Review Article

Agroforestry and the Improvement of Soil Fertility: A View from Amazonia

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This paper discusses the effects of trees on soil fertility, with a focus on agricultural systems in Amazonia. Relevant literature concerning the effects of trees on soil physical and chemical properties in tropical, subtropical, and temperate regions is reviewed, covering both natural ecosystems and agroecosystems. Soil carbon, in the form of organic matter, is considered as an indicator of biological activity as well as in relation to policy issues such as carbon sequestration and climate change. In the case of tropical soils and Amazonia, information on the effects of trees on soils is discussed in the context of traditional agriculture systems, as well as in regard to the development of more sustainable agricultural alternatives for the region. Lastly, attention is given to a case study in the savanna region of Roraima, northern Brazil, where a chronosequence of indigenous homegarden agroforestry systems showed clear effects of management practices involving trees on soil fertility. The use of diverse tree species and other practices employed in agroforestry systems can represent alternative forms of increasing soil fertility and maintaining agricultural production, with important practical applications for the sustainability of tropical agriculture.

1. Introduction

According to a study by the World Agroforestry Centre, ICRAF, 43% of the planet's agricultural lands (more than a billion hectares) has more than 10% tree cover [1]. A lesser but still significant area of agricultural land, 160 million hectares, has more than 50% tree cover. The potential of trees to bring improvements in nutrition, income, housing, health, energy needs, and environmental sustainability in the agricultural landscape has guided ICRAF's mission, with the presence of trees being the principal component of an "evergreen agriculture" [2]. Within the array of benefits brought by trees, an important element is the positive effect of trees on soil properties and consequently benefits for crops. This paper explores current knowledge as to this relation between trees and soil, based on agroforestry systems research, as well as studies innon-agricultural or natural environments that demonstrate effects of trees on soil. Although we consider information from various ecosystems and biomes, the focus

will be on Amazonia, where the authors have most of their experience. This focus on Amazonia is also due to the strong policy demands for the development of more sustainable agricultural systems in the region, as alternatives to forms of land use that have shown significant and negative impacts on natural resources and ecosystem services, such as deforestation for extensive cattle ranching. In this scenario, agroforestry systems have been indicated as one of the more promising alternatives to achieve a more sustainable agriculture, in greater equilibrium with the environment [3].

The presence of trees in farming systems, although an ancient practice, began to gain institutional attention during the 1970s and 1980s, with the beginning of studies on "agroforestry systems". One of the principal definitions employed in this context was that proposed by Lundgren and Raintree in 1982: "*Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals,*

Figure 1: Agroforestry system with rubber (*Hevea brasiliensis*), cacao (*Theobroma cacao*), and açaí (*Euterpe oleracea*) in Tomé-açu, Pará, showing the litter layer that is typically found in such multistrata systems.

Figure 3: Multistrata agroforestry system in Tomé-açu, Pará, with harvest of hogplum (*Spondias mombin*) grown as the upper canopy over cacao and açaí.
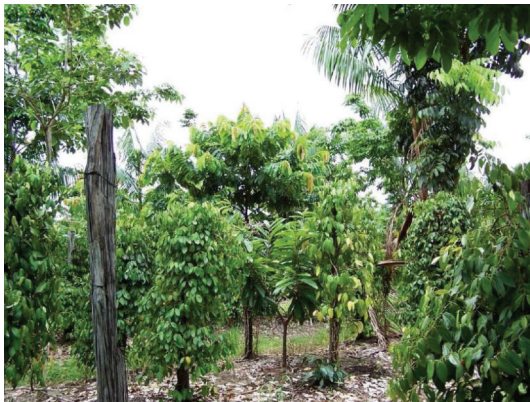

Figure 2: Agroforestry system in initial phase, with black pepper (*Piper nigrum*) as principal cash crop, interplanted with cupuaçu (*Theobroma grandiflorum*) and açaí (*Euterpe oleracea*) for future fruit production, as well as timber trees (mahogany—*Swietenia macrophylla* and ipê—*Tabebuia* sp.) and Brazil nut (*Bertholletia excelsa*) as long-term products.

in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economical interactions between the different components" [4] (Figures 1, 2, and 3).

While trees in general can provide a number of environmental benefits in both rural and urban landscapes, and play key roles in ecosystem services provided by natural areas, in this paper we will restrict our focus to the effects of trees on soil fertility, in the specific context of agricultural systems. Although the benefits that trees can provide on rural properties such as food security, household income, economic stability, and thermal comfort (shade) are most often associated with their products, such as fruit, timber, or other items, the inclusion of trees in agricultural systems can also optimize nutrient cycling and have positive effects on soil chemical and physical properties. This process is especially important in tropical soils, where a high degree of weathering has created deep, leached soils that are poor in

plant nutrients [5, 6]. Although poor in nutrients, tropical soils are very rich in biodiversity, with higher diversity and biomass of microorganisms than temperate soils, with these being the principal agents mediating the supply of nutrients to the soil by means of the decomposition of organic matter, derived from the vegetation [7–9].

In the humid tropics, the removal of surface litter or organic matter generally results in the depletion of soil fertility in a few years [10, 11]. In agricultural systems practiced by traditional peoples, this limitation is circumvented by using the land for a short period (generally 2-3 years), after which the cultivated areas are left to fallow with natural regeneration of secondary vegetation. The associated ecological interactions reestablish nutrient cycling and recuperate soil qualities, after which the area can once again be used for agriculture [12, 13]. This is the basis for shifting cultivation in Amazonia, a system that has permitted native populations to manage their natural resources over centuries, with small-scale environmental impacts that do not exceed the support capacity and resilience of ecosystems. However, the present-day situation of population growth and increasing pressure on agricultural lands lead to situations where there is demand for more intensive land use. This most often implies in repeated burning, the cheapest way to prepare land for planting, which can interrupt processes of nutrient cycling and accumulation, leading to loss of soil fertility and consequently slowing the recuperation of natural vegetation during fallow cycles [14].

In light of the present-day situation of Amazonia, where there are now good reasons and policy demands to balance conservation with development, it is necessary to think in terms of agricultural systems that optimize nutrient cycling and permit permanent or semipermanent production, as well as minimize dependence on external inputs and have low environmental impact. The inclusion of diverse tree species is a key element in maintaining the production of organic matter and generating other positive benefits, as well as allowing the diversification of products. However, before we discuss topics specific to tropical soils and Amazonia,

the following sections will review general information about the influence of trees on soil and their role in accumulation of soil carbon stocks.

2. A General View of the Influence of Trees on Soil Fertility

One of the pioneer studies to measure the effects of individual trees on soils was that by Zinke [15], who looked at pines growing on dunes in northern California, USA. His study found that under trees, certain soil properties exhibited a pattern of radial symmetry, with changes in pH, nitrogen, cations, and cation exchange capacity varying according to distance from the tree trunk, with a peak in these characteristics at a certain distance.

Subsequent studies also demonstrated patterns in the variation of soil characteristics as influenced by trees, such as in tropical savannas [16, 17], deserts [18], and areas of temperate forests [19–23]. In analyzing soil characteristics under individual tree crowns in Kenyan savannas, Belsky et al. [16] found greater levels of mineralizable N, microbial biomass, P, K, and Ca underneath the crowns when compared to open savanna. Burke et al. [17] explain that in dry savannas the strong limitation on water availability permits only punctuated establishment of trees and shrubs but that under crowns cycling occurs in a different form than in open grasslands, with the possibility of soil enrichment in a scale of decades. However, such soil changes can be reverted with the death of the tree or by fires. Belsky et al. [16] also point out the effect of nutrients deposited in dung by birds and large mammals that utilize trees as resting places or roosts.

Such patterns form what have been called "islands of fertility" or "resource islands" created by trees or bushes, generally in savannas or desert areas. The microenvironment of these "islands" can also influence the composition of the herb stratum [16, 19], soil density [19, 20], and earthworm activity [20, 23] among other factors, allowing the creation of positive feedbacks that favor plant establishment and productivity [23, 24]. At the same time, these patterns can be important indicators of stability or risk of desertification in such areas [17, 18].

Studies of forests in temperate climates indicate variations in soil that can be related to individual tree species. Besides the expected correlations, such as greater levels of N under legumes [20] or lower pH under species that produce acidifying litter, such as *Pinus* spp. [20, 23], other interesting interactions show that different species can alter soil in distinct ways, with variations in the increment of soil carbon [20], exchangeable Ca and Mg and per cent base saturation [21, 23].

In a study of 14 tree species in Poland, Reich et al. [23] found varied effects on soil characteristics; however, these effects were significantly related to the level of Ca in litter, independent of the species. Trees producing litter rich in Ca were associated with soils with greater pH, exchangeable Ca, and per cent base saturation, as well as greater rates of forest floor turnover and greater diversity and abundance of earthworms. Dijkstra [22] emphasizes that the rate of mineralization of organic Ca is a fundamental factor in this process, since it determines the immediate availability of this nutrient in the soil and can vary between species.

The study of vertical patterns of the distribution of nutrients in soil can indicate other phenomena that are not detected when only the horizontal distribution of nutrients is examined. In an evaluation of more than 20,000 globally distributed soil profiles, the greater part in temperate climates, Jobbágy and Jackson [25] found that cycling mediated by plants exerts a marked influence on the vertical distribution of nutrients in the soil, especially in the case of more limiting nutrients such as P and K. Patterns of greater concentration of these nutrients in surface layers (0–20 cm) were attributed to the fact that since these are more important to plants, they are subject to greater uptake and cycling, being absorbed from deeper layers and returned to the soil surface through litterfall and rain water throughfall. This process of uptake functions in opposition to leaching, which moves nutrients downward and acts more strongly on those nutrients that are in lessdemand by plants. If a nutrient is not limiting, its movement in the soil profile will be more influenced by leaching than by cycling and it will present higher concentrations at greater depth, as occurs with Na, Cl, and Mg [25]. In Poland, Ulery et al. [20] found this sort of pattern in soils influenced by the presence of four planted tree species, with increments of almost 3 times as much K in the surface layer in relation to the original soil before planting, while below 20 cm this increment was absent or negative. Their study also showed a high degree of leaching of Na, which is less in demand by plants.

Associated with biological cycling and leaching, other processes that influence the vertical distribution of nutrients in soil are atmospheric deposition and weathering (Trudgill, 1988 as cited by [25]). However, atmospheric deposition is considered minor when compared to the annual uptake by plant communities and generally has little influence on the vertical distribution of nutrients [25, 26]. The degree of weathering, however, appears to have a marked influence on the vertical distribution of nutrients, such that in more weathered soils the pattern of concentration in the surface layer is accentuated [25]. This emphasizes the importance of biological cycling in supplying nutrients in weathered soils, as is found in the greater part of the tropics and will be discussed in a subsequent section.

3. Trees and Soil Carbon

Trees add organic matter to the soil system in various manners, whether in the form of roots or litterfall or as root exudates in the rhizosphere [27]. These additions are the chief substrate for a vast range of organisms involved in soil biological activity and interactions, with important effects on soil nutrients and fertility. In participating in these complex processes, trees contribute to carbon accumulation in soils, a topic that is increasingly present in discussions on the mitigation of greenhouse gases associated with global warming and climate change. Although carbon (C) constitutes almost 50% of the dry weight of branches and

30% of foliage, the greater part of C sequestration (around 2/3) occurs belowground, involving living biomass such as roots and other belowground plant parts, soil organisms, and C stored in various soil horizons [28].

In a study that gathered information from sites around the world, Nair et al. [29] found values for soil organic C stocks ranging from 6.9 to 302 Mg ha^{-1}. Despite the great amplitude of these values, attributed to the variation between systems, ecological regions, and soil types, the study revealed a general trend of increasing soil C sequestration in agroforestry when compared to other land-use practices, with the exception of forests.

Although the ability of soils to accumulate C is generally related to characteristics that are little influenced by management, such as texture (clay soils typically accumulate more C than sandy soils), some management practices can influence soil C sequestration, particularly the insertion of trees in agricultural systems. Soils in various sites studied by Takimoto et al. [30] in the African Sahel were not markedly different among each other in terms of their characteristics such as pH, bulk density, and particle size, such that variations in their C contents seemed to be related to the influence of trees. In 8-year-old alley-cropping systems with five different species, for example, the authors found that greater C content is nearer to the trees. However, the greater part of this C was found in the form of particles of size between 250–2000 μm, fractions that are considered to be large and less stable. In systems where trees where present for more than 30 years (parklands), there was a predominance of soil C in smaller fractions (<53 μm), which are more stable and thus represent a more "protected" form of C.

In homegardens in India, Saha et al. [31] found levels of soil organic C to be 30% and 114% greater than in coconut plantations and rice paddies, respectively, when homegardens where small (less than 0.4 ha) and levels 18% and 94% greater in larger homegardens (larger than 0.4 hectares). Although the authors do not elaborate on the reasons for decrease in soil C in the larger homegardens, this may be related to a drop off in the deposition of organic residues, which generally occurs in proximity to dwellings. In the Northeast of Spain, Howlett et al. [32] studied the levels of soil C in silvopastoral systems composed of different species, and found that systems with birch (*Betula pendula*) presented greater levels of soil C than systems with pine (*Pinus radiata*). This difference was attributed to the fact that *P. radiata* create an understory environment that is less conductive to plant growth by the formation of a slowly decomposing duff layer, which inhibits germination and growth of other species and, over time, reduces C inputs to the soil. Both silvopastoral systems presented levels of C similar to pastures without trees, and in the case of the more stable C fractions (<53 μm) in the upper layers (0–50 cm), the pasture without trees presented greater levels than the silvopastoral systems. However, the authors observed that these levels may not accurately represent long-term C sequestration potential, since pasture tillage led to more free (unoccluded) silt+clay-sized fraction recovery, which translated into more storage in the pasture as compared with the pine and birch stands. In other situations tillage is reported to cause significant loss of surface soil organic C and disruption of the process of macroaggregate formation, increasing bioavailable sources of C from smaller aggregates [28, 30–32]. Tonucci et al. [33] consider that on the short term, C levels in pasture soils can be greater than under systems with trees due to the faster turnover of the grass root system, as well as the greater bulk density of soils in pasture systems, that can lead to higher C values than found in less dense soils.

The lag inachieving positive results in terms of soil C accumulation under trees are similar to what has been observed in the transition to continuous no-till agriculture. According to Derpsch et al. [34], clear increases in soil organic matter only appear 5–10 years after the adoption of this form of cropping system. Climate conditions also affect C accumulation in soils, since temperature and humidity greatly affect the activity of microbial communities and the breakdown of organic matter [28]. Takimoto et al. [30], for example, attributed, at least partly, To the low levels of C found in their study of soils in the African Sahel to the high temperatures in that region.

4. Trees and Soil Biodiversity

In Amazonia, the diversity and density of macroinvertebrates in the soils of natural forests are considered high, and the conversion of these ecosystems to other forms of land use can cause severe changes in their populations [35, 36]. Barros et al. [37] cite soil macroinvertebrates as sensitive indicators of natural systems, land use, and management, with agroforestry systems presenting a greater abundance and diversity when compared to other forms of agricultural land use. Tapia-Coral et al. [38] found greater densities and biomass of Diplopoda and Isopoda in the litter layer of agroforestry systems than in adjacent secondary forests. Secondary forests, however, presented greater values for Isoptera, principally during the rainy season. This is an indication that such systems can support sufficiently abundant and diverse communites of these organisms that play an important role in ecological processes such as breakdown and cycling of organic matter. However, agroforestry systems encompass a range of practices, such that there is considerable variation in the quality of organic matter produced and the effects of vegetation on soil humidity and temperature regime, with significant effects on the soil macrofauna community [37].

In a study to evaluate the occurrence and diversity of arbuscular mycorrhizal fungi in soil under different land uses in Amazonia (high forest, old secondary forest, young secondary forests, agroforestry systems, crops, and pasture), Leal et al. [39] found great variation in species richness among samples, independent of the land use system. On the other hand, in these same systems Jesus et al. [40] observed that the principal differences in the composition and structure of the bacterial community were related to alterations in soil attributes, which in turn are correlated to land use. Community structure changed significantly along gradients of cation saturation and pH. The similarity observed between

the communities of primary and secondary forest indicates the recuperation of the bacterial community during the process of succession that occurs after the abandonment of areas used for agriculture, with the return of arboreal vegetation.

5. Trees on Tropical Soils

In contrast to temperate ecosystems, where soils generally are more fertile and a greater part of the nutrients is supplied by the weathering of parent material, conditions of high temperatures and rainfall in the tropics accelerate soil processes, including loss of nutrients, so that the greater stock of nutrients is found held in the biomass and made available through decomposition [5–7, 9]. Although there are exceptions to this rule, such as soils of more recent volcanic origin in Asia, or the floodplains of the Amazon River that annually receive sediments from the Andes, the majority of soils in the Amazon Basin are typical examples of low-fertility tropical soils, having been formed on ancient sediments. The high temperature and humidity of tropical climates are conducive to the decomposition of organic matter, so that there is not only the release of nutrients but also the formation of negatively charged particles, which help to retain cations such as K, Ca, and Mg and maintain them in constant interface with the soil solution, where they can be absorbed by plants. In tropical systems, therefore, a soil cover of organic matter is essential to maintain adequate conditions for the soil micro, meso, and macrofauna that carry out this cycling [41]. As such, many of the studies on the effects of trees on tropical soil concentrate on the importance of organic matter made available in great part through litterfall.

Litter production can be a very important contribution in systems where perennial crops such as cacao and coffee are grown under the shade of trees. Souza et al. [42] observed that litter production in a coffee plantation shaded with diverse tree species was similar to that of native forests in the same region. Araujo and Collier [43], working in an agroforestry system with four fruit trees in a transition region between savanna and Amazonian forest in Brazil, indicated the importance of litterfall in the dry season, when compared to conventional cropping systems. Jaramillo-Botero et al. [44], in analyzing the effects of native trees planted as shade for coffee in southeastern Brazil, found that the quantity of accumulated litter and level of K in the soil was positively influenced by the number of trees present in a distance of 0 to 3 meters from the coffee bushes. Since K is a very mobile element, K enrichment may be partly due to throughfall and stemflow, as observed by Pinho et al. [45] in coffee agroforestry systems in the same region. Also in coffee systems, Jesus et al. [46] found higher pH and base saturation in areas intercropped with rubber (*Hevea brasiliensis*) than in monocultures. These studies suggest that roots of trees occupy deeper soil layers that may not be accessible to other crops, or that they are more efficient in extracting nutrients, due to their greater size and biomass or to other factors such as mycorrhizal associations. As such,

when compared to other agricultural systems in tropical conditions, agroforestry can accumulate greater amounts of carbon and can help maintain soil fertility through a more efficient cycling of nutrients and a reduction of losses through leaching and erosion.

In a number of situations, intercropping with legume species that fix atmospheric N means that this element will be provided through decomposition to other plants, a practice commonly known as "green manuring" [47, 48]. Mochiutti and Queiroz [49], working in the state of Amapá, eastern Amazonia, found that N levels were two times higher in the litter under improved fallows planted with the native legume taxi-branco (*Sclerolobium paniculatum*), when compared to fallows with natural regeneration. In a floodplain ecosystem in central Amazonia, Kreibich et al. [50] found that the flux of mineral N in the soil at 0–20 cm was 3-fold greater under native legume species than under nonlegumes, indicating the importance of legumes in that ecosystem.

A continent-wide study in Africa found that green manuring increases maize production, with important benefits for food security [51, 52]. The great variety of legume species with potential for use as green manures offers a number of possibilities for intercropping. Quick-growing herbaceous species include *Cajanus cajan, Crotalaria juncea, Stizolobium aterrimum*, and *Calopogonium mucunoides*, which decompose rapidly and improve soil within 2-3 months [53–55]. In contrast, tree legumes with slower growth, such as *Gliricidia sepium* and *Leucaena leucocephala*, are important for supplying organic matter with different characteristics, such as greater C/N ratios, polyphenol, or lignin contents. While organic matter with a low C/N ratio will decompose more quickly and rapidly releasing nutrients for use by crop plants, in certain situations a slower decomposition rate may be desirable, in order to maintain soil cover and control growth of weeds [56, 57].

However, the diversification of species is important to also diversify the characteristics of the biomass that are generated and incorporated in the soil, such that there is better mix in terms of nutrient contents. This may require planting or managing other species, besides legumes. In the study previously cited by Mochiutti and Queiroz [49] it was found that litter produced in an area with natural secondary forest regeneration had a higher content of Ca than litter from the area planted with the legume taxi-branco. A study by Gonçalvez et al. [58], in the Atlantic Rainforest of Brazil, found marked differences in levels of macro- and micronutrients in litter produced by native tree species, reinforcing the need to consider a mix of species in agroforestry systems.

6. Trees in Amazonian Agriculture

Over millennia, traditional populations have diversified their agricultural systems with trees, and intentionally or not, have benefitted from their products and other services that result from this management. In Amazonia, many indigenousl societies and their multiracial descendants,
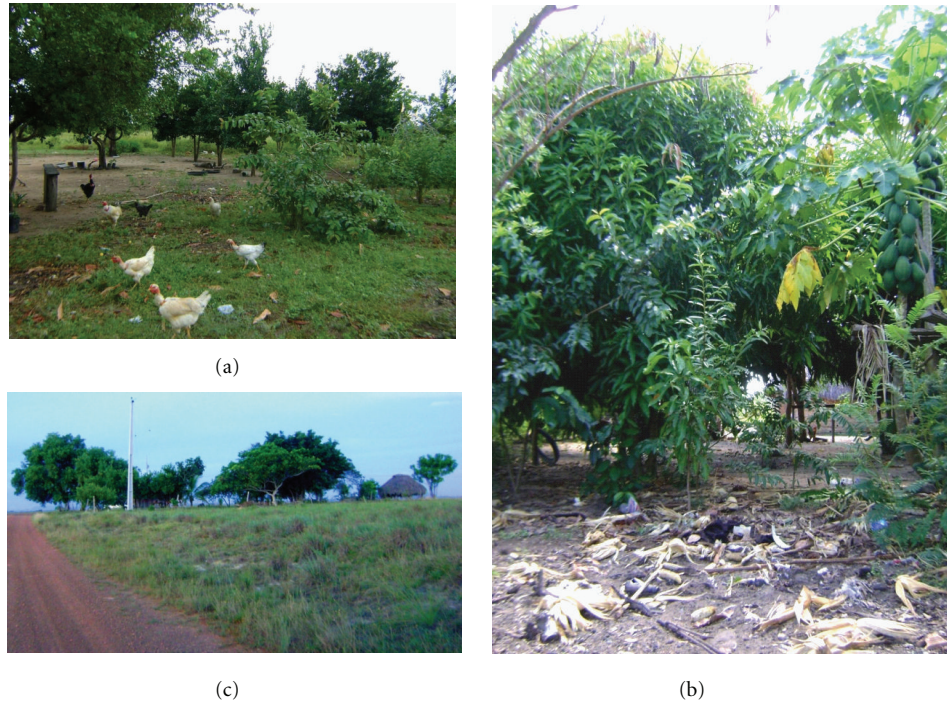
FIGURE 4: (a) Delimitation between the swept and weeded bare earth "yard" that surrounds the dwelling (left) and the outside area (periphery) where the residues are directed to (right). (b) Accumulation of organic domestic residues in the periphery of a homegarden, where frequent small burns of these residues may occur, together with other organic materials derived from sweeping and weeding the "yard"; (c) outside view of an indigenous homegarden in the "Lavrado" (savanna) of Roraima, Brazil (Araçá Indigenous Land, Brazil).

the *caboclos* or *ribereños*, practice forms of agriculture involving trees, whether in homegardens around their dwellings or more extensive systems involving intercropping in swidden fields [59–61]. These practices consist of a set of techniques developed by traditional populations over the years or centuries, based on observation and experimentation.

According to Clement [62], when Europeans first arrived in the Americas, Amazonian communities had already domesticated more than 130 species, of which around 80 are fruit bearing, such as avocado (*Persea americana*), abiu (*Pouteria caimito*), biribá (*Rollinia mucosa*), cashew (*Anacardium occidentale*), genipap (*Genipa americana*), papaya (*Carica papaya*), passion fruit (*Passiflora edulis*), and murici (*Byrsonima crassifolia*), among others. It is believed that the domestication of plants and other management practices of tree species originally occurred in areas surrounding dwellings, where discarded seeds of wild species may have germinated, to be cultivated by observant protofarmers [63, 64]. In the locations around dwelling the deposition of residues resulting from domestic activities is commonplace (husks, bones, ashes, etc.) and has led to the creation of some of the most productive soils in Amazonia, the "black earths" or "*terra preta de índio*" [56, 65–67].

Many of the practices that created such soils are still in use today, as can be observed in the modern-day homegardens of indigenous and *caboclo* farmers, which have a diversity of tree species, frequent additions of organic matter as well as occasional low-intensity burning of residues

[64, 68–73] (Figure 4). In indigenous communities of the Lavrado (savanas) region of Roraima, northern Brazil, homegardens have a great variety of plants, mostly fruit bearing and are important to food security [74]. In a study of soil nutrients under a chronosequence of these homegardens in Araçá Indigenous Land, Roraima, Pinho et al. [75] found a progressive increase in levels of P, K, Ca, Mg, organic matter, and pH, as well as a decrease in Al (Table 1). In these otherwise infertile savanna soils [76], cultivation of fruit trees around dwellings is made possible by this gradual increment in nutrients, a result of nutrient imports from surrounding ecosystems, deposited in the form of residues and possibly the internal cycling by trees that also contribute to the system by means of their litter.

While dwellings and associated homegardens represent relatively stable features on the landscape, slash-and-burn or swidden agriculture fields shift around a broader area, because for every field under cultivation, a greater area must be kept recovering under a fallow of secondary vegetation. Under low population density, this traditional system is adequate for crop production, with long fallows between cropping cycles guaranteeing the recovery of soil physical and chemical qualities. However, with population growth and pressure on land, more areas of forest are being converted to agriculture, with a concurrent reduction in fallow cycles, such that the sustainability of this system is threatened by reduced soil fertility [14]. In the savanna region of Roraima, intensive agricultural use of the scattered forest patches or

Table 1: Levels of nutrients, organic matter, and acidity, by depth, in homegardens and savanna soils in Araçá Indigenous Land, Roraima, and Brazil. Homegarden values followed by * or ** are statistically different from savannas, with $P \leq 0,05$ and $P \leq 0,001$, respectively, by Mann-Whitney test (U-test).

	Savanna ($n = 15$)	New homegardens ($n = 5$) (0–10 years-old)	Estabilished homegardens ($n = 5$) (15–35 years-old)	Old homegardens ($n = 5$) (40+ years old)
P (mg Kg^{-1})				
0–10 cm	2,1	14,3**	26,5**	43,7**
10–20 cm	1,1	8,5*	12,2**	37,9**
20–30 cm	0,6	7,5*	7,5**	31,2**
K (cmolc Kg^{-1})				
0–10 cm	0,07	0,08	0,11*	0,18**
10–20 cm	0,06	0,08	0,10*	0,15**
20–30 cm	0,06	0,07	0,10*	0,13**
Ca (cmolc Kg^{-1})				
0–10 cm	0,32	0,66*	1,48*	1,93**
10–20 cm	0,22	0,24	1,02*	1,41**
20–30 cm	0,17	0,18	0,63*	1,03**
Mg (cmolc Kg^{-1})				
0–10 cm	0,16	0,18	0,30	0,48**
10–20 cm	0,09	0,10	0,24**	0,33**
20–30 cm	0,06	0,07	0,18*	0,28**
Fe (mg Kg^{-1})				
0–10 cm	25,2	21,4	39,8	135,6*
10–20 cm	22,7	17,8	37,4	104,4*
20–30 cm	20,3	12,6	26,5	81,0*
Zn (mg Kg^{-1})				
0–10 cm	1,9	3,1	12,9**	13,9**
10–20 cm	2,1	1,5	8,11**	11,6**
20–30 cm	2,6	1,4	8,63**	11,4*
Mn (mg Kg^{-1})				
0–10 cm	22,4	32,4	29,91	40,6
10–20 cm	16,7	23,9	18,02	24,7
20–30 cm	15,3	23,4	14,93	18,5
Cu (mg Kg^{-1})				
0–10 cm	0,86	0,74	1,70	1,17
10–20 cm	0,87	0,67	1,37	1,17
20–30 cm	0,84	0,62	1,28	1,13
Organic matter (g Kg^{-1})				
0–10 cm	12,9	12,2	20,6	27,6**
10–20 cm	10,0	7,9	14,6	19,5*
20–30 cm	8,3	6,9	10,4	14,3*
Al (mg Kg^{-1})				
0–10 cm	0,13	0,07	0,08	0,05*
10–20 cm	0,17	0,12	0,09	0,08
20–30 cm	0,19	0,11	0,11	0,10
pH (H$_2$O)				
0–10 cm	5,34	5,39	5,48	5,45
10–20 cm	5,16	5,28	5,39	5,49
20–30 cm	5,13	5,29	5,30	5,32

islands, with shorter fallow cycles, has led to a reduction in soil fertility and a greater proportion of the area under secondary forest. A study by Freitas [77] showed that in this situation fallows, can contribute to an increase in soil P but not to an increase in K, suggesting that these two nutrients are limiting factors for agricultural production in the forest islands. On the other hand, in a cambisol in the Upper Solimões region, Soares [78] observed that five years of fallow were the minimum time necessary to achieve levels of exchangeable Ca and Mg equivalent to that found in twenty year-old fallows.

Modern agricultural technologies offer the possibility of continuous crop production in the same area, without the need for fallows, through the use of machinery and chemical inputs. However, this model of agricultural production can lead to soil erosion as well to the reduction in biological processes that are important in tropical soils, along with a dependence on external inputs [9]. Based on the soil improvement that naturally occurs under secondary forests, lessons can be obtained as to the possibility of including trees as components of a more sustainable agriculture for Amazonia [79]. Choices as to which tree species to include can consider those that offer useful products or that speed-up processes of soil improvement, such as legumes that provide green manures.

A recently released study classifying land use in areas deforested up to 2007 in the Brazilian Amazon indicates that 62.2% of the area deforested has been occupied by pastures. In productive terms, however, 25% of the area under pasture can be considered as degraded or "weedy" [80]. Such areas left behind the advancing agricultural frontier are now the prime concern for initiatives of landscape recovery that seek to restore ecosystem services, such as riparian buffer strips to protect hydrological resources and provide connectivity for other landscape functions such as biodiversity. Current Brazilian environmental legislation requires that rural properties in Amazonia maintain 80% of their area with forest cover, a figure that is reduced to 50% in regions that have established a zoning system. As a result, many properties must recuperate areas that were deforested if they wish to access government programs such as agricultural credit. While ecological restoration can be quite expensive on its own, recuperation of areas of degraded pasture with agroforestry systems for production of food, commodities, and timber products may be a viable alternative. Choice of the proper tree species is critical to the success of any such initiatives, not just from an economic point of view, but also from the biological point of view in terms of rejuvenating soil properties.

Research with native legumes in Amazonia has shown that more than 60% are nodulating species [81, 82] and thus have a great potential for use in agroforestry. Other tree species may be chosen based on either ecological or production functions. However, planning of successful agroforestry systems must alsoconsider cash flows and choose appropriate species accordingly.

Although the number of practical examples is limited, another potential role of trees in Amazonian production systems is as components of silvopastoral systems. Andrade et al. [83] indicate that at least one legume species, *Stryphnodendron guianensis*, has positive effects on soil fertility and forage production. However, this is due in part to this tree's crown architecture, which does not create an excess of shade.

7. Conclusions

Trees in agroecosystems can be present in an infinite number of arrangements and species combinations that depend mostly on farmers' objectives as well as the environmental characteristics of the region. In general, it is safe to say that a greater diversity of species is more favorable, as it results in a more complete occupation of space above and below the soil, and the variation in the characteristics of the litter produced can maintain a greater level of soil biodiversity, with positive effects on fertility [10, 79].

The intentional use of trees in farming systems occurs in many parts of the globe; however, many of their benefits, that go much beyond soil improvement, are still difficult to visualize or quantify in economic terms or only appear in the long term [47, 84], such that many farmers are hesitant to invest in trees. A better understanding of the positive effects of trees on soils, and an economic analysis of what this represents in terms of nutrients and other benefits, is an important step towards increasing the use of trees on farms.

Soil improvement under trees and agroforestry systems is in great part related to increases in organic matter, whether in the form of surface litter or soil carbon. Therefore, besides their role in above-ground carbon sequestration, agroforestry systems also have a great potential to increase carbon stocks in the soil and certainly merit consideration in mechanisms that propose payments for mitigation of greenhouse gas emissions to reduce climate change.

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