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AGROFORESTRY IN ACID SOILS OF THE HUMID TROPICS

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I. INTRODUCTION

The majority of the soils in the humid tropics are acid and infertile. Oxisols and Ultisols comprise two thirds, and Psamments and Spodosols together account for another 7% of the humid tropical land mass (Table I). On a continental basis, Oxisols and Ultisols are most prevalent in tropical South America and are present to a lesser extent in Africa and Asia.

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Table I

Distribution of Acid Soils in the Humid Tropics[a]

	Humid tropical America		Humid tropical Africa		Humid tropical Asia and Pacific		Total humid tropics	
Soil order	(10^6 ha)	%	(10^6 ha)	%	(10^6 ha)	%	(10^6 ha)	%
Oxisols	332	50	179	40	14	4	525	35
Ultisols	213	32	69	16	131	35	413	28
Psamments	6	1	67	15	17	4	90	6
Spodosols	10	2	3	1	6	2	19	1

[a] From Sanchez (1989).

Constraints to plant production on these soils are primarily low nutrient availability and aluminum toxicity (Table II).

It has been suggested that agroforestry systems are the most appropriate forms of sustainable, productive management of soils in the humid tropics because perennial woody vegetation can recycle nutrients, maintain soil organic matter, and protect the soil from surface erosion and runoff (Nair, 1984). Data supporting this contention, however, are scarce (Sanchez, 1979, 1987). Moreover, those systems most often cited as examples of successful agroforestry are found in areas dominated by base-rich naturally fertile soils such as Alfisols and Andosols. These systems include the homegardens of Asia and Africa (Michon *et al.*, 1986; Fernandes *et al.*, 1984), coffee and cacao production systems in Latin America (Russo and Budowski, 1986), and alley cropping (Kang *et al.*, 1990).

Table II

Extent of Major Soil Constraints in the Humid Tropics[a]

Soil constraint	10^6 ha	% of humid tropics
Low nutrient reserves	980	66
Al toxicity	850	57
High P fixation	565	38
Acid, but not Al toxic	270	18
High erodibility	255	17
Poor drainage	195	13
Low CEC	165	11

[a] From Sanchez (1989).

A. THE KNOWLEDGE GAP

Notwithstanding the importance of such favored systems on fertile soils, agroforestry is considered especially applicable to marginal soils of the tropics. However, it remains to be determined whether the three main functions of agroforestry (nutrient recycling, soil organic matter maintenance, and protection from erosion and runoff) can be attained in acid soils. If so, agroforestry may represent a major alternative to slash-and-burn agriculture. In their recent review on alley cropping Kang *et al.* (1990) cited the urgent need to evaluate agroforestry systems in humid tropical areas dominated by acidic soils with high levels of extractable aluminum and low fertility.

This article summarizes 6 years of agroforestry research conducted primarily at the Yurimaguas Research Station in the Amazon Basin of Peru. The project was initiated in 1982 with diagnosis of the factors limiting agricultural productivity and how these might be overcome with the use of agroforestry techniques. It is conducted jointly by Peru's Instituto Nacional de Investigación Agropecuaria y Agroindustrial, the International Council for Research in Agroforestry, and North Carolina State University (Torres *et al.*, 1983). Research is supported by the U.S. Agency for International Development and Canada's International Development and Research Centre.

B. DIAGNOSIS OF THE YURIMAGUAS REGION

Yurimaguas is located in the lowland rainforest zone of the Amazon basin of Peru (76° 05′ W longitude, 5° 45′ S latitude, 182 m above sea level). Climatic conditions and soil constraints are fairly typical of much of the western half of the basin. Annual rainfall averages 2,200 mm with precipitation exceeding evapotranspiration 9 months of the year, and monthly temperature averages 26°C with little variation. Upland soils under these conditions are highly weathered and consist primarily of fine-loamy, siliceous, isohyperthermic Typic Paleudults with pH values between 4.2 and 4.7, aluminum saturation values of 60–80%, low cation-exchange capacity, and low reserves of nitrogen, phosphorus, and exchangeable nutrient cations (Tyler *et al.*, 1978).

Shifting cultivation is the predominant farming system in the region and is characterized by the extensive use of land and the intensive use of labor. The majority of farm holdings are less than 20 ha, of which 1 to 2 ha are in production at any time with the remainder in secondary forest fallow. Rice or corn are grown for cash and are usually followed by subsistence plantings of cassava and plantain before fields are allowed to revert to fallows. Grain yields are usually on the order of 2 t/ha or less. Fallow periods generally range from 5 to 15 years in duration, but due to land use pressure periods of approximately 5 years are most common (Bidegaray and Rhoades, 1987).

Land clearing, planting, and harvesting are seasonally regulated by rainfall patterns, creating a peak demand for labor that is felt simultaneously by most farmers in the region. As a result, labor shortages currently constrain overall productivity by preventing farmers from clearing and tending larger areas. Moreover, the lack of savings and credit, or cash-generating off-farm employment opportunities prevents farmers from hiring additional labor to overcome these shortages (Torres *et al.*, 1983). Given the current high rates of migration to the region and restricted availability and access to land, decreasing soil fertility due to shortened fallow periods also constrains productivity.

Three agroforestry systems were identified by the study team as possibilities to overcome these constraints to production: (1) alley cropping systems; (2) managed leguminous fallows to accelerate the restoration of soil fertility and reduce the duration of the fallow period; and (3) fruit tree-annual crop sequential cropping systems.

These technologies represent a range of agroforestry options, the suitability of which will vary with the relative availabilities of land, labor, and capital (Raintree, 1987). For example, alley cropping may contribute to the maintenance of soil fertility under annual cropping by improved nutrient cycling, but the system's total labor and possibly capital requirements are likely to be greater than those with shifting cultivation. Hence, the system seems appropriate for situations of limited land availability. In contrast, managed fallows might reduce the duration of the fallow period and improve productivity per unit time by accelerating weed suppression and nutrient accumulation in the fallow biomass. This system requires relatively small quantities of labor and capital, but like most fallow-based systems, it requires moderate to high land availability. Finally, cultivation of fruit trees can help alleviate labor and capital constraints by spreading labor over periods of low demand and by providing additional income through the sale of fruits and other products. In this case, labor and capital requirements are low to moderate, but the requirement for land availability is moderate to high.

This project may be the first systematic research effort on agroforestry options for strongly acid soils of the humid tropics. Unlike most other locations where agroforestry is being conducted, the fundamental challenge is how to recycle nutrients in soil–plant systems that have limited quantities of them.

II. ALLEY CROPPING

Research on alley cropping, or hedgerow intercropping, at Yurimaguas has concentrated on (1) identifying species potentially adapted to acid, infertile soil conditions, (2) measuring their pruning and nutrient yields, (3) characterizing rates of decomposition and nutrient mineralization from prunings, and (4) quantifying the effects of pruning additions on soil chemical properties, weed biomass, and crop yields.

A. GERMPLASM SELECTION

The need for selecting woody legume species tolerant to acid soil conditions became evident during an initial evaluation of native and exotic species. Species widely used in Africa, *Leucaena leucocephala* and its more acid-tolerant relative, *Leucaena diversifolia,* failed to develop adequately probably due to aluminum toxicity. *Cajanus cajan,* a species that appears to be aluminum tolerant also was eliminated due to its limited life-span. Two Amazonian species, *Inga edulis* and *Erythrina* sp., showed excellent biomass production and coppicing ability, while two other acid-tolerant legumes (*Desmodium gyroides* and *Cedrelinga cataeniformis*) did not (Szott *et al.,* 1987a). A subsequent trial of one year duration identified several additional promising species: *Cassia reticulata, Inga felulei,* and to a lesser extent, *Calliandra calothyrsus, Samanea saman,* and *Gliricidia sepium* (Salazar and Palm, 1987; Salazar *et al.,* 1989) (Table III). Many Amazonian as well as exotic species failed due to susceptibility to leaf-cutter ant attacks. For those species with high survival and coppicing ability, biomass production was comparable to levels reported for other species at more fertile sites (Kang *et al.,* 1981, 1984, 1985, 1990; Yamoah *et al.,* 1986a; Duguma *et al.,* 1988).

Under actual alley cropping, pruning yields of the most promising species encountered to date (*Inga edulis, Cassia reticulata, Gliricidia sepium,* and *Erythrina* sp.), have ranged from 2 to 5 kg/m hedgerow, equivalent to 5–12.5 t/ha/yr at a 4-m interhedge spacing with 3 to 4 prunings per year (Szott, 1987; A. Salazar, unpublished data). These biomass yields, as well as the nutrient concentrations of the prunings (Table IV), compare well with those reported for other species from more fertile sites (Kang *et al.,* 1981, 1984, 1985; Kass, 1985; Yamoah *et al.,* 1986a,b; Duguma *et al.,* 1988).

Pruning production by *Inga edulis* and *Erythrina* sp. did not respond to one application of 2.5 tons lime/ha (Szott, 1987), and *Cassia reticulata* and

Table III

Survival, Growth Rate, and Pruning Yields of Various Leguminous Tree Species during the First Year after Planting on an Ultisol[a]

Tree species	Type[b]	Survival (%)	Growth rate (cm/mo)	Pruning yield (kg/m/yr)
Cassia reticulata	N	100	40.9	3.54
Inga felulei	N	100	30.9	4.12
Calliandra calothyrsus	E	80	23.0	1.42
Samanea saman	N	100	20.3	1.90
Gliricidia sepium	N	85	15.9	2.70
Cassia sp.	N	100	12.4	—
Schizolobium amazonicum	N	70	10.3	—
Pithecellobium dulce	N	100	9.5	—
Acacia auriculiformis	E	70	7.6	—
Flemingia congesta	E	0	6.0	—
Albizia procera	E	0	2.3	—

[a] From Salazar and Palm (1987).
[b] N, native; E, exotic.

Gliricidia sepium showed little response to low rates (11–25 kg/ha) of applied phosphorus (A. Salazar and C. A. Palm, unpublished data). The similarity in biomass and nutrient accumulation ability between these acid-tolerant species in Ultisols and *Leucaena leucocephala* in Alfisols is striking and suggests that the former are well adapted to extremely acid soil conditions.

Table IV

Average Tissue Nutrient Concentration of Four Periodically Pruned Tree Species Used in Hedgerow Intercropping Systems on Ultisols[a]

	Tissue nutrient concentrations (%)									
	Leaf					Branch				
Species	N	P	K	Ca	Mg	N	P	K	Ca	Mg
Cassia reticulata	3.9	0.35	1.6	1.1	0.29	0.8	0.13	1.3	0.8	0.12
Gliricidia sepium	3.4	0.24	1.7	1.0	0.41	0.9	0.20	1.3	0.6	0.12
Erythrina sp.	3.3	0.24	1.7	0.8	0.33	1.4	0.20	0.9	0.4	0.20
Inga edulis	3.1	0.20	0.9	0.7	0.19	1.2	0.15	1.1	0.4	0.10

[a] Sources: Szott (1987), Palm (1988), and A. Salazar (unpublished data).

It should be noted that the native species included in these trials were not systematically selected. Improved performance of woody perennials can be expected with proper provenance selection. For example, provenances of *Gliricidia sepium* presently being evaluated show large differences in growth and biomass production. Provenance 14/84 (Oxford Forestry Institute International *Gliricidia sepium* Provenance Trial) from Retahuleu, Guatemala appears to be better adapted to acid soil conditions at Yurimaguas than other provenances in the study (Fernandes, 1990). Provenance selection and improvement are areas of agroforestry research deserving more attention since relatively simple techniques, easily applied under developing country conditions, can result in large improvements in tree performance.

B. NUTRIENT CONTENT

Prunings of *Inga, Erythrina, Cassia,* and *Gliricidia,* at levels of production noted above, are potentially capable of supplying most of the macronutrients required for moderate production levels of upland rice. Quantities of some nutrients supplied in prunings (Table V) compare favorably with the amounts required for an average upland rice grain yield of 2 t/ha (Table VI). Comparing Tables V and VI, nutrients accumulated in prunings exceed requirements for calcium (20 vs. 5 kg Ca/ha) and magnesium (6 vs. 3.4 kg Mg/ha), but not those of the other major elements. Quantities of nitrogen in prunings exceed plant growth demand by a narrow margin (66 vs. 55 kg N/ha); potassium accumulation is slightly inferior (33 vs. 37 kg

Table V

Average Quantities of Nutrients Contained in Prunings of Four Leguminous Tree Species Used in Hedgerow Intercropping Systems[a]

	Nutrient contents per pruning (kg/ha)[b]				
Tree species	N	P	K	Ca	Mg
Cassia reticulata	72	7	37	25	6
Gliricidia sepium	64	5	37	22	8
Erythrina sp.	67	6	36	16	7
Inga edulis	62	5	24	15	4
Mean	66	6	33	20	6

[a] Sources: Szott (1987), Palm (1988), and A. Salazar (unpublished data).

[b] Values given are for average dry matter yield of 2.5 t/ha per pruning, and one pruning per crop.

Table VI

Nutrient Uptake of an Upland Rice Crop[a,b]

	Nutrient (kg/ha)				
Plant part	N	P	K	Ca	Mg
Grain	46	9	13	2	0.4
Straw	9	1	24	3	3.0
Total	55	10	37	5	3.4

[a] Calculated from Sanchez (1975).

[b] Crop yield was 2 t/ha grain and 2 t/ha straw.

K/ha), but only 60 percent of phosphorus needs are balanced by prunings additions (6 vs. 10 kg P/ha). Therefore, based on nutrient budgets, the recycling potential of these alley cropping systems is clearly inadequate for phosphorus and potassium and marginal for nitrogen, even for upland rice, which has low nutrient requirements. These balances would be even less favorable if more nutrient-demanding crops like maize are used or if higher levels of yield are expected. As an example, in higher fertility Alfisols, the phosphorus content of *Leucaena leucocephala* prunings (Kang and Wilson, 1987) is inadequate for one crop of maize.

C. NUTRIENT RELEASE FROM PRUNINGS

The previous calculations assume complete nutrient transfer efficiency from prunings to crop. Nutrient transfer efficiencies from pruned material have yet to be determined at Yurimaguas. Such transfers depend on the synchrony between nutrient mineralization from the pruned material and the timing of plant nutrient demand. Mineralization rates vary with the particular nutrient and the quality of the prunings (Swift *et al.*, 1981). Mulch or litter quality is a term used for the comparative rate of decomposition of plant residue (Anderson and Swift, 1983; Swift *et al.*, 1979). High quality is associated with rapid decomposition and nutrient release. However, high-quality material may not always be desirable because nutrient release may exceed plant nutrient demands resulting in asynchrony between supply and demands (Swift, 1987), as found with green manures incorporated in maize systems in Oxisols of the Cerrado of Brazil (Bowen, 1988).

Leguminous materials are generally high in nitrogen and have low carbon : nitrogen ratios. Hence, it is frequently assumed that decomposition of these materials will rapidly release large quantities of nitrogen. This assumption forms part of the rationale for including leguminous perennials in alley cropping systems, since it is expected that rapid mineralization of nitrogen from prunings will result in increased nitrogen availability to the associated crops. In laboratory incubations and field studies, Palm and Sanchez (1991) found that legume leaves with high contents of soluble polyphenols (*Inga edulis* and *Cajanus cajan*) decomposed and mineralized nitrogen less rapidly than those with low polyphenol contents (*Erythrina* sp.) (Fig. 1). Hence, although most leguminous material has low carbon : nitrogen ratios, it should not be expected that all material will serve as a readily available source of nitrogen. The polyphenolic : nitrogen ratio of leguminous materials may serve as a useful index of mulch quality (Palm and Sanchez, 1990; Fig. 2).

The relationship of mineralization of other nutrients to legume quality was generally similar to that of nitrogen (Palm and Sanchez, 1990). In general, mineralization of phosphorus, potassium, calcium, and magnesium is faster from high-quality *Erythrina* leaves than from those of low-quality *Inga edulis* or *Cajanus cajan* leaves. *Erythrina* leaves mineralized approximately 40% of their initial phosphorus and calcium contents and 75% of their magnesium and potassium contents within 4 weeks; all elements were reduced to 25% or less of initial levels by 20 weeks. With leaves of *Cajanus cajan* and *Inga edulis*, however, there was little net mineralization of phosphorus, calcium, and magnesium during the first 8–12 weeks. At 32 weeks, phosphorus was reduced to approximately 40%,

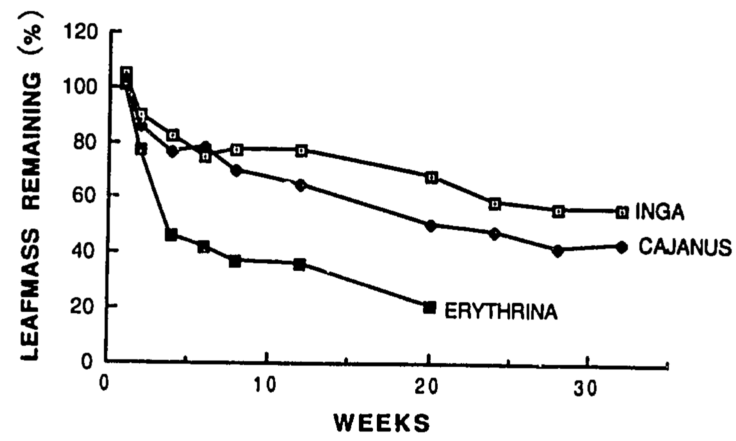

Fig. 1. Decomposition of the leaflets of three leguminous species at Yurimaguas. (Source: Palm and Sanchez, 1991.)

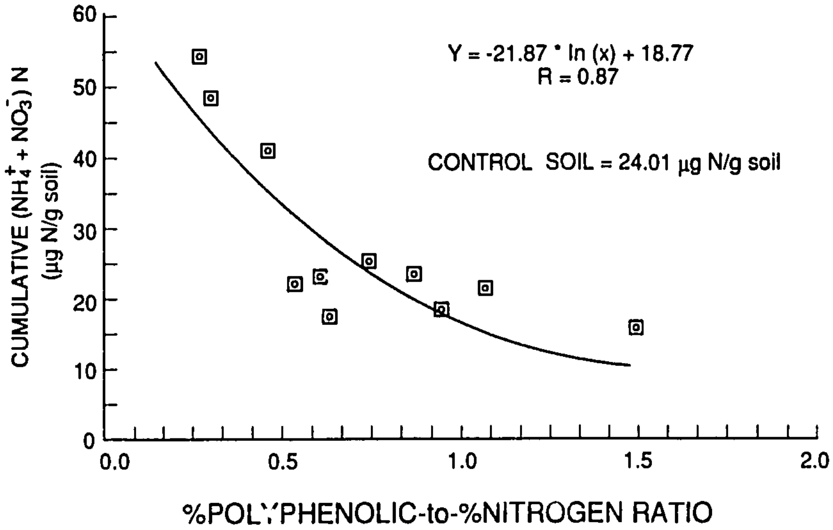

Fig. 2. Nitrogen release patterns from the leaves of leguminous trees as related to their polyphenolic–nitrogen ratio at Yurimaguas. (Source: Palm and Sanchez, 1990.)

and calcium and magnesium to 50–80% of their initial contents. By 32 weeks the percentage of initial potassium remaining in the material was 10% for both species.

D. WEED SUPPRESSION

Weed suppression by prunings is related to mulch quality. Slowly decomposing mulches such as *Inga* suppressed weeds more effectively than mulches that decomposed more rapidly (Table VII). Weed suppression by prunings, however, is also modified by factors such as previous history of the field, weather during the cropping period, and crop competitiveness.

E. SOIL PROPERTIES

It is often hypothesized that additions of prunings in the alley cropping systems should increase levels of exchangeable nutrient cations, organic carbon, and total nitrogen compared to soil without pruning additions (sole cropped). This has not proven true. In both alley-cropped and sole-crop systems, neither of which received inorganic inputs, exchangeable nutrient cations declined to similar levels with time (Fig. 3). Possible reasons

Table VII

Weed Biomass in Alley-Cropped Upland Rice Systems in Relation to Quantity and Type of Prunings Applied[a]

Alley crop species	Prunings applied (t/ha)	Weed biomass (kg/ha)
None	0.0	535
Inga edulis (low quality)	3.3	287
	6.7	10
Erythrina (high quality)	3.3	531
	6.7	575

[a] From Palm (1988).

for this are: (1) the quantity of prunings, hence nutrients, applied to the hedgerow intercropped plots (Table V) were too low to produce differences in soil nutrient levels; (2) the nutrients applied in the prunings were retained in organic or inorganic forms that are not detectable by the routine analytical techniques used (Hunter, 1974); and (3) the nutrients were removed by crop harvest or otherwise lost. Lime and fertilizer applications in other control plots did increase topsoil base status and available phosphorus simply because the amounts added were in excess of the amounts likely to be removed. Soil acidity, however, increased with time, as measured by pH decreases and increases in exchangeable aluminum, suggesting a strong acidification effect of fertilization.

F. CROP YIELDS

There are two main questions related to crop yields obtained with alley cropping compared to those from sole-cropped systems: (1) within a given cropping period, are yields greater in the alley cropping systems?; and (2) are yields in the alley cropping systems more sustainable over time? Tables VIII and IX provide some relevant data. Crop yields shown in Table VIII were measured in mulched areas of plots lying outside the competitive influence of the hedges. Rice crop residues were also removed, hence the yields show only the effect of mulch applications. The results show that rice yields from plots receiving high quality *Erythrina* mulch were always superior to those of the check plot, and that after the first crop, a similar situation occurred with the low quality *Inga* mulch. In both cases there was a yield response to mulch that was similar to that

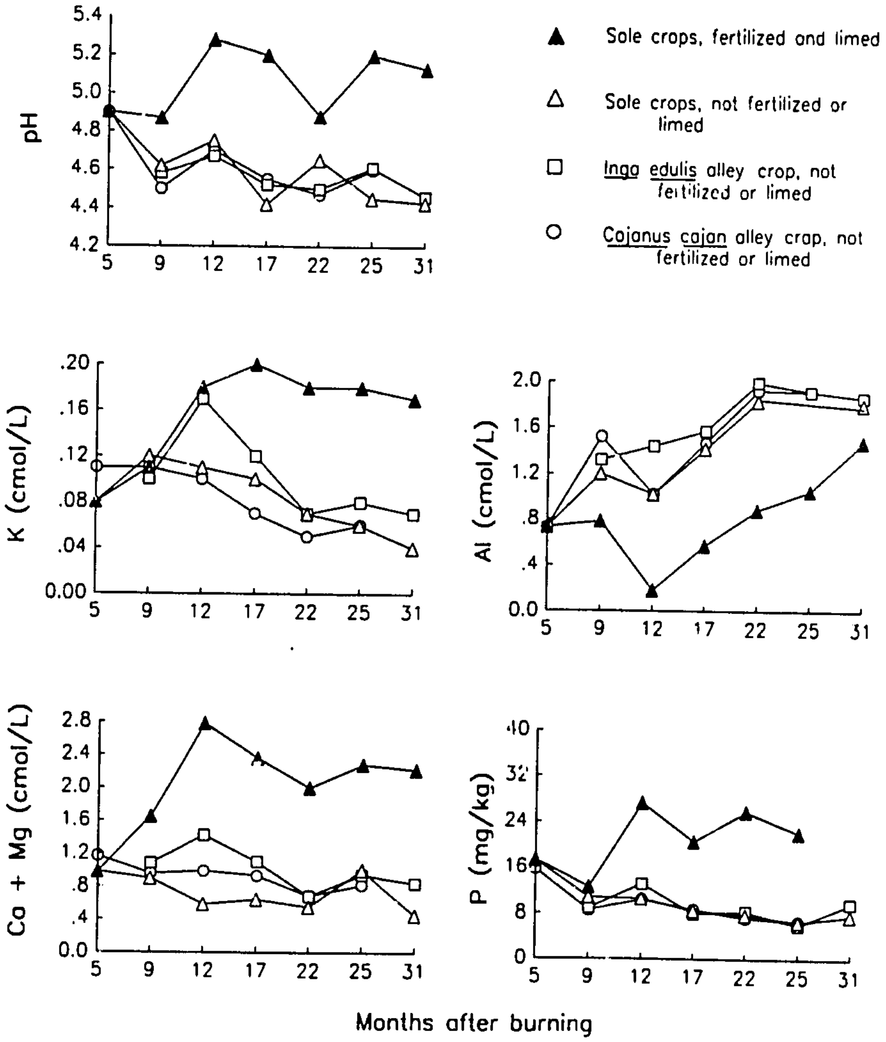

Fig. 3. Changes in soil chemical properties (0–15 cm) in systems alley cropped with *Inga edulis, Cajanus cajan*, or cropped without trees. One of the treeless controls received lime and fertilizer, the other did not. (Source: Szott, 1987.)

obtained with inorganic nitrogen fertilization. Without organic or inorganic inputs however, rice yields decreased with time. This decline was less pronounced if mulch or fertilizer nitrogen was applied.

A different study in which crops were not isolated from the effects of hedges of *Inga edulis* presents a different picture (Table IX). For a given crop, yields in the alley cropping systems were less than or similar to those from the nonfertilized, treeless control. Yields generally increased with

Table VIII

Upland Rice Grain Yield for Four Crops[a,b]

Input applied	Pruning rate per crop (t/ha)	Rice grain yields per crop (kg/ha)			
		1	2	3	4
Inga edulis (low quality)	6.7	1,306	2,235	1,103	930
Erythrina sp. (high quality)	6.7	2,748	1,718	1,197	1,303
Fertilizer (100 kg N/ha per crop)	—	1,844	2,104	1,159	1,173
Not mulched or fertilized	0	1,921	690	187	541

[a] From Palm (1988).

[b] Yield as affected by two mulch sources, in comparison with nitrogen fertilization and a check plot during a period of 20 months. There were no hedgerows present; therefore there was no competition from leguminous shrubs.

Table IX

Relative Grain Yields by Distance from the Hedge in an *Inga edulis* System on an Ultisol[a]

Distance from the hedge (m)	Relative grain yield (%)[b,c]				
	Cowpea	Rice	Rice	Cowpea	Rice
0.75	40	27	48	64	69
1.25	49	59	54	73	120
1.75	54	44	55	74	129
2.25	55	43	79	76	113
Check yield (kg/ha)[d]	1,064	488	306	527	382

[a] From Szott (1987).

[b] Data include both mulch and hedge effects.

[c] In each crop, the yield from plots without hedges, prunings, or fertilizers was used to calculate % relative yield. In the hedgerow intercropped plots, the distance between hedges was 4.5 m.

[d] No hedges or prunings.

distance from the hedges and crop yields in all systems declined with time, despite crop residue return and hedgerow intercropping.

We hypothesize that the crucial difference between the two studies was the competition between the hedges and the crop plants. Patterns of tree and rice root distribution in relation to distance from the hedges suggest that belowground competition for water and nutrients reduce crop yields near the hedges. Approximately 30% of the root mass on an *Inga edulis* hedgerow was in the upper 20 cm of soil and 85% was within 1.75 m of the hedgerow (L. T. Szott and R. J. Scholes, unpublished). Cannell (1983) suggested that frequent aboveground pruning of hedges reduces belowground competition with crops because root growth is checked as the hedges adjust their root : shoot ratio. We have observed that fine root mortality of *Inga* hedges increases after pruning, but coarse roots remain viable and give rise to new fine roots within a few weeks (Fernandes, 1990).

G. CONCLUSIONS

Although it is possible to find woody species that grow and coppice well in acid soils, and whose prunings can benefit associated annual crops, these benefits are much reduced due to competition with the hedges. Further work on the belowground interactions between the hedgerows and crops is needed. This work should include relatively simple studies quantifying root distribution and more dynamic measures of water and nutrient uptake by the different plant components in these systems. Measurements of the effects of various management techniques for reducing belowground competition, such as the frequency and height of aboveground pruning of the hedges, root pruning of the hedges, tillage, and arrangement of hedgerows to minimize the hedgerow–crop interface, are critical; also needed is research on management techniques to reduce the labor inputs required in alley cropping.

To date, much of the work on alley cropping has been in the context of continuous cropping. The emerging picture, is that such a system is not sustainable on acid, infertile soils without additions of chemical fertilizers, chiefly due to the native infertility of the soil and the insufficient recycling of nutrients from prunings. We suggest that current concepts of alley cropping on acid, infertile soils emphasize its use in situations where it is clearly beneficial (e.g., in areas where land availability is severely limited or for erosion control terrace formation on slopes) and/or as a "head start" to fallow regrowth in improved shifting agriculture systems. At this point, our results do not show sufficient evidence to recommend alley cropping for continuous cropping on acid soils of the humid tropics.

III. MANAGED FALLOWS

Farmers practicing shifting cultivation most often abandon their fields due to the increasing difficulty of weed control and/or declining soil fertility. Use of managed fallows that suppress weeds and restore soil fertility more rapidly than natural secondary vegetation would allow farmers to increase the crop : fallow ratio and productivity per unit time.

These concepts were examined during 4.5 years of managed leguminous fallow growth in an abandoned shifting cultivation field (Szott, 1987; Szott *et al.*, 1987b; Palm and Szott, 1989). The managed fallows included the following acid-tolerant leguminous species: *Centrosema macrocarpum*, *Stylosanthes guianensis*, and *Pueraria phaseoloides* (all stoloniferous plants); *Cajanus cajan* and *Desmodium ovalifolium* (shrubs); and *Inga edulis* (a tree). All were planted in monospecific stands and were allowed to grow unmanaged. Aboveground biomass accumulation by weeds and other vegetation and changes in aboveground and belowground nutrient stocks under these treatments were compared to those of a natural secondary forest fallow. A summary of the results based on the previously cited reports follows.

A. Weed Suppression

Some managed fallows proved more effective than the natural fallow in weed suppression. Within 8–17 months after fallow planting, weed biomass was reduced to less than 1 t/ha in the fallows with stoloniferous legumes compared to 3 t/ha in the natural forest fallow (Fig. 4). Viable weed seeds in the topsoil were also significantly lower in these fallows compared to others (Fig. 5). Such rapid reductions in weed biomass were related to the establishment of a dense, uniform, and extensive vegetation canopy by the stoloniferous fallows.

Over longer periods of time, patterns of weed suppression varied among managed fallows. After 1.5 years of fallow growth, weed biomass in the *Pueraria* and *Centrosema* treatments remained at low levels due to the continued presence of the planted fallow species. Except for *Stylosanthes*, weed biomass also declined in the other treatments, and was related to biomass accumulation and, presumably, shading by trees. By 4.5 years after fallow planting, weed biomass was low in all treatments except the *Stylosanthes* treatment, which had little legume aboveground biomass or cover.

In summary, weed suppression was achieved in 3.5–4.5 years in most

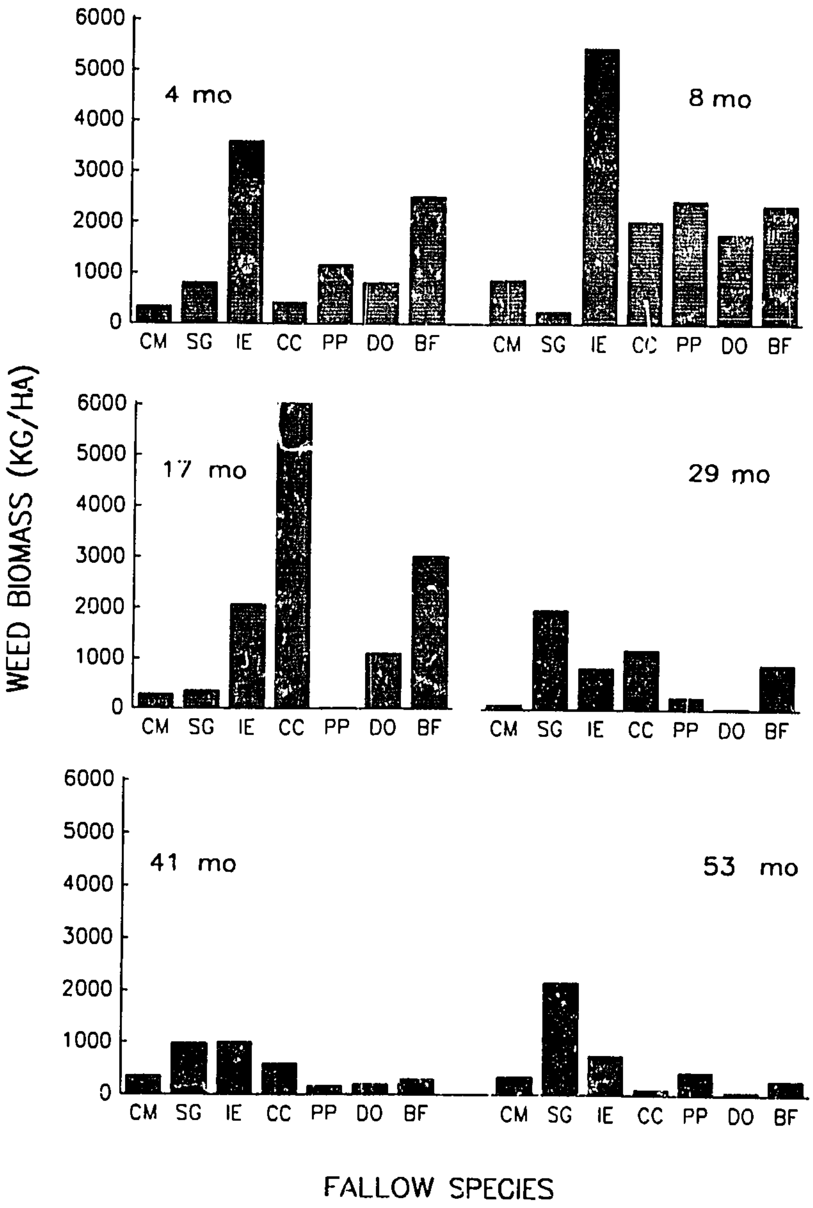

Fig. 4. Changes in weed biomass with time after planting of different managed fallow treatments. Weed biomass includes grasses, sedges, and broad-leaved herbaceous plants. Fallow treatments are: *Centrosema macrocarpum* (CM), *Stylosanthes guianensis* (SG), *Inga edulis* (IE), *Cajanus cajan* (CC), *Pueraria phaseoloides* (PP), *Desmodium ovalifolium* (DO), and natural secondary vegetation (BF).

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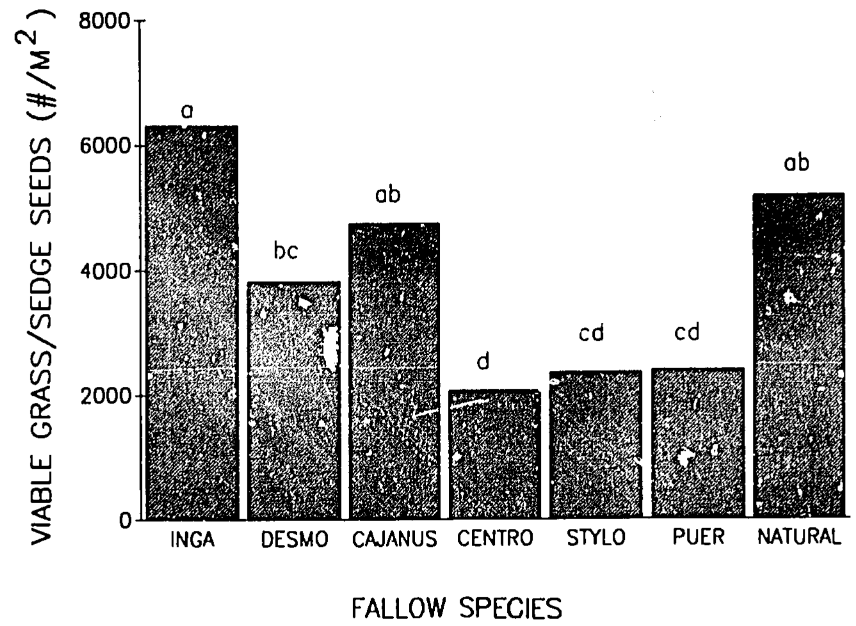

Fig. 5. Number of viable weed seeds found in the top 5 cm of soil in the fallow treatments 33 months after fallow planting. Treatments with different lower case letters are significantly different ($p < .05$).

fallow treatments, including the natural fallow, but was achieved earlier by some of the stoloniferous species: *Pueraria*, *Centrosema*, and *Desmodium*. The use of such fallows should be considered in situations where problems of weed control is a main cause of field abandonment.

B. Biomass and Nutrient Stocks

Biomass and nutrient stocks in aboveground vegetation, litter, and soil to a 45-cm depth were measured at varying intervals during 4.5 years following fallow planting. Legume and total aboveground biomass increased in all treatments during the first 2 years (Fig. 6). After 2.5 years, legume biomass declined in all treatments, but total aboveground biomass decreased only in the *Centrosema* and *Pueraria* treatments. Increases in total biomass were primarily due to increases in tree biomass; tree invasion was suppressed by the stoloniferous *Centrosema* and *Pueraria* and delayed by *Stylosanthes*, a bush-type legume.

During the first 2.5–3.5 years of fallow growth, aboveground stocks of

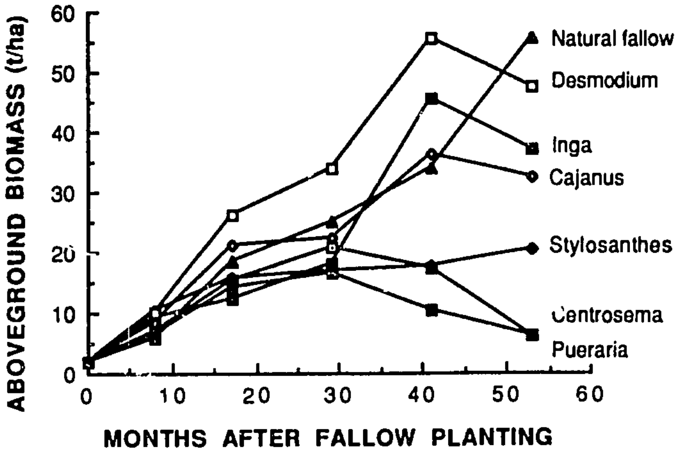

Fig. 6. Aboveground accumulation of living biomass + litter in the different fallow treatments, Yurimaguas, Peru.

nitrogen and phosphorus in most planted fallows were greater than those in the natural fallow. This was attributed to greater biomass accumulation and/or higher tissue concentrations of these elements than that attained in the natural fallow. Increases in aboveground nitrogen during early stages of most fallows, associated with high legume biomass production suggests that the nitrogen status of a fallow system might be enriched by the inclusion of legumes. However, this nitrogen advantage disappeared as legume biomass decreased at later dates. Accumulation of all other nutrients varied with total biomass accumulations; that is, there was no disproportionate effect of the legumes on accumulation of these nutrients.

Quantities of nutrients present at various times during fallow growth compared to those present at field abandonment provide an indication of the time course of nutrient recovery. By 24 months, total nitrogen (vegetation + soil) and total available potassium (vegetation + exchangeable soil) in the best fallow treatments (*Desmodium*, *Inga*, and natural fallow) exceeded levels measured at abandonment (Fig. 7).

Phosphorus (vegetation + modified Olsen extractable soil phosphorus) in the same treatments increased rapidly, and quantities present after 4.5 years greatly exceeded those at abandonment. Presumably, most of this phosphorus was mineralized from organic forms, converted from inorganic forms not readily extractable by the modified Olsen extractant, or was taken up from below the 45-cm depth. Further work on phosphorus transformations during fallow growth, focusing on soil organic phosphorus and microbial biomass phosphorus pools, is needed.

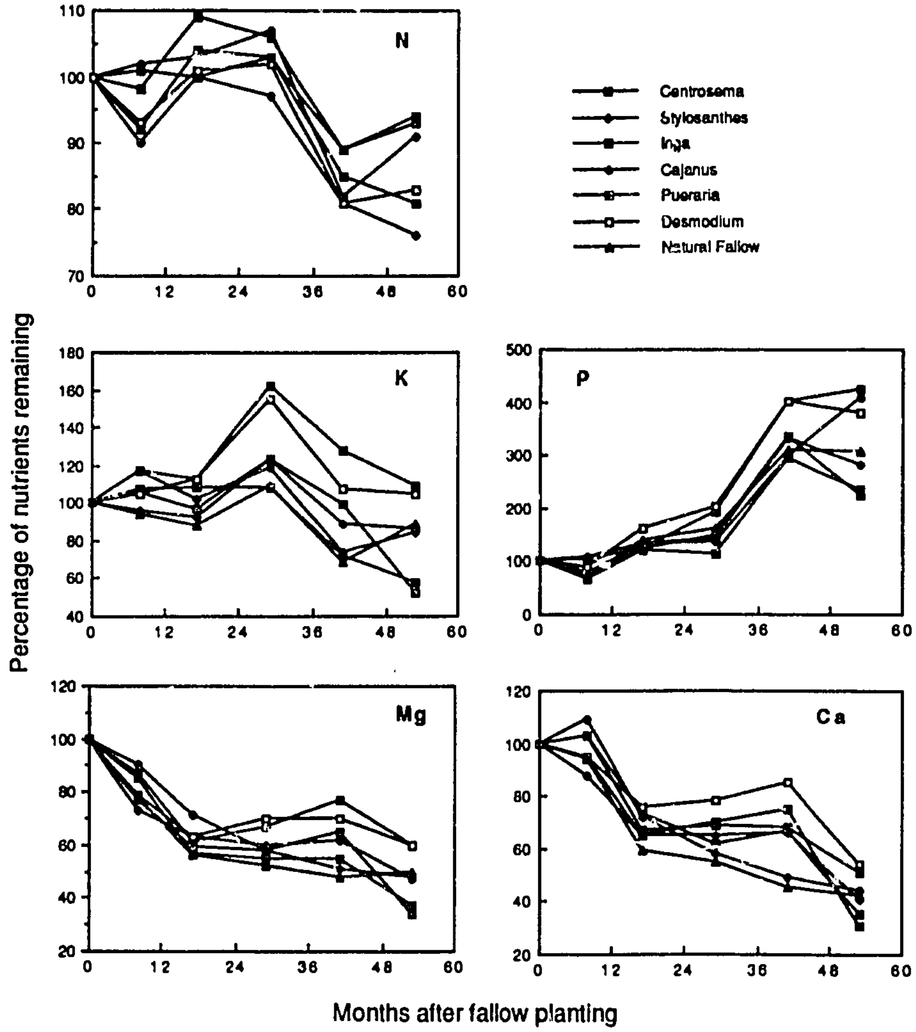

FIG. 7. Changes in total nutrient stocks (living biomass + litter + soil) in the managed fallow treatments relative to quantities present at field abandonment, Yurimaguas, Peru.

Calcium and magnesium stocks (vegetation + exchangeable soil Ca + Mg) declined rapidly during the first 17 months after abandonment and remained relatively stable at succeeding sampling dates. Potassium stocks (vegetation + exchangeable K) increased slightly for the first 2 years and then decreased in most treatments. Loss of calcium, magnesium, and potassium likely involve soil acidification caused by soil organic matter decomposition and proton extrusion by growing vegetation, and the leaching action of large quantities of rainfall. Much of the "lost" calcium, magnesium, and potassium may have accumulated below the 45-cm sample depth and may eventually be recycled by deep-rooted species. This would require a relatively long period of time and it is uncertain whether calcium and magnesium stocks would be completely replenished. On acid soils, in which quantities of exchangeable calcium and magnesium are small, such apparent losses seriously call into question the long-term sustainability of fallow-based production systems.

It is open to question whether long-term enrichment of the nitrogen and phosphorus status of managed fallows can be improved even further by associating fast-growing, relatively long-lived leguminous trees with a rapidly establishing leguminous cover crop. It is also interesting to speculate whether the maintenance of biomass accumulation by forage legumes through cut-and-leave management would aid in increasing biomass and nutrient stocks in managed fallow systems.

C. ECONOMICALLY PRODUCTIVE FALLOWS

Apart from fallows that are biologically enriched with legumes, fallows enriched with trees or other vegetation that produces economically important products may also be a significant agroforestry option for improving shifting cultivation systems on acid soils. Economically enriched fallows are also more likely to be adapted by farmers compared to biologically enriched fallows (Raintree, 1987). Vegetation that produces fruits or forage for grazing animals over long periods of time would effectively remove the land from the shifting cultivation cycle since farmers would be reluctant to cut a valuable source of income. The actual form of these systems will depend on the biological requirements for light, water, and nutrients of the associated species, farmers' preferences for annual field crops, the amount of land available, marketing possibilities, and the amount of labor that could be invested in fallow maintenance.

IV. FRUIT CROP FOOD PRODUCTION SYSTEMS

Annual tree crop food production systems may be one of the agroforestry options that is most attractive to resource-limited small farmers. Such systems can produce a variety of products for home consumption or sale in the market, provide a steady flow of income, reduce risks, spread labor demand through time, and may have more "closed" nutrient cycles than annual cropping systems.

A variety of species with market potential have been identified for acid soil conditions in the Peruvian Amazon. These include peach palm (*Bactris gasipaes*), achiote (*Bixa orellana*), arazá (*Eugenia stipitata*), guaraná (*Paullinia cupana, P. sorbilis*), and Brazil nut (*Bertholletia excelsa*). We intend to use our experience with peach palm to illustrate some of the research lines and questions that can be addressed for each of these species in the establishment and management of fruit crop production systems.

Peach palm (*Bactris gasipaes* syn. pijuayo, pejibaye, chontaduro, pupunha) is native to the Amazon basin and parts of Central America. The palm possesses several characteristics that make its inclusion desirable in agroforestry systems on acid, infertile, upland soils (Clement, 1989; Clement and Mora Urpi, 1987). It is well adapted to acid, infertile soil conditions; it has a relatively small canopy, lessening the possibility of shading associated plants; it grows and reaches reproductive stage fairly rapidly; and it can be coppiced regularly. Economically, the tree produces a variety of useful products: fruit, heart of palm, and parquet material. The fruit has significant quantities of nutrients and can be used for human or animal consumption while heart of palm is an important export product. The palm reaches fruit-bearing age in approximately 5 years and produces about 10–20 t of fresh fruit per ha per year for 15 years. Heart of palm, requires 18–24 months for the first harvest; subsequent coppicing shoots can be harvested every 12–18 months.

A. THE NEED FOR SELECTION AND IMPROVEMENT

Peach palm, like many other potentially promising fruit tree species for acid soils, is semidomesticated and requires selection to improve its agronomically important characteristics. A first step in this process is collecting and characterizing germplasm. Approximately 300 lines of peach palm were collected throughout the Amazon Basin and are being evaluated in Peru and other tropical Latin American countries. Results from the first 6 years of evaluation show that considerable variability exists with respect to precocity and the quantity and quality of fruit production. Although most plants reached commercial production within 5 years, some began to produce after 2 years. At 5 years, production reached up to 18 t/ha fresh weight in some varieties; most varieties, however, produced between 3.5 and 9 t/ha, depending on the soil type. It is expected that production will increase with time up to approximately 10 years of age before leveling off.

Peach palm fruits vary widely with respect to their protein, fat, fiber, and vitamin contents (Pérez, 1984; J. Mora Urpi, personal communication), thus providing wide scope for future selection and improvement for specific agroindustrial purposes such as flour, animal feed, and oil. The development of specific fruit types will depend on selection for useful characteristics, such as the position of fruit set as well as various parameters of fruit quality, the determination of inheritance patterns of these characteristics, and the development of controlled pollenization and vegetative propagation techniques including tissue culture, for their rapid multiplication.

B. AGRONOMIC MANAGEMENT

The development of agroforestry systems for acid soils requires an understanding of how the components respond to low soil fertility and high aluminum levels.

Peach palm has been established simultaneously with annual crops using a low-input rice–cowpea rotation described by Sanchez and Benites (1987). Income from grain yield in these systems exceeded the cost of plantation establishment and acted as a source of income during the early, vegetative stage of plantation growth.

Following 2 years of annual crops, the needs for soil protection, weed control, and a source of nitrogen and organic matter suggest that leguminous cover crops have an important role to play in peach palm and other fruit crop systems. The types of cover crops, the timing of their planting, and subsequent management are important questions that must be considered. In the case of peach palm, growth was affected differently by a variety of leguminous ground covers (e.g., *Mucuna cochichinensis, Pueraria phaseoloides, Desmodium ovalifolium,* or *Centrosema macrocarpum*) and by time of establishment. Palm growth with a *Mucuna* cover crop planted after 2 years was greater than that with other leguminous cover crops and was similar to that resulting from applications of 100 kg N/ha/yr (J. M. Pérez, unpublished data). Simultaneous planting of leguminous cover and palms, however, resulted in reduced palm growth and increased maintenance costs, since the covers tended to grow over and smother the small palm trees. Interplanting with acid-tolerant food crops for 1 or 2 years before establishing the cover crop appears to be the best option. Further work is needed on the resource allocation between trees and other plant species in mixed intercropping systems.

Although it is clear that peach palm is adapted to acid, infertile soil conditions, it is also apparent that its growth is affected by soil nutrient levels (Pérez *et al.*, 1987; Szott *et al.*, 1991). Growth during the first 5 years, in a field previously cleared by bulldozer, was strongly affected by nitrogen (Fig. 8) and potassium but not phosphorus, lime, or magnesium, despite topsoil properties of 90% Al saturation and 0.1 cmol/L Ca + Mg. In this experiment fertilization was terminated after 5 years but residual

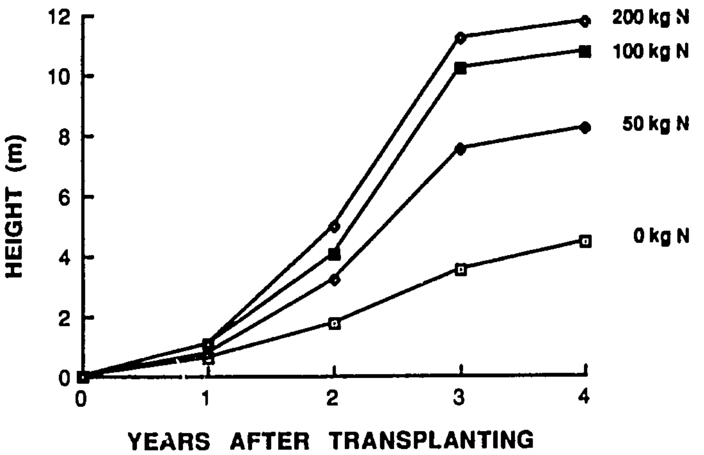

FIG. 8. Growth response of peach palm to various nitrogen fertilizer rates applied during 4 years following outplanting.

nutrient effects on fruit production were apparent in subsequent years. At 7 years of age (first year of commercial production), there was a tendency for fruit yield to increase with rates of nitrogen applied previously. In a different plantation, potassium fertilization initiated simultaneously with the onset of commercial fruit production resulted in a quadratic response in fruit yield (Fig. 9). Similar responses to potassium have been reported for fruit production of other palm crops (Kelpage, 1979).

More work is also needed on applied aspects of fertilizer management, especially for heart of palm, and the residual effects of fertilization. Analyses of plant biomass and nutrient partitioning should be included as important complementary components of these studies. Besides applied research, more basic work is also required on mechanisms of Al tolerance and nutrient uptake, including the importance of mycorrhizal infection by the palm tree.

V. RESEARCH NEEDS

Alley cropping, managed fallows, and fruit crop systems are potentially useful agroforestry systems for acid, infertile soils in the humid tropics. However, major questions remain regarding these systems' ability to overcome the chemical constraints to plant production imposed by these soils:

1. In alley cropping, further work on patterns of water and nutrient uptake by the crops and hedges is needed. Research on management

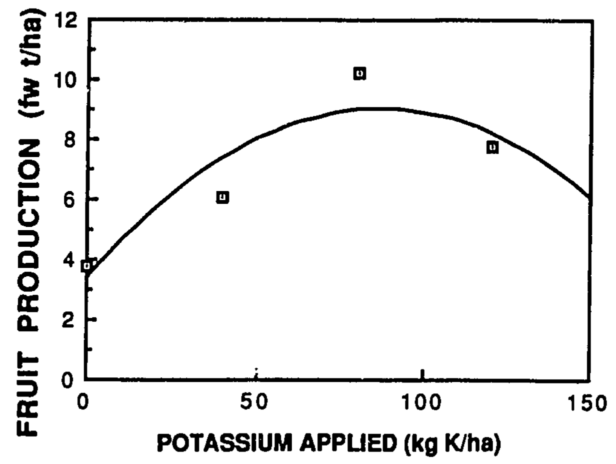

FIG. 9. Peach palm fruit production as related to K fertilization rates.

techniques for reducing hedge–crop competition is critical. Studies of the long-term dynamics and internal cycling of nutrients contained in the hedgerow prunings are also required.

2. Although some managed leguminous fallows can suppress weeds more rapidly than natural secondary vegetation, their ability to accelerate restoration of nutrient cations, such as Ca and Mg, remains in question. The mechanisms involved in phosphorus transformations and in cation loss and techniques for avoiding these losses require further investigation.

3. For peach palm, and other relatively unknown acid-tolerant fruits, more collections and evaluation of germplasm, followed by selection, are needed. Agronomic research on nutrient requirements and management techniques, especially related to leguminous cover crops, are required. Studies on resource allocation by different plant components in mixed species systems are needed, but will be specific to the system in question.

4. In all these systems, selection and improvement of acid-tolerant germplasm is very important and should continue. It may also be necessary to select for plant characteristics that are favorable in mixed-species systems.

5. The suitability of these and other agroforestry systems will vary with the biological and socioeconomic environment at a given site. The latter

factors should be allowed to guide the formulation and research of agroforestry alternatives.

VI. SUMMARY

Several agroforestry systems are successful in relatively fertile soils but little work has been done on food-production agroforestry systems in acid soils of the humid tropics. The main constraints in this ecosystem are aluminum toxicity, low nutrient reserves, and weed encroachment. Of these, aluminum toxicity can be overcome by selection of tolerant germplasm. Low nutrient reserves impose major limitations for nutrient cycling while weed encroachment must be controlled primarily by the rapid development of a complete ground cover.

Investigations at Yurimaguas, Peru have focused on three agroforestry options: alley cropping, managed fallows, and tree-crop production systems as alternatives to or improvements of shifting cultivation. Several acid-tolerant, fast-growing, coppicing hedgerow species have been identified: *Inga edulis*, *Erythrina* sp., *Cassia reticulata*, and *Gliricidia sepium*. Nutrient release patterns from prunings vary widely according to their lignin and total soluble polyphenolic contents. The needed synchrony between nutrient release from hedgerow prunings and crop nutrient uptake has not been achieved on a sustainable basis. Phosphorus appears to be the most limiting nutrient. Crops are severely affected by root competition from hedgerow species. As a result, the desirability of alley cropping on humid tropical acid soils has not been conclusively proven, except for the obvious soil erosion control in steep slopes. Managed leguminous fallows may decrease the length of the fallow period for shifting cultivation. Several stoloniferous species were more effective in suppressing weeds than the natural secondary forest fallow during a 4-year period. Nutrient stocks (vegetation plus available nutrients in the top 45 cm of soil) increased over that at abandonment in the *Inga edulis, Desmodium ovalifolium*, and the secondary bush fallow. Nitrogen and phosphorus stocks increased consistently during the 4-year period while calcium and magnesium stocks decreased drastically during the first 2 years and leveled off. The processes involved need to be investigated. Fruit crop production systems established with a low-input upland rice–cowpea rotation and followed by a legume cover crop, seem highly promising for the region and as a way to move from shifting cultivation to settled farming. The potential for fruit crop production systems is great, but much work remains to be done in germplasm selection and improvement, and the development of management techniques to optimize positive interactions among the plant components of multispecies systems.

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