10 Phosphorus Dynamics In Slash-and-burn And Alley Cropping Systems Of The Humid Tropics

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Shifting Cultivation

Shifting cultivation has been carried out over thousands of years in all areas of the humid tropics. Even in temperate zones, slash-and-burn has been widely used for land clearing (Montelius, 1953; Rowley-Conwy, 1981). In a broad pan-tropical belt spanning the rain forest, through semi-deciduous forest to forest/savanna transition zones, it has almost invariably taken the classic form of swidden- forest fallow -swidden, exhibiting generally longer fallow periods (perhaps 15 years or longer) in the more base-poor and strongly P-sorptive soils (Nye and Greenland, 1960, 1964; Vasey, 1979).

The widespread adoption and survival for several millennia of slash-burn shifting agriculture indicates that, under low human population pressure in forested areas, the system is ecologically and logistically sound. Shifting cultivation not only addressed the problems of regeneration of soil fertility and weed control but also many other aspects of sustainability or crop security. Our own observations of predatory and parasitoid wasps and of ant populations suggest that the small size of cultivated plots set amongst the matrix of forest may be crucial for pest control. Plant diseases may similarly be kept in check. Change of location and vegetation under the system are thought to act against the build-up of root nematodes (Ewel, 1986). The most important reasons for shifting are the intolerable build-up of weeds and the depletion of nutrients. Weeds and nutrient depletion in slash-burn agriculture are not independent factors. Both our study and that reported by Jordan (1989) show declining yields in swiddens, in spite of normal weeding during the critical early-growth stage of the crops. It is even probable that nutrient-cycling through weeds plays a role in maintaining production in the swidden except in the first crops. Nevertheless, weeds that survive the burn or germinate to be overwhelmed by the vigorous first crop growth will return in subsequent years and overwhelm in their turn. Some of the most pernicious weeds are the perennial, stoloniferous grasses that are actually favoured over other types by repeated weeding with a cutlass. The weeding of swiddens may well have to be curtailed at an early date in order to ensure woody, rather than grassy, fallows.

Classic shifting cultivation provides virtually no scope for intensification that does not result in topsoil degradation or erosion and irreversible weed invasions, but expanding human populations, changing aspirations and the need for cash crops, aggravated by the alienation of indigenous agriculturists from richer river-bank alluvia by plantation agriculture, have all combined to cause system breakdown. It is clear that for many cultivators the choice to burn new swidden was removed long ago. Population pressure results in attempts to shorten fallows or extend cropping periods, and consequently, previously productive areas are now in decline over a large portion of the humid tropics (Whitmore, 1990; Vasey, 1979; Myers, 1980). A new subsistence agricultural strategy has to be found that is simple, economic and effective, and able to support worldwide possibly 300 million families, who are, or have been, engaged in shifting agriculture.

Great research efforts have provided strategies to improve the antagonistic soil chemistry of acid soils through fertilizer applications and liming, but, as the basis for a widespread subsistence strategy, this approach is unconvincing. In the subsistence strategies that our work is concerned with, no single system is likely to find universal application, and a range of responses must be researched and made available. The lessons from historical examples of intensification in the humid or sub-humid tropics are revealing. Almost all examples of indigenous agricultural intensification involve transformations of the entire environment (Donkin, 1979; Farrington, 1985; Harrison and Turner, 1978), such as: the terracing or bunding for paddy rice, the raising of fields in the chinampas swamp systems, dry-terracing in the Maya regions of Peten/Yucatan, mounding of topsoil for yams in West Africa or Papua New Guinea, or multi-storey house gardening in Thailand and Indonesia. It is possible that alley cropping (AC) represents an analogue of the Mayan dry terrace system, and it may provide some solutions as a possible dryland subsistence cropping system for the future.

Nutrient cycling under forests and slash-burn

To understand the processes that govern or limit nutrient cycling in cultivated tropical forest soils, it is necessary first to examine the undisturbed forest and what changes are induced by slash-and-burn treatments. Phosphorus cycles of oligotrophic rain forest ecosystems are essentially closed, and rates by which nutrients become available from the decay of plant litter and roots are balanced by nutrient uptake (Medina and Cuevas, 1989). In the more acidic, P-sorptive ultisols and oxisols of the rain forest zone, three important mechanisms for P conservation in the natural forest have commonly been seen:

- The P-content of litter is lower than in more eutrophic forest systems, nutrients having been re-translocated prior to senescence (Vitousek, 1984).

- Fine roots are concentrated in the uppermost soil layers and in root-mats which suffuse the decomposing litter above the soil where shading, moisture and physical protection permit this (Jordan and Herrera, 1981; Anderson, 1981).

- Intense mycotrophism is seen in these roots (St John, 1980; St John *et al.,* 1983; Jordan and Herrera, 1981) with the development of dense mycorrhizal mycelia. The hyphal mass functions as an absorptive wad in the surface soil. The forest ecosystem appears to depend upon the ability of this layer to capture P mobilised from decomposition and thus preempt sorption in the subsoil. In the soils examined in Costa Rica (see below), these zones of fine-root concentration also coincide with the zone of earthworm casting. The uppermost few cm of soil are thus markedly different from the remainder of the profile, and appear critical for the functioning of the nutrient cycle.

The classic "pulse" of fertility generated by the slash and burn and its subsequent decline (Sanchez, 1976; Kellman, 1984; Uhl, 1987; Jordan, 1989) can be attributed to several processes in the post-burn swidden:

- Nutrient additions of the ash derived from the burned forest biomass and litter although important, may be available in the surface soil layers for a very limited period (De Las Salas and Folster, 1976; Nye and Greenland, 1960; Brinkman and De Nascimento, 1973).

• Soil organic matter builds up under forest in fractions ranging from the highly resistant to the labile. One constraint on organic matter decomposition is low pH, which is raised after the burn, resulting in a pulse of decomposition, further accelerated by soil exposure, wetting, drying and enhanced percolation through the upper layers after the removal of the canopy and litter layer (Bruijnzeel, 1990; Jackson, 1977; Birch, 1960). Surface soil temperatures under midday sun on our Costa Rican sites commonly reached 45 to 55 °C.

• Exploitation of the shallow top soil by fine-roots and VAM may be curtailed by even short exposure to high temperatures and desiccation. At one site near San Carlos, the original root mat survived the burn and persisted for three years of cropping, presumably allowing exploration of the decomposing litter layer by fine roots (Jordan, 1989). In another experiment in the area, the root-mat was cleared, crops grew poorly and the site was abandoned (Uhl,1987).

• Nutrients released by these processes can, in the more-leached soils, move rapidly below the rooting zone. Cations and their balancing anions may leave the profile altogether, whilst both organic and inorganic P may leach or be sorbed. Terrain and percolation are important in this regard. Conversion of forest to cropland through slash-burn on a flat, leached Oxisol resulted in little P loss, while, over 6 years cropping, some transformations from organic to inorganic P occurred, the latter strongly sorbed (Tiessen *et al.*, 1992). Jordan (1989) also concluded that declining P availability due to transformation, rather than loss, was the likely cause for the decline in productivity at San Carlos. This contrasts with findings on the sloping site of Ewel *et al.*, (1981) at Turrialba (Hands 1988) where a vegetation-free plot, following the burn, lost 116 kg P ha-1 from the top 20 cm of soil over 7 years.

• The nutrient supply from litter is virtually eliminated, although nutrient-cycling through weeds, crop and root residues may partly compensate for this. The study at San Carlos, like the San Juan study reported below, involved thorough weeding before and during crop growth. Yield declines occurred in the absence of serious weed competition and we regard the recycling of P through weed residues as tending to prolong, rather than curtail, cropping.

A 'spectrum of disturbance' of the original forest nutrient cycles from the intact self-sustaining rain forest ecosystem with an essentially closed cycle to the intense open-field monocropping systems with open cycles requiring high inputs of agrochemicals is presented in Figure 1. Systems to the right of the spectrum are practised because they provide cash returns above the relatively high maintenance cost. It is our contention that low-input subsistence agriculture must emulate, as far as possible, nutrient cycles of forests, if it is to be sustainable. The significance of low-input systems is that they provide a choice to the farmer in the crucial transition from shifting to sedentary cultivation. Whether they continue to be useful will depend on how the farmer chooses to integrate subsistence and cash cropping, and how much value society attaches to specific forms of land management or conservation.

The Phosphorus Cycle

Phosphorus dynamics are critical to the productivity of ultisols and oxisols which are highly P-fixing and are depleted of all primary P-containing minerals. Although these soils make up around half the land surface of the humid tropics, and despite the critical nature of P, relatively little research effort has been targeted on P dynamics in slash-and-burn, shifting cultivation and AC systems.

Few studies have investigated changes in the total P reserves immediately following a slash-and-burn operation, but the general view is that P is not mobile in highly fixing soils. However, some results of our own show that the entire ash P content derived from the burnt forest biomass may pass through the top 20 cm of soil within a few weeks of the burn (Hands, 1988; Hands and Bayliss-Smith, unpublished data). The P in the forest biomass, amounting to an estimated 50 kg P ha-1 'returned to soil' by the burn, was not detectable in the surface soil seven weeks post-burn. On this flat terrace, P losses from the top soil can be explained by the downward leaching of P, in spite of the soil's high P fixing capacity. The soil, when shaken with a 200 mg P l-1 solution sorbed almost all P, but in the field, under 4000 mm rain per year, very rapid infiltration and percolation is likely to occur through macro- and meso-pore flow of frequent pulses of rain (Sollins, 1987). This may also explain the high post-burn losses (23 kg P ha-1 in 5 months) reported by de Las Salas and Folster (1976), who state "leaching of P need not be considered...". Perhaps it should be.

Leaching is, if it can be confirmed, important because in the cropping systems which follow the burn, virtually all the fine roots of the crop plants are concentrated in the top few cm of soil. Fine roots are almost absent from soil depths below 20 cm. In open cultivation plots, the worm-cast layer with its high concentrations of available P also disappears after about two years of exposure to the more severe extremes of microclimate and the decline in worm populations.

Changes in total P down to 20 cm depth on the bare soil plot of Ewel *et al.* (1981) corresponded to a decline in estimated microbial biomass P (using the methodology of Brookes *et al*., 1982)(Hands, 1988). Similar differences in total P in the San Juan plots (4 years post-burn) are commensurate with differences in soil microbial biomass P between plots receiving high and low organic matter inputs over the four year period. If losses in microbial P account for much of the total P reduction, the 10% loss in top soil P represents a colossal loss of the soil's active P.

Fig 1 will be posted here soon

The burn, through ash deposition, pH change and soil exposure, causes a "pulse" of nutrient availability. This short-lived pulse will only be partially intercepted by annual crop plants. This interception supports shifting subsistence, but it is not enough to break "the shifting imperative". To avoid shifting, five or six years of acceptable production must become possible on plots located near the dwelling and rotated to allow a short fallow period. In such a limited rotation, nutrient cycles may be kept active if nutrients removed in cropping are replaced. The manner in which this can be achieved with small affordable inputs forms the basis of this paper. Towards this goal we predict at least the partial success of AC (Wilson and Kang, 1984).

Alley cropping

The general benefits of alley or hedgerow cropping are that it i) takes advantage of trees as soil improvers, ii) enhances amounts of organic matter returned to soils through the use of tree prunings as a mulch, iii) improves the nitrogen status of the system if N-fixing species are grown as hedgerows, iv) suppresses weed growth under mulch from hedges and v) protects soils from the erosive effects of heavy rainfall which can be a major cause of fertility loss.

Much research so far carried out on these systems relates to seasonally-dry areas and on relatively fertile soils which will sustain leguminous trees such as *Leucena leucocephala*.

Relatively few studies have examined the productivity and sustainability of AC systems on the more leached soils of the humid tropics. Furthermore nearly all soil fertility research on AC systems has concentrated on nitrogen cycling and fixation processes. Yet in large areas of the tropics, P availability is the dominant factor limiting crop production (Nye and Greenland, 1960; Sanchez, 1976) and the success of AC systems (Palm *et al.*, 1991).

With AC we place great emphasis on the nutrient effects and the physical presence of the mulch. The idea of "nutrient pumping" from depth does not apply in our context of extremely poor subsoils. The idea of timed pruning in order to present freshly decomposing material to the developing annual crop plant also does not appear as important to us as it does to other researchers. We see the important characteristics of this alley-cropping system as:

- Continuous mulching of nutrient-rich, green foliage derived from leguminous trees grown *in situ*.

- Using permanent cover of durable mulch to do what the forest environment achieves, i.e. to shade; to condition and to feed those surface soil layers.

- Maintaining by these means a vigourous activity of VAM. Most coppicing legumes are reportedly highly mycotrophic, and the species in our trials are exceptionally so (Azcon pers comm.). Beans and at least the less highly-bred maize varieties are both reportedly obligate mycotrophs.

- If the conditions of the forest surface soils can be maintained, and the rooting-zone of the system encouraged upwards and into the mulch, it should be possible to add small, affordable quantities of P fertilizer; not into the soil itself where it may become strongly sorbed, but into the mulch where a proportion may enter the microbial biomass and hence follow the same decomposition pathways as does the forest's recycling P. It will be in this layer that some added P may enter the raised fine-rooting system directly.

Phosphorus inputs may have to be in the form of ground phosphate rock. Soluble phosphate fertilizers are likely to be transported rapidly downwards in percolation and, once below the organic horizons, strongly sorbed. Because changes of as little as 10 ppm in labile fractions of the top 5 cm of soil can account for annual crop exports, differences in sorption capacity between even very shallow soil layers can be significant, provided that the roots and VAM can exploit those layers.

Preliminary work suggests that the soil microbial biomass of the topsoil represents a very major proportion of the active soil P. It is possible that, in conditions of P stress, the uptake of added P by organisms may be substantial and rapid. Recent work by Brookes *et al.* (pers. comm.) shows that measurable effects can occur within days. Phosphorus cycling during decomposition of organic material and soil organic matter itself will be important. By feeding energy and P simultaneously to the microbes, the system should simulate processes of the mature forest itself, or perhaps accelerate them.

The P cycle under alley cropping

We suggest that the P dynamics in AC systems, compared to equivalent low-input open field cultivation, are different in that:

- mulching with tree prunings can increase surface rooting of hedges and crops enhancing P uptake, through direct uptake from the mulch layer,
- increased root activity results in reduced P loss through leaching or eluviation,
- where supplementary P must be added to sustain crop production, it is applied to the mulch layer, rather than to the highly P-fixing mineral soil; therefore the utilisation efficiency of low levels of fertilizer P applied is increased,
- use of tree mulch in addition to crop residues significantly enhances soil biological activity i.e. increases microbial biomass and faunal populations,
- there is a significant increase in P recycling through the use of tree prunings in addition to crop residues,
- trees may access soil P not available to the main crop,
- weed suppression 'redirects' cycling P from weeds to hedges and crops,

To investigate the potential differences and the sustainability of AC systems on ultisolic soils, two AC experiments were established in 1989 in northern Costa Rica at La Conquista (LaC) and at Co-operativa San Juan (CSJ). The assessments of these experiments are in still progress (Hands *et al.*, 1993), but are at a stage where the broad implications can be reviewed here.

The experiment at CSJ was established immediately following slash-and-burn of a 15-20 year secondary forest. The experiment at LaC was established after clearing and burning a 3 year secondary forest regrowth, following previous slash-burn and cropping. The site shows signs of advanced soil degradation on what was an inherently poorer soil than that of CSJ. At each site, the four experimental treatments were open-field and AC plots with and without applied P. Plot sizes were 20 x 20 m and hedges were 2.5 m apart and 1.5 m high.

Two leguminous trees *Gliricidia sepium* and *Erythrina fusca* were grown as alternate hedgerows in the AC treatments. These species are common in lowland areas along field boundaries and are reportedly more acid tolerant than other AC species. Twenty, 40 and 40 kg P ha-1 as North Carolina rock phosphate were broadcast over three years. The systems were managed for high output, with two crops (maize and beans in accordance with local practice) and four hedge prunings per year. In year two, during early maize growth, hedge pruning was delayed resulting in reduced yields at both sites. Prunings formed the main mulch inputs. All crop and weed residues were returned. Before each pruning, weeds were slashed and the regrowth treated with paraquat, to return all plots to an identical starting condition. Additional trials were also established to test the potential of *Inga edulis* and other Inga species as the hedgerow component of AC systems.

It can be argued that at the subsistence level of farming, labour rather than land is the main production constraint. Once established, the AC system helps to control weeds and requires less effort than open cropping, and the extra area required for hedgerows may be less important.

Biomass and P budgets (Figures 2 and 3) were developed for the third year after establishment at CSJ to illustrate the P dynamics in the different treatments. At CSJ, P export in crops was higher under AC, while at LaC, the unfertilised AC system performed poorly, with the exception of the Inga plots. Total P cycling through all vegetation and P returns in plant residues are both greater under AC, i.e. there is a greater P 'availability' in AC systems than in the open-field (Table 1, Figure 3). At CSJ, the amounts of P taken up increase in the order Control -P < Control +P < Alley crop -P < Alley crop +P.

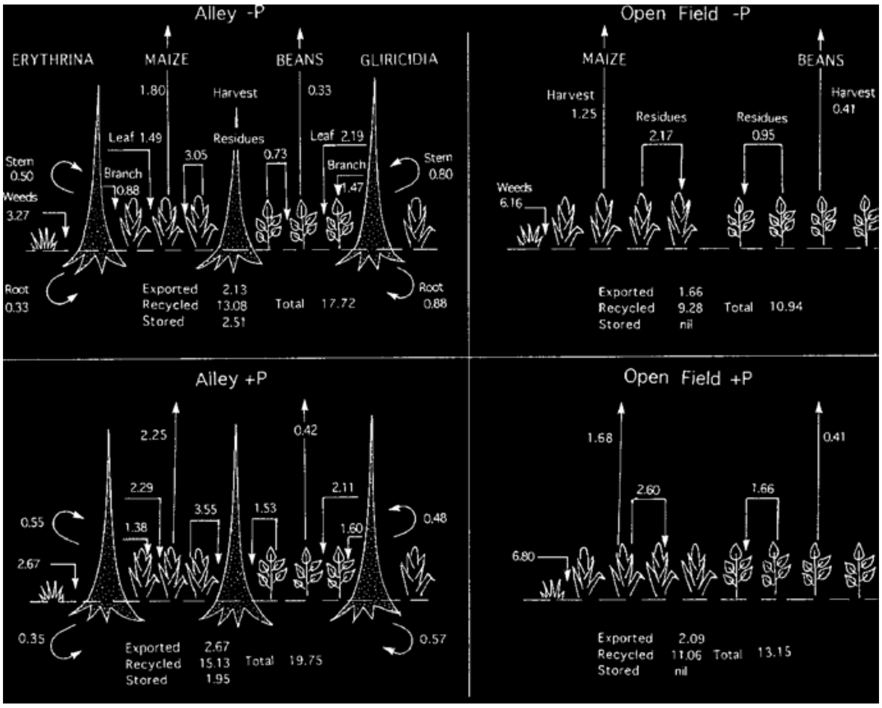

Figure 2. Biomass production with and without applied rock phosphate in open field and alley crop plots in year 3 in tonnes ha-1 at Co-ope San Juan.

On the more nutrient depleted LaC site, the P uptake by the alley system without rock phosphate cannot match that of the open cultivation plot given rock phosphate. Both the greater P uptake and the greater residue return under AC support the hypothesis that the hedge, particularly *Inga edulis*, has access to P not available to the maize and bean crops. This may be a function of the more continuous uptake over the year or may represent access to P pools not tapped by the crop. After correcting the data in Table 1 for the smaller number of crop plants on the AC sites (16,200 maize plants instead of 21,600 and 50,000 instead of 60,000 bean plants ha-1), AC compares more favourably (Table 2).

The P returned in residues and prunings may be important for subsequent crop nutrition. Prunings from *Erythrina* and *Gliricidia* (at 2.5 t ha-1) can provide some 60% of the P requirements of upland rice (Szott *et al.*, 1991), and the role of litter in recycling P in cacao interplanted with laurel (*Cordia alliodora*) and poro (*Erythrina peoppigiana*) has been shown elsewhere (Heuveldop *et al.,* 1988).

Table 1. Amounts of cycling P in different field treatments (kg ha-1y-1)

Treatment	Plant Uptake	Residue Returns	Crop removal	Tree storage

C. San Juan	*(Year 3)*			
Open Field -P	16.3	11.4	4.9	0
Open Field +P	24.9	17.8	7.1	0
Alley Crop -P	27.7	19.5	6.1	2.1
Alley Crop +P	39.1	26.7	10.3	2.1
La Conquista	*(Year 2)*			
Open Field -P	13.2	11.3	1.9	0
Open Field +P	21.7	18.4	3.3	0
Alley Crop -P	18.4	14.8	1.5	2.1
Alley Crop +P	25.9	19.9	3.0	3.0
Inga, Crop +P	46.4	34.3	4.6	7.5

Table 2. Phosphorus in crop export per ha of cropped area in open plot and alley crop plots (kg ha-1y-1).

	Open Field		Alley Crop		Inga
	+P	-P	+P	-P	+P
CSJ	4.9	7.1	8.0	13.5	-
La C	1.9	3.3	1.8	3.7	5.51

1 bean crop only, no maize that year

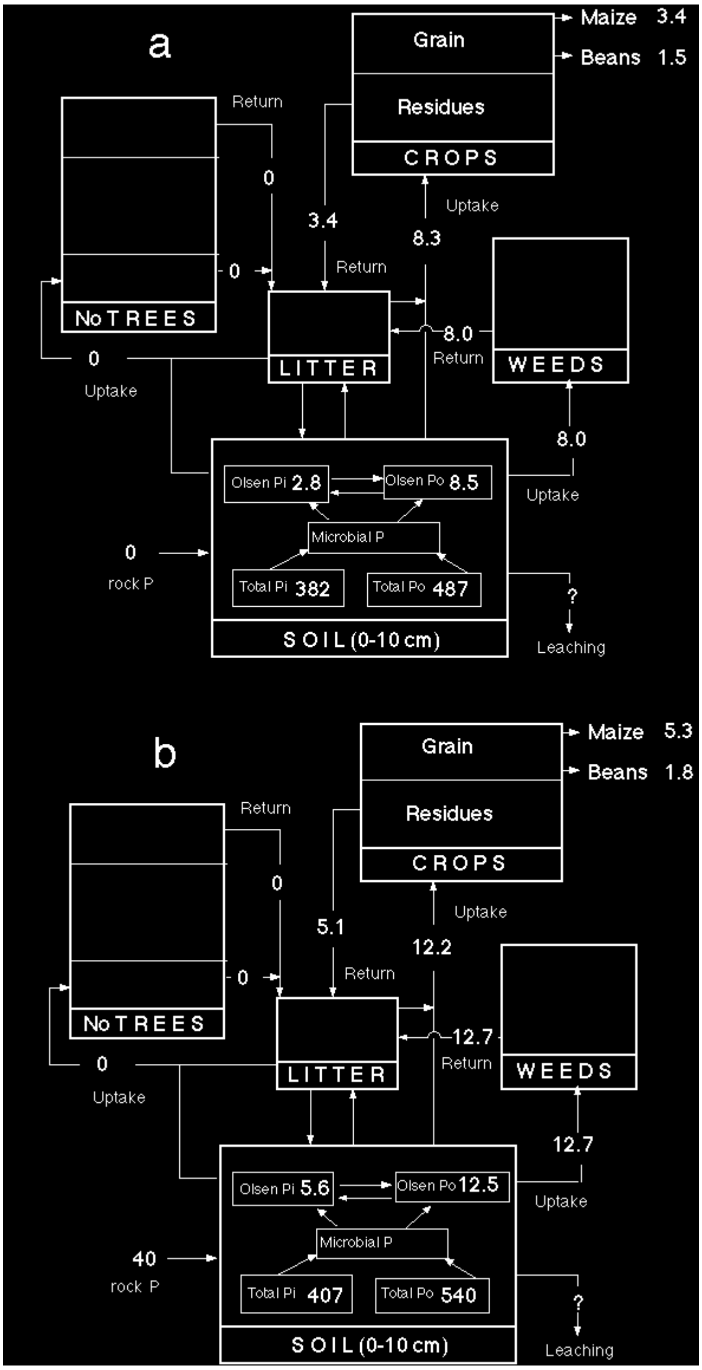

Figure 3. Comparison of P cycling at CSJ in open fields without (a) and with (b) rock phosphate application.

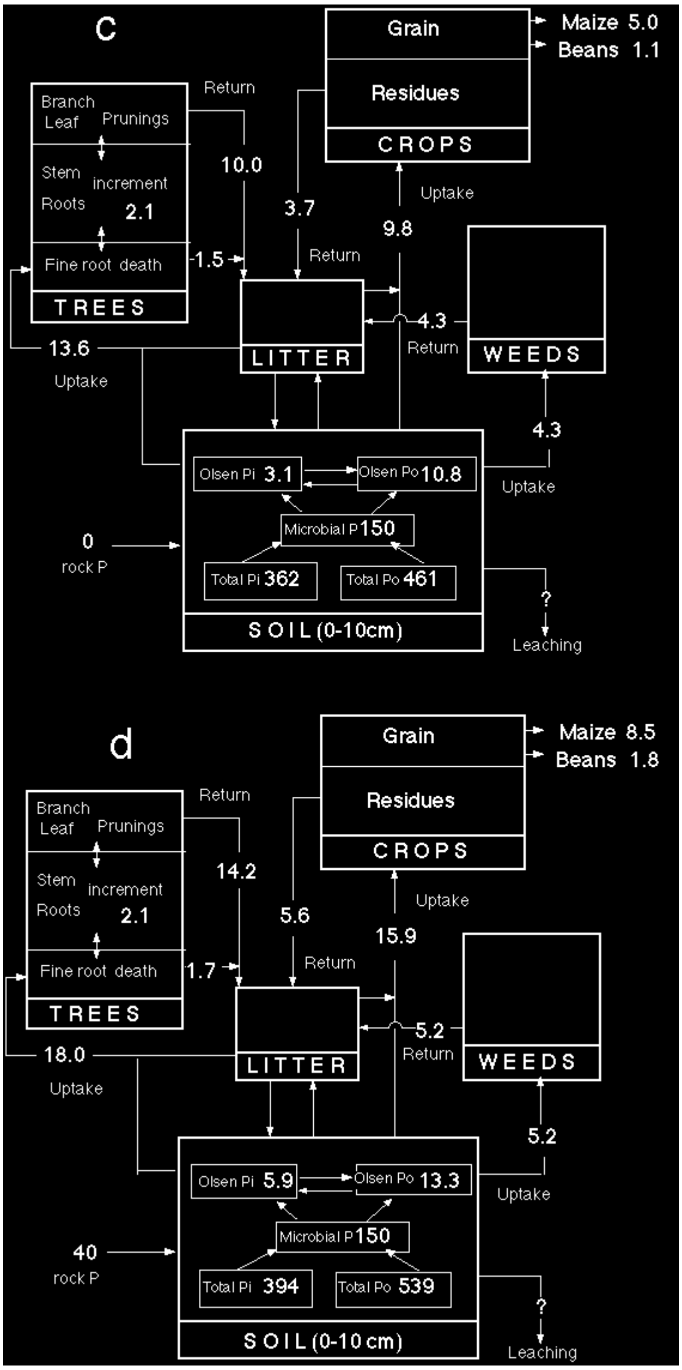

Figure 3 cont. Comparison of P cycling at CSJ in alley plots without (c) and with (d) rock phosphate application.

At CSJ, but not at LaC, there are greater increases under AC in plant P uptake due to rock P addition, indicating improvements in fertilizer use efficiency. It appears that, where AC resulted in a significant increase in P uptake, the rock P becomes incorporated into the P cycle to a greater extent, perhaps as a result of greater demand during the critical dissolution phase (reducing sorption and loss) or due to a more rapid dissolution under AC.

The P cycling budgets (Figure 3) show that P is 'redirected' from competing weeds to crops. The weed growth response to applied rock P in the open field did not occur under AC where weed growth is smothered by the mulch and shaded-out by the hedges. Such shading effects on weed production have been demonstrated in other mixed-cropping studies (Jama, *et al.*, 1991; Nestel and Altieri, 1992).

Increased amounts and quality of organic matter returns under AC appear to have enhanced soil biological activity relative to open fields. Greater earthworm populations were observed under AC, related not only to the increased organic matter providing extra food but also to the better moisture conditions under the mulch. *Gliricidia* and maize residues have increased earthworm populations (Tian *et al.*, 1993). Soil fauna have an important role in organic matter decomposition (Swift *et al.*, 1979) and earthworms are known to enhance P 'availability' and organic matter turnover in soils (Mansell *et al.*, 1981; Syers and Springett, 1984; Fragoso *et al.,* 1993; Brussaard *et al.* 1993), and to increase the availability of P in phosphate rock (Mackay *et al.,* 1983). Ant and termite populations are more prolific in the AC compared to open field plots (Tian *et al.*, 1993).

Increased organic matter returns through the mulch of hedge prunings can have a marked influence on the hedge and crop rooting pattern and the development of mycorrhizae. Under AC we observed an intense, very seasonal, fine root activity in the top 10 cm of mineral soils, with an almost complete absence of deep taproots. The dense network of fine roots will also extend up into the mulch layer where it is persistent, particularly under Ingas. Fine roots of crop plants also tend to follow the shallow rooting habit, with significant intra-mulch rooting when conditions there are suitable. With the *Erythrina/Gliricidia* hedges, rooting in the mulch occurred during the first two years but declined as mulch returns have declined with over-all decreasing productivity (Figure 4). Hedge pruning induced a marked mortality of fine roots, possibly exceeding 75% of the biomass. This root death provides a significant subterranean organic matter input. The importance of the rooting pattern under AC systems is that hedge and crop roots are able to take P directly from the mulch layer and from the dead hedge root mass generated after pruning. This direct uptake circumvents the need for roots to recover P from the highly P-sorbing and Al-toxic mineral layers below.

Gliricidia, Erythrina and Inga roots are strongly mycorrhizal (Azcon, pers. comm.), with well developed hyphal networks spreading through the organic layer. Crop plants therefore can become mycorrhizal at an early growth stage. Mycorrhizae, mainly VAM (St John, 1980; Janos, 1986), are important in the nutrition of trees and crops by i) in effect increasing root extension to access and absorb P, ii) transferring P from organic layers to roots (St John *et al.*, 1983, Herrera *et al.*, 1978; Jordan, 1989), iii) stimulating the production of phosphatase in the extended rhizosphere (Jayachandran *et al.*, 1992; Dalal, 1982; Halm *et al.*, 1971), iv) taking up P efficiently under P-deficient conditions (Mosse, 1977; Hayman, 1983) and v) possibly enhancing P uptake from rock phosphate (Mosse, 1977; Barea *et al.*, 1983; Azcon-Aguilar *et al.*, 1986).

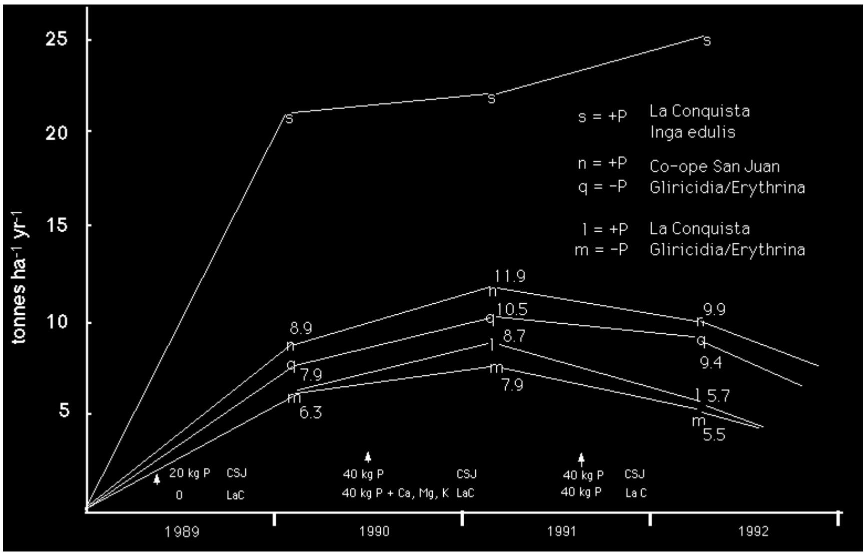

Figure 4. Net annual production of tree components (excluding fine roots) for alley plots (alleys 2.5m, 10,000 trees ha-1), showing relatively high Inga production.

Tinker (1984) contends that the plant alone would, in producing exudates, acquire its P more efficiently than through costly symbiotic relationships. Claims of direct litter breakdown by VA mycorrhizae (e.g. Went and Stark, 1968; Herrera *et al.,* 1978) are now largely discounted. The role of mycorrhiza therefore seems to be largely one of physical root extension yielding greater penetration of soil micro-aggregates and greater contact area between absorbing surface (the hypha) and the surface films from which orthophosphate anions are absorbed (Sanders and Tinker, 1973). At the scale at which mycorrhizal hyphae operate, 1 to 2 orders-of-magnitude lower than that of the finest roots, the soil no longer exhibits the uniformity implied by laboratory analyses. Phosphorus availability varies greatly on a microscale, say between a quartz or sesquioxide particle and a fragment of soil organic matter. Mycorrhizae may act as a better "mop", covering the ground, but also as an injection system of high resolving power, targeting microscopic regions where P-rich resources may temporarily exist. Resolution at this scale and fast response time to temporarily rich micro-zones are one of the pre-eminent qualities of microbes compared with higher plants. Microbial decomposition of litter and soil organic matter, and P uptake by mycorrhiza may combine to enhance P availability in adverse soils. It is known that the recycling of litter P is important in oligotrophic forests (Medina and Cuevas, 1989). The raised rooting habit and strong mycorrhizal development are also viewed as important mechanisms in the enhancement of P cycling under the AC system. If the mulch layer is amended with rock phosphate, the P applied may be cycled more directly resulting in enhanced fertilizer use efficiency. All these processes suggest that the AC system has a tighter P cycle resembling that of the forest. This conclusion concurs with provisional analytical results, that total P contents of the surface 0 - 20 cm soils after four years open-field cropping at CSJ are lower than those of either the original forest or the AC treatments.

Decline in production

Maize yields in the open cultivation plots showed the classic decline common to all studies in slash-burn agriculture, falling from about 150 g plant-1 dry matter (3240 kg ha-1) to approximately 125, 58 and 41 in the subsequent 3 crops respectively (Figure 5). The second maize crop in the alley system was strongly suppressed by a failure to carry out the second pruning early enough. Root competition between the alley and the crop may also be a factor limiting crop production (Fernandez *et al.*, 1993). The third crop showed marked responses, with the +rock P treatment maintaining a significantly higher production than all other treatments. Bean yields were more variable and showed a steady decline from the peak in the second year. The December 1991 sowing of beans had to be completely resown following a massive slug attack. Nonetheless, the whole system clearly is declining by the third year. Despite this decline, there are still residual effects of rock phosphate applications evident in the growth and yield of the fifth maize crop within both open field and alley cropping treatments three years after the last rock P application.

An adjacent open field factorial experiment of increasing rock P and dolomitic lime applications to maize indicated that P availability is the key factor providing yield increases with P applications up to 50 kg ha-1.

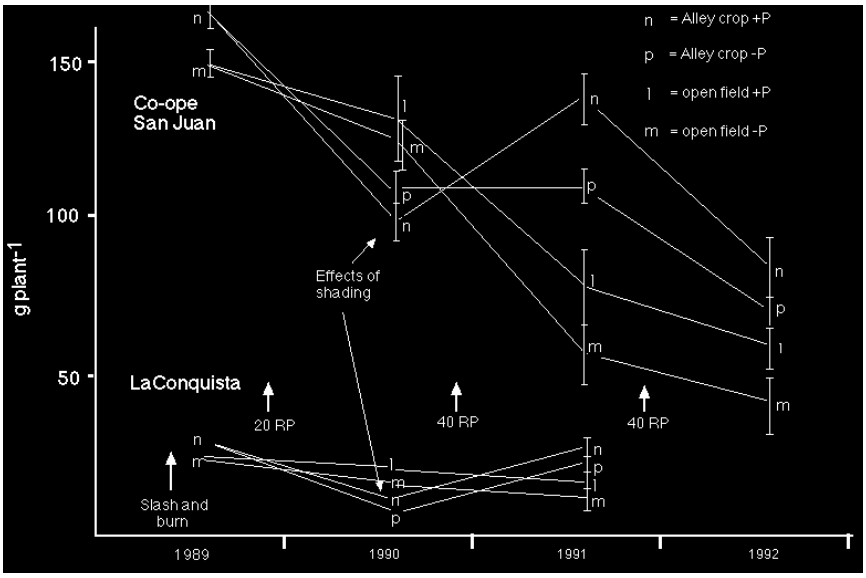

Figure 5. Maize production in open field and alley plots.

Subsistence farming options

What then are the options for the subsistence farmer for sustaining crop production on an ultisolic soil following slash-and burn? Alley cropping, using the appropriate species, spacing and management offers an advantage over open field cropping when only low levels of rock P can be afforded. The alleys must be established as soon after the burn as possible to retain as much P cycling within the system as possible. Yields decline even in the AC system. The system in these trials has been placed under considerable stress with double cropping (maize and beans each year), four hedge prunings and a tree density of 10,000 stems ha-1, near the upper limit of published studies. Despite this high density, the *Erythrina/Gliricidia* system could not sustain enough mulch to cover the soil beyond the first 1-2 years.

Possible management options for greater sustainability appear to be i) reduced pruning combined with a single crop each year on a greater area of land, ii) selecting hedge species for better production and/or soil acidity tolerance and providing a more durable mulch, iii) increasing the rock P inputs together with supplementary lime and other nutrients.

Reduced pruning may take the form of a year-by-year rotation of cropping and free growth of alleys. *Erythrina/Gliricidia* hedges pruned only twice yearly and under-sown with beans appear to be able to maintain a reasonable mulch production, at the same time achieving enough shading to suppress weed growth. This system might be more likely to succeed on better soils or where more land is available.

Through a change of hedgerows to acid-tolerant species producing greater quantities of more durable mulch, such as *Inga edulis*, the system will be drawn towards a semblance of the more oligotrophic tropical forests (Figure 1). The minimum condition for the sustainability of such systems is the replenishment of crop P exports. Moreover the system may have to be driven by further supplements, and there may be a need to counter soil acidification and enhance decomposition rates of the more recalcitrant mulches through applications of dolomitic lime. Lime and P applications have produced clear benefits.

Ingas are successful in alley cropping systems (Table 1) (Szott *et al.,* 1991), because of i) their considerably greater growth rate and productive capacity than either *Gliricidia* and *Erythrina*, ii) the greater mass of mulch derived from prunings giving a complete ground cover, iii) their ability to recycle greater amounts of P (Table 1), iv) their ability to maintain higher proportions of its highly-mycorrhizal feeder roots in the superficial soil and mulch layers, facilitating recycling of more P directly from the mulch, v) its tolerance of more acidic soil conditions, vi) the almost complete weed suppression by the organic mulch layer, vii) the slow decomposition rate of the mulch providing a slower rate of P release for more efficient crop uptake. It is likely that the more recalcitrant nature of the foliage, i.e. the higher phenolic content (Palm and Sanchez 1991) of species such as *edulis* or *oerstediana* could be partially overcome by light applications of ground limestone; higher pHs reduce the protein-binding potential of phenolic substances and make the formed complexes more readily decomposable.

Conclusions

1. To understand the options for subsistence agriculture in the humid tropics, one has to place them in the context of the original rain forest under which these soils were formed and which itself provides a model of sustainable production.

2. The slash-and-burn operation is highly effective in mobilizing P stored in soil organic matter by enhancing mineralisation. It is useful to consider the mobilisation as a 'pulse' of P (and other nutrient) availability, the intensity and duration of which will depend on the inherent characteristics of the soil and the nature of the vegetation prior to the burn.

3. The 'pulse' of mobilized phosphorus is set in motion by the burn, whether or not there are crops or weeds to intercept it. Continued bare soil may accelerate the processes and significant amounts of P may be lost through leaching under high rainfall conditions (despite soil high P fixation capacity).

4. Decline in crop production in open field plots occurs despite rigorous weed control. Weed growth therefore need not be the primary cause of reductions in crop yields in slash and burn subsistence agriculture.

5. The conventional agricultural approach seeks to dominate the physicochemistry of the mineral soil rooting zone, whereas alley cropping options outlined here seek to by-pass the antagonistic properties of the mineral soil by elevating the plant fine-root network, mycorrhizal and microbial activities into the uppermost layers of the mineral soil (say 5 cm) or into the litter/mulch layer itself.

6. Once the system is fully established, alley cropping enables more P to be cycled and incorporated into grain yield, and permits a greater efficiency of utilisation and retention of rock phosphate than open field cultivation systems.

7. Sustainable crop production may require that cropping on one site be carried out for perhaps no more than 5-6 years, followed by rotation to an adjacent site. A system of two or three such plots each alley-cropped and fallowed in turn, appears to be a possible alternative sufficient to break "the shifting imperative".

8. Options involving acid-tolerant, productive legume trees and durable mulch will require light additions of rock phosphate and lime to replace crop export of P and overcome possible induced soil acidity respectively. The raised rooting habit of permanent mulch systems may facilitate access to such additions with greater efficiency than if they were added to the mineral soil in the conventional way.

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Back to table of contents

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