CHAPTER 11

EARTHWORMS IN TROPICAL TREE-PLANTATIONS: EFFECTS OF MANAGEMENT AND RELATIONS WITH SOIL CARBON AND NUTRIENT USE EFFICIENCY

Xiaoming Zou[1] and Grizelle González[2]

[1]*Institute for Tropical Ecosystem Studies, University of Puerto Rico, P.O. Box 363682, San Juan, PR 00936, USA*

[2]*International Institute of Tropical Forestry, USDA Forest Service, P.O. Box 25000, San Juan, PR 00928, USA*

ABSTRACT

With the vast amount of abandoned tropical land due to non-sustainable farming practices, tropical tree-plantations become an effective means in restoring soil productivity and preserving ecosystem biodiversity. Because earthworms are the dominant soil fauna in moist tropical regions and play an important role in improving soil fertility, understanding the mechanisms by which forest management practices affect the abundance and community structure of earthworms will be crucial in designing future reforestation programmes. Forest management practices include site preparation, tree species selection, fertilization, and harvesting. While native earthworms are often negatively affected by using exotic tree species, they can often be preserved in plantations using native tree species. Conventional practices of site preparation and harvesting often favor exotic endogeic earthworms and impose negative impact on native epigeic earthworms. The effects of chemical fertilization on earthworms vary with soils and fertilizers. These management practices alter soil properties such as soil C and N levels, and change the quantity and quality of plant litter. Under similar climate and soil conditions, earthworm abundance is positively correlated with soil C and N levels. High earthworm density is associated with high litter quality and low nutrient use efficiency of tree-plantations. We conclude that forest management practices can drastically affect earthworm populations and that maintaining a healthy population of earthworms can further promote forest nutrition in tropical tree-plantations.

Key Words: Earthworms, tropical tree plantations, forest management, forest fertilization, soil carbon, nutrient use efficiency.

Human deforestation has nearly claimed half of the world's native forest, and human demand for wood will increase 50% in the next decade. For the last century, deforestation has expanded at an accelerating rate throughout tropical regions. Deforested tropical lands have reached 1.9 billion ha by late 1980s (Grainger, 1988). Because of non-sustainable farming practices, these deforested lands have been abandoned at a rate of 12×10^6 ha y^{-1} (Lal and Stewart, 1990). These vast amounts of abandoned lands have drawn attention from land managers and ecologists to search for strategies to restore land productivity and reserve biological species diversity (Shukla *et al.*, 1990; Saunders *et al.*, 1991; Schulze and Mooney, 1993). One such strategy is to establish tropical tree-plantations. By late 1980s, tropical tree plantations accounted for 1% of total tropical forested areas.

Earthworms are recognized to accelerate the decomposition of soil organic matter and to increase soil fertility (Lee, 1985; Lavelle, 1988; Edwards and Bohlen, 1996; Bohlen *et al.*, 1997). Under moist climatic conditions, they often dominate soil macrofauna biomass (Fragoso and Lavelle, 1992; Hendrix, 1995). However, few studies have examined earthworms in tropical tree-plantations. This chapter intends to show how forest management practices affect the abundance and community structure of earthworms in tropical tree-plantations, and the chapter will also examine the correlation between soil properties and earthworm abundance.

EARTHWORMS AND FOREST MANAGEMENT

Forest management practices can influence earthworm communities through changing physical and chemical properties of soil, net primary productivity, or plant litter chemistry (Fig. 1a,b). These practices typically include site preparation, tree species selection, fertilization, and harvesting (Nyland, 1996). Site preparation can alter soil structure and plant communities. Tree species differ in above- and below-ground net productivity and in plant litter chemistry, thus vary in decomposition and nutrient cycling processes. Fertilization can directly change plant nutrition and soil properties, and consequently plant production and

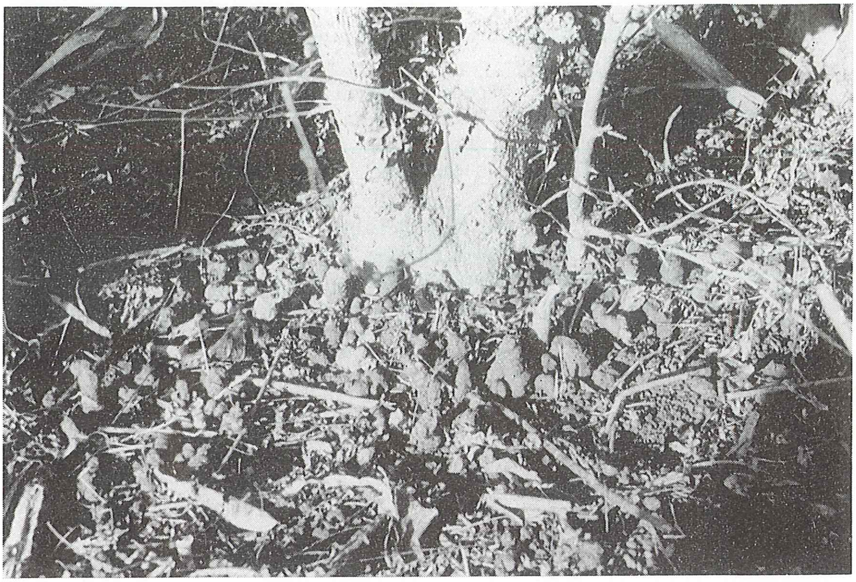

Fig. 1a Wormcast of *Hyperiodrilus africanus* under *Leucaena leucocephala* hedgerows grown on high base status Afisol in southwestern Nigeria.

litter chemistry. Harvesting may impose direct effects on soil structure, plant species composition, and plant production.

Responses of earthworm to forest management practices may differ among various worm communities. Earthworms are classified into three categories (Bouche, 1977): the endogeic worms, the epigeic worms, and the anecic worms. Endogeic earthworms live and predominantly feed within the mineral soil layer. The epigeic earthworms live and feed within the surface litter layer. The anecic worms live in the mineral soil layer but predominantly feed on organic materials in the surface litter layer. Changes in physical and chemical properties in the mineral soils can have drastic impact on the endogeic worms, whereas changes in the quantity and chemistry of plant materials in forest floor mass may predominantly affect the epigeic worms. Changes either in mineral or plant litter layers can affect the anecic worms.

Site Preparation

Site preparation includes clearing vegetation and plowing soil. Clearing vegetation has direct effects on the net primary productivity and plant species composition, thus can affect earthworm communities. Because epigeic earthworms live and feed in plant litter layer, clearing vegetation may impose immediate effects on epigeic and anecic worms. Plowing

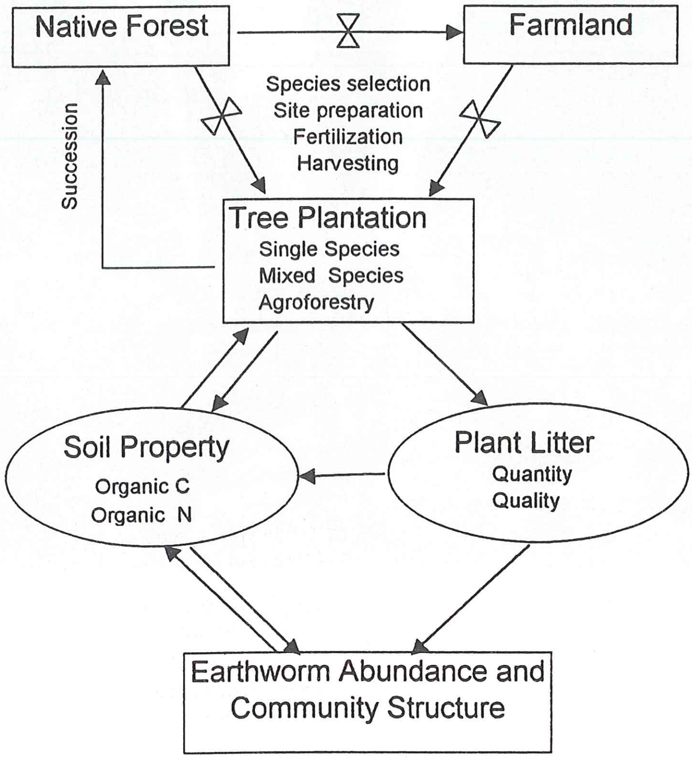

Fig. 1b Forest management practices (species selection, site preparation, fertilization, and harvesting) that affect earthworm abundance and community structure in tropical tree plantation. Native forest refers to forests that are not disturbed by human activities. Farmland includes crop fields, pastures, and other land use types like mine fields. Soil properties include chemical, physical, and biological factors such as soil C and N level, pH, microbial activity (Modified from González *et al.,* 1996).

disturbs soils and causes earthworm mortality due to injuries from machinery and predation by animals after worms are exposed to soil surface. In agricultural fields, plowing can reduce earthworm density by as much as 20%. Additionally, plowing buries plant litter into sub-soils layers, thus improves soil aeration, accelerates soil erosion, mixes mineral soils with plant materials, and redistributes plant seeds (Lee, 1985; Edwards and Bohlen, 1996). Plant productivity will be reduced for a short period of time ranging from a few months to a few years. Soil bulk density will often decrease by about 10% after plowing. Changes in soil bulk density can affect soil moisture conditions, often by increasing effective soil water storage capacity (the difference between field water holding capacity and plant wilting point). Increase in the effective soil water storage capacity improves soil water conditions for the survival and growth of earthworms, especially during dry seasons.

The effect of plowing on soil erosion is the balance of two processes: reduction in soil surface runoff water and increase in soil erodibility. Plowing increases large soil pore space and consequently soil water infiltration rates. However, the newly exposed soils are not protected by vegetation and litter, thus are under direct impact of raindrops and surface runoff. Effects of plowing on soil erosion are rarely studied in tropical tree-plantations. But many studies from agricultural fields indicated a general pattern of increasing soil erosion after plowing (Soil Conservation Service, 1988). Accelerated soil erosion can have long-term impact on earthworm communities. It may reduce worm species diversity and population abundance.

Much of the forest floor mass can be buried into sub-soil layers after plowing. The incorporation of plant materials into soil may favor endogeic worms, but may reduce the abundance of anecic and epigeic earthworms.

By redistributing plant seeds in soil profile, plowing affects the survival and gemination rates of plants, thus alters the species composition of plant community. Changes in composition of plant species can have drastic impact on earthworm communities (Zou, 1993; Zou and González, 1997; Zou and Bashkin, 1998; González and Zou, 1999a; González *et al.*, 1999). Furthermore, plowing may suppress infectious diseases and this may have positive effect on worms, but little information is available.

Species Selection

Plant species differ in above- and below-ground carbon allocation patterns. They also differ in the chemistry of plant litter. In tree-plantations at Hawaii, fine litterfall was 8.25 mg ha^{-1} y^{-1} in an *Albizia falcataria* (L.) Fosb. plantation as compared to 5.04 mg ha^{-1} y^{-1} in an *Eucalyptus saligna* Sm. plantation (Binkley *et al.*, 1992). Nitrogen content of Albizia litter is much higher than the Eucalyptus litter. A high nitrogen content in litter materials was correlated with high earthworm density (Zou, 1993). In another study in the tropical island of Puerto Rico, above-ground net primary productivity was higher in tree plantations of *Pinus caribaea* Morelet and *Swietenia macrophylla* King than in adjacent secondary forest (Lugo, 1992). Litter nitrogen content was higher in the secondary forest than in the plantations. Earthworm density was found higher in the secondary forests (González *et al.*, 1996). Standen (1988) also showed a reduction of earthworm abundance in pine plantations as compared to pastures.

Tree plantations with exotic species are often not favored by native earthworms. In Puerto Rico, exotic worm species occurred in plantations of both *P. caribaea* and *S. macrophylla* (exotic species) as well as in secondary forests of native species, but native worm species occurred only in the secondary forests (González *et al.*, 1996). In New Guinea, establishment of pine plantations on grassland reduced the number of native earthworms and introduced exotic species (Standen, 1988). In contrast, the establishment of *Araucaria* did not show a strong negative effect on the native earthworms. The negative effects of pine plantations on earthworms were pronounced as the plantations get older (Yeates, 1988).

Changes in composition of plant species often occur during secondary succession (Horn, 1974; Reiners *et al.*, 1994; Zou *et al.*, 1995). In Hawaii, secondary plant communities developed from abandoned sugarcane fields supported a higher earthworm population and diverse community structure (Zou and Bashkin, 1998). In Puerto Rico, changes in composition of plant species from grass dominated pasture to woody species corresponded to a reduction of earthworm density from 850 to 200 worms per square metre. On the other hand, earthworm diversity increased from endogeic *Pontoscolex corethrurus* community in the pasture to both endogeic and anecie worm community in the secondary forests.

Variation in plant litter chemistry and decomposition may also affect soil chemical properties such as pH. A greater uptake pattern of cations than anions by plants can also enhance soil acidification. Decrease in soil pH in acid soil is not favored by most earthworms (Lee, 1985; Edwards and Bohlen, 1996).

Forest Fertilization

Forest fertilization refers to the application of organic and inorganic fertilizers in forests. Organic fertilizers include plant and waste materials such as plant residues, farmyard manures, animal slurries, municipal sewage wastes, and industrial wastes from breweries, paper pulp, or potato processing. In most studies, organic fertilizers increase earthworm density and biomass (Marshall, 1977). Earthworm abundance can be doubled or tripled within a year after the application of organic materials. However, exceptions exist in the cases of applying fresh animal manure that has not been aged or composted, or in the cases where soil inorganic chemistry such as pH has drastically changed due to the application of organic materials (Curry, 1976). Information on using organic materials in tropical tree-plantation is limited.

Chemical fertilization may increase or decrease earthworm abundance and biomass. Application of nitrate fertilizers often acidifies soil pH, thus may have negative effect on earthworm communities. However, addition of N without decrease in soil pH may have positive effect on earthworm communities through increasing plant production and improving litter quality. In a tropical wet forest of Puerto Rico, the application of complete inorganic fertilizers (N, P, K, Ca, Mg, and micronutrients) decreased soil pH values and earthworm density (Zou, unpublished data).

HARVESTING

Logging of trees can reduce forest productivity and change plant species composition. The machinery used may also compact soils and injure earthworms. Because epigeic worms inhabit forest floors, they are most likely be affected by logging activities (Camilo and Zou, 1999). Harvesting can be divided into selective logging, strip clearing, and large-scale clearing. In a tropical wet forest of Puerto Rico (Zou *et al.*, 1995), epigeic, anecic, and endogeic worms all exist fifty years after selective logging (González and Zou, 1999a; González *et al.*, 1999). However, selective logging also introduced exotic earthworms *P. corethrurus* and *Amynthas rodericensis* into the forest. Strip harvesting may impose a stronger effect on epigeic earthworms than selective logging. Epigeic earthworms were not found in strip logged sites, whereas both anecic and endogeic worms survived the disturbance in the same wet forest in Puerto Rico (Camilo and Zou, 1999). Large-scale clearings often show the strongest effect on earthworms. Converting forests to pasture reduced worm species from five (3 native and 2 exotic) to one exotic species (Zou and González, 1997), and no epigeic or anecic worms survived the disturbance.

In Australia, Abbott (1985) also reported that exotic earthworm species occurred in pasture or orchards after forests were cleared. These data support the conclusions from studies in the temperate region that human disturbance reduces the abundance of native earthworms and increase the abundance of exotic earthworms (Kalisz and Dotson, 1989).

EARTHWORMS IN RELATION TO SOIL CARBON AND NUTRIENT USE EFFICIENCY

SOIL CARBON AND NITROGEN

Converting forest to agricultural lands often reduces soil C and N levels (Post and Mann, 1990), although pasture lands are known to remain the same level of soil C (Lugo *et al.*, 1986; Reiners *et al.*, 1994). Soil organic C often recovers after establishment of tree plantations on abandoned agricultural lands (Makeschin, 1994). In Hawaii, C and N levels in native forest soils reached 15.9% and 0.57%, respectively. Fifty years of sugarcane cultivation reduced soil C and N levels to 6.45% and 0.32%, respectively. The subsequent establishment of *Eucalyptus* plantations increased surface soil C (0–25 cm) and N by 30% (Zou and Bashkin, 1998). Meanwhile, earthworm population increased from 0 in the sugarcane fields to 398 individuals per square metre in the 10 years old *Eucalyptus* plantation. There is a positive correlation between earthworm abundance and soil C and N levels (Fig. 2). However, this correlation

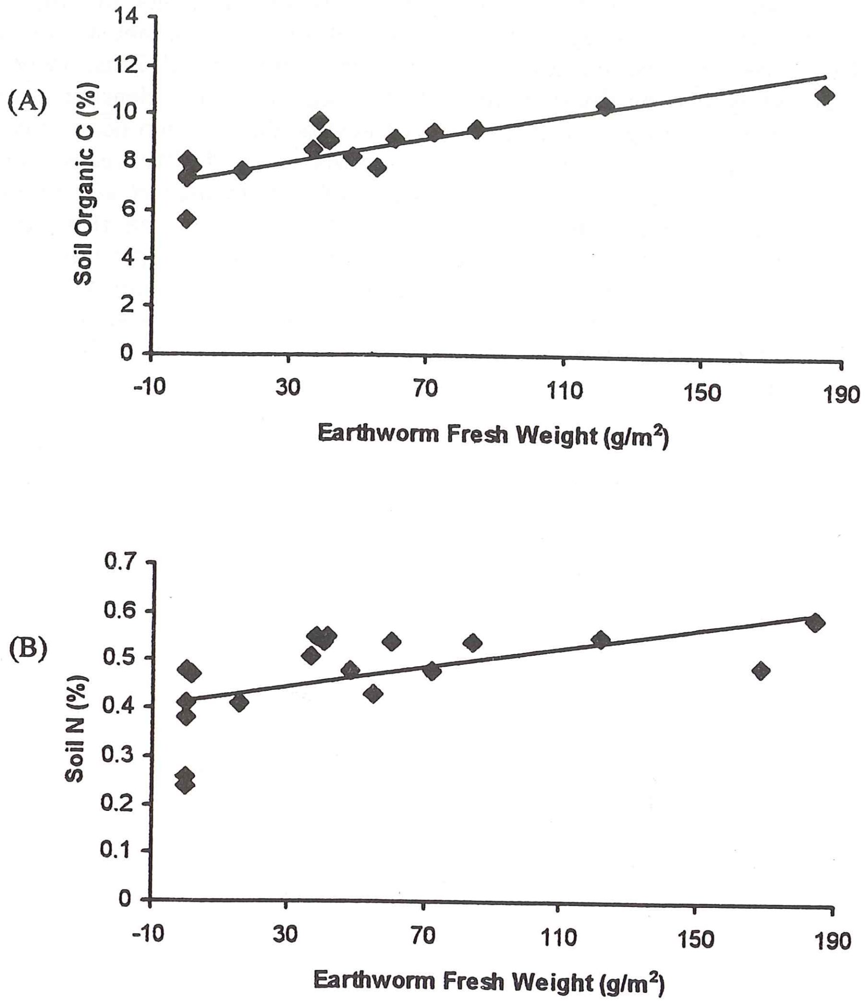

Fig. 2 Correlation between soil C (A) and N (B) levels and earthworm fresh weight in tropical tree plantations of *Eucalyptus* in Hawaii.

may not exist when data are derived from plantations with different tree species or soil types because tree species and soils themselves alone can affect earthworms.

Nutrient Use Efficiency

Nutrient use efficiency is practically defined as the ratio of above-ground net primary productivity to the quantity of nutrients in annual litterfall (Vitousek, 1982). It differs among tree species. In Hawaiian plantations, both nitrogen and phosphorus use efficiencies were the highest in the pure *Eucalyptus* stands, lowest in the pure *Albizia* stands, and medium in the mixed stands. Earthworm density was negatively and exponentially correlated with both N and P use efficiencies of these stands (Fig. 3), suggesting either a competition for nutrients between trees and earthworms or earthworm increased soil nutrient availability to trees through accelerated decomposition of soil organic matter. Although field experiments showed an increased decomposition rate when earthworms were excluded (Bohlen *et al.*, 1997), little information is available to address the competition hypothesis in tropical tree-plantations. James and Seastedt (1986) reported that there were no increase in above-ground plant biomass but there was a reduction in root biomass when earthworms were excluded. González and Zou (1999b) also demonstrated that reduction in earthworms reduced soil N availability but did not increase the growth of *Cecropia scheberiana,* a tropical pioneer tree species. Edward and Lofty (1980) with barley and Stockdill (1982) in pasture also showed that exclusion of earthworms actually reduced plant growth. These evidences tend to support that earthworms may not compete for nutrients with trees, but increase soil nutrient levels by accelerating decomposition.

FUTURE PERSPECTIVES

With vast abandoned agricultural lands, tropical tree-plantations are an effective strategy for the restoration of ecosystem productivity and preservation of biodiversity. However, little is known about the role which earthworms play in tropical tree-plantations, or vice versa. Much research is needed in order to establish sound management practices.

Among research priorities, relationship between tree species and earthworms appears to be essential. There are two approaches to examine this relationship. One is to manipulate either earthworm populations (e.g. James and Seastedt, 1986; González and Zou, 1999a) or tree species (e.g. Zou, 1993, González *et al.*, 1996; Zou and Bashkin, 1998). The other approach is to examine earthworm populations in areas surrounding

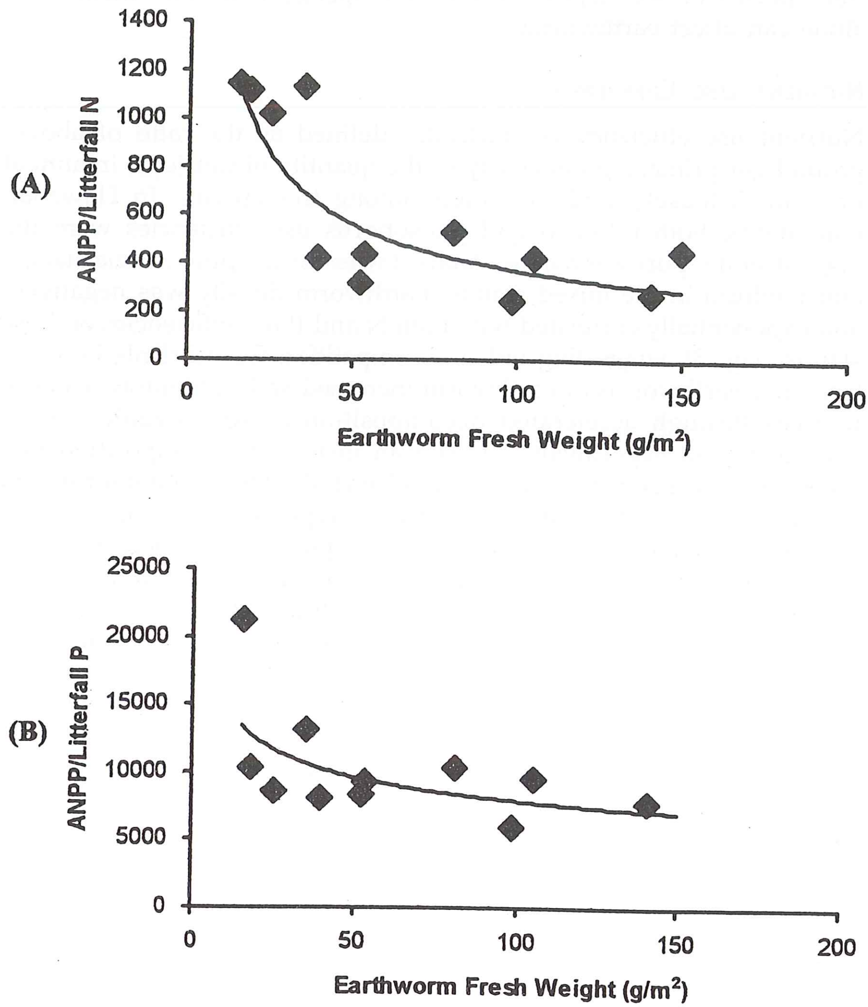

Fig. 3 Relations between nitrogen and phosphorus use efficiency and earthworm fresh weight in tropical tree plantations of *Albizia* and *Eucalyptus* in Hawaii.

one particular species and area outside the influence of this plant species (e.g. González and Zou, 1999a).

The second need is to examine the role that earthworms play in forest production and nutrient cycling in field experiments. Many early studies were conducted in agricultural fields in the temperate region.

These studies showed promising results. For example, an earthworm manipulation experiment in cornfields of Ohio showed worms can accelerate the decomposition of corn residues and increase soil nitrogen availability for plant growth (Bohlen *et al.*, 1997; Bohlen *et al.*, 1999). Research topics can expand to include the earthworm effect on green house gas production, soil inorganic and organic C fluxes, soil erosion, and water balance.

Thirdly, there is a need to assess earthworm biodiversity and its role in regulating soil processes and soil food web dynamics. Does earthworm diversity matter? How does earthworm diversity affect soil food webs and the flow of energy and elements? How do earthworm species interact with each other? This information is crucial in making management policies for tropical tree plantations, but little is available. These questions are most likely to be addressed in green-house experiments with incubation chambers. Although field experiments to manipulate earthworm populations are possible, they would be expensive.

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PART—III: SOIL-NUTRIENT DYNAMICS

— *Eucalyptus* plantation in Brazil: Their soil nutrient dynamics and management.
A. Spangenberg and *H. Folster* (ISSFN, Germany).

— Nitrogen fixing leguminous trees in forestry and agroforestry systems.
D.L.N. Rao (I.I.S.S., India).

— Nutrient flux control by trees for improving soil fertility in tropical agroforestry. *Johannes Lehmann* (UB and FRIFP, Germany).

— Accretion of carbon and nutrients in the forest floor and mineral soil of *Casuarina equisetifolia* plantations on the coastal sand dunes of Senegal.
Daniel Mailly (MRN, Canada) and *H.A. Margolis* (UL, Canada)