Plant-soil interactions in multistrata agroforestry in the humid tropics

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Abstract

Multistrata agroforestry systems with tree crops comprise a variety of land use systems ranging from plantations of coffee, cacao or tea with shade trees to highly diversified homegardens and multi-storey tree gardens. Research on plant-soil interactions has concentrated on the former. Tree crop-based land use systems are more efficient in maintaining soil fertility than annual cropping systems. Certain tree crop plantations have remained productive for many decades, whereas homegardens have existed in the same place for centuries. However, cases of fertility decline under tree crops, including multistrata agroforestry systems, have also been reported, and research on the causal factors (both socioeconomic and biophysical) is needed. Plantation establishment is a critical phase, during which the tree crops require inputs but do not provide economic outputs. In larger plantations, tree crops are often established together with a leguminous cover crop, whereas in smallholder agriculture, the initial association with food crops and short-lived cash crops can have both socioeconomic and biological advantages. Fertilizers applied to, and financed by, such crops can help to 'recapitalize' soil fertility and improve the development conditions of the young tree crops. Favorable effects on soil fertility and crop nutrition have been observed in associations of tree crops with N_2-fixing legume trees, especially under N-deficient conditions. Depending on site conditions, the substitution of legume 'service' trees with fast-growing timber trees may lead to problems of competition for nutrients and water, which may be alleviated through appropriate planting designs. The reduction of nutrient leaching and the recycling of subsoil nutrients are ways to increase the availability of nutrients in multistrata systems, and at the same time, reduce negative environmental impacts. These processes are optimized through fuller occupation of the soil volume by roots, allowing a limited amount of competition between associated species. The analysis of temporal and spatial patterns of water and nutrient availability within a system helps to optimize the use of soil resources, e.g., by showing where more plants can be added or fertilizer rates reduced. Important research topics in multistrata agroforestry include plantation establishment, plant arrangement and management for maximum complementarity of resource use in space and time, and the optimization of soil biological processes, such as soil organic matter build-up and the stabilization and improvement of soil structure by roots, fauna and microflora.

Introduction

In this paper, the term multistrata agroforestry comprises all tree crop-based land use systems that have two or more vegetation layers and include more than one tree species. This includes simply-structured plantations of coffee (*Coffea* spp.), cacao (*Theobroma cacao*), or tea (*Camellia sinensis*), often with a monospecific overstorey of shade trees (Beer et al., 1998), as well as highly diversified systems with a forest-like structure, such as homegardens and 'agroforests' (Michon and de Foresta, 1999; Torquebiau, 1992). Multistrata agroforestry systems are wide-spread in the humid and subhumid tropics of the world, including lowland and mountainous regions (Nair and Muschler, 1993). The simpler systems are of major importance for the world markets. The more complex, homegarden-like systems are locally important for the subsistence of smallholder farmers and contribute to the conservation of germplasm diversity of tree crop species and to the maintenance of niches for fauna and flora in the agricultural landscape (Michon and de Foresta, 1999; Perfecto et al., 1996).

Investigation of plant-soil interactions in multistrata agroforestry systems has largely concentrated on the less complex systems, presumably because of their economic importance and their relatively simple structure, which facilitates research. The complex nature of homegarden-like systems poses major challenges for the study of plant-soil interactions. In his review of tropical homegardens, Torquebiau (1992) concluded that these systems possess several attributes of biophysical and social sustainability, although many assumed benefits are poorly quantified.

In this review, we attempt to provide an overview of the available information on plant-soil interactions in multistrata agroforestry systems based on tree crops in the humid tropics. We analyze their benefits in comparison with less diverse systems, such as tree crop monocultures and systems based on annual crops. We identify problems for the maintenance of soil fertility under tree-based land use systems and propose ways of optimizing these systems and maximizing their environmental benefits.

Soil fertility in tree-based cropping systems in the humid tropics

Maintenance and decline of soil fertility under tree crops

There is little doubt that under humid tropical conditions, tree crops are better suited for the maintenance of soil fertility than annual crops (Ewel, 1986). This is a consequence of the permanent soil cover and perennial root systems of the trees, which provide continuous soil protection, a favorable environment for soil biological processes and more efficient nutrient cycling than systems based on annual crops. Evidence for the sustainability (including the maintenance of soil fertility) of tropical homegardens is provided by their long-term existence on some sites (e.g., over 200 years in some parts of Thailand; Gajaseni and Gajaseni, 1999). Although the mechanisms responsible for this stability are poorly studied, they certainly include permanent soil protection as well as additions of nutrients and organic matter in domestic wastes, ashes, manure, etc. (Torquebiau, 1992).

In contrast to the complex homegardens, the development of soil fertility under simpler, tree-based systems, such as monoculture plantations of tree crops, shaded coffee and cacao plantations, has repeatedly been studied, with variable results. Kowal and Tinker (1959) found no decrease of chemical soil fertility during 16 years under oil palm (*Elaeis guineensis*) after secondary forest on a Nigerian Alfisol, except for losses of K and Mg which would have to be replaced by fertilizer. Soil organic matter tended to increase. In contrast, Ollagnier et al. (1978) found decreases of total soil C to 60% and of total N to 75% of the levels under adjacent forest in oil palm plantations of up to 14 years age on an Ultisol in the southern Côte d'Ivoire. The reduced fertility levels were considered adequate for oil palm, since these sites still supported productive plantations after 60 years. However, problems with the long-term productivity of oil palm were encountered on the sandy ferralitic soils of the Dabou savanna in Côte d'Ivoire, where yields decreased by 20 to 30% from the first to the second rotation. Poor development of palms and a cover crop were explained by soil compaction and consequently reduced water availability and root development.

The structural degradation was related to the replacement of divalent by monovalent cations on the exchange complex, caused by the heavy K fertilization, as well as the use of heavy machinery in plantation management, felling and site preparation for the second rotation (Caliman et al., 1987). Obviously, this degradation was more related to the management of the plantation than to the crop itself.

Ayanlaja (1987) attributed declining productivity of most cacao plantations in Nigeria after about 10 years to inadequate site selection of many farms. Other authors working in the same region found that the soil under cacao degraded progressively even in shaded plantations. In a 15-year-old cacao plantation with cola (*Cola nitida*) shade trees on an Alfisol in SW Nigeria, the soil under cacao and cola trees tended to have less C, P, K, Ca and Mg, and a lower pH than the soil between the trees, but there was no difference between the tree species (Ekanade, 1987a). After 40 years, the soil under cacao showed significantly lower fertility values than the soil under the shade trees and between the two tree species (Table 1). The same author found less favorable physical and chemical soil properties on cacao farms than adjacent forest (Ekanade, 1987b). Similarly, Ahenkorah et al. (1987) reported decreasing soil C contents during 16 years under cacao with different shade densities (no shade or two levels of *Terminalia ivorensis*

shade) and two levels each of N, P, and K fertilizer on an Alfisol in Ghana. They mentioned that humus loss was independent of shade intensity and fertilization (detailed data were not given), although the shade trees seemed to have a positive effect on the soil P status. The reported humus losses under cacao in Ghana were in contrast to increasing soil organic matter contents over 10 years under shaded cacao on a Typic Humitropept in Costa Rica (Beer et al., 1990). The reason for the contrasting findings was certainly that Ahenkorah's experiment had been established after forest, and Beer's experiment after sugarcane (*Saccharum* sp.), indicating that shaded perennial crops are more favorable for the soil organic matter balance than (regularly burned) sugarcane but less so than forest. This is consistent with severe C losses under sugarcane in comparison to primary forest in a Brazilian Oxisol (Woomer et al., 1994).

Do decreasing fertility parameters always indicate unsustainability?

These examples demonstrate that, compared with the soil under forest, certain fertility parameters can decrease under tree crops when planted either in monoculture or in multistrata agroforestry systems. Such decreases do not always indicate unsustainable soil use. When forest is converted

Table 1. Chemical characteristics of an Alfisol under a 40-year-old plantation of cacao (*Theobroma cacao*) with shade trees of cola (*Cola nitida*) in the Nigerian cacao belt.[a]

	Depth (cm)	Under shade trees	Between shade trees and cacao	Under cacao
Organic matter	0–15	3.1 a	3.0 a	2.2 b
(%)	15–45	2.1 a	2.3 a	1.7 a
Available P	0–15	9.4 a	9.2 a	5.2 b
(Bray 1, mg kg^{-1})	15–45	8.0 a	8.3 a	6.0 a
Exchangeable K	0–15	89 a	104 a	61 b
(mg kg^{-1})	15–45	60 b	79 a	55 b
Exchangeable Ca	0–15	260 a	256 a	151 b
(mg kg^{-1})	15–45	237 a	241 a	188 b
Exchangeable Mg	0–15	120 a	128 a	100 b
(mg kg^{-1})	15–45	88 a	93 a	85 a

[a] From Ekanade (1987a). Values followed by the same letter in a row are not significantly different at $P < 0.05$ (LSD test).

to plantation agriculture, a fertility parameter, such as soil organic matter content, may equilibrate on a lower level, which may, however, still be adequate for the respective crop. A limited decrease in soil fertility may not threaten long-term productivity, especially of relatively un-demanding crops such as oil palm, as long as the nutrient requirements of the crop are satisfied through fertilizer application (Ollagnier et al., 1978). In contrast, fertility loss under relatively demanding crops, such as cacao, may be more problematic. If fertility decline causes severe yield decreases, the area may be abandoned or transformed into a less demanding land use, such as extensive pasture, and a new forest plot may be cleared for the second rotation instead of replanting the same site. For a number of reasons, of which declining soil fertility is apparently one (Ekanade, 1987b), this 'pioneer strategy' has traditionally been practiced for cacao and has made a substantial contribution to deforestation in Latin America and Africa (Jarrige and Ruf, 1990).

Thus, the sensitivity of a crop species to reduced soil fertility is one factor that determines whether, or at which stage, fertility decline causes unsustainability. Another factor is obviously *which* fertility parameters decrease. Decreasing nutrient availability in the soil is relatively easy to correct with mineral fertilizers, provided that these are available and that their application is economic. This is often not the case, especially in remote regions, when credits are not available, and when fluctuating weather conditions and market prices increase the financial risks. Decreasing soil organic matter contents indicate loss of cation exchange capacity and organically bound nutrients and may result in increased P fixation by Fe and Al oxides, destabilization of the soil structure and reduced soil biological activity (von Uexküll, 1986). Once soil organic matter levels have decreased, they are generally slow to recover (Webster and Wilson, 1980). Also, soil physical degradation is generally difficult to correct and must be considered a threat to sustainability. The same is true for the build-up of nematode and other disease and pest populations. This latter topic is discussed in a separate review (Schroth et al., 2000a).

Approaches to optimizing tree-based land use systems

Although certain tree-based, tropical land use systems have remained stable and productive over time periods ranging from decades to centuries, the maintenance of soil fertility under tree crops in the humid tropics can clearly not be taken for granted. It is, therefore, important to identify the factors which contribute to fertility maintenance or decline in such systems. The equilibration of the nutrient balance with mineral fertilizers is an economic rather than a technical problem. However, the efficiency with which available nutrients are taken up by crops can be improved, and unproductive nutrient losses reduced, through the design and management of land use systems. Where suitable crop associations increase farmers' income, fertilizers become more easily accessible. The management of soil physical and biological properties is more complex and much less under-stood than nutrient management, but some prin-ciples are nevertheless outlined below. The choice of the principal crop species in a land use system is based on socio-economic considerations and cannot easily be altered, even if the species are not optimal from a soil fertility perspective. More flexibility exists with secondary species, such as shade trees, and with respect to system design and management. These are, therefore, the focus of the following discussion.

Maintaining and replenishing soil fertility during plantation establishment

Tree crops usually take several years to reach com-mercial production. In particular during establish-ment, many tree species are slow-growing and require intensive protection against weeds, pests and diseases. Unless the tree crops are established under an existing tree stand, rapid soil protection by herbaceous plants is important to reduce erosion and surface runoff, compaction of the soil surface by direct rain impact, and humus loss caused by high soil temperature, increased decom-position rates, and reduced litter input (Sanchez et al., 1985). For tropical homegardens, the bridging of this 'lag phase' during which the plantation

requires inputs but does not provide outputs has been identified as an important research topic (Torquebiau, 1992).

Cover crops vs. temporary intercrops

In larger commercial plantations, the most efficient way to protect the soil and provide favorable growth conditions for young tree crops is usually to establish a leguminous cover crop, such as *Pueraria phaseoloides* or *Centrosema pubescens*. These species rapidly cover the soil, fix up to 150 kg ha^{-1} yr^{-1} of atmospheric N_2 (Giller and Wilson, 1991), suppress weeds and increase the activity of soil organisms such as earthworms (Agamuthu and Broughton, 1985; Sanginga et al., 1992). However, the use of cover crops requires a certain labour input, first for their establishment and then for protecting the tree crops from climbing legumes. Also, vigorous cover crops may compete with the tree crops for nutrients and water, especially during the dry season (Lehmann et al., 2000b).

Smallholder farmers usually prefer to associate their young tree crops with annual and semi-perennial food crops such as rice (*Oryza sativa*), cassava (*Manihot esculenta*) and bananas (*Musa* sp.), until either the shading by the trees becomes too intensive or the fertility of the soil, which is temporarily increased by burning the previous forest or fallow vegetation, has been exhausted (Sanchez et al., 1985; Sousa et al., 1999). These intercrops help to bridge the 'lag phase' (Rodrigo et al., 2001) and can also have direct advantages for the initial development of the tree crops. In the central Côte d'Ivoire, the association of (fertilized) coconut palms (*Cocos nucifera*) with food crops such as cassava and yam (*Dioscorea* sp.) during the first two years, and subsequent installation of the cover crop *Pueraria javanica*, led to faster palm growth than when the cover crop was planted in the first year (Zakra et al., 1986). Apparently, the palms profited from soil tillage and weeding of the food crops, especially through improved water supply. Similar effects have been observed with rubber trees on a ferralitic soil in the same region (Kouadio et al., 1996) and with peach palm (*Bactris gasipaes*) on a Typic Paleudult in the Peruvian Amazon (Szott et al., 1991). These observations are, to some extent, parallel to results

from timber plantations established with the Taungya method (Kapp and Beer, 1995).

Intercrops for 'recapitalization' of soil fertility

On acid, nutrient-poor soils, a critical period in the development of a young tree crop plantation is often a few years after planting, when the declining soil fertility prevents annual cropping before the tree crops have attained their productive phase. Sousa et al. (1999) report that on central Amazonian Oxisols, young tree crops such as cupuaçu (*Theobroma grandiflorum*) are often planted into a cassava crop which is grown after slashing and burning the forest. Without fertilizing and liming, annual cropping has to be given up after about two years, and the land is then temporarily abandoned. The developing fallow vegetation is only cleared several years later when the tree crops start flowering. Such poor development conditions for the trees slow down their vegetative growth, delay the beginning of the production phase and reduce yields.

In order to avoid this temporary abandonment of the area, some external inputs (especially P fertilizer) are required, either to prolong the annual cropping or to establish a leguminous cover crop. Under suitable market conditions, such inputs can be financed with the products of semi-perennial species such as papaya (*Carica papaya*), passion fruit (*Passiflora edulis*) and banana, which can be associated with the young tree crops. On some soils, fertilizers that are applied to such demanding, high-value intercrops can 'recapitalize' soil fertility for several years after these crops have been removed from the plot. On a central Amazonian Oxisol, cupuaçu planted in association with papaya during the first three years gave earlier and greater yields than when planted in monoculture (Figure 1). This was partly because of the residual fertilizer in the interrows between the trees (Schroth et al., 2001a) and partly because of the improved development of the leguminous cover crop, which also profited from the increased fertility and effectively suppressed competitive grass weeds (G. Schroth, pers. observation). The relatively large mineral and organic fertilizer rates applied to papaya (see legend to Figure 1) are more realistic for intensive homegardening than
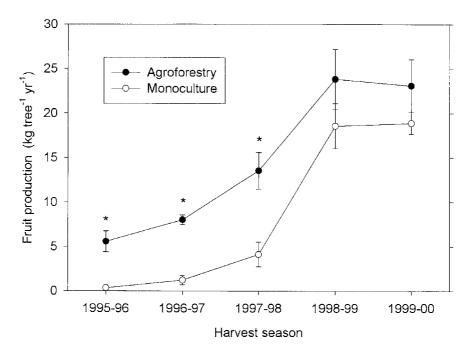
Figure 1. Annual yields of cupuaçu (*Theobroma grandiflorum*) in a multistrata agroforestry system and in monoculture on a central Amazonian Oxisol. In the agroforestry system, the cupuaçu was associated with peach palm (*Bactris gasipaes*) and rubber trees (*Hevea* sp.). Papaya (*Carica papaya*) was grown between the tree crops in the agroforestry plots from planting in 1993 until 1995 and was fertilized with 420 kg N, 93 kg P, 175 kg K, 1.5 t of dolomitic lime and 36 m³ of chicken manure ha⁻¹ (totals of three years). Asterisks indicate significant differences at $P < 0.05$.

for larger-scale agriculture. Thus, it may often be more efficient to establish tree crops in small, intensively managed plots, whose area is progressively increased, than in larger plots with more extensive management.

Permanent associations with food crops

Annual intercrops in young tree plantations can make an important contribution to food production in regions dominated by tree crop agriculture. In pioneer areas, where many new plantations are established, the food produced in this way can exceed the demand from plantation owners and local markets (de Rouw, 1987). On the other hand, in areas where the land is largely occupied by tree crops and few new plantations are established, food production can be limited by the availability of land for annual crops (Lawrence et al., 1998; Vaast, 1988). Modified planting designs for tree crops, which allow permanent intercropping with food crops, have been proposed to avoid this situation. These include cacao rows alternating with

strips of annual crops (Decazy et al., 1988) and oil palm planted at increased spacing so that the interspaces can be used for food crops during the rainy season (Daniel et al., 1996). The latter technique also increased tree survival during drought years. The problems of soil fertility maintenance under permanent annual cropping will not be discussed in this review (see Smyth and Cassel, 1995).

Effects of shade trees on soil fertility and crop yields

Tree legumes for shade and soil improvement

N_2-fixing legume trees are most commonly used as shade trees for coffee, cacao and tea (Beer et al., 1998). Some species provide useful products, e.g., fruits and firewood from *Inga* spp. Other species, such as *Gliricidia sepium* and *Erythrina* spp., are used mainly for their 'service functions', especially biological N_2-fixation, production of nutrient-rich litter and shade. According to Beer

(1988), the biological N_2-fixation of legume shade trees can reach about 60 kg N ha^{-1} yr^{-1}, which is a relevant amount in smallholder plantations with little or no N fertilization. On a Tropudalf in Brazil, total soil N was higher within about 4.5 m distance from *Erythrina glauca* and *E. poeppigiana* shade trees than under the surrounding cacao. Accordingly, the soil under unshaded cacao and under cacao shaded by non-leguminous trees had much lower total N than the soil under *Erythrina* shade (Santana and Cabala-Rosand, 1982). On a hydromorphic soil in the same region, significant yield increases of 10 to 19-year-old cacao with decreasing distance from the shade trees (8.4 to 2.5 m) could partly be explained by higher total C, N, and exchangeable bases in the soil close to the trees, although extractable P tended to be higher at greater distance. The cacao growing close to the shade trees also had more fine roots in the topsoil and a deeper root system than that growing at greater distance, probably because the shade trees locally improved subsoil aeration with their roots (Zevallos and Alvim, 1967).

Pronounced favorable effects of N_2-fixing trees on associated tree crops have also been observed when regenerating a degraded coconut plantation on a poor coastal sand in the Côte d'Ivoire (Zakra et al., 1996). After long-term coconut cropping in association with cassava, without use of fertilizers and with regular removal of harvest residues, the soil was degraded to an extent that herbaceous cover crops could not be established. When

replanting the site, *Acacia mangium* and *Acacia auriculiformis* were arranged in double-rows alternating with two palm rows. The *Acacia* trees were pruned every four years. Leaves and small branches were used as mulch and larger branches and trunks were exported from the system as firewood. When N-fertilization of the palms was discontinued in the fifth year, the association improved the N status and coconut production of the palms compared with the unfertilized control (Table 2). There were, however, concerns about K exports in the firewood. *Casuarina equisetifolia*, another N_2-fixing species, was less efficient than the two *Acacias* in improving coconut yields, although it was highly suitable as a windbreak to protect the sensitive legume trees from sea spray (de Taffin et al., 1991).

N_2-fixation by legume trees, and thus the potential for N transfer to the crops, is influenced by the management of the trees, especially by shoot pruning. The frequency and intensity of shoot pruning of shade trees are determined by microclimatic requirements of the crop, site fertility, pest and disease pressures, and management intensity (including fertilizer inputs) (Beer et al., 1998; Schroth et al., 2000a). Shoot pruning and mulching recycle tree biomass and reduce the immobilization of nutrients in the trees. Pruning also reduces tree transpiration and thereby competition with the crops for soil water. However, drastic pruning, with removal of the entire leaf biomass, that is practiced in some coffee-shade

Table 2. Effect of the N_2-fixing tree species *Casuarina equisetifolia*, *Acacia mangium* and *Acacia auriculiformis* on the production of associated coconut palms (*Cocos nucifera*) planted in 1986 on a degraded coastal sand in the Côte d'Ivoire.[a]

Year	Coconut monocrop; no N fertilizer[b]	Coconut monocrop; with N fertilizer[c]	Coconut + *C. equisetifolia*; no N fertilizer[b]	Coconut + *A. mangium*; no N fertilizer[b]	Coconut + *A. auriculiformis*; no N fertilizer[b]
			(nuts tree^{-1})		
1989–1990	4.7 ab	5.8 a	2.1 ab	3.4 ab	1.1 b
1990–1991	38.5 a	43.4 a	21.4 bc	23.6 b	13.1 c
1991–1992	54.5 b	91.5 a	63.0 a	67.3 a	70.3 a
1992–1993	16.7 b	53.8 a	48.9 a	52.4 a	49.7 a
1993–1994	21.9 c	52.3 b	56.6 b	71.3 a	76.8 a
Total (per ha)	3504	8368	6113	7700	8294

[a] From Zakra et al. (1996) and N. Zakra, personal communication. Values followed by the same letter in the same year are not significantly different at $P < 0.05$.
[b] In these treatments, the last N fertilization of the coconut palms was in 1990.
[c] In the treatment with N fertilizer, the coconut palms received 225 g N tree^{-1} year^{-1} (as urea) from 1991 to 1994.

tree systems, may cause nodule death and strongly reduce nodule activity, as has been observed for *E. poeppigiana* in Costa Rica (Nygren and Ramírez, 1995) and for *Leucaena diversifolia* in Burundi (Snoeck, 1995). More frequent partial pruning of the trees may be preferable to biannual complete pruning (Snoeck, 1995), although the labour requirements may also be higher (Muschler, 1999).

N_2-fixation by legume trees is most likely to constitute a relevant input to a cropping system when the site is poor in N and when N fertilization is low. At high N fertilization rates (e.g., up to 270 kg N ha^{-1} yr^{-1} for coffee in Costa Rica), N_2-fixation is insufficient to justify the selection of economically worthless leguminous shade tree species (Beer, 1988), especially as high nitrate levels in the soil typically inhibit biological N_2-fixation (Giller and Wilson, 1991). Under these conditions, legume shade trees may be selected mainly because of their ease of pruning and rapid regrowth. High biomass production, which helps to maintain adequate soil organic matter levels, may then be more important than N_2-fixation for the overall effect of shade trees on soil fertility (Beer, 1988).

Timber trees as shade

The legume shade trees in coffee and cacao plantations often do not have commercial products, although they require labour investments for establishment, pruning and mulch distribution. In many regions, coffee and cacao are traditionally grown under the shade of timber and fruit tree species, which are either retained when clearing the forest or specifically planted (especially fruit trees; see de Rouw, 1987, on cacao plantations in the Côte d'Ivoire). In Bahia, Brazil, the shade tree layer of traditional cacao plantations includes valuable timber species such as *Dalbergia nigra* and *Cedrela odorata* as relics of the Atlantic rainforest (Johns, 1999). Non-leguminous shade trees are also used in intensively managed plantations. Many Costa Rican coffee farmers have recently replaced N_2-fixing legume shade trees with fast-growing timber trees, especially *Eucalyptus deglupta*. Among the advantages of this species, farmers mentioned fast growth (leading to rapid establishment of the shade), relatively light shade,

reduced pruning requirements and (to a lesser extent) the additional value of the timber (Tavares et al., 1999).

As mentioned above, many Costa Rican coffee plantations receive high rates of N (and other) fertilizer, and negative effects of the substitution of legume by timber trees on the N balance of the system would not be expected. This argument does not hold in other coffee and cacao producing regions, where little or no fertilizer is applied (Beer, 1988). In contrast to regularly pruned legume trees, timber trees accumulate nutrients in their growing biomass and this accumulation tends to be highest for the economically attractive, fast-growing species. If these nutrients are not taken into consideration when determining fertilizer rates, or where no fertilizer is used, nutrient availability for the crops may be reduced (Beer, 1988).

Negative effects of timber trees on yields of associated tree crops have repeatedly been reported. Under conditions of moderate fertilizer inputs and little or no water limitation in Costa Rica, cocoa yields were 20% greater under *E. poeppigiana* than under *Cordia alliodora* shade during the first five years, but were similar during the second five-year period (Beer et al., 1990). The reason for the initial yield difference is not known, although cocoa yields seemed to be mainly limited by light at the end of the experiment (J. Beer, pers. comm.). In the aforementioned shade-and-fertilizer experiment in Ghana, Bonaparte (1967) measured significant yield decreases of six to seven-year-old cacao with decreasing distance from *T. ivorensis* shade trees (from 6.5 to 2.2 m), in contrast to the aforementioned yield *increases* of cacao in the proximity of leguminous shade trees (Zevallos and Alvim, 1967). Competition with the shade trees for soil K may have occurred, since cacao responded to K fertilization. However, Bonaparte (1967) suggested that competition for light rather than soil resources was the main reason for the observed yield depressions since yields were closely correlated with light incidence, the water supply was relatively abundant, and the yield gradient with increasing tree distance was not influenced by fertilization. It should be mentioned that this latter argument does not exclude the possibility of competition for nutrients (Schroth, 1999).

In regions with a pronounced dry season, com-

petition for water between shade trees and tree crops can become limiting. Soil water contents during the five months dry season in the Central Valley of Costa Rica were lower under coffee with *E. deglupta* shade than under coffee with *E. poeppigiana* shade or unshaded coffee, and the coffee associated with *E. deglupta* visibly suffered more from drought stress than in the other two treatments (Jiménez and Alfaro, 1999). Similarly, in the Abengourou region near the northern (dry) limit of the cacao-growing area of the Côte d'Ivoire, several planters reported that, during drought periods, their cacao suffered more under forest tree shade than without shade. This effect had been especially pronounced in 1983, a very dry year (G. Schroth, unpublished results of a farm survey 1992).

Competition between shade trees and crops can be reduced through tree spacing and pruning, although pruning may be difficult for large trees. If microclimatic protection by the trees is a goal, but strong above- and belowground interactions with the crops are to be avoided, shade trees can be planted on the plot boundary, in contour rows between plots, etc. (Schroth, 1999). For example, cacao has been planted in 'hollow square' plantings or 'box-plots' in association with timber trees or other tree crops in West Africa and Sabah (Egbe and Adenikinju, 1990; Lim, 1980), and tree planting in shelterbelts around coffee plots has been recommended for seasonally dry sites in East Africa (Foster and Wood, 1963).

Such arrangements may reduce, but not always eliminate negative root interactions. Murray (1975) noted that the use of mahogany trees (*Swietenia mahagoni*) as windbreaks for cacao in the West Indies led to root competition and reduced cocoa production, extending for two or three rows into the plantation. Such problems could possibly be reduced by controlling the lateral root development of the trees. Attempts to achieve this by planting grass strips with dense but laterally restricted root systems, similar to those used in erosion control, along tree rows, have given promising results for young timber trees in Costa Rica, although the effect on older trees requires further study (Schaller et al., 1999).

Through their litter, throughfall and stemflow, timber trees contribute to the cycling of organic matter and nutrients; e.g., five tons of leaf litter

ha^{-1} yr^{-1}, containing 79 kg N and 4.5 kg P, in a 'typical' cacao farm shaded by forest trees in West Africa (Murray, 1975) and 5.7 t ha^{-1} yr^{-1} of litter, containing 114 kg N, 7 kg P and 54 kg K, from *C. alliodora* shade trees in a Costa Rican coffee plantation (Beer, 1988). However, the return of organic material and nutrients from leguminous shade trees can be much higher: up to 20 t ha^{-1} yr^{-1} of biomass obtained from biannual pruning of *E. poeppigiana* shade trees (Beer, 1988). Accordingly, Beer et al. (1990) reported a more favorable effect of *E. poeppigiana* than of *C. alliodora* on the soil organic matter balance of shaded cacao plantations after 10 years.

In summary, fast-growing timber trees should not be associated with (tree) crops on sites where water and nutrient availability strongly limit crop growth, although they can be an option for diversifying the production of tree crop plantations in areas with sufficient rainfall and fertile soils, or with adequate fertilization. In order to reduce the risk of competitive effects on the crops, e.g., during drought years, specific planting arrangements which reduce interspecific interactions should be considered, especially for fast-growing, aggressive species.

Reduction of nutrient leaching

Nutrient leaching in tree-based land use systems

Nutrient leaching reduces the availability of nutrients to crops and trees. Nitrate leaching is also a major cause of soil acidification and may cause groundwater contamination. When soil moisture is above field capacity, leaching of soluble nutrients can occur wherever the sum of nutrients applied as fertilizer, released from litter and mobilized in the soil (especially N mineralization), temporarily or permanently exceeds the capacity of the vegetation to assimilate these nutrients. Nutrient leaching is particularly a problem on soils with high infiltration rates and low nutrient retention, such as sandy soils and well-structured ferralitic soils with low-activity clays (von Uexküll, 1986).

Nutrient leaching is not restricted to systems with annual crops, but also occurs in tree crop-based systems. Under a fertilized coffee plantation in Kenya, accumulations of 2200 kg nitrate-N ha^{-1}

have been found at 1 to 5 m soil depth (Michori, 1993, cit. in Buresh and Tian, 1998). Nitrate accumulations in the subsoil have also been reported from different tree crop plantations on central Amazonian Oxisols (Schroth et al., 2000b; Schroth et al., 1999a).

The factors which influence nutrient leaching from tree crop-based systems in the tropics have rarely been studied in detail. Babbar and Zak (1995) reported lower N leaching rates from shaded than from unshaded coffee cultivation in Costa Rica (9 *vs.* 24 kg ha^{-1} yr^{-1}), a difference caused by higher nitrate concentrations in the soil solution of the unshaded plantation. However, the plantations differed also in the density and pruning regime of the coffee plants, and the data are therefore difficult to interpret. Imbach et al. (1989) measured lower concentrations of K, Ca, and Mg in the percolating soil water at 1 m depth in a cacao plantation with *C. alliodora* instead of *E. poeppigiana* shade trees on a Humitropept in Costa Rica; a finding possibly due to the aforementioned nutrient accumulation in the timber trees *vs.* a high level of nutrient recycling through *Erythrina* prunings. Although the authors stressed that there were no technical or economic problems to the replacement with fertilizers of the relatively small nutrient losses, their finding illustrates the possible influence of individual tree components and their management on the efficiency of nutrient cycling in multistrata systems.

Stabilizing nutrient uptake over time

Other factors which affect nutrient leaching from cropping systems have been identified in a comparison of a multistrata system of cacao, banana and *C. alliodora* with an annual cropping system of maize (*Zea mays*) on a Typic Dystropept in Costa Rica (Seyfried and Rao, 1991). The multistrata system had lower nutrient concentrations in the soil solution at 90 cm depth and lower nutrient leaching than the annual crop (Table 3), despite approximately similar nutrient inputs to the soil from fertilizer (higher under maize) and litterfall (higher under tree crops). The superior efficiency of the multistrata system in retaining nutrients was attributed to the perennial root systems, the continuous nutrient uptake, the presence of a litter layer where nutrients could be adsorbed or microbially immobilized, and the lower percolation due to the continuous presence of a transpiring canopy. A higher soil organic matter content and consequently cation exchange capacity in perennial systems should possibly be added to this list.

These system properties indicate how tree crop-based systems should be designed to reduce leaching losses. The most crucial point may not be that multistrata systems with various tree species have denser root systems than monocultures, as the root systems of annual and perennial monocultures can also be quite dense (Ewel et al., 1982). More important may be the fact that, at any given time, at least some of the plants in the system should be actively growing and taking up

Table 3. Water balance and nutrient leaching in a maize (*Zea mays*) monocrop and a multistrata agroforestry system with cacao (*Theobroma cacao*), plantain (*Musa* sp.) and *Cordia alliodora* on a Typic Dystropept in Costa Rica.[a]

	Maize field[b]	Multistrata system[c]
Total rainfall (cm yr^{-1})	111	111
Actual evapotranspiration (cm yr^{-1})	45	55
Deep percolation (cm yr^{-1})	66	57
Leaching losses (kg ha^{-1} yr^{-1}):		
N	57	1
K	3	1
Ca	43	3
Mg	21	3

[a] From Seyfried and Rao (1991).
[b] Fertilized with 240, 55 and 40 kg ha^{-1} yr^{-1} of N, P and K, respectively.
[c] Fertilized with 140, 30 and 20 kg ha^{-1} yr^{-1} of N, P and K, respectively.

nutrients, thereby reducing the nutrient concentration in the soil solution, and should have a transpiring canopy, thereby reducing water percolation. This situation is probably more difficult to achieve in a monoculture plantation than in an association of several tree species that differ in their phenology, growth rhythms and response to changing weather conditions (Ewel, 1986). Modest competition between species, leading to increased nutrient uptake of one species when that of competitors is reduced, could help to stabilize nutrient uptake over time and could then be an advantage (see Doak et al., 1998). Although contrasting root dynamics of associated cacao and shade trees have been demonstrated (Muñoz and Beer, 2001), there seem to be no data in the literature to test the hypothesis of more continuous nutrient uptake in systems composed of several tree species than in tree crop monocultures. However, the question deserves studying.

In many multistrata systems, including the one studied by Seyfried and Rao (1991), a large percentage of the nutrients entering the soil is derived from organic sources, such as tree litter and prunings, rather than from mineral fertilizer, and this can help to stabilize the nutrient supply over time and further reduce nutrient losses (Lehmann et al., 1999). Snoeck (1995) applied ^{15}N-enriched urea or biomass from *L. leucocephala* or *Desmodium intortum* to coffee plants on an Oxisol in Burundi and measured the distribution of the N in undecomposed biomass, coffee plants and soil after one year (Table 4). The percentage of the applied N that was taken up by the coffee was much smaller for the biomass than for the fertilizer, which partly may have been due to the different amounts applied. However, whereas almost half of the urea-N was lost from the system, presumably by gaseous losses and leaching below 30 cm, most of the N released from biomass was still encountered in the topsoil, with only a minor fraction missing.

Optimizing spatial patterns of nutrient uptake

Another possible way to reduce nutrient leaching in tree crop-based systems is by making optimum use of the *spatial* patterns of nutrient availability in the soil. The aforementioned studies treated the investigated multistrata systems essentially as homogeneous entities with respect to the quantity and nutrient load of the percolating soil solution. However, nutrient leaching from a system can occur at spots with a temporary or permanent nutrient surplus, even if the same nutrients are in short supply at some other spot within the system. In this situation, spatial averaging may suggest an equilibrium between supply and demand which in reality does not exist. Some degree of spatial heterogeneity of water and nutrient availability in the soil, and thus of nutrient leaching, is inevitable in any agricultural system, but especially so in tree crop-based systems because of the wider plant spacing compared with annual crops and the often localized fertilizer application. In agroforestry systems composed of several different tree and crop species, spatial patterns of nutrient cycling also arise from differences between species with respect to growth, fertilizer rates, pruning intensities, litter quantity and quality, root distribution, water requirements, and effects on soil physical properties such as macroporosity.

The effect of spatial patterns of nutrient availability and uptake on nutrient leaching is illus-

Table 4. Distribution of ^{15}N labelled nitrogen one year after application to coffee (*Coffea arabica*) plants, as urea or biomass of *Leucaena leucocephala* or *Desmodium intortum*, on an Oxisol in Burundi.[a]

N source	N applied	N remaining in biomass	N taken up by coffee (g)	N in soil (0–30 cm)	N lost from system
L. leucocephala	34.4[b]	5.9 (17%)	2.1 (6%)	25.6 (74%)	0.8 (2%)
D. intortum	20.5[c]	2.4 (12%)	1.2 (6%)	16.4 (80%)	0.5 (2%)
Urea	9.2	0 (0%)	2.1 (23%)	2.9 (31%)	4.2 (46%)

[a] From Snoeck (1995).
[b] As 1225 g biomass with 2.81% N.
[c] As 682 g biomass with 3.01% N.

trated by the distribution of nitrate in a central Amazonian Oxisol under a 14-year-old oil palm monoculture (Figure 2). The mineral N in the soil was incompletely utilized by the system, as evidenced by the nitrate accumulation in the subsoil likely resulting from nitrate leaching between the palms, although the nitrate concentration in the soil under the palms was close to the detection limit. This nitrate was mainly derived from the mineralization of soil organic matter, as the plots had never been fertilized with N (Schroth et al., 2000b). It seems likely that associating the palms either with a shade-tolerant understorey crop or small-crowned trees would have increased N-uptake from the soil in the interspaces, reduced N leaching, and increased the productivity of the plot without any additional N inputs (although probably at the price of additional inputs of other nutrients such as P). Non-competitive species would have to be used, as oil palm is sensitive to both shading and competition for water (Jacquemard, 1995).

Spatial patterns of nitrate accumulation in the subsoil have also been found under four tree crop species (cupuaçu – *T. grandiflorum*, peach palm – *B. gasipaes*, Brazil nut – *Bertholletia excelsa* and annatto – *Bixa orellana*) and a leguminous cover crop (*P. phaseoloides*) in a multistrata system on a central Amazonian Oxisol (Schroth et al., 1999a). Despite modest rates of N fertilization, nitrate had accumulated in the subsoil under all species. However, significantly more nitrate was found under the cover crop, which received no N fertilizer, than under all tree species except cupuaçu. The inefficient N use in the system could be explained by analyzing the spatial patterns of N mineralization and N uptake by the trees. Figure 3 shows N mineralization rates in the topsoil of a slightly different multistrata system at the same site. The N mineralization rates were high in all positions of the system; however, approximately twice as much N was mineralized under the cover crop than under cupuaçu and peach palm, under which the soil was kept free of vegetation. Under the rubber trees, where the soil was covered by *P. phaseoloides*, intermediate N mineralization rates were found. Tracer studies indicated that cupuaçu and peach palm took up little N from the soil under the cover crop, presumably because of the generally high N availability in the soil (Lehmann et al., 2000a). These data suggest that N leaching could be reduced by omitting N fertilization of the trees to increase their demand for mineral N under the cover crop, and planting semi-perennial crops in the spaces between the trees for as long as possible to make use of surplus mineral N in the
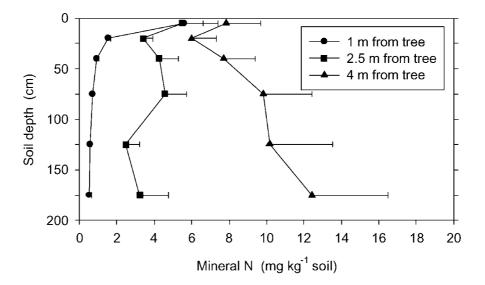

Figure 2. Distribution of mineral N in a central Amazonian Oxisol under a 14-year-old oil palm plantation (*Elaeis guineensis*) at three tree distances. The palms were planted at 9 by 9 m triangular spacing. The soil was covered by spontaneous vegetation after the leguminous cover crop had been shaded out. The plots had never been fertilized with N (from Schroth et al., 2000b).
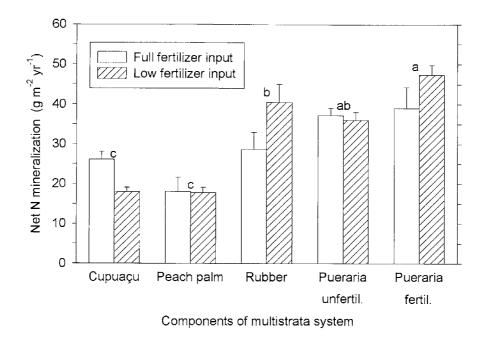
Figure 3. Net soil N mineralization (0–10 cm) during one year under three tree crops and a cover crop in a multistrata agroforestry system (age five years) at two fertilization levels on a central Amazonian Oxisol. '*Pueraria* fertilized' had a more fertile soil than '*Pueraria* unfertilized' due to a previous papaya intercrop (see legend to Figure 1). The letters above the column pairs indicate significant differences between sampling positions (from Schroth et al., 2001a).

soil (Schroth et al., 1999a). At sites with lower N availability in the soil, the cover crop could be allowed to grow right to the stem of the tree crops to increase N mineralization in their rooting zone, although the effort of protecting small trees from this climbing legume would also increase. These measures could increase plot yields while economizing N fertilizer (although, again, other nutrients would have to be applied to additional crops).

The spatial distribution of fertilizers (e.g., localized or broadcast) may influence the uptake of fertilizer nutrients by tree crops, but may also have secondary effects on tree root distribution, and therefore on the spatial uptake patterns of water and other nutrients from the soil. Fertilizers are commonly applied on a weeded circle around the stem of tree crops to maximize benefits and reduce competition from weeds or cover crops. Over the years this practice can lead to steep fertility gradients with increasing distance from the stem. In the oil palm plantation of Figure 2, the available P concentration (Mehlich 3) between 0 and 10 cm soil depth decreased from 165 mg kg^{-1} at 1 m from the stem, where the fertilizer had always

been applied, to 4 mg kg^{-1} at 2.5 m from the stem. Over the same distance, exchangeable acidity increased from 27 to 84% of the effective cation exchange capacity. These steep gradients were probably a reason for limited lateral root development of the palms and therefore inefficient exploration of the soil. A gradual increase of the fertilized area during the early years of the plantation would have presumably increased lateral root spread of the palms and thus the utilization of nitrate and water from the soil between the trees, thereby reducing nutrient leaching (Schroth et al., 2000b).

The application of soluble fertilizer too close to the stem of certain tree species is also inappropriate because of increased water infiltration, and thus leaching risk, in this zone. In the aforementioned multistrata system in Amazonia, average water input into the soil per unit area in throughfall and stemflow in the proximity of peach palms and Brazil nut trees was, respectively, 152% and 145% of rainfall, due to the high stemflow of these species (Schroth et al., 1999b). High stemflow is a common feature of palms (Lloyd and Marques,

1988) which are components of many homegardens and other multistrata systems.

The analysis of spatial patterns of water and nutrient availability in the soil thus provides insights into the effects of individual plant species, their spatial arrangement and management on nutrient cycling within a system, and thereby shows where nutrients are used inefficiently and are in risk of being leached. Based on such information, fertilizer can be economized or distributed more efficiently, additional crops added or the spacing of the existing crops adjusted to achieve better exploration of the soil volume without creating severe competition. The objective would be a system where modest belowground competition between species guarantees efficient uptake of water and nutrients over the whole plot area and thus little nutrient leaching. Severe root competition, which depresses crop yields and may cause the death of tree crops, obviously has to be avoided. In strongly seasonal climates, this may be achieved by including annual crop species that are harvested before the onset of the dry season, thereby avoiding competition with the trees for water (Daniel et al., 1996).

Nutrient recycling from the subsoil

It is a common (though poorly quantified) agroforestry hypothesis that, in annual cropping systems, nutrient recycling from the subsoil can be increased by the integration of deep-rooting trees. If the subsoil contains substantial amounts of nutrients (such as leached nitrate), is sufficiently moist to allow nutrient transport and uptake, and the trees have sufficient amounts of fine roots in the respective depths, nutrient uptake from the subsoil is likely to occur (van Noordwijk et al., 1996). In systems with tree crops, the integration of deep-rooting trees may however not always be an advantage. Depending on crop species, climate and soil conditions, the crops may have sufficiently deep roots themselves. Rooting depths of 4.5 m or more have been reported for Arabica coffee (Webster and Wilson, 1980) and 5 to 6 m for tea (Willey, 1975). In the latter study, the tea bushes wilted later and seemed to be deeper-rooted than the associated shade trees. In other cases, however, there is a clear potential for deep-rooted trees to take up nutrients from the subsoil under tree crops, as has been shown above.

Deep nutrient capture by trees increases total nutrient availability in the system. However, an important difference between fallow systems and tree-crop associations is that, in the latter, the nutrients in the tree biomass do not necessarily become available to the crops. Nutrients are released from trees into the soil through prunings, litter and dying roots, or are leached from the crown by throughfall and stemflow (Schroth et al., 2001b). However, the trees compensate these losses through nutrient uptake from the soil to produce new leaves and roots. Therefore, the integration of deep-rooting trees into a system only increases the nutrient availability in the topsoil if the quantity of nutrients taken up from below the crop rooting zone is greater than the quantity stored in the tree biomass (and in undecomposed tree litter) (Willey, 1975). This is most likely to occur in soils with high subsoil fertility (which are rare in the tropics) or if the crops compete efficiently with the trees for nutrients in the topsoil. Competitive crops may force the trees to take up a large part of their nutrients from the subsoil and may then scavenge these nutrients from the decomposing tree litter.

A favorable effect of deep nutrient uptake is most likely to occur in the case of leguminous 'service trees', whose nutrient-rich leaf and branch biomass is regularly returned to the soil as prunings, and the net nutrient accumulation in the trees is small. For timber and fruit trees, which are not regularly pruned, low competitiveness is particularly important. If these trees are more competitive in the topsoil than the (tree) crops, their integration into a cropping system will reduce rather than increase nutrient availability, even if the trees are deep-rooting. Additional fertilizer may then be necessary to prevent yield depressions.

Even if deep-rooting trees do *not* increase nutrient availability for associated crops, their integration into a system can nevertheless be useful, because by increasing the total rooting volume of the association, the total nutrient uptake by the system can increase. In this case, the advantage of deep nutrient capture comes from additional tree products (e.g., wood, fruits) and effects not related to nutrient cycling (e.g., improved

microclimate or lowering of shallow water tables). Management measures for increasing the rooting depth of trees have been discussed elsewhere (Schroth, 1999).

Conclusions

Land use systems based on tree crops, such as multistrata agroforestry systems, have clear advantages over annual cropping systems for the maintenance of soil fertility in the humid tropics. These include permanent soil protection, a more favorable environment for soil biological processes which affect litter decomposition and soil structural improvement, and more efficient nutrient cycling. However, soil degradation under such systems has repeatedly been observed. Well-designed, medium- to long-term, process-oriented soil fertility studies are necessary to enable us to define more clearly the conditions for the sustainability and productivity of tree crop-based land use systems in the humid tropics.

Soil fertility maintenance in multistrata (and other land use) systems depends on both socioeconomic and biophysical factors. During the establishment and early development of tree crops, an important socioeconomic objective is to reduce or avoid the 'lag phase', during which the plantation requires inputs but does not provide outputs. This can be achieved through appropriate associations of trees with annual and semiperennial intercrops, which can be replaced after a few years by leguminous cover crops. Under suitable market conditions, the returns from such intercrops can be used to finance an initial 'recapitalization' of soil fertility through fertilizer inputs, from which the tree crops may profit for several years. During later years, the diversification of the output through association of different species for domestic use and commercialization, including valuable timber trees, is an important objective. Such measures can increase the access to external nutrient sources and thereby help to equilibrate the nutrient balance of the system.

On the biophysical side, there are a number of measures which could help to maintain and improve soil fertility under tree crop-based systems in the humid tropics, although the effects of few of them have been quantified. N_2-fixing legumes have been shown to improve the N status of the soil, as well as N nutrition and yields of associated tree crops on N deficient sites and under conditions of low N fertilization. On sites with sufficient availability of water and nutrients, legume trees can often be complemented or replaced by timber trees, although this will often require additional fertilizer inputs and specific planting designs to avoid competition with the crops, especially during drought years. The reduction of nutrient leaching and recycling of subsoil nutrients by deep-rooting trees can improve the availability of nutrients in the system and reduce negative environmental impacts. However, information about the spatial and temporal patterns of water and nutrient availability is required to design effective measures; e.g., optimal spacing of the trees, inclusion of additional crop species, altered management of a cover crop, or reduced quantities and altered distribution of fertilizer. Such measures can be combined to create a limited amount of competition between the plants in a system, which is necessary to achieve optimum use of soil resources in both space and time.

Measures which help to equilibrate the nutrient balance of a system will not necessarily avoid problems of soil organic matter loss and soil structural degradation. The latter can be addressed through measures such as permanent soil cover, a low degree of mechanization, stimulation of plant root development, and the production of large quantities of litter and prunings, which help to maintain a high level of soil microbial and faunal activity. In many cases, the negative effects of certain tree crops on the soil can probably be reduced or avoided by associating them with trees and cover crops with a more favorable effect (Vohland and Schroth, 1999).

The conduction of soil research in multistrata agroforestry systems poses methodological difficulties, which are partly related to the spatial and temporal complexity and heterogeneity of these systems. A synthesis of two complementary approaches seems promising: the comparison of complex multistrata systems with simpler annual and perennial cropping systems on the 'whole-plot' level; and the analysis of 'within-plot', spatio-temporal patterns of soil fertility and nutrient cycling in complex associations, similar to the analysis of single-tree effects in forest and

savanna ecology (Kellman, 1979; Zinke, 1962). The first approach is necessary for evaluating the total economic and environmental costs and benefits of a certain system type, but the results are very specific to the systems studied and give little information on how their characteristics would be affected if one crop species or management measure was exchanged for another, or how the systems could be improved with respect to a certain characteristic. The second approach ('single-tree effects') provides insights into the effects of certain plant species or management measures on plant-soil processes within tree crop-based land use systems. Species and management practices can then be identified to manipulate the systems' properties into a certain direction; e.g., towards more efficient nutrient cycling or soil carbon enrichment in order to improve productivity and sustainability. The results may sometimes be more difficult to scale up than those from the first approach, but they are easier to transform into practical recommendations.

Thematically, the following questions deserve particular attention:

1. How can multistrata systems be established most efficiently under conditions of infertile soils, especially when limited availability of markets and credits makes access to fertilizers difficult?
2. How can crop and tree species be arranged and managed for maximum complementarity of resource use in space and time, especially in seasonal climates and under conditions of periodic drought?
3. How can soil biological processes, such as soil organic matter build-up and the improvement and stabilization of soil structure by roots, fauna and microflora, be optimized in tree-based land use systems?

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