ranged from 70 to 95 percent of that in the thinned plantations. But, surprisingly, the ultimate volume of standing timber plus thinnings was 5 to 33 percent greater in the thinned plantations than in the unthinned ones.

Tests with *P. caribaea* in South Africa, where sawtimber is the final product but there is also a market for pulpwood, showed the advantages of initial close spacing and a heavy pulpwood thinning (Anon. 1954e). Plantations initially spaced at 2.1 by 2.1 m, rather than at the more conventional 2.7 by 2.7 m, yielded 21 m^3/ha more wood from the first thinning. This, plus the increase in diameter resulting from the thinning, more than compensated (in terms of cellulose yield) for the slower growth of individual trees at the closer spacing before the first thinning.

At Nilambur, India, a systematic first thinning has been followed by selection of about 10 percent of the elites for a total of 80 crop trees per hectare on site I and 120 per hectare on site III (Kaushik 1960). These crop trees have been released progressively.

Table J-2.—Thinning effects on volume growth of *Pinus elliottii* in the Southern United States

Age at thinning	Increment in cubic meters per hectare 10–13 yr.	13–16 yr.	16–19 yr.
10, 13, 16	89	79	77
13, 16		72	79
16			68
Unthinned	100	100	100

Source: Mann and Enghardt 1972.

Table J-3.—Diameter growth of largest trees after thinning of *Pinus elliottii* in the Southern United States

Age at thinning	Increment in cubic meters per hectare 10–13 yr.	13–16 yr.	16–19 yr.
10, 13, 16	105	133	148
13, 16		133	156
16			119
Unthinned	100	100	100

Source: Mann and Enghardt 1972.

Table J-4.—Effects of thinning on an *Araucaria angustifolia* plantation in Misiones, Argentina, treated at age 4 and measured at age 11

Treatment at age 4	Mean d.b.h. (cm)	Basal area (m²/ha)	Mean annual increment (m³/ha/yr)
Unthinned, 1 by 1 m	9.8	44.4	24.2
Thinned to 2 by 2 m	12.5	26.9	14.6
Thinned to 4 by 4 m	18.0	14.5	7.9

Source: Cozzo 1958.

Teak *(Tectona grandis)* thinning in India is generally from below (Mathauda 1954c). The thinned teak trees are highly marketable, which favors thinning long before sawtimber is produced. In Trinidad, the thinned trees are ripped with gangsaws and treated with preservatives to make fencing (Ross 1958). Slabs are converted to broom handles.

Open-grown teak in Thailand has wider crowns than most other trees. In youth, the root system extends beyond the crown, but the crown overtakes root spread later (table J–5). The implication here is to thin as heavily as possible without causing epicormic branching (Ngampongsai 1973).

In Ivory Coast, a 4,000-ha teak plantation was thinned at 7, 12, and 20 years, yielding a total of 75 m³/ha of small poles (Tariel 1966). For the final felling at 60 to 80 years, 150 trees per hectare remained and were expected to attain a diameter of 30 to 70 cm at that time.

Table J-5.—Tree dimensions of open-grown teak *(Tectona grandis)* in Thailand

Age (yr)	D.b.h. (cm)	Crown diameter (m)	Root system diameter (m)
5	9.0	4.2	4.6
10	14.2	7.7	5.4
15	16.9	8.5	5.6
20	26.1	10.0	5.7

Source: Ngampongsai 1973.

A thinning schedule recommended for teak in Nigeria (Horne 1966) for site quality I was based on crop height rather than age (table J–6).

A different regime has been used for thinning teak in eastern Nicaragua, where annual rainfall is 290 cm and initial spacing is 3.5 by 3.5 m (816 trees per hectare). Stands were thinned 50 percent at 9 years, leaving 408 trees per hectare (Weidema 1965b). A second thinning at age 19 left 245 trees per hectare. The two thinnings yielded 104 m³/ha.

An early thinning regime for *Cupressus lusitanica* in east Africa, directed toward limiting knots to a 10-cm core, was as follows (Graham 1945):

Age (yr)	No. of trees left/ha.
7	990 to 1,110
9	860 to 990
11	740 to 860
14	620 to 740
17	490 to 620
20	370 to 490
25	250 to 350

By 1955, thinning was slightly heavier, leaving only 740 trees per hectare at age 9 and 620 at age 11 (Pudden 1955). With the first thinning at age 7, about 620 crop trees were selected per hectare, even though others were left for a total of 990 to 1,110 trees per hectare.

Thinning of *C. lusitanica* in Kenya has been based on dominant tree height (Wormald 1967). Comparable thinning schedules for *Pinus patula* and *P. radiata* in Kenya appear in table J–7.

Table J-6.—Teak (*Tectona grandis*) thinning schedule in Nigeria for site quality I based on crop height

Crop height (m)	Age (yr)	No. of trees to leave per hectare
8	3	1,490
12	6	750
18	10	270
23	15	190
27	20	120
32	30	90

Source: Horne 1966.

Table J-7.—Thinning schedules for three species in Kenya

Dominant height (m)	No. of trees to leave per hectare[a]		
	Cupressus lusitanica	*Pinus patula*	*P. radiata*
11–12	840	690	840
15–17	490–560		
17–18			420
18–21	330		
21–23		520	
26	250		
27		350	
30–31			280
37			200

Source: Wormald 1967.

[a] Data shown only for times of thinning.

A review of pine plantations in Kenya led to revisions in thinning practice (Paterson 1967b) based on the conclusion that denser stands could be carried without serious detriment to crop growth. The *P. patula* crop was expected to average 42 cm in d.b.h. at age 30 and 44 cm at age 35. The corresponding figures for *P. radiata* would be 54 cm and 58 cm (table J–8). Such a regime produces a final crop averaging 48 cm in d.b.h. and about 21 cubic meters per hectare per year in volume.

For *Araucaria hunsteinii* in Papua New Guinea, trees are spaced initially at 7 by 7 m (476 per hectare), and at 10 years, stands are thinned to 250 per hectare (Godlee and White 1976). At 20 years, they are reduced to 200 trees per hectare and at 25 years, to 100 per hectare. That final stocking level (100 per hectare) is maintained until harvest at 40 years.

In Misiones Province, Argentina, *A. angustifolia* plantings have been spaced at 2 by 2 m (2,500 trees per hectare) (Fraser 1965). At age 6, half the trees were removed, leaving 1,250 per hectare. At age 10, density was further reduced to 800 trees per hectare. At age 15, 500 trees per hectare were left. At age 20, the final thinning left 250 trees per hectare for a harvest at age 25.

Tests of three broadleaf tree species in Africa suggest that no thinning is necessary for at least 10 years if initial spacing is 2.4 by 2.4 m (Lowe 1970). Unthinned *Nauclea diderrichii, Terminalia ivorensis,* and *Triplochiton schleroxylon* exceeded mean diameters of 20, 32, and 22 cm, respectively, by age 10. Basal-area growth culminated at 7 to 8 years for *Terminalia ivorensis* and *Triplochiton schleroxylon* and at 10 to 12 years for *N. diderrichii.* Even after 15 years without thinning, the growth of the crop trees was still acceptable.

Table J-8.—Thinning schedules for *Pinus patula* and *P. radiata* in Kenya

Age (yr)	No. of trees to leave per hectare	
	P. patula	*P. radiata*
7	990	990
12	740	400
20	300	200

Source: Paterson 1967.

In contrast, the extremely fast-growing tree *Ochroma lagopus* needs heavy thinning. Trees of this species were planted in Nigeria at the rate of 2,200 trees per hectare, or an average spacing of about 2.1 by 2.1 m, and thinned at 18 months to 1,550 per hectare. From these residuals, 400 potential crop trees were selected (Anon. 1961f, White and Cameron 1965). A year later, another thinning reduced the stand to 760 trees per hectare. At 3.5 years (another year later), a final thinning reduced the stand to 100 trees per hectare, and the harvest came in the 5th year.

Thinning experience with *Aucoumea klainiana* in west Africa suggests two general practices: (1) space initially at 11 by 11 m within natural forests and avoid thinning, and (2) space more closely and thin gradually to obtain 90 good dominant trees per hectare (Catinot 1969a). The first of these, which is well adapted for underplanting, keeps basal area less than 10 m²/ha until nearly the 20th year. The final crop would attain a mean d.b.h. of 65 cm and a basal area of about 40 m²/ha. The second practice calls for thinning to 180 to 200 trees per hectare at ages 8 to 10 and to 110 to 120 trees per hectare at age 15, or both thinnings may be combined at age 10. A complication with this species is serious epicormic branching. Heavy thinning (50 to 75 percent of the trees) brings about catastrophic crown descent. Thinning should be done early to confine any subsequent branching and consequent knots to what will eventually be the central core of the trees.

Thinning of *Gmelina arborea* plantations at Monte Dourado, Brazil, for products larger than pulpwood was projected for 3, 5, and 7 years (Anon. 1979e).

Appendix K
Publications on Plantation Pests and Diseases

Ford, L.B. 1980. A survey of pests in forest plantations in Costa Rica. Turrialba, Costa Rica: CATIE. 53 p.

Hilje, L.Q.; Araya R., C; Scorza R., F., eds. 1991. Plagas y enfermedades forestales en America Central. Manual de consulta y guia de campo. Manual Tecnico CATIE 3 and 4. Turrialba, Costa Rica. CATIE. 263 p.

Hodges, C.S.; Reis, R.S. 1976. A canker disease of *Eucalyptus* in Brazil caused by *Diaporthe cubensis* Bruner. FAO Field Document 14. Brasilia, Brazil: Food and Agriculture Organization of the United Nations. 6 p.

Hodges, C.S.; Reis, R.S. 1976. The influence of basal cankers on sprouting of *Eucalyptus*. FAO Field Document 17. Brasilia, Brazil: Food and Agriculture Organization of the United Nations. 4 p.

Hodges, C.S.; Reis, R.S.; Ferreira, F.A. 1976. A new needle disease of pine in Brazil caused by *Cylindrocladium pterridis*. FAO Field Document 18. Brasilia, Brazil: Food and Agriculture Organization of the United Nations. 4 p.

Hodges, C.S.; Reis, R.S.; May, L.C. 1976. Two diseases in plantations of exotic forest tree species in Brazil. FAO Field Document 15. Brasilia, Brazil: Food and Agriculture Organization of the United Nations. 8 p.

Reis, M.S.; Hodges, C.S. 1976. Status of forest diseases and insects in Latin America. FAO Field Document 12. Brasilia, Brazil: Food and Agriculture Organization of the United Nations. 10 p.

Silva, J.N.M. 1976. Aspectos principais de estudo sobre pragas de eucalipto. Comunicacion Tecnica 4. Brasilia, Brazil: PRODEPEF. 11 p.

Appendix L
Tree Species Appropriate for Agroforestry

Lists of tree species appropriate for agroforestry intercropping have been compiled from several sources. Those of special apparent potential for tropical America, many of which have been tried or are in use, are listed below (Armour 1959, Crane 1945, Douglas and de Hart 1976, Kaul and Ganguli 1962, Nair and others 1984, Purseglove 1968, Sagreiya 1940, and Weaver 1979a):

Scientific name	Common name	Rural use
Acacia spp.	Acacia	Fodder, gums (latex)
Albizia lebbeck		Shade
Alnus acuminata	Jaul	Shade
Anacardium occidentale	Maranon	Food (nuts, fruits), pots
Andira inermis	Moca	Shade
Annona sp.		Food (fruit)
Artocarpus altilis	Panapen	Food (fruit)
A. integrifolia	Jaca	Food (fruit)
Arundinaria spp.	Bamboo	Fodder (twigs, leaves)
Bauhinia spp.	Bauhinia	Food (seeds, pods)
Bertholletia excelsa	Brazil nut	Food (nuts)
Bixa orellana	Achiote	Food (seeds)
Brosimum spp.	Ramon	Fodder (leaves), latex
Cajanus cajan	Gandul	Live fences, food
Calliandra calothyrsus		Fodder
Canarium commune	Java almond	Food (fruits, nuts), seed oil
Caryocar spp.	Soruari nut	Food (nuts)
Casuarina equisetifolia	Casuarina	Shelterbelts
Ceratonia saliqua	Carob	Food (nuts)
Chrysophyllum cainito	Caimito	Food (fruits)
Citrus spp.	Naranja	Food (fruits)
Cocos nucifera	Coco	Food (fruits)
Crescentia cujete	Higuera	Vessels (fruits)
Cynometra cauliflora	Nannam	Food (pods)
Cystus spp.	Tree lucerne	Fodder (leaves)
Dalbergia sissoo	Sissoo	Fodder
Derris indica		Fodder
Detarium senegalense	Tallow tree	Food (fruits, seeds), fodder
Dialium ovoideum	Velvet tamarind	Food (fruits), fodder
D. oxyalis	Kei apple	Fodder (foliage)
Diphysa robinoides		Live fences, shelterbelts
Elaeis guianensis	Aceite palmera	Edible oil (seeds)
Enterolobium cyclocarpum	Guanacaste	Shade, browse
Erythrina spp.	Bucayo, poro	Forage (leaves), posts
Ficus spp.	Figs	Fodder (foliage), posts
Gliricidia sepium	Madre de cacao	Live fences, forage
Gnetum gnemon		Food (leaves, flowers)
Inga spp.	Guaba	Food (fruits), shade
Inocarpus edulis	Polynesian chestnut	Food (seeds)
Leucaena leucocephala	Tan tan	Food (fruits), fodder (foliage)
Macadamia ternifolia	Macadamia	Food (nuts)
Malpighia glabra	Acerola	Food (fruits)
Manilkara sapota	Chicozapote	Food, latex
Melia azedarach (and *Azadirachta indica*)	Neem	Forage (leaves), tannin bark
Pangium edule	Pangi	Fodder (fruits), oil (seeds)
Parkia spp.	African locust	Forage (pods)
Parmentiera cerifera	Candle tree	Fodder (fruits)
Persea americana	Aguacate	Food (fruit)
Pisonia albida	Corcho	Food (leaves), fodder (leaves)
Pithecolobium spp.	Saman	Fodder (pods), nitrogen fixation
Prosopis spp.	Algarrobo mesquite	Forage (pods)
Senna siamea	Siamese cassia	Forage (leaves), tannin (pods)
Sesbania grandiflora	Gallito	Food (petals, leaves, pods)
Simarouba spp.	Simaruba	Edible oil (kernels)
Spondias spp.	Jobo	Food (fruits), line posts
Tamarindus indica	Tamarind	Food (fruits)
Terminalia catappa	Almendro	Food (seeds)
Theobroma cacao	Cacao	Food (fruits)
Zizyphus jujuba	Aprin	Food (fruits)

Many of these species are legumes and are considered especially suitable for planting near or among other crops because of their capacity to fix much of their nitrogen requirement. Not all legumes, however, are appropriate for this purpose everywhere. Some are much less efficient than others as nitrogen producers and can become troublesome weeds. A review of legume introductions revealed 146 species that have become weeds (Hughes and Styles 1987). Of these, 29 have become major pests; among them are species of *Acacia, Albizia, Leucaena, Prosopis,* and *Senna.*

Appendix M
Silvical Information of Importance

I. Latin name and author(s)

II. Common, local, and trade names

III. Introduction
  A. Relative size of tree, also maximum height, diameter, and crown spread attained
  B. Special features (nonwood uses)—medicinal, poisonous, biomass, fodder, tannin, fruits, nuts, nitrogen fixation, green manure, ornamental, soil stabilization, windbreaks, drought and frost resistance
  C. Most important uses, wood specific gravity, color, figure, working characteristics, durability, natural resistance to insects and decay, preservative treatment and uses of treated products, other good and bad features

IV. Dendrology
  A. Drawings of leaves, twigs, bark, flowers, fruits, general shape of open-grown tree
  B. Map and verbal description of the geographic range, elevational range, latitude, and artificial extension of range

V. Habitat
  A. Temperature and rainfall, annual maxima and minima and seasonal variations
  B. Soil taxonomy if known; type of soil on which tree is most commonly found
  C. Soil conditions to which the tree is suited; e.g., pH, drainage, and texture
  D. Landscape settings; e.g., valley bottoms, rolling topography, steep side slopes, etc.; also tolerance to degraded (refractory) sites, salinity, flooding, drought, other desirable or undesirable species or site relationships, etc.
  E. Tolerance of shade and other factors not previously listed; associated trees and shrubs by name

VI. Life History
  A. Pollination, flowering, and fruiting
  B. Size of fruits and/or seeds, number of seeds or fruits per tree or flower cluster
  C. Age or size at which trees start and reach peak seed production; seed dispersal, durability, germination
  D. Conditions for natural regeneration; sites, shade, associates
  E. Silvical role in natural forests; occurrence, abundance, gregariousness, degree of dominance
  F. Growth in natural forests; relative to size, crown position and dimension, age, yields per unit of area and time
  G. Natural maturity, age, size, growth trends, mortality

VII. Silviculture
  A. Inducement of natural regeneration, early response to weeding and liberation
  B. Growth acceleration of established trees in response to treatment, rotations, potential yields
  C. Silvicultural systems for natural forests
  D. Seed technology, recommended conditions for storage, durability, germination pretreatment, germination percentage expected
  E. Nursery technology; bed conditions or containers; soil; sowing density; use of shade, water, fertilizers, and pesticides
  F. Recommended planting stock age, size, standards, preconditioning
  G. Planting technique, land preparation, spacing, depth, critical care
  H. Plantation responses to fertilization, pruning, and thinning
  I. Need for and control of insects, pathogens, and unwanted vegetative competition
  J. Growth and yields from plantations, rotation age
  K. Potentials as an associate with other crops
  L. Postharvest regeneration

VIII. Genetic races, varieties, hybrids, goals, and accomplishments to date

IX. Seed sources

X. Literature

Bibliography

The following references include those cited in the text and, in addition, others that are believed to contain useful information related to the subject of this book. The size and composition of this bibliography reflect three outstanding characteristics of information on tropical forests:

1. Much more in the way of research results and experience is at hand than is generally recognized.

2. By far the greatest progress has been not in tropical America but in the Eastern Hemisphere and merits review by foresters in the neotropics.

3. Much pragmatic research and experience in tropical forestry took place more than 20 years ago.

The references included in this bibliography, although not all cited in the text, have all been reviewed and judged to be contributions to the subject of the book. The fact that places of publication and publishers for some of them are shown as "unknown" does not mean that no such assessment was made. Rather, it reflects the exigency of citing requirements placed on this work after the information passed from the hands of the author and means the full facts of publication are available neither in the library of the International Institute of Tropical Forestry nor from principal bibliographic sources such as *Forestry Abstracts.*

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13 Anonymous. 1948c. Two-story mangrove forest. Malayan Forester. 11(4): 173.
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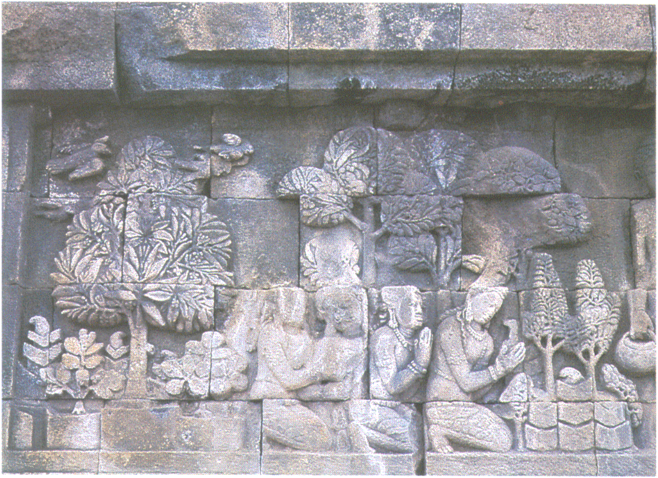

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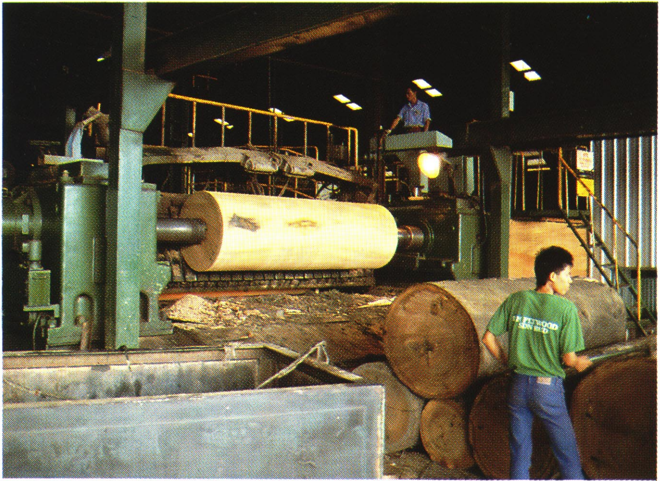

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