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# The apparent paradox of reestablishing species richness on degraded lands with tree monocultures

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## Abstract

The proliferation of degraded tropical landscapes in need of rehabilitation and the reduction of primary forest area have forced a closer collaboration between ecologists and land managers. This collaboration has led to new paradigms of forest management (combined in the term ecosystem management), new insights into forest ecology through comparative ecological research, a more objective analysis of the ecology of tree plantations and a better understanding of the ecological functioning of these ecosystems. Plantation forests can have the same functions as secondary forest stands. However, because of their species composition, structure and management history, plantations can be more susceptible to disturbances than paired secondary forest stands. Plantations can be designed for maximization of particular outputs such as timber, or for specific land rehabilitation objectives such as protection of soils from erosion. Observations of plantation understories in Puerto Rico suggest that high species richness could occur under the shade of monocultural stands. This led to the hypothesis that reestablishment of tree species richness on degraded sites with arrested succession could be facilitated through plantings of tree monocultures. This phenomena was demonstrated experimentally in small plots and through observations at the landscape scale. Restoring tree species richness by planting tree monocultures works because the manager can match species to particular site conditions and thus overcome limiting factors that prevent the regeneration of species-rich forests on degraded sites. Once a forest canopy is established, microsite conditions change and wildlife is attracted. Animals are likely to disperse tree species from surrounding forest patches and regeneration of shade-intolerant species can be inhibited. Nine lines of research are suggested. © 1997 Elsevier Science B.V.

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## 1. The problem of land degradation

In the early 1970s Gómez-Pompa and Vázquez-Yanes (1974) observed that most tropical countries of the world had a larger area of secondary than of primary forest. Accordingly, they termed that time as

the 'era of secondary vegetation'. Secondary forests are forests that appear spontaneously after natural or anthropogenic disturbances to primary vegetation (Brown and Lugo, 1990). Two decades later, the perceived area of degraded tropical lands (*sensu* Grainger, 1988) is similar to the perceived area of mature tropical forest. Grainger reported that there was 2.0 billion ha of degraded tropical lands (desertified drylands, logged forests and deforested watersheds), whereas the FAO (1993) reported that there was 1.8

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billion ha of mature tropical forest. The estimated annual rate of tropical deforestation increased from about 0.6% between 1976 and 1980 to about 0.8% between 1980 and 1990 (FAO, 1993). Some 0.7 billion ha of deforested lands could be rehabilitated through reforestation (Grainger, 1988). By rehabilitation is meant the return to a functioning forest of any converted or damaged forest land (Brown and Lugo, 1994).

The area of tropical tree plantations increased over the last 2 decades from about 10 million ha in 1980 to about 44 million ha in 1990 (FAO, 1993). However, even such an increase in the area of tree plantations cannot overcome the rate of tropical deforestation. Tropical deforestation is predominantly caused by the conversion of forest lands to agricultural lands, mostly to make up for the degradation of site productivity resulting from poor agricultural practices (Harwood et al., 1993).

The simultaneous increase in the area of secondary forest vegetation and degraded forest lands at the expense of mature forests is a matter of serious concern because of the implications that this trend has for the human carrying capacity of the land and quality of life in tropical countries. Losses of biodiversity, including species extinction, and the rate of change in the concentration of some atmospheric gases will also increase if this trend is not arrested (Lugo, 1988a; Dale et al., 1993; Heywood and Watson, 1995; Lugo and Brown, 1996).

Land degradation is a complex process with many causes and outcomes that vary according to socio-economic and ecological conditions (Barrow, 1991). Whatever the origin or cause, land degradation changes the growth conditions of vegetation by changing soil, microclimate and seed sources. These changes can be reversed through succession when land degradation is of low intensity. Alternatively, vegetation establishment and succession can be arrested when anthropogenic effects are extreme as it occurs in mined areas or sites subjected to chronic human alteration (Knabe, 1965; Ang, 1994; Yu et al., 1994).

The area of degraded tropical lands is increasing due to the increasing demand for agricultural land, fiber, fuelwood and other forest products by growing human populations and our greater technological ability to modify landscapes. This in turn is rapidly frag-

menting landscapes and creating new conditions to which vegetation must adjust. Examples of these new conditions include different atmospheric gas concentrations, eroded soils, changing air temperatures, changed soil conditions such as nutrient status, texture, moisture and pH, changed levels of water tables, the possibility of accumulation of toxic substances, changed disturbance regimens and reduced supplies of plant propagules (cf. Knabe, 1965; Buschbacher et al., 1992; Dale et al., 1993; Ang, 1994). These degradation trends can be reversed through land management (Harwood et al., 1993). However, the intensification of land management raises the possibility that new combinations of species will prevail in the rehabilitated lands (Lugo, 1994a; Moravčík, 1994).

## 2. The era of land and vegetation rehabilitation

Land and vegetation rehabilitation are countermeasures that can reverse the trend of land degradation that now prevails in the tropics (Brown and Lugo, 1994). These activities require an understanding of ecosystem functioning and the means and willingness to manage the process of ecological succession. For example, the success of some rehabilitation efforts may depend on knowing when to arrest or allow succession to proceed unaided, or knowing when to replace native species with exotic ones, or deciding when to modify sites completely to facilitate a particular successional pathway. In this article the focus is on the acceleration of succession, a key strategy for dealing with degraded lands.

The rehabilitation of degraded sites throughout the tropics will require judgment based on an understanding of ecosystems. Such rehabilitation efforts should be based on sound science. The role of exotic or native species in rehabilitation needs careful consideration because we may have to use species combinations (native, exotic, or a combination thereof) that are capable of surviving in the new edaphic, atmospheric and climatic conditions created by humans (Lugo, 1994a; Moravčík, 1994).

Based on the rapid increase in the rate of tree plantation establishment in the tropics (FAO, 1993) and the greater global awareness of the importance of managing biodiversity (di Castri and Younès, 1996;

Szaro and Johnson, 1996), it seems that the era of secondary vegetation may be giving way to the era of land and vegetation rehabilitation. The difference is that this new era involves aggressive management of biodiversity as opposed to passive observation of successional change. The new approach to land management is termed ecosystem management (Lugo, 1994b). The focus is on reversing the negative aspects of human activity. Human activity can have both positive and negative effects on the land, either through land degradation and native vegetation removal, or through conservation and rehabilitation. It is to be hoped that through ecosystem management the balance of human activity will tilt towards conservation and rehabilitation. To be successful in the rehabilitation effort, it may be necessary to intensify site management through the use of tree plantations (Lugo, 1988b, 1992a).

### **3. Use of tropical tree plantations for rehabilitation**

There are many approaches to land and vegetation rehabilitation (Brown and Lugo, 1994). These depend on the severity of damage to the land resource, the goals of rehabilitation and the availability of resources for repairing the damage. The most intensive rehabilitation schemes are sometimes termed reclamations because the damage to sites is so severe that soils have to be replaced and the landscape may have to be reshaped before vegetation can be reestablished (Knabe, 1965; Bradshaw, 1987; Ang, 1994). Less dramatic efforts are needed in degraded sites where vegetation is present but succession is arrested and does not progress towards the reestablishment of forest cover. Lamb and Tomlinson (1994) believe that the first objective of degraded land rehabilitation is the prevention of further degradation. Tropical tree plantations can be an effective tool for arresting site degradation and a catalyst for land and forest vegetation rehabilitation (Lugo, 1988b, 1992a; Parrotta, 1992, 1993, 1995).

Tropical tree plantations can be designed for a variety of purposes but plantation forestry is a controversial conservation issue (Bowen and Nambiar, 1984; Evans, 1986, 1992; Ewel, 1986; Vermeij, 1986; Lugo et al., 1988; Mueller-Dombois, 1992; Berger, 1993;

Dupuy and Mille, 1993; Harwood et al., 1993; Potton, 1994; Rosoman, 1994, 1995; Smith, 1994). The questions that are raised against the use of tree plantations usually center on the negative effects of monocultures, i.e. low stability, low resource use efficiency, a low level of biodiversity, the tendency to use exotic species believed to negatively impact site conditions, escape into pristine habitats and displace native species and the effects of intensive land management on site conditions including soils and water. Counter arguments in defense of plantation forestry can be found in Dyson (1965), Whitehead (1982), Hughes and Styles (1987), Shepherd (1993), Hughes (1994), Allen et al. (1995), O'Loughlin (1995) and Purey-Cust (1996).

Much of the discussion about tree plantations is concerned with the issue of land use change as a result of the establishment of large areas of monoculture plantations in areas previously occupied by natural vegetation (Armstrong and van Hensbergen, 1996; Armstrong et al., 1996). This discussion could benefit from objective, quantitative and long-term research in support of effective land use policies and management prescriptions in the tropics (cf. Poore and Fries, 1985; Soni and Vasistha, 1991; Lugo, 1992b; Spellerberg, 1996). Rather than addressing this broader issue, the focus in this paper is on plantations used for rehabilitating degraded lands.

Land rehabilitation benefits from plantation establishment because it allows managers to 'jump-start' succession to provide shade, modify microclimate and act as cover for other tree species under extreme conditions of site damage (Thompson et al., 1986; Ang, 1994; Awang, 1994; Khemnark, 1994; Majid et al., 1994; Mungkordin, 1994; Shepherd, 1994). Recent studies show that tropical tree plantations allow the establishment of high concentrations of native tree species in their understory (Lugo, 1988a,b, 1992a,b, 1993; Soni and Vasistha, 1991; Parrotta, 1992, 1993, 1995; Lamb and Tomlinson, 1994; Yu et al., 1994; Guariguata et al., 1995; Fimbel and Fimbel, 1996). The use of plantation monocultures to restore diverse tree vegetation seems paradoxical, but research results help clarify why this use of tree plantations may be an effective tool for land and vegetation rehabilitation. Some of the relevant results of our research program in Puerto Rico and elsewhere are briefly summarized below.

#### 4. The ecology of tropical tree plantations

Forest lands in Puerto Rico have already experienced extensive deforestation, agricultural use and degradation (Birdsey and Weaver, 1987; García Montiel and Scatena, 1994). Over 60 years ago, some of these lands were reforested with monoculture plantations (Francis, 1995) and considerable research was conducted to document the successes and failures of this reforestation (Wadsworth, 1995). This history of land use and land management provide an opportunity to observe the long-term development of tree monocultures established in deforested lands previously degraded by agricultural activity.

In the early 1980s the International Institute of Tropical Forestry began long-term and comparative ecological studies on paired plantation and secondary forest stands developing on degraded agricultural lands (Lugo et al., 1990a,b, 1992a,b; Cuevas et al., 1991). We found that tree plantations accumulate more aboveground biomass and at faster rates than paired secondary forests (Lugo et al., 1990a, 1992b; Cuevas et al., 1991). However, secondary forests accumulate more root biomass and at faster rates than paired tree plantations. In one comparison, the total net production (aboveground plus belowground) of a *Pinus caribaea* pine plantation was identical to that of the paired secondary forest (Cuevas et al., 1991). This suggests that both forest types had similar productive potential but different biomass allocation.

In a comparison of plantations and mature forests, Brown and Lugo (1990) found that litterfall in plantations and mature forests returned on average the same amount of Ca and P, but different amounts of N to the forest floor. Litterfall in plantations returned less N to the forest floor than litterfall in mature forests. In the same comparison, Brown and Lugo (1990) found that for each unit of P and N in litterfall, plantations returned more organic matter to the forest floor than mature or secondary forests. For each unit of Ca in litterfall, mature forests returned more mass than plantations.

Lugo (1992b) reported that tree plantations accumulated more mass and nutrients in litter than did secondary forests of a similar age. These results underscore the aboveground storage function of plantations. On degraded sites, high storage of nutrients and organic matter in litter and aboveground biomass

may be critical for facilitating the invasion of vegetation to the understory of plantations.

Many studies in Puerto Rico and elsewhere show that tree plantations improve soil conditions by increasing the mass and concentration of organic matter and available nutrients and by decreasing the soil's bulk density (Lundgren, 1978; Miller, 1984; Balagopal and Alexander, 1985; Sánchez et al., 1985; Jurgensen et al., 1986; Anderson, 1987; Bernhard-Reversat, 1988; Sánchez Irizarry, 1989; Lugo et al., 1990b, 1992b; Wang et al., 1991; Parrotta, 1992, 1995). The selection of the planted species significantly affects these results. Some species accumulate mass and nutrients more than others, or they can influence the accumulation of a particular nutrient and not another. Other species may not have an effect on soil chemistry (Lugo et al., 1990a; Montagnini et al., 1995).

During our comparative studies we also had the opportunity to evaluate the relative effects of hurricane disturbances on plantations and paired secondary forest stands. Rodríguez Pedraza (1993) found that plantations experienced a greater amount of wind damage after Hurricane Hugo than paired secondary forests near the eye of the storm. This was attributed primarily to forest structure and management. For example, the higher aboveground biomass of plantations resulted in a greater amount of mass fall due to hurricane damage. The planting of trees in rows allowed for wind tunneling through the plantation, and the thinning history made the plantation vulnerable to wind damage by opening the stand. Plantation recovery of stand density and basal area after the hurricane was as fast as that of paired secondary forests (Fu et al., 1997). Plantation monocultures are also more vulnerable to disease than adjacent secondary forests as is now evident with the pink mealybug (*Maconellicoccus hirsutus*) attack on *Tectona grandis* and *Hibiscus elatus* plantations in Grenada, WI (Chouthy, 1995; Pollard, 1997).

Where the ecological functioning of plantations is compared with that of paired secondary forests, one finds differences in rates and allocation of organic matter production and its decomposition, but no other consistent differences between the two forest types (Lugo, 1992b). Tree monocultures can be more vulnerable to disturbances and disease than native forests because their structure (e.g. rows of

even-aged trees) and management history (e.g. thinning) make them more susceptible to wind damage and biotic invasions. When lands are degraded, the growth of secondary forest can be retarded whereas that of the plantation need not be because the manager has the option of matching species to site conditions and protecting the plantings. Plantations continue to accumulate mass and nutrients aboveground by increasing the efficiency of nutrient use. This in turn contributes to the enhancement of soil fertility and improvement of site conditions.

With the simultaneous modification of microclimatic conditions (shade, temperature and soil moisture) and attraction of wildlife (Cruz, 1987, 1988; Mitra and Sheldon, 1993; Ledgard, 1995), the plantation then offers an opportunity for the dispersal of seeds and establishment of other tree species that otherwise could not have grown in the conditions under which the plantation was initially established. Because plantation species are usually shade intolerant, they usually fail to regenerate in their species-rich understories. This further contributes to the substitution of tree species and allows the opportunity to select the species composition of the next stand. However, species like *Leucaena leucocephala* or *Swietenia macrophylla* can grow under their own shade but nevertheless allow the establishment of other tree species as well (Lugo, 1992a; Parrotta, 1995).

Parrotta (1995) found that in certain cases the overstory species makes a difference in the establishment and composition of a plantation understory. A more diverse and dense understory developed under a *Leucaena* plantation than under a *Casuarina* plantation, and intermediate values were found under a *Eucalyptus* plantation. Understory colonization rates within mixed-species stands were intermediate between those of single-species stands of the trees comprising their overstories. Seedling density and understory species richness were inversely correlated with litter depth and litter mass. Roosting by frugivores, especially bats, on edge trees partly explained the higher colonization rates near the peripheries of plantations.

## 5. Future research

The comparative research reported above is a pro-

misising approach to provide enlightenment on particular plantation issues and has analytical power because it combines the methods of ecology with the practices of forestry (Bradshaw, 1993). It is important to formulate research questions to be addressed by the integration of the ecological and forestry sciences in relation to land and vegetation rehabilitation in degraded tropical lands (cf. Lamb and Tomlinson, 1994).

Above are cited examples of situations where tree plantation monocultures allowed the reestablishment of tree species richness on degraded sites. The sequence of events that lead to success seems to be the following: (1) trees are successfully established through site preparation, careful species selection, planting and initial care through the critical early stages of development. Survival of some tree species can be greatly enhanced through inoculation with mycorrhizal fungi (Haselwandter and Bowen, 1996); (2) trees modify site conditions by providing shade and improving humidity, temperature, soil structure and chemistry; (3) a woody understory develops when protected from fire, harvesting, weeding, or grazing; (4) this understory provides forest structure and food for wildlife which is attracted to the site; (5) propagules in surrounding areas are dispersed into the plantation by wind, water and wildlife (cf. Parrotta, 1995); and (6) most of the time, the planted species fails to regenerate under its own shade or becomes less dominant at the site, allowing other species to reach the canopy and reproduce.

This sequence has been observed pantropically but is only now beginning to be systematically documented, as is done in this special issue. Observations have led to numerous research questions based on the fact that so far the research in this area has taken advantage of tree plantations established for purposes other than the reestablishment of species richness. For this reason, it is necessary to outline research questions that need to be resolved before the use of tropical tree plantations for the reestablishment of species richness in degraded sites can be fully understood and applied widely with confidence of success. The following are general questions presented with the caveat that for each ecological life zone it is necessary to address local conditions for proper selection of species and rehabilitation approach. Each question is

accompanied by a brief comment to place it in context.

*5.1. Can succession be accelerated in tree plantations designed specifically for the re-establishment of species richness?*

We know that native tree species can grow in the understory of tree plantations established for lumber production or a variety of other forestry purposes. We do not know which silvicultural techniques, including species selection criteria, can be applied to accelerate further the establishment, development and reproduction of tree species in degraded sites. If the answer to this question is 'yes', then the next logical question is What would be the management prescriptions for such plantations?

*5.2. Could native tree species be more efficient in accelerating succession than exotic species?*

Native species can be grown in plantations on degraded lands (Kartawinata, 1994; Shepherd, 1994; Knowles and Parrotta, 1995; Butterfield, 1996) but because of insufficient silvicultural knowledge, exotic tree species continue to be favored in rehabilitation projects (Ang, 1994; Awang, 1994; Khemnark, 1994; Majid et al., 1994; Mungkordin, 1994; Shepherd, 1994). Research is needed to determine the appropriate conditions under which species selection criteria favor one type of species over another. In practice, the manager will use the species that does the job for the least cost and effort. Research is needed to help optimize the ecological outcome of this decision.

*5.3. Can succession be accelerated, or is there a time tax (sensu Lugo, 1988b) that cannot be short-circuited due to site degradation?*

The rate of species accumulation in plantations and secondary forests seems to be similar (Lugo et al., 1993). We do not know if the rate can be accelerated. We do know that management actions can overcome arrested successions, even on sites dominated by dense growths of ferns and grasses (Parrotta, 1992, 1993, 1995; Kadeba, 1994; Kartawinata, 1994; Cohen et al., 1995; Guariguata et al., 1995; Otsamo et al., 1995, 1996). The author knows of no research

that shows acceleration of the rate of species additions to a site over the rate observed in normal ecological succession once the initial barriers to succession are surmounted.

*5.4. Are there key species processes missing in successions that occur on degraded sites?*

Parrotta et al. (1997) show that animals that disperse large seeds were under-represented in 10-year-old plantations established on degraded bauxite mine sites. Their absence seemed to delay the entry of certain mature forest tree species to the site. In another example, Haselwandter and Bowen (1996) found that tree establishment and survival in degraded sites was handicapped by the absence of mycorrhizal fungi. By inoculating trees, they improved tree establishment and their survival. Thus, it seems that the absence of particular species may retard the progress of succession in degraded sites. If this is true, these missing species need to be identified along with a method to facilitate their introduction.

*5.5. Can species be introduced at any time in a succession, or do they require a particular stand history before they can survive?*

It is not known if once a particular species is found to be absent, it can be introduced at any time and still be effective by accelerating succession. Ward et al. (1995) found that the timing of management interventions is critical for the success of a rehabilitation. On the other hand, some forest structures and functions require time to develop, e.g. epiphytes that trap atmospheric nutrients (Lugo and Scatena, 1992) and stimulate insect activity and biodiversity when they fall as litter (Floater, 1995). The introduction of these and other forest legacies such as snags and large trees are time dependent and it is not clear if their appearance can be accelerated in developing stands. Research is needed to establish the timing of particular management interventions in managed succession to improve the effectiveness of resource use and accelerate rehabilitation.

*5.6. What is the role of animals?*

Majer (1989a) reviewed the role of animals in

reclaimed lands. The activities of groups such as ants and earthworms improve soil structure, accelerate litter decomposition and nutrient cycling, increase primary productivity, alter plant species composition, influence the status and dispersal of mycorrhizal associations, facilitate seed dispersal and pollination and encourage the presence of feral species (Majer, 1989b). Soil fauna decrease a soil's bulk density; increase pore space, accelerate mixing, aeration and drainage and improve water holding capacity and soil aggregation (Abbott, 1989).

Because animals act as ecosystem managers in the sense that they can direct succession, their role becomes critical to human management of rehabilitation. Majer (1989a,c) showed that the accumulation of ant species and the number of individuals can change over time, space and land use. In lands rehabilitated with *Eucalyptus* plantations, for example, fewer species but a greater number of ants accumulated than in lands rehabilitated through secondary forests. Similarly, the accumulation of ant species over time in rehabilitated lands usually exhibits a humped-curve with peaks after about 10 years (Majer, 1989b,c). A single ant species can completely change the accumulation rate of species. Research is needed to find out if these patterns are common to other animal groups and to determine the effects of species invasions on the speed of recovery of forest ecosystems on degraded lands.

#### 5.7. *Is self-organization or self-design (sensu Odum, 1988) a viable alternative to intensively managed succession?*

Cost always limits the size of areas that can be intensively managed, in part because as systems become more artificial their survival requires continuous human intervention or management (Cairns, 1993). An alternative strategy is to balance human intervention with ecosystem self-design. Self-design allows natural factors to operate on ecosystems so that the resulting combination of organisms develop structure, functioning and species composition that are naturally sustainable under the environmental conditions of the site (Odum, 1988, 1996). The advantages of self-design are (1) survivability of the initial conditions of succession,

(2) permanency on the site beyond the initial phases of succession and (3) low cost. The disadvantage is that the system may change in a direction that is undesirable or at least unexpected (Ewel, 1980). Through careful monitoring, the manager can follow the succession of the system and make the necessary adjustments to assure the management goals are attained. Any changes that have no effect on the objectives of management are allowed to remain because they may add redundancy and resilience to the emerging ecosystem.

An example of self-design would be an unmanaged plantation that is allowed to change through the natural invasion of its understory by trees and other plant species. This invasion of species within plantations of exotic tree species led to the consideration of the enhancement of the process through management to accelerate the establishment of species richness in degraded lands. Research on these aspects of self-design is needed to lower the costs of management while increasing the permanence of biotic solutions to changing environmental conditions.

#### 5.8. *What characteristics of tree plantations lead to arrested successions and how can they be avoided?*

Not all tree plantations develop species-rich understories but remain instead as tree monocultures. Low light intensity below the canopy, distance to seed sources, inhospitability to seed dispersers, poor soil or litter conditions for seed germination or seedling growth, intensive root competition with the planted species, chemical inhibition and other forms of allelopathy and plant interactions, plantation design, or periodic disturbances by organisms or any external factor are likely causes that require study.

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