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Restoring Productivity to Degraded Pasture Lands in the Amazon through Agroforestry Practices

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The conversion of primary forest for subsistence agriculture, industrial logging, and pasture establishment continues to be the predominant cause of tropical deforestation (Laurance, 1999). In the last 30 years, an estimated 58.8 million ha of primary forest have been cleared in the Brazilian Amazon alone (INPE, 2004). Of this, 24 million ha were converted to pastures during the 1970s and 1980s, making this the most common land-use change in the Amazon region (Serrão et al., 1995).

Although pastures for beef cattle continue to dominate deforested landscapes in the Brazilian Amazon, many formerly productive pastures have become degraded and are now abandoned, left to be colonized by secondary vegetation (Fearnside and Guimaraes, 1996; Silver et al., 2000). Based on an analysis of Amazonian land-use data, Fearnside (1996) estimated that 47% of all deforested land in the Amazon is currently in some form of regenerating forest on degraded or abandoned pastures. Owing to the large area of degraded pastures in the Amazon, a number of local research and development agencies are investigating the possibility of rehabilitating the productivity of degraded pasturelands as a means of deflecting the continuing pressure to establish agricultural lands at the forest frontier. Multispecies agroforests have been identified as promising alternatives for rehabilitation of degraded pasturelands (Fernandes and Matos, 1995; Parrotta et al., 1997).

Many of the original pastures in the Amazon were established with revenues from the sale of high-value timber trees. Mahogany as the most valuable species has been severely overexploited (Verissimo et al., 1995). This chapter reviews the successful reintroduction of large-leafed mahogany to degraded pasture lands in the Amazon via an agroforestry approach that harnessed local agroecological knowledge together with scientific information on integrated nutrient management (INM) and integrated pest management (IPM) appropriate for the Amazon.

21.1 Characteristics of Pasture Systems and Abandoned Pastureland in the Amazon

Despite their previous support of lush rainforest, plant growth on deforested soils can be severely constrained by generally low levels of available soil nutrients and high acidity. Deficiencies of available calcium (Smyth and Cravo, 1992), available phosphorus (Gehring et al., 1999), and nitrogen (Davidson et al., 2004) are commonly reported. Cochrane and Sanchez (1982) estimated that only 7% of the land area in the Brazilian Amazon is free from major limitations for plant growth. Soil phosphorus deficiencies (<7 mg kg^{-1}) are said to constrain productivity in 90% (436 million ha) of Brazilian Amazonia, and aluminium toxicity (Al saturation of $>60\%$) occurs over 73% of this area. Another significant problem is the high amount and intensity of rainfall (1800–3000 mm yr^{-1}) which facilitates the loss of nutrients via leaching and surface runoff from bare soil.

In the Brazilian Amazon, pastures are established by felling primary forest, burning the forest biomass to release the nutrients it contains, and planting pasture grasses (Brachiaria spp.). Once established, poor management of both livestock and pastures usually results in pasture degradation within 7 to 10 years. Rueda (2002) found that, paradoxically, low livestock stocking rates, resulting in low grazing pressure, has led to a rapid decline in pasture palatability and productivity. Ranchers rejuvenate the pasture by burning the poorly palatable forage, and this leads to the direct loss of nutrients (especially nitrogen) and facilitates the loss of nutrients in the residual ash via surface runoff and leaching. The disruption of communities of soil macrofauna, microfauna, and microflora, and of their functions, plus the depletion of forest-species seed pools, are key biological reasons for pasture degradation and poor subsequent forest regeneration (Fernandes et al., 1997).

Degraded pastures are characterized by depletion of available soil nutrient stocks, low vegetation biomass, depleted seed banks of forest species, high seed predation, and low stump sprouting (Nepstad et al., 1990), as well as soil surface sealing and compaction (Eden et al., 1991). The speed with which abandoned pastures are colonized by tree and shrub vegetation is directly related to the intensity of their use as pastures. The greater the grazing pressure and the longer the period grazed, the slower is the development of the fallow vegetation and the time for recovery of site productivity (Uhl et al., 1988; Nepstad et al., 1990). The principal pasture grasses (Brachiaria spp.) are aggressive C4 plants that are easily able to dominate establishing seedlings of forest species (mostly C3 species). Feldpausch et al. (2004) found that regenerating secondary forests on abandoned pasturelands could rapidly accumulate biomass, but this resulted in an equally rapid depletion of soil phosphorus and calcium stocks.

Although many degraded pastures are currently at different stages of secondary forest regeneration, there is an absence of long-term empirical data on the quality and dynamics of the regenerating secondary vegetation on abandoned pastures in the Amazon. A study near Manaus showed that regenerating forest vegetation is unable effectively to capture leaching soil nitrogen (Schroth et al., 1999). Similar to forest fallows that follow several cycles of cropping (Chapter 29), the emerging research data from abandoned pasture sites suggest that the regeneration may be limited by critically low levels of available soil nutrients, soil compaction, and low seed pools (Keller et al., 2004). An alternative pathway to natural regeneration on degraded pastures is the establishment and management of biologically diverse, integrated tree-, crop-, and livestock-based systems that are modeled upon native and migrant farmer systems found in the region. Such systems generally involve agroecological approaches to land management that optimize biological processes and, wherever possible, the use of locally available organic inputs (Pretty, 1995; Fernandes et al., 1993b).

21.2 Indigenous Knowledge and Scientific Data for Developing a Sustainable Timber–Pasture System for Degraded Pasturelands

We adopted the following sequential approach to develop appropriate cropping systems to rehabilitate degraded pasture land in the Amazon:

- A review of the Amazonian literature on indigenous technical knowledge and on local agroecosystems;
- A review of the international literature on conceptual approaches to develop improved natural resource management models for the humid tropics and the Amazon;
- A survey of approximately 30 local communities in settlement areas to identify farmers' priorities and approaches to develop productive agroecosystems; and
- Use of the knowledge and information gained from the reviews and surveys to generate specifications of adapted and biologically-robust production systems with potential to rehabilitate the productivity of degraded pasture lands.

21.2.1 Key Characteristics of Robust and Productive Agroecosystems

Our reviews of the literature suggested that both biological diversity and INM are consistent practices in long-lived, integrated farming systems. Biological diversity is required in a structural as well as functional sense. Native stocks of available plant nutrients need to be managed to avoid outputs exceeding inputs and, where necessary, these stocks need to be supplemented from external (organic and/or chemical) sources in order to sustain system function and productivity.

21.2.1.1 Structural and Biological Diversity of Integrated Farming Systems

The great majority of productive and long-lived, traditional farming systems have high species diversity and species associations of different age classes spread over several sites (Chang, 1977; Clawson, 1985; Thrupp, 1998). In Latin America, much of the production of staple crops occurs in polycultures. More than 40% of the cassava, 60% of the maize, and 80% of the beans are intercropped with each other or other crops (Francis, 1986).

The strategy of reducing risk by planting several species and varieties of crops stabilizes yields over the long term, provides a range of dietary nutrients, and maximizes returns under low levels of technology and limited resources (Harwood, 1979). These system characteristics maximize labor efficiency per unit area of land, minimize risk of catastrophic crop failure due to drought or severe pest attack, and guarantee the availability of food at medium to high levels of species productivity. In most multiple-cropping systems developed by small farmers, yields per unit area are often 20 to 60% higher than under sole cropping with the same level of management (Beets, 1982). These differences can be explained by a combination of factors that include the reduction of losses due to pests and disease and a more efficient use of the available resources of water, light, and nutrients.

Another benefit of multiple species associations is the creation of additional niches for pollinators, decomposers, and natural enemies of crop pests (Andow, 1991). The plant diversity provides alternative habitat and food sources such as pollen and nectar, and alternative hosts to predators and parasites (Altieri, 1995; Ackerman et al., 1998). Both above- and belowground species and processes are affected and can contribute to agroecosystem productivity and stability (Tillman et al., 1996; Giller et al., 1997). Such integrated farming systems sustain a higher level of agrobiodiversity than intensively managed, monoculture crop systems (Perfecto et al., 1996; Power, 1996).

Turner et al. (1995) have suggested that there exists a three-way interaction among biodiversity, ecosystem processes, and landscape dynamics. Any land management practices that increase biodiversity at a landscape level are also likely to benefit ecosystem services, such as nutrient, water, and soil conservation, biological pest control, and efficient nutrient cycling (Cullota, 1996; Tilman et al., 1996). Although it appears that obtaining appropriate species mixtures rather than maximizing species numbers is more important in the provision of ecosystem services, high species richness may increase agroecosystem resilience following any disturbance by increasing the number of alternative pathways for the flow of resources (Silver et al., 1996). Table 21.1 lists a range of species encountered in traditional systems in the Amazon.

21.2.1.2 Elements of Integrated Nutrient Management

A common feature of many traditional and other farming systems that have sustained populations over several decades and, in some cases centuries, is the continuous use of locally-available, biological and organic resources to minimize nutrient losses from the system. Plant nutrients are usually removed from the system via harvests of grain, tubers, fruit, and wood, and by surface erosion and subsurface leaching. The literature on INM documents the following key requirements for effective nutrient management and sustainable cropping.

TABLE 21.1

Tree and Crop Species Encountered in Surveys of Agroforests in the States of Acre, Amazonas, Para, Rondonia, and Roraima (Fernandes and Matos, 1995)

Common Name	Scientific Name	Uses
Avocado	*Persea Americana*	Fruit, cash crop
Coconut	*Cocos nucifera*	Food, oil, cash crop
Guaraná	*Paulinia cupana*	Drink, cash crop
Tucumã	*Astrocaryum aculeatum*	Fruit, fibre
Breadfruit	*Artocarpus altilis*	Seeds
Jackfruit	*Artocarpus heterophyllus*	Fruit, seeds
Guava	*Psidium guajava*	Fruit
Lime	*Citrus aurantifolia*	Fruit, cash crop
Mango	*Mangifera indica*	Fruit, cash crop
Peach palm	*Bactris gassipaes*	Fruit, palm heart
Cashew	*Anacardium occidentale*	Fruit, nut cash crop
Pineapple	*Ananas comosus*	Fruit, cash crop
Cupuaçu	*Theobroma grandiflorum*	Fruit, cash crop
Annatto	*Bixa orellana*	Seeds for dye
Acerola	*Malpigia glabra*	Fruit, cash crop
Black pepper	*Piper nigrum*	Spice, cash crop
Cacao	*Theobroma cacao*	Beverage, cash crop
Banana	*Musa* spp.	Fruit, cash crop
Coffee	*Coffea canephora*	Beverage, cash crop
Hog plum	*Spondias mombin*	Fruit, juice
Ingá	*Inga edulis*	Fruit, fuel wood
Biriba	*Rollinia mucosa*	Fruit, cash crop
Soursop	*Anona muricata*	Juice, cash crop
Açai	*Euterpe oleracea*	Fruit, heart of palm, cash crop
Araça boi	*Eugenia stipitata*	Juice
Jambu	*Eugenia jambos*	Fruit
Pitanga	*Eugenia uniflora*	Fruit, juice
Papaya	*Carica papaya*	Fruit, cash crop
Caimito	*Pouteria caimito*	Fruit
Sapotilla	*Manilkara zapota*	Fruit, chewing gum
Bacuri	*Platonia insignis*	Fruit
Genipapo	*Genipa Americana*	Fruit, wood
Araticum	*Anona Montana*	Fruit
Bacaba	*Oenocarpus bacaba*	Wine, wood, leaf baskets
Cassava	*Manihot esculenta*	Tubers for starch, cash crop
Passion fruit1	*Passiflora nitida*	Fruit
Passion fruit2	*Passiflora macrocarpa*	Fruit
Umari	*Poraqueiba sericea*	Fruit
Rubber	*Hevea brasiliensis*	Latex, cash crop
Mapati	*Pourouma cecropiaefolia*	Fruit
Cubiu	*Solanum sessiliflorum*	Fruit
Pitomba	*Talisia esculenta*	Fruit
Carambola	*Averrhoa carambola*	Fruit
Buriti	*Mauritia flexuosa*	Fruit

21.2.1.2.1 Eliminate Soil Erosion and Leaching

The most effective way to reduce soil erosion and leaching is to maximize soil cover via the use of cover crops and mulches and by integrating perennials in vegetative strips along the contours to further stabilize the soil (Fernandes et al., 1993a). Where soil depth is adequate, contour vegetative strips permit interstrip erosion and result in a gradual leveling of the slope and terrace formation without the need for labor-intensive, manual terrace formation.

21.2.1.2.2 Cycle All Flows of Organic Nutrients

One method is to return all crop residues to the field of origin. In many cases, however, crop residues are fed to livestock. Ideally, the livestock should be fed the residues in the field so that the manure goes directly on to the soil. If the residues are removed and fed to livestock elsewhere, then the manure should be returned to the field as soon as possible. The transport and spreading of manure on fields, however, is often a problem owing to labor constraints.

Many farmers combine crop residues with manure to "make the manure go further." In scientific terms, this represents the use of the lignin and polyphenol compounds in crop residues to tie up the nitrogen that would have otherwise been lost through volatilization and leaching. The composting of vegetable residues and animal manure is an efficient way to conserve farm nutrients. Making this knowledge available to all farmers could make a significant improvement in nitrogen/nutrient budgets of small farms.

21.2.1.2.3 Enhance Biological Sources of Nutrients

Nitrogen-fixing trees, shrubs, herbaceous, and crop species can fix nitrogen from the atmosphere and make it available to subsequent crops via biological or associative nitrogen ha^{-1} fixation (Chapter 12). Data from several studies show that it is possible to contribute between 15 and 200 kg of nitrogen to cropping systems via biological nitrogen fixation (Peoples and Herridge, 1990).

21.2.1.2.4 Compensate for Nutrient Exports by Adding Nutrients First as Green or Animal Manure, and if Necessary Supplement with Inorganic Fertilizers

Where soil nutrients have been severely depleted, it is often necessary to restore the minimum levels required for adequate plant growth and yield. Sanchez et al. (1997) have argued for phosphorus replenishment in sub-Saharan Africa as a means of priming the biological nitrogen-fixation process and improving crop productivity. Animal manure and plant litters are generally low in phosphorus, and unlike nitrogen, phosphorus cannot be fixed from the atmosphere. Phosphorus deficiency is a major constraint to effective nitrogen fixation because phosphorus is an important nutrient in the process of nodulation and nitrogen fixation. Guano and rock phosphate can be good sources for phosphorus (and guano also for nitrogen) where such materials are available locally (e.g., Peru, Madagascar, Zaire, West Africa).

21.2.1.2.5 Select and Use Adapted Efficient Species as Components of Improved Systems that are Designed to take Advantage of the INM Concept

Some leguminous tree species (e.g., Inga spp.) are able to fix nitrogen at very low levels of available soil phosphorus (Fernandes, 1998). Interestingly, many Inga species are used to provide shade and mulch in traditional integrated farming systems (Pennington and Fernandes, 1998). The grain legume *Cajanus cajan* has been shown to be able to absorb phosphorus from insoluble calcium–phosphorus complexes in high pH soils (Ae et al., 1990). Leguminous crops that combine some grain yield with high root and leaf biomass, and thus have a low nitrogen harvest, offer a useful compromise of meeting farmers' food security concerns and improving soil fertility (Snapp et al., 1998). Promising genotypes include Arachis, Cajanus, Dolichos, and Mucuna spp. On-farm nitrogen budgets indicate that legumes with high-quality residues and deep root systems are effective ways of improving nutrient cycling.

In addition to soil protection, the fibrous root systems of leguminous cover crops, such as *Centrosema macrocarpum*, *Desmodium ovalifolium*, and *Pueraria phaseoloides*, can also improve soil physical properties (Broughton, 1977). In the Peruvian Amazon, Arevalo et al. (1998) measured improvements in soil physical properties and increased livestock weight gains when cattle were managed in a silvopastoral system with peach palm and *Centrosema macrocarpum* compared with a traditional grass-based pasture. In the western Amazon, Rueda et al. (2003) reported significantly improved pasture and livestock productivity in Brachiaria pastures that contained the herbaceous legume *Pueraria phaseoloides* (see also Chapter 37).

Farmers who have no access to markets and limited capital to invest in synthetic and fertilizers or pesticides can rely more on biological methods and synergies to minimize their pest problems, reduce nutrient losses, and enhance nutrient inputs, e.g., via nitrogen fixation. Thurston (1997) has identified many traditional systems in the tropics that rely upon INM approaches.

Our review of findings suggested that the presence of one or more leguminous species in managed systems can significantly enhance not only the protection of existing soil productivity functions but can also provide critical biological leverage points to improve the resilience of the managed systems against ecological and climatic shocks. The several leguminous crop species available to farmers are generally short-duration species (3 to 15 months). As long-term components of managed systems, multipurpose, leguminous tree species that do not need replanting every season can help to sustain the critical biodiversity and INM functions as the system evolves.

21.3 Traditional Tree–Crop Systems as Models for Sustainable Farming Systems on Degraded Pasturelands

Amerindian peoples of the Amazon have long planted and managed trees for a variety of products and services in close association with annual and perennial food crops (Posey, 1985; Denevan and Padoch, 1987). The Kayapó create "resource islands" of trees, shrubs, herbs, and root crops at the forest margin and also in open grasslands. These species are generally collected as seedlings in the forest and transplanted to clearings and campsites. Over a hundred species have been encountered in these "agroforestry" islands (Kerr and Posey, 1984; Posey, 1984).

In many traditional systems, farmers crop the deforested land for a few years and then allow the regeneration of forest species during a fallow period of between 5 and 50 years (Chapter 29). Most of the Amazonian trees (*Bactris gassipaes*, *Euterpe* spp., Theobroma spp., Inga spp.) and other food crops (e.g., cassava, capsicum, native solanaceae) that are in use today were probably domesticated via these traditional fallow-based, mixed-species systems (see Table 21.1). In addition to high species diversity, such indigenous agroforests are characterized by a variety of species associations of different age classes spread over several sites. These system characteristics maximize labor efficiency per unit area of land, minimize the risk of food crop failure due to drought or severe pest attack, and guarantee the availability of food even at relatively modest levels of species productivity.

Tree-based homegardens (agroforests) include both native and exotic species for fruit, timber, shade, medicines, spices, and forage. In the Amazon, agroforests have been reported to involve around 30 perennial and annual plant species in Para, Brazil (Subler and Uhl, 1990) and over 70 species in Peru (Paddoch and de Jong, 1991). Agroforests are not unique to the Amazon and as many as 190 plant species at various stages of domestication have been recorded in tropical agroforests (Fernandes and Nair, 1986). The spatial and temporal associations of components are highly dynamic, and although the plant diversity may be low at any given point in time, agroforests can be very biodiverse over their rotations of 50 to 100 years. In Africa, where deforestation is resulting in significant loss of biodiversity, agroforests have been identified as important *in situ* germplasm banks of food, fruit, and medicinal species, whose wild relatives are fast-disappearing as primary forest is cut down (Okafor and Fernandes, 1987).

Our reviews of reports on indigenous technical knowledge from the Amazon showed that the native leguminous genus Inga was a common component of traditional agroforestry systems. This genus, with 258 described species (Pennington, 1997), is used in managed fallow systems as a trap crop for edible caterpillar species, and as a shade tree for perennial crops such as cacao, coffee, and tea (León, 1966; Carrasco, 1971). Lawrence (1995) reported that the main reasons why farmers like Inga as a shade tree are because "the leaves are a good fertilizer, the shade is perennial, the litter and shade provide good weed control, and the shade keeps the soil humid."

Of the 258 species described, the most commonly used species is *Inga edulis*, which occurs as a component in traditional Amazonian agroforestry systems (León, 1966; Pennington and Fernandes, 1998). The qualities that make *I. edulis* an ideal species to facilitate INM in managed systems include:

- Fast growth and ability to tolerate two to three shoot prunings a year that yield between 8 and 10 ton of biomass ha^{-1} yr^{-1} (Szott et al., 1991b).
- Nitrogen fixation potential of 10 to 50 kg N ha^{-1} yr^{-1} depending on soil conditions and plant management (Fernandes et al., 1997).
- Good adaptation to acid, infertile soils and capacity to nodulate effectively with native Rhizobia in soils with high aluminum saturation and low available phosphorus. Studies also show that Inga is a good host for native mycorrhizal fungi that enable the trees to exploit low levels of available soil phosphorus (Fernandes, 1990).
- Moderate to high nutrient concentrations in leafy biomass (e.g., 2.0–3.5% N, 0.2–0.3% P, 1–3% K, and 0.5–1.5% Ca). Leafy biomass derived from vigorously growing trees of *Inga edulis* grown on an Ultisol contained the following concentration of micronutrients: Mn 112, Cu 13, Zn 35, and Fe 95 mg kg^{-1} (Fernandes et al., 1993a).
- Recalcitrant litter that decomposes slowly over 3 to 5 months and thus forms an effective mulch layer on the soil surface that is beneficial for soil protection, soil moisture conservation, and a microhabitat for soil invertebrate populations.

Our community surveys revealed that although Inga is greatly appreciated for its edible fruit (often called "ice cream bean") and its soil-improving properties, many respondents also indicated that the tree attracts undesirable insects, such as stinging ants, as well as more desirable ones, such as spiders as insect predators. There was good reason to anticipate that Inga would be a good species to facilitate IPM in managed systems in the Amazon.

In the 1990s, ranchers not only deforested large tracts of the Amazon to establish extensive pastures, but also used the revenues from the sale of high-value timber species to finance the deforestation and pasture establishment. One timber species that has been aggressively harvested, to the brink of extinction (CITES Appendix II 2003), is large-leafed mahogany (*Swietenia macrophylla* King.). To reverse the negative ecological impacts of the first-generation Amazonian pastures, and the growing local and international demand for range-fed beef, we decided to develop a mahogany-based improved pasture system to restore the productivity of degraded pastures in the Amazon.

21.4 Accounting for Plant–Insect Relationships in the Design of a Biodiverse Mahogany–Pasture System

Previous attempts to manage mahogany in plantations in the neotropics have not been successful due to constant attacks by the mahogany shoot borer, *Hypsipyla grandella* Zell, a lepidopteran (moth) pest (Patiño Valerra, 1997). Repeated attacks by the shoot borer can kill young trees because they thwart the growing shoots (meristems) of the canopy. If the tree survives, the attacks produce a witch's broom effect and excessive branching that adversely affects the commercial quality of the timber.

Given the scientific knowledge on Inga's biological nitrogen-fixation potential and the numerous reports of Inga as a host plant for potential predators of the mahogany moth, we reviewed the literature to determine the potential usefulness of Inga as a nurse species for mahogany, protecting it against the mahogany moth. This showed that:

1. Many of Inga's more than 280 described species have extrafloral nectarines, i.e., plant glands located outside the flowers (Koptur, 1984). The secretion of nectar occurs as the leaf unfolds, and continues through its mature and expanded state. Since new leaves are produced year-round, this extrafloral nectar is almost always available (Koptur, 1984).
2. Many species of ants, while visiting the foliar nectaries of Inga, provide protection of both young and mature leaves against a variety of insect herbivores by predation or by disturbing the herbivores until they leave (Koptur, 1984). Leston (1973) suggested that shade trees that support an "ant mosaic" in commercial plantations may increase protection of the crop plant by natural enemies.
3. In addition to ants, Inga attracts a variety of other insect species. Our own field observations revealed the presence of several insect predators (spiders, wasps) in Inga canopies.

We expected that by using Inga as a nurse species for mahogany we could reduce shoot borer attacks because of the following three factors:

1. Inga has a dense canopy that would physically shield the mahogany trees and make it difficult for *H. grandella* to locate them.

2. Inga attracts a variety of insect species including ants, which defend their territories against other insects, and could thus prevent *H. grandella* from reaching the mahogany.
3. The insects that frequent the foliar nectaries of Inga attract predators such as spiders and birds, which are also potential predators of *H. grandella*.

21.5 Design and Establishment of the Components of a Biodiverse Mahogany–Pasture System

Degraded pastures near Manaus, Brazil were identified and characterized for soil, vegetation, and above- and belowground biodiversity. The average aboveground biomass was 17 ton ha^{-1}, the majority of which was found in the standing litter and tree components. Species richness on the pastures was low, with the majority of the biomass being represented by many individuals of a few species. The most important species on the site included *Brachiaria humidicola* Rendle, the original introduced pasture grass; *Borreria verticillata* (L.) G.F.W. Mey. and *Rolandra fruticosa* (L.) Kuntze, both invasive weeds; plus the tree species *Laetia procera* (Poeppig) Eichler, *Vismia amazonica* Ewan, *Vismia lateriflora* Ducke, and *Vismia cayennensis* Jacq (McKerrow, 1992).

The degraded pasture biomass contained 150 kg N, 4.8 kg P, 87 kg K, 20 kg Ca, and 83 kg Mg per hectare. Slashing and burning the vegetation, which is normal practice in the region for establishing pastures and other cropping systems, resulted in a loss of 132 kg N, 43 kg K, 29 kg Ca, and 6 kg Mg, all per hectare. Since pastures take several years to establish before they can be productively grazed, and the mahogany timber trees would be grown on a long rotation (>50 years), we designed the system to produce rice (*Oryza sativa*), maize (*Zea mays* L.), cowpea (*Vigna unguiculata*), and cassava (*Manihot exculenta* Crantz.) for the first 4 years. Also, because the slashing and burning of the degraded pasture vegetation resulted in a low net contribution of nutrients to the soil, and the soils showed significant surface compaction, we compared two soil amendment treatments:

1. Slashing and burning of the natural regeneration on the degraded pasture, followed by a single application of 20 kg ha^{-1} P (as triple superphosphate) and then cropping with rice, cowpea, and cassava.
2. Slashing and burning of the natural regeneration on the degraded pasture, an application of lime (1 ton ha^{-1} $CaCO_3$ equivalent), mechanization to break up surface compaction and to incorporate the lime, followed by applications of 50 kg N, 20 kg P, and 70 kg K ha^{-1} and then cropping with maize, cowpea, and cassava.

Our strategy for protecting mahogany from the shoot borer moth was targeted to providing maximum physical shielding and niches for moth predators during the first 5 to 6 years of mahogany growth. The design involved two guard rows of Inga (6 m apart) and a central row of mahogany. To obtain overhead protection we interplanted the mahogany with a fast-growing native tree species, *Schizolobium amazonicum*, which served as a light canopy. The design resulted in a vegetative tunnel with sideways protection of the mahogany by dense canopies of Inga loaded with foliar nectaries and mahogany moth predators, with overhead protection by a sparse canopy of Schizolobium. Since mahogany is a light-demanding species, it is important to provide adequate overhead light while retaining a physical shield against the moth. The dense lateral shade and dappled overhead shade mimics conditions in forest gaps, where mahogany seedlings regenerate in the primary forest, and quick upward growth of the mahogany is forced with a minimum of lateral branching.

21.6 Results of the Inga-Mahogany Experiment

During the first 5 years following establishment, the low-phosphorus-input system produced 0.8 ton of rice and 16 tons of cassava, and approximately 4 tons Inga fuelwood per hectare. The mechanized, lime plus NPK, moderate-input system produced 2 tons maize, 0.5 ton of cow pea, 20 tons cassava, and 7 tons Inga fuelwood per hectare. Thus, priming the systems with adequate nutrients (lime + NPK) significantly improved the crop productivity and growth of the Inga and mahogany trees. Over 10 years of growth, the aboveground biomass in the system accumulated per hectare 260 kg N, 24 kg P, 195 kg K, 173 kg Ca, and 36 kg Mg (McCaffery, 2003).

Pasture productivity, especially that of grasses, was significantly enhanced by the initial application of moderate amounts of lime and NPK relative to only phosphorus applications (Table 21.2). A major benefit of improved herbage productivity was the reduction of weed invasions in the pasture. As most of the invading weeds are not grazed or only poorly palatable, the initial nutrient and lime inputs had significant direct and indirect impacts on pasture productivity and palatability.

Results after 4 years of growth showed that the Inga nurse trees significantly delayed the onset of *H. grandella* attacks on interplanted mahogany. Mahogany trees in adjacent plots growing without the protection of Inga were attacked at heights of around 2 m by *H. grandella.* in the second year after field establishment. In the Inga-mahogany association, however, the attacks took place largely in the fourth year and at heights of 6 to 7 m. Interestingly, 90% of the trees in the low-input, sparse-canopy Inga-mahogany system were attacked vs. 70% in the high-input, denser Inga canopy system.

The attack of *H. grandella* on mahogany increased once the mahogany trees grew taller than the Inga (6 m) as evidenced by the bushy growth and bifurcation of the mahogany stems. The delayed attack by *H. grandella* on mahogany that was interplanted with Inga is significant because the older trees were better able to survive the attack than the younger, open-grown mahogany trees. In addition, the mahogany trees that were not attacked in the first 3 years developed a single stem, which makes the tree more valuable for sawn timber than stems that are branched. In the Ecuadorian Amazon, a similar approach of interplanting mahogany in groves of *I. edulis* or *I. ilta* has also resulted in significantly reduced attacks by *H. grandella* compared with control plots where mahogany was not protected by Inga (Niell and Revello, 1998).

Tapia-Coral et al. (2004) have reported on the development of a substantial and persistent litter layer in Inga-mahogany systems. Although naturally regenerating secondary vegetation control plots had a significantly higher litter layer than the mahogany-pasture system, the latter maintained a good litter layer in both dry and wet seasons (Figure 21.1). In a separate study, Barros et al. (2003) reported that the build-up of the litter layer in the mahogany–pasture system resulted in significantly improved soil invertebrate populations and soil structure. Nine years after its establishment, the mahogany–pasture system accumulated 16 ton aboveground C ha^{-1} ($\sim$1.8 ton ha^{-1} yr^{-1}), which is significantly better than the carbon losses (-0.2 to -0.6 ton ha^{-1} yr^{-1}) reported for tropical pastures (Sanchez, 2000) (Table 21.3).

TABLE 21.2

Biomass of Pasture Components (Grass, Legume, Weeds) in 5-Year-Old Low Phosphorus Input (ASP1) vs. Mechanized and Limed (ASP2) Inga-Mahogany Systems Established on Degraded Pastures Near Manaus, Brazil

	Planted Species			Natural Regeneration			Biomass	
Treatment	**Legumes**	**Pasture Grass**	**Subtotal**	**Unpalatable Weeds**	**Other Weeds**	**Subtotal**	**Total**	**Litter**
Dry matter (t ha^{-1})								
ASP1	3.89 a[a]	0.90 b	4.79 b	1.76 a	1.30 a	3.06 a	7.85 a	6.40 b
ASP2	3.36 a	3.38 a	6.74 a	0.60 b	0.58 b	1.17 b	7.91 a	7.29 a
Total dry matter (%)								
ASP1	49.58 a[a]	11.40 b	60.98 b	22.43 a	16.60 a	39.02 a	100	—
ASP2	42.46 a	42.70 a	85.16 a	7.55 b	7.29 b	14.83 b	100	—

[a] Numbers in each column with the same letter are not significantly different at $P > 0.01$ by Tukey test. *Source*: Authors' data.

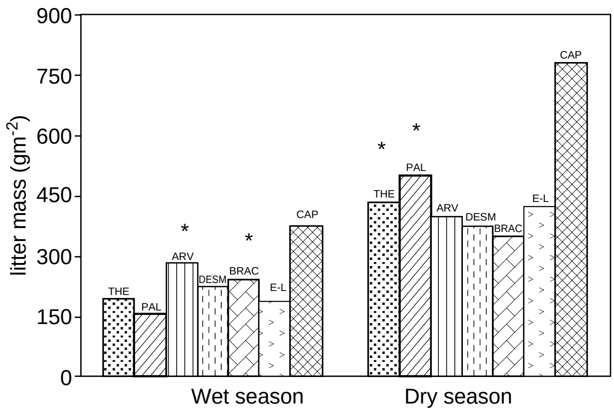

FIGURE 21.1
Litter-layer mass in the wet and dry seasons under agroforestry systems and secondary forest in central Amazonia, Brazil. ARV, Mahogany trees; DESM, Desmodium; BRAC, Brachiaria; E–L, inter-rows and CAP, second growth. *Source*: From Tapia-Coral, S.C., Luizao, F., Wandelli, W., Fernandes, E.C.M., *Agroforest. Syst.*, **65**, 33–42 (2004).

21.7 Discussion

The degraded pastures in the Amazon, although highly altered, can be valuable for human use and provide important ecosystem services, such as watershed protection, biodiversity niches, soil fertility recovery by improved fallows (Szott et al., 1991a, 1991b), and sinks for carbon (Fearnside and Guimaraes, 1996; Silver et al., 2000).

The Inga-mahogany–pasture system described is a promising approach to reintroducing mahogany to deforested and degraded lands in the Amazon and upgrading their economic value as well as biological productivity. Our results confirm that mahogany can be sustainably produced by smallholder farmers in association with food crops and pasture species using a range of INM and IPM strategies. However, owing to the severe nutrient mining and soil degradation prevalent on many degraded pastures, it will be necessary for farmers to have access to modest inputs to prime the system to facilitate the efficient functioning of biological nutrient and pest management strategies. For example,

TABLE 21.3

Aboveground Biomass and Nutrient Stocks in 9-Year-Old Mahogany–Pasture System Established on Degraded near Manaus, Brazil

Species	Biomass (t ha^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})
Schizolobium amazonicum (Paricá)	5.86	23.3	3.4	17.9	25.6	2.0
Swietenia macrophylla (Mahogany)	5.23	16.4	3.3	14.3	31.5	2.2
Brachiaria humidicola/brizantha	4.19	46.1	4.19	45.3	19.04	8.6
Desmodium ovalifolium	4.49	67.3	4.5	32.1	35.7	11.0
Invasives[a]	2.25	35.8	2.8	37.0	19.5	5.0
Gliricidia sepium (live fence)	10.48	73.13	5.43	47.5	41.5	7.3
Totals	32.5	262.03	23.62	194.1	172.8	36.1

Nutrient values are weighted averages, calculated as nutrient level *x* dry weight of trunk + branch + leaves, multiplied by aboveground biomass contribution species^{-1} ha^{-1}.

[a] Predominantly *Rollandra fruticosa* and *Borreria verticillata*.

Rueda et al. (2003) found that in the western Amazon of Brazil, more intensive beef production by judicious fertilization of grass-legume pastures and greater stocking density was the preferable strategy for owners of cattle systems to improve economic returns under current conditions. Ranchers in the state of Acre have also stopped burning pastures to improve pasture palatability and instead use solar-powered electric fencing to facilitate rotational grazing of grass-legume (*Pueraria phaseoloides*) pastures with marked improvement in productivity and sustainability of the pastures.

In 2001, Brazil banned the further exploitation and export of mahogany because of fears that the remaining populations are rapidly becoming endangered. In its native range, mahogany normally occurs at a density of one to three trees per hectare. In our trials we were able to establish approximately 30 mahogany trees per hectare with clean, straight stems, using a combination of INM and IPM techniques that minimized stem damage and mortality by *H. grandella*.

The cultural preferences for beef cattle systems in Brazil will continue for the foreseeable future. The demand and price for Brazilian beef has increased dramatically in recent years because Brazil has largely eliminated foot-and-mouth disease in its beef herd, and consumers are increasingly wary of "mad cow" disease (BSE) in European and North American herds. Our mahogany–pasture system can be applied to supply two of the major commodities (mahogany and beef) via intensively managed systems established on already deforested or degraded pasturelands. Given that these systems also sequester carbon over long rotations, farmers could be provided with payments for carbon sequestration to offset the installation and maintenance costs of the system in the early years.

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