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AGROFORESTRY SYSTEMS IN LOWLAND TROPICS: IS PHOSPHORUS IMPORTANT?

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INTRODUCTION

Agroforestry is often recommended as the preferred agricultural system for the humid tropics. Reasons given generally pertain to the role of trees in maintaining soil fertility by recycling nutrients via litterfall and prunings, thereby mimicing the natural forest ecosystem. In addition, trees have deeper rooting systems and can tap and recycle a source of nutrients initially unavailable to most annual food crops. There is however, little data to support or refute such claims.

The high productivity of tropical forest ecosystems on infertile soils is attributed to efficient nutrient cycling with relatively small nutrient losses. Nutrient cycling processes and pathways in agroforestry systems are similar to those of natural forest ecosystems. There are, however, important differences in the relative sizes or fluxes, of certain nutrient cycling pathways between the two types of systems and even among different agroforestry systems. The major flux difference between natural forest ecosystems and agroforestry systems is that of nutrient losses. Whereas nutrient losses via leaching, erosion, and gaseous emissions are probably similar for the two systems agroforestry systems have an additional loss pathway through product harvest that does not exist in natural systems. These differences will result in different nutrient budgets that will determine the productivity and sustainability of various agroforestry systems.

Most nutrient cycling research in agroforestry to date has dealt with nitrogen cycles and budgets. The use of nitrogen-fixing, leguminous trees in most agroforestry systems provides a source of N that can partially, or in some cases completely offset the loss of N through crop or product exports. Little attention has been given to the cycles and budgets of other nutrients. Whereas trees can recycle these other nutrients they cannot provide a new input of these nutrients to the system as they can for N. It therefore becomes crucial to understand the nutrient cycling processes and budgets of these nutrients in agroforestry systems in order to ascertain the necessary management practice for continued productivity of the system. Among these other nutrients, P is particularly important considering the extent of P fixing soils in the tropics and the large proportion of P extracted by plants that is exported in crop harvest (Sanchez et al., this volume).

The objectives of this paper are to look at P cycling and budgets and soil P changes in several different agroforestry systems, to evaluate the long term consequences of agroforestry systems on P availability, and to consider the role of trees in the P cycle of agroforestry systems. Much of the data referred to comes from research conducted in Yurimaguas, Peru by the Tropical Soils Research Program of North Carolina State University

(Caudle and McCants, 1987; Caudle, 1989). The soils are acid (pH 4.5), infertile Ultisols with relatively low P-fixing capacity. The remainder of the data comes from research on a variety of tropical soils of varying fertility and P-fixing capacities.

Phosphorus cycling and budgets, and soil phosphorus in various agroforestry systems

Agroforestry systems vary considerably in the amount of P cycled in litterfall or prunings and the amount of P exported in products on a yearly basis. These differences have important consequences to long-term productivity and sustainability. Several types of agroforestry systems will be compared that differ in the intensity of management and subsequent nutrient export.

Shifting Cultivation and Improved Fallows. Shifting cultivation, the traditional farming system of the tropics, could be considered the original simplest, and least intensive agroforestry system (Raintree, 1987). It is a temporal agroforestry system in that crops are grown for a year or two and replaced by trees as the natural fallow vegetation regrows. In this system, as with all agroforestry systems, nutrient losses occur with forest clearing and burning and during the establishment phase. Further P losses via crop harvest are generally small, less than 10 kg ha^{-1} over a two year period (Sanchez et al., this volume). These losses are partially recuperated during a 10 to 15 fallow phase from atmospheric P inputs of 0.1-1 kg ha^{-1} yr^{-1}. One of the purposes of the fallow is to restore soil fertility by accumulating nutrients in the vegetative biomass. This process represents a transfer of nutrients from the soil to the vegetation and should not be considered a net addition to the system. The nutrients stored in the biomass become a source of ash fertilizer when the vegetation is cut and burned.

Improved or managed fallows are different from natural fallows of shifting cultivation in that specific trees, shrubs, or cover crops are intentionally planted following crop abandonment rather than allowing the natural vegetation to recover. Improved fallows are similar to shifting cultivation in that recycling of nutrients by the vegetation is maximized and nutrient exports are generally low. One of the purposes of improved fallows is to restore nutrient stocks in the vegetation more rapidly than natural fallows. By accumulating nutrients more rapidly, improved fallows should provide for higher production by allowing more frequent cropping. More frequent cropping, however, also has implications to long-term productivity.

A study in Yuirimaguas comparing a natural fallow (BF) to six leguminous fallow treatments, *Centrosema macrocarpum* (Cm), *Stylosanthes guinanensis* (Sg), *Pueraria phaseloides* (Pp), *Cajanus cajan* (Cc), *Desmodium ovalifolium* (Do), and *Inga edulis* (Ie) showed that the fallows stored P from a low of 15 kg ha^{-1} (sg) to a high of 35 kg ha^{-1} (Do) during the first 29 months (Figure 1; Szott, 1987). Only the *Desmodium* and *Inga* treatments stored more P than the natural fallow. Those two treatments also had the highest total and tree biomass (Table 1). The improved fallows without trees, *Stylosanthes* and *Pueraria*, stored less P and less biomass than the natural fallow in 29 months. The remaining two treatments were similar to the natural fallow.

Table 1. Above-ground biomass in six managed fallows and a natural fallow at 29 months (Szott, 1987)

Fallow treatment	Biomass ($Mg\ ha^{-1}$)
Centrosema macrocarpum	9.8
Stylosanthes guianensis	8.6
Pueraria phaseoloides	7.7
Cajanius cajan	12.4
Desmodium ovalifolium	21.9
Inga edulis	24.3
Natural fallow	16.4

Available soil P averaged 15 kg ha^{-1} and did not differ among the treatments at 29 months. There was however, a decline of about 10 kg in available P during the 29 months in all treatments (Figure 1). This decline was obviously due to the transfer of P from the soil to the vegetation. It is interesting to note that there was an overall increase in the sum of the P in the vegetation and that available in the soil (Figure 1). This increase indicates a transfer of P from some of the unavailable forms in the soil to more available forms. In fact, as much as 20 kg ha^{-1} would have to come from this unavailable soil P to satisfy the amount of P found in the vegetation of some of the treatments. The differences in the P stored in the various fallows may in part reflect differences in the P uptake kinetics of different species and/or their ability to tap more unavailable forms of soil P.

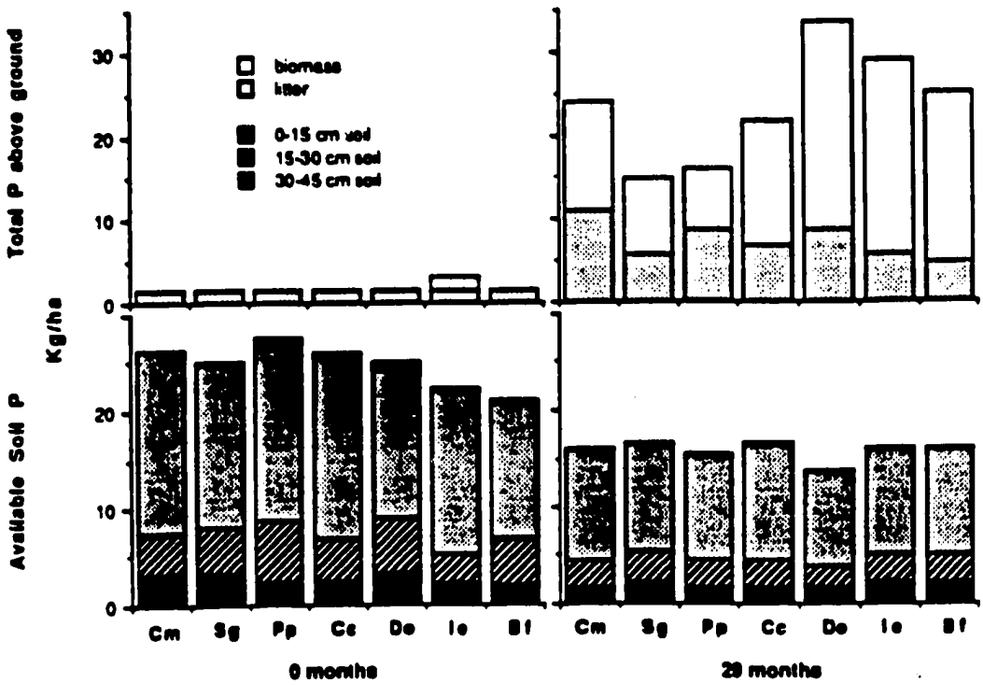

Figure 1. Changes in total P stored in the biomass and in available P in six improved and a natural fallow in 29 months (Szott, 1987).

It appears that certain improved fallows have the potential to store P in the vegetation more quickly than the natural fallow but this depends on the biomass accumulation capacity of the specific vegetation and therefore probably on the presence of trees. The ability of the various fallow species to take up soil P may also be crucial. The relevance of these differences in rates of P accumulation to improved crop yields and shorter crop-fallow cycles is currently under investigation.

The fact that fallow vegetation draws on total soil P and that P is exported in crops has implications to the sustainability of these systems. In the case cited above, the fallow vegetation drew down the total soil P by 10 kg ha^{-1}, or less than 5% of the original soil P. The question arises as to how many crop-fallow cycles are possible if P is not added to the system. Perhaps some of the P stored in the vegetation becomes available upon burning but some of it may also be fixed in the soil and become unavailable again. Understanding the P transfers between soil and vegetation and the transformations in the soil during fallow recovery, clearing, and cropping will aid in the management of these systems.

Alley cropping. Alley cropping is an agroforestry system in which arable crops are grown in the alleys between hedgerows of trees or shrubs. The hedgerow trees, preferably legumes, are periodically pruned to prevent shading and to supply mulch to the crop. Alley cropping is similar to fallow systems in that part of the land is planted to trees and is permanently in fallow. The purpose of the trees is to provide nutrients for the arable crop by fixing nitrogen, recycling nutrients, and extracting nutrients from the subsoil. Alley cropping is more intensive than shifting cultivation or improved fallows because two or three crops are grown per year, and total annual nutrient exports in crops are higher.

The extent to which trees actually provide nutrients for the crops grown in the alleys has not been studied in sufficient detail. Data from alley cropping experiments on both Alfisols (Kang and Wilson, 1987) and Ultisols (Szott, 1987) indicates that tree prunings may provide sufficient nitrogen, potassium, and calcium to meet crop demands, while P demands are not met (Table 2). The data are often confounded because P, calcium, and potassium fertilizers are added to the crops because nitrogen has been the nutrient of interest. The data in Table 2 stress that P will be the primary limiting nutrient. Prunings of *Leucaena leucocephala* and *Inga edulis* do not contain enough P to produce one corn or rice crop. Again, the soil P reserves are being drawn down to produce the crops and there is a net loss of P from the system. The productivity of alley cropping systems will decrease much faster than shifting cultivation because of more frequent cropping.

Decreases in extractable soil P were also found in an alley cropping system on an Alfisol after four years of maize production with *Leucaena leucocephala* as the hedgerow species (Kang et al., 1981). These decreases were found even with annual additions of 20 kg ha^{-1} of P. Similar decreases were found after 32 months of alley cropping on an unfertilized Ultisol with *Inga edulis* and *Cajanus cajan* as the hedgerow species (Szott, 1987).

Phosphorus is obviously the nutrient of most concern to the success of continuous crop production in alley cropping systems. Research in many areas is necessary to improve this situation. Selection and management of trees with higher leaf biomass production and higher P concentrations in

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the leaves may help by providing more P in prunings. Phosphorus availability from the prunings may also depend on the quality of the leaf material and the resultant decomposition and mineralization processes. Pruning additions may actually increase P availability by converting more recalcitrant inorganic forms of soil P taken up by the trees to organic forms supplied in the prunings. Some trees may have deeper rooting systems and be less competitive for nutrients with arable crops than trees with shallow, spreading root systems. Any improvement in the efficiency of P cycling in alley cropping systems will help maintain crop production over the short term but it is obvious from simple input-output budgets that additional inputs of P will be necessary for long term production.

Table 2. Nutrients added in prunings and removed in crop harvest in two alley cropping systems in Nigeria.(Adapted from Kang and Wilson, 1987; Sanchez, 1976) and Peru (Adapted from Szott 1987; Sanchez 1976).

	Biomass	N	P	K	Ca	Mg
	Mg ha^{-1} per crop	kg ha^{-1} per crop				
Ibadan, Nigeria (Alfisol)						
Leucaena prunings	3.0	98	8	74	40	6
Corn*						
Grain	3.0	75	18	45	9	6
Straw	4.5	45	9	54	13.5	9
Yurimaguas, Peru (Ultisols)						
Inga edulis prunings	2.5	62	5	24	15	4
Rice**						
Grain	1.5	35	7	10	1.4	0.3
Straw	1.5	7	1	18	2.6	2.2

*Fertilized with 20 kg P, 20 kg K each crop
**No fertilizer

Tree-Crop Production Systems. Perennial tree crop production systems range from monoculture tree crops such as oil palm and rubber plantations to multispecies, multistrata systems such as coffee plantations with interplantings of *Erythrina*, for shade and prunings, and *Cordia alliodora*, for timber. Tree crop systems are perhaps the most successful and well known agroforestry systems. They also depend on trees for recycling and extracting nutrients from the subsoil. When compared to shifting cultivation systems they are more intensively managed and have much larger, annual nutrient exports in the form of product harvests. Phosphorus removal by harvest can be as high as 25 kg ha^{-1} yr^{-1} as for oil palm plantations to a low of around 4 kg ha^{-1} yr^{-1} for rubber plantations (Table 3). To maintain crop production in these systems, P must clearly be added.

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Table 3. Phosphorus removed in crop harvests from various tree crop plantation systems (Turner and Gillbanks, 1974)

Crop	Yield	P
		kg ha^{-1} yr^{-1}
Oil Palm	25 t fruit bunches	11.0
Coconut	2400 kg copra	6.8
Cocoa	1125 kg dried beans	5.0
Coffee	1125 kg made coffee	7.3
Tea	1350 kg dried tea leaves	4.5
Rubber	1928 kg dry rubber	3.8

One explanation for the continued production in agroforestry systems is that nutrient cycling via litterfall provides enough P to balance exports. An example is shown for a cacao plantation in Costa Rica in which 4 kg P ha^{-1} yr^{-1} are extracted from the system in cacao fruits but litterfall adds as much as 14 kg ha^{-1} yr^{-1} to the soil surface (Table 4, Heuveldop et al., 1988). It is necessary to keep in mind that P additions to the soil surface from litterfall are only an internal transfer of P between the soil and vegetation pools in the system, not a new source. As with alley cropping or any other agroforestry system, trees may extract P from recalcitrant pools or from the subsoil and make it available for annual crops or other trees via decomposition of litterfall. Crop and litterfall production should be expected to decrease with time if external sources of P are not added. In fact, P fertilizers were added to these plantations at an annual rate of 29 kg ha^{-1} (Fassbender et al., 1988). Crop and leaf production were maintained by an external input of P; the system was not self-sustaining.

Table 4. Phosphorus removed in fruit harvest and P in litterfall in cacao plantations under *Cordia alliodora* or *Erythrina poeppigiana* (Heuveldop et al., 1988)

Turrialba, Costa Rica (Dystropept)	
Nutrient extractions in cacao fruits	kg P ha^{-1} yr^{-1}
T. cacao/*C. alliodora*	4.0
T. cacao/*E. poeppigiana*	4.3
Nutrients in litterfall	
T. cacao/*C. alliodora*	13.9
T. cacao/*E. peoppigiana*	8.8

*29.3 kg $ha^{-1}yr^{-1}$ phosphate application

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Data from a low-input based (no fertilizer additions) multistrata system in Yurimaguas shows again the high level of P extraction in product harvest (Table 5). Crops were interplanted with the trees of *Inga edulis*, *Bactris gasepaes*, and *Cedrelinga caeteniformis* during the first two years. After the second year, the trees shaded out the crops and a shade-tolerant cover crop, *Centrosema macrocarpum*, was planted. In the fourth year, the *Inga edulis* trees were pruned for fuelwood. A total of 26 kg ha^{-1} of P was removed from the system in 4 years compared to much smaller additions from atmospheric inputs. Despite the high rates of P extraction from the system and no additions of P fertilizer, the trees continue to grow rapidly (Alegre et al., 1989) at soil P levels below that for crop production. Once again recalcitrant forms of soil P are probably being used by the trees.

Table 5. Phosphorus extracted from a low-input, multistrata tree production system during the first four years of establishment (Alegre, Szott, and Palm unpublished data)

Product harvested	Year	Yield t ha^{-1}	P kg ha^{-1}
Rice	1	1.7	8
Rice	1	1.2	6
Cowpea	1	0.9	4
Rice	2	0.6	3
Fuelwood	4	13.0	5
		TOTAL	**26**

Summary and Research Imperatives

In conclusion, the large amount of P extracted in product harvest coupled with the low P availability of most acid tropical soils makes P an important and potentially limiting nutrient in most agroforestry systems. Many agroforestry systems remain productive only because of large annual inputs of P fertilizers, but some agroforestry systems remain productive even without P fertilizers, indicating that trees play a special role in P cycling, transformations, and availability.

These observations raise two important questions relevant to all agroforestry systems: How long can tree-based systems maintain production without external inputs of nutrients, particularly P? And, what are the processes and mechanisms by which trees can maintain high rates of growth and production under conditions of extremely low available soil P?

Several questions address these research imperatives: 1) What are the relative extraction rates and uptake kinetics of P by trees at different depths in the soil as compared to annual crops? 2) What are the sources or pools of soil P tapped by trees and what are the mechanisms? And, 3) What are the P transformations in the soil as a result of litterfall and decomposition and how does that affect P availability?

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