CHAPTER 5. THE USES OF *INGA* IN THE ACID SOILS OF THE RAINFOREST ZONE: ALLEY-CROPPING SUSTAINABILITY AND SOIL-REGENERATION

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INTRODUCTION

In this chapter, the potential role and uses of *Inga* are set against the extensive and environmentally-damaging failure of traditional shifting cultivation systems to sustain intensification under increased population pressure (Brookfield, 1988). The case of Central America and more recently, Amazonia, is a sufficiently poignant example, but there are many more such examples in all of the world's three great humid tropical regions. In the humid neotropics, this vast forest zone, sparsely populated in historical times at least, has, in recent decades, been opened up to logging; this is often followed by the invasion of slash-and-burn subsistence farmers displaced from elsewhere; and, in South and Central America, at least, by the final conversion of exhausted swidden land to extensive cattle ranching (Schmink & Wood, 1984; Hecht, 1985; Denslow & Padoch, 1988).

Over-intensive swidden agriculture is an essentially consumptive use of temporarily available forest soil fertility. As rural populations grow on marginal lands and as plantation agriculture expands over more fertile river basin soils, so access to fresh forest fallows diminishes. The system is now failing widely in tropical America.

The emphasis here will be placed upon experimental evidence and upon the potential role of *Inga* as a component of low-input, sustainable, subsistence systems of agriculture; and, increasingly, in measures designed to regenerate the fertility of land which has already been degraded by over-use. Low (or zero)-input strategies need to be available to farmers as an alternative to failing swidden systems, and as a means of regenerating those landscapes in which shifting agriculture has already failed. Such strategies must lie within the control of the farmers themselves and must not expose them to debt or dependency upon externalities. If it were the case that they had additional resources, if they could afford to purchase and transport those soil supplements that help to maintain fertility, then so much the better.

In this chapter, the possible role of nitrogen-fixing trees (NFTs) in sustainable cropping systems is outlined in general terms; this is followed by a more detailed treatment as to why the outstanding productivity and acid soil tolerance of *Inga* are potentially so important in this context. A number of the most salient qualities claimed for *Inga* as a coppicing legume in alley-cropping, and as a pioneer regenerator of fertility in degraded soil, are covered in more detail below; they are summarised in Table 1; but much more needs to be known.

TABLE 1. A summary of characteristics of *Inga*; claims and comments.

CLAIMED FOR *INGA*	EVIDENCE OR COMMENT
1. High productivity on, and tolerance of, acid tropical latosols	Commonly observed; also see data below
2. Tolerance of coppicing or pruning	Commonly observed in *Inga* shade over coffee; but manner of pruning can be important
3. Nitrogen fixing ability	Difficult to quantify, but consistent with observed high production of foliage
4. Recalcitrant mulch; physical protection of the uppermost and most important layers of soil from heat and desiccation by the sun and from structural damage, erosion by rain	Observed in a number of studies. Emerging from these studies (see below) as one of the most important characteristics of alley-cropping with *Inga*
5. Apparent resistance to important root pathogens; eg. Root-knot nematodes	See observations from San Juan site, below, re. *Meloidygone spp.*
6. The possible biological protection of intercropped cultivars due to the presence of aggressive ants and other insect predators associated with extra-floral nectaries	Some supporting data and informal observations, but not fully explored. In addition to many ant species, predatory and parasitoid wasps, widely observed on *Inga* at the two sites reported below
7. Weed suppression beneath mulch in alley-cropping or beneath the canopy in free-growing situations	Observed in a number of studies. Strong weed suppression observed at San Juan site (see below)
8. Flexibility: Sufficient diversity between species (and species groups) to enable differing growth and foliage characteristics to be chosen for a specific role	Some broad characteristics observed, but a very small proportion of the total 300 species have been placed under trial
9. Multiple uses; regeneration of degraded soil, formerly under forest and now degraded by exposure, cattle range, etc. *Inga* is also a preferred firewood	Growth form and characteristics of many *Inga* species should lend them to these uses. Early results of trials support this contention

Some of the characteristics listed here are beginning to emerge as being of paramount importance in alley-cropping; they are given in more detail below. Before such detailed treatment, however, it is important to set the context in which the properties of *Inga*, particularly in alley-cropping, can be expected to function. The critical context is taken to be that of failed shifting cultivation systems on the acid latosols of the humid tropics. In other tropical contexts, indigenous agricultures have provided the basis for an intensification capable of feeding a vastly increased human population (e.g. padi rice). On acid soils there are no such examples to provide a starting point; and, today, it is clear that shifting, fallow systems cannot withstand intensification. The world's humid tropics have never before seen the levels of subsistence and economic pressure which bear upon them today and which result in a consumptive and accelerating destruction of these regions' remnant primary and secondary forest cover.

It will be argued below that the only model available to us, of sustainability on zero inputs, is that of the tropical rainforest itself. The special characteristics of "oligotrophic" rainforest ecosystems on acid humid tropical latosols (Jordan, 1985; 1989) are taken here as the unavoidable minimal conditions that will have to be incorporated into any low-input, sustainable alternative to shifting cultivation. Shallow rooting and high dependence on mycotrophism are just two such characteristics.

The soil types in which sustainable alternatives to shifting agriculture will be expected to function were themselves formed under the biological, chemical and climatic conditions of rain-forest. A case is made here that, in simulation of the soil-litter conditions of the forest itself, any alternative agricultural system would have to generate, *in situ*, input levels of organic matter (OM) which are comparable to those of the forest.

Any such system would differ from that of the forest in that (it is assumed) higher levels of biologically fixed nitrogen would be in flux; and that the litter component, being green leguminous mulch, would contain higher quantities of N and P than dead litter. In these respects, and because maintenance levels of soil supplements will almost certainly have to be added from time-to-time, the system is being "driven" in comparison to the forest ecosystem. Finally, the case is made for *Inga* as outstanding acid-soil-tolerant leguminous trees, to be grown in alley configuration.

The tough mulch of *Inga* is seen here as particularly important in, firstly, encouraging shallow-rooting, beneath its protection, and away from the antagonistic, acid mineral soil; and, secondly as a major suppressor of weed growth.

Acronyms used are as follows:

A-C   Alley-cropping
a-g   Above-ground (e.g. above-ground biomass).
b-g   Below-ground.
CEC   Cation Exchange Capacity
CR   Costa Rica
CSJ   Co-operativa San Juan (one of the a-c trial sites in Costa Rica).
DM   Dry-matter (all data refer to oven-dry weights).

E/G   *Erythrina - Gliricidia* alleys.
La C   La Conquista, Sarapiqui, Costa Rica (one of the a-c trial sites).
NFT   Nitrogen-fixing tree.
NPP   Net Primary Production (of an ecosystem or agro-ecosystem).
OM   Organic Matter.
SOM   Soil Organic Matter.
S-C   Shifting cultivation.
VAM   Vesicular-arbuscular Mycorrhiza.

Viable alternatives to traditional shifting cultivation systems are urgently required; not only, as sustainable low-input alternative systems for staple food and cash-crop production; but also, as low-cost strategies for regenerating the fertility and condition of formerly forested soils which are now degraded by years of exposure under swidden and cattle range. The need is for systems to function viably, within the control of the farmer, at least during the transition from shifting to settled forms of subsistence (assuming such forms are possible on the more acid, leached tropical soils) and, if possible, to function sustainably in their own right.

Alley-cropping (A-C) has been promoted as one such sustainable agricultural system (Kang & Wilson, 1984), among few, if any, feasible alternatives; it has been widely researched on the more fertile of tropical soils, often with emphasis upon nitrogen inputs (e.g. Kang *et al.*, 1990). However, it may be argued that the major unsolved problem of an alternative strategy to slash-and-burn/shifting cultivation lies in the widespread, leached, acid soils of the humid tropical forest zones (Jordan, 1989) (oxisols, ultisols, etc.) which together comprise some 63% of the the humid tropical zone worldwide and some 75% of the Central and South American Humid tropics (Sanchez, 1976). It can also be argued that, whereas findings emerging from studies on acid soils may well prove to be useful when translated to more favourable soil types, the reverse would not be true.

In the context of the history of humid tropical agriculture, the widespread colonisation and intense use of acid soils in the humid tropics is relatively recent. The colonisers are almost invariably poor and have commonly been displaced from the margins of other agricultural contexts; by failure of shifting agriculture, by warfare, by government policy or by economic necessity. Many indigenous examples of shifting agriculture, on the other hand, are thought to have arisen millennia ago on the fertile levées and terraces of tropical river basins where fishing and river transport would also have been integral to those cultures. The effects of population expansion alone would eventually have driven farmers away from the valley alluviums and on to the older, more deeply weathered and acid upland soils which are typical of the continental shields and uplifted landforms. Over extensive areas of the humid and sub-humid tropics, the classic effects of population pressure have transformed secondary forest/fallow mosaics into extensive perennial grassland, commonly as fire-climax vegetation. Such pressures of population are widely manifested in the cropping cycle as shortened periods under fallow and over-prolonged periods under cropping, or attempted cropping (Plates 1A & B).

Today, plantation agriculture on the fertile river terraces, among many other factors, has alienated many indigenous farmers from their traditional lands. Factors such as these, together with the more recent phenomena of transmigration schemes in Malaysia and Indonesia and examples of mass colonisation in the Amazon basin, have combined to place great pressure of subsistence agriculture on the acid soils of the humid and sub-humid tropics on a scale never seen before. Added to this, the aspirations of many former subsistence farmers have, not surprisingly, changed in recent decades to include the need for cash-cropping.

It is suggested here, that the role of NFTs in general, and *Inga* in particular, will have to be seen in the contexts of, firstly, acid-soil tropical rainforest ecology and, secondly, the ecology of the slash-and-burn clearance of those forests (Jordan, 1989).

The forest as a model of sustainablity

The adaptations to acid soils of the forest itself, one of the world's most productive ecosystems, is a starting point for the development of sustainable agroforestry systems. The tropical rain forest itself, is biologically a highly productive and sustainable ecosystem, yielding annually a dry-matter Net Primary Productivity (NPP) of perhaps 15–25 tonnes per ha (Kira cited in Whitmore, 1975). Many secondary forests, are scarcely less productive. This productivity contrasts with that of the newly burned swidden which might typically produce 2 tonnes of maize grain, as export, and a similar biomass of crop residue; moreover, this is a level of production which typically cannot be sustained on acid, leached tropical latosols beyond the second year. However, as all farmers and some researchers know, weed production following the first crop can be prolific.

The characteristics of acid tropical soils

The principal chemical characteristics of acid tropical soils have been well described by, among others, Sanchez (1976); Lal (1991) and Fisher & Juo (1995). This is the chemical context in which trees compete and have evolved tolerance (Plate 2A). Briefly summarised, these characteristics are:

i)   High levels of exchangeable H, Al and Mn on the exchange complex; the toxicity of these cations to plants.
ii) Low Phosphorus (P) availability (expressed as the readily extractable orthophosphate anion).
iii) High P fixation (sorption) capacity of added phosphate (laboratory criteria).
iv) Low base-cation availability.
v)   Low retention capacity (CEC) of those bases that may be added.
vi) High leaching rates of mobilised nutrients, whether derived from slash-and-burn, mineralisation or soluble fertiliser additions.

What has been described above is, to an acid-soil-intolerant plant, a fundamentally antagonistic soil-chemical environment and, moreover, one that actually competes with the roots for critical nutrients such as P. This is an environment characterised by low availabilty of major nutrients and low

ability to retain and exchange those nutrients when they have to be added. It should, however, be emphasised that, in many forest soils, a marked stratification of surface soils has developed in which many of the more antagonistic properties of the mineral soil are strongly ameliorated by complexation with organic matter derived from litterfall and root turnover. The fine root concentrations that may be observed in these superficial layers may be interpreted as both a cause and a consequence of this stratification. The conservation of such superficial layers, possibly just a few cm in depth, remains one of the paramount conditions for a sustainable agricultural system in acid soils.

A number of marked characteristics have been observed in those rain forests growing on poorer tropical soils (Herrera *et al.*, 1978; Jordan, 1985; 1989), leading Jordan & Herrera (1981) to distinguish "oligotrophic" and "eutrophic" forest ecosystems; a distinction based mainly on soil base-status. The idea of phosphorus-limited ecosystems was carried further by Vitousek (1984) who, having compiled published accounts of N and P contents of forest litter, was able to demonstrate a strong correlation between litterfall and P content of litter in a substantial sub-set of tropical forest ecosystems.

Among the floristic adaptations to nutrient limitations listed by these authors are some (e.g. sclerophylly) which are probably of little use to a farmer, but a number of others appear highly significant; among them the following:

1) The P content of litter is lower than in more eutrophic forest systems (Vitousek, 1984). Nutrients are retained more tightly in the system and translocated prior to leaf-fall and, presumably, prior to fine root dieback, although information on the latter is lacking.

2) In the more extreme examples of oligotrophic systems (Herrera *et al.*, 1978) (e.g. "white-sand" vegetation), the tree rooting systems may tend to form superficial root mats; often clear of the mineral soil altogether and suffusing the decomposing litter where shading, moisture and physical protection allow this to happen. In less extreme examples, fine roots may be found clear of the soil surface under litter but, in any case, are frequently found concentrated in the uppermost few cms of soil.

3) Increased dependence of the forest trees upon symbioses with VA mycorrhizal fungi tends to correlate with increased oligotrophic status.

All of these features can be interpreted as tending towards more efficient retention, retrieval and recycling of P, in a soil context typified by low pH, low base-status, high H and Al toxicity (at least in subsoils), high P fixing capacity, shallow-rooting, etc.; they are part of a distinct, cohesive and global humid tropical pattern.

Well before the inception of the trials described here, phosphorus availability had been identified as one of the key constraints upon sustainable subsistence on these soils; firstly, because they typically possess low levels of available P; secondly, very high capacity for P fixation in the soil is common

(Sanchez & Uehara, 1980), especially in lower soil layers, and, thirdly, because these weathered and leached tropical latosols retain few primary minerals which, in younger soils, might have constituted a weatherable phosphorus resource.

Nearly all soil fertility research on alley-cropping systems concentrates on N cycling, yet in large areas of the tropics, it is more likely that phosphorus availability is the dominant factor limiting crop production. Jordan (1985, 1989) concluded from the San Carlos study that the post-burn decline in production he observed was most likely due to a reduction in P availability; and both Szott *et al.* (1990) and Palm *et al.* (1991) considered that P is the nutrient of most concern to the success of continuous crop production in A-C systems on ultisols.

As long ago as 1960, in their much quoted seminal volume, Nye & Greenland (1960) cited P availability as the most likely limiting factor in shifting cultivation in the humid tropics. Aspects of the phosphorus ecology of natural oligotrophic rainforests, slash-and-burn agriculture and alley-cropping are described in more detail in Hands *et al.* (1995) and, since the date of that paper, more data (see below) confirm the primacy of phosphorus in the sustainability of subsistence systems on acid soils of the Humid Tropics.

How trees adapt to acid soils

The roots of certain tree species tolerate or respond to acid soils in a number of ways, as described by Fisher & Juo (1995); trees are capable of resisting, complexing or sequestering Al^n ions. We can add "avoiding" to the list, for this is at least one outcome of root mat formation. Much more work on root physiology is needed before a clear picture emerges of the different strategies evolved by trees, but, from the characteristics given above, the following may be inferred:

1) The high dependence of many legumes on Vesicular-Arbuscular mycorrhizae (VAM) probably reflects their need for phosphorus in support of N fixation and would pre-adapt them for strong competitive ability on acid soils. It appears to be the case, but needing clarification, that the presence of some VA mycorrhizae can lead to the mobilisation of forms of organic phosphorus which are not otherwise available to plants (Dalal, 1982; Jayachandran *et al.*, 1992). High dependence on mycotrophism also implies a condition that systems be managed in the absence of tillage or soil compaction (which are known to disrupt the functioning of VAMs) and obviously, in the absence of fungicides. Mulching with organic matter would be expected to encourage and maintain mycorrhizal development (Dalal, 1982).

In the few studies that have been conducted on mycorrhizae and legume root systems, a number of *Inga* species were shown to have very high VAM infection densities (St John, 1980; Azcon, pers comm). In the absence of more specific data for individual species and soil types, the working assumption would be that *Inga*, as a highly dependent mycotrophic perennial, would tend to maintain high densities of mycelium and, presumably, spores. This could be expected to benefit any mycotrophic intercrop. Certainly, in the two trial sites outlined here, beans responded strongly to alley-cropping with *Inga*, and this may have been a factor.

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2) That durable mulch material from certain legume tree species can encourage shallow or surface-rooting by physically protecting fine roots from desiccation and direct sunlight. Where rock phosphate and other supplements must be added to the cropping system, nutrients will be more efficiently retained and recycled by those raised fine roots (both of the trees and of the crop) than in bare soil or tillage systems in which the roots must compete with an antagonistic soil chemistry for available phosphate. It may therefore be the case that mulching for physical protection of the soil surface would constitute one of the overriding aims of a cropping system (such as alley-cropping), unless that protection is achieved, as it is under some perennial systems (e.g. coffee under shade), by a combination of shade and litterfall from the trees. In the case of alley-cropping with *Inga*, the triple aims of physical protection of the soil's structure, weed control and efficient nutrient retrieval are all achieved by the same physical factor; namely, durable mulch.

In view of the fact that *systems* research into the uses of NFTs generally, in acid soils, is at a very early stage, all that can be claimed is that the few case studies cited below provide the outlines of a far-from-complete picture. The spectra of species, techniques, constraints and possibilities that are available to farmers remain largely theoretical. Systems that are too finely tuned and which depend, for example, upon a particular selected provenance of NFT are unlikely to possess the resilience and adaptability for long-term success with farmers. Too little is known about the functioning of *whole systems* for any easy assumptions to be made about exactly what it is we are asking the trees to accomplish. The merits and demerits which have been claimed for alley-cropping are tabulated in Tables 2 and 3, together with some relevant arguments and qualifying statements:

THE ROLE OF *INGA* IN ALLEY-CROPPING AND THE RESTORATION OF DEGRADED SOILS

Almost all examples of alley-cropping (A-C) with NFTs on acid soils exist on experimental stations or as on-farm trials. The system is under investigation and development as a direct response to the need for sustainable systems in the context of failed slash-and-burn agriculture. However, early experiences with a number of *Inga* species planted in alley configuration have shown that they are also effective as a form of managed fallow or as a remedial measure for the regeneration of degraded cattle rangeland into cropping use.

Findings from Yurimaguas; lowland Costa Rica and elsewhere indicate that sustainable staple crop production in this acid-soil context will only be possible with the addition of critical nutrients. Soil supplements such as rock phosphate, dolomitic lime, etc. are likely to be the forms available, if at all, to resource-poor farmers and the crucial function of the trees in the cropping system, apart from N fixation, may be that their presence enables those supplementary nutrients to be retained and recycled tightly in the system and thus to be applied in small, affordable quantities.

Some acid-soil-tolerant NFTs respond strongly to light additions of these supplements and it may be reasonable to assume that systems in which they comprise a substantial component should be self-sufficient in nitrogen by

TABLE 2. Alley-cropping with *Inga*: Claims, comments and observations.

FACTORS OF A MAINLY PHYSICAL NATURE	COMMENTS
1. Permanent mulch cover from slowly decomposing prunings protects the vital surface soil layers from extremes of temperature and loss of its organic matter due to desiccation/ saturation episodes (The "Birch* Effect").	In open soil, these factors tend rapidly to degrade the quality of SOM reserves and hence lead to the loss by leaching of the nutrients held in those reserves. The contention is supported by temperature observations.
2. Permanent mulch cover breaks the erosive force of heavy rain and preserves the structure and permeability of the surface soil aggregates.	Widely observed property of mulches in general. Supported by informal observations at the two sites outlined below.
3. Permanent mulch cover breaks the capillary pathways by which the soil loses moisture during drought periods; thus maintaining cool, consistently moist sub-mulch conditions and high levels of biological activity.	" " " "
4. Raised fine rooting systems: reproducing the patterns found in the rainforest. Physical protection afforded by deep mulch enables the system's fine roots to suffuse the organic surface soil layers and the mulch itself.	This has a number of very important physical, chemical and biological effects. See San Juan site data, below.
FACTORS OF A MAINLY CHEMICAL NATURE	
5. High organic matter inputs ameliorate, in the uppermost soil layers, the principal antagonistic soil characteristics associated with acidity.	SOM can complex aluminium ions; important in countering P fixation.
6. High inputs of fresh foliage would be expected to maintain high levels of the more active, labile forms of SOM.	Predictable, but not actually demonstrated.
7. Efficient retention and recycling of plant nutrients within the system.	Some evidence to support this; more needed.
8. Efficient retrieval of those plant nutrients that have to be added to the system.	P added as rock phosphate recovered in *Inga* prunings; San Juan data.
9. Nutrients raised from deeper soil layers.	Probably not true in the case of very superficial rooting patterns in acid soils.

* Birch (1960)

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TABLE 2 continued.

FACTORS OF A MAINLY CHEMICAL NATURE (CONTINUED)	COMMENTS
10. Nitrogen inputs, derived from biological fixation, from the decomposition of fresh foliage.	Difficult to quantify, but the claim is consistent with observed high foliage production. Fine root and nodule dieback observed following pruning.
11. Much of the cation exchange capacity (CEC) in an acid soil resides in its soil organic matter (SOM) content and in its SOM/clay complexes. High OM inputs should maintain or enhance CEC.	Probable, but not proven in alley-cropping.
12. Carefully timed pruning claimed to present readily decomposable OM to the developing crop.	Probably not true in the case of recalcitrant *Inga* foliage
FACTORS OF A MAINLY BIOLOGICAL NATURE	
13. Shallow and mulch rooting could reduce or nullify the effects of root pathogens.	See observations outlined for the two experimental sites below.
14. Increased biological diversity within the alley system compared to monocropping.	This is self-evidently true, but its significance is yet to be fully understood.
15. Weed germination and growth smothered by deep mulch.	One of the most important findings. See case histories, below.
16. The slight weeding that is necessary is easily carried out.	Consistently observed at both sites (see below). Weeds that do establish share the shallow rooting pattern of the trees and crops; they are easily hand pulled.
17. Extrafloral nectaries on *Inga* attract a wide diversity of insect predators; wasps, aggressive ants, etc.	Many species observed; some evidence of benefit to intercropped cultivars.
18. High levels of invertebrate activity beneath the mulch may enhance weed-seed predation.	Suggested by observations in alleys; not formally proved.
19. Maintenance of soil symbionts by the legume trees. (eg: VA mycorrhizae, rhizobia, etc).	High infection density of VA mycorrhizas in *Inga* roots.

TABLE 3. Alley-cropping: possible disadvantages; possible responses.

POSSIBLE DISADVANTAGE	POSSIBLE RESPONSE
1. Trees shade crops.	Very high potential for shading by *Inga*. Responses: prune shortly before sowing of the crop; reprune some weeks into crop development. Alley alignment and management have an effect here; also stem height is important. See below for options.
2. Trees can compete with crops below ground.	Significant fine root dieback observed at trial sites (see below) following pruning; presumably reinforced in second pruning. Root pruning found to affect yields at Yurimaguas but may not be necessary if 2 prunings carried out, as above.
3. Legume trees could harbour the same pathogens that affect other legumes; eg. beans.	Root knot nematode infection (*Meloidogyne spp.*) observed in beans in clear plots and in deeper roots in alleys; also observed in *Erythrina fusca* (see below). No infection observed in any *Inga* species under trial at either site in CR. Infected plants able also to root into mulch were little affected by the pathogen; this may be a very important, and unexpected effect of deep mulch. Nature of *Inga* resistance unknown.
4. The use of more durable mulch species could acidify the soil due to the nature of decomposition.	Little is known about long-term effects; presumably they are easily corrected by light additions of wood-ash, lime, etc. In the case of raised rooting systems, the soil volume in question is small and, hence, easily ameliorated.
5. Fast growing trees could acidify the rooting zone by very efficient base extraction.	Possible: but Ca, Mg, K, etc. returned in prunings; soil CEC enhanced by OM inputs. There could be a long-term system requirement for dolomitic lime. Long-term K economy unknown. Cash-crops could be needed to purchase light soil supplements as a minimum condition of sustainability.
6. A-C could involve more labour than open-plot systems.	A little more labour required in the year of establishment; nurturing small trees, etc. Once established, the key advantage lies in effective weed control under *Inga* mulch; very great labour saving compared to open plots.
7. A-C takes up more land area, compared to open plots, for a given area of crop.	True, but usually unimportant compared to the very high fallow/crop ratio of shifting agriculture or bush-fallow systems. No farmer in present trials (see below) has expressed any reservation in this regard; they are more concerned with yield per unit *effort* than per unit *area*.

biological fixation. At the very least, phosphorus and base cations removed in cropping will have to be replaced and it is useful to envisage successful alley-cropping systems on these soil types as efficiently retaining and recycling P, K, Ca, Mg, etc. rather than raising them from deeper soil layers which is commonly invoked as explanation for the functioning of alley-cropping on more favourable soils.

Although interest in the uses of *Inga* in alley-cropping appears to be growing, comparative data are somewhat scant. In particular, data describing the performance of *whole systems*, over long periods of time, are needed, together with data showing the long-term fates and fluxes of soil supplements which have been added to the mulch of a fully functioning alley system. Eventually, we could hope for a broader picture on how individual species or species groups are responding. The issue of 'sustainability or non-sustainability' could hinge on this knowledge. There appears to be little doubt that minimal soil supplements are an unavoidable condition for sustainability in any agricultural system. The key difference will be between maintenance supplements to a tight, "parsimonious" system and a complete fertiliser strategy. The latter is, in fact, an attempt at chemical domination of the soil and carries with it all the attendant costs and leakages which may be tolerable in other contexts and economies, but not in this.

Field trials in lowland Costa Rica

The case histories outlined below cover two long-term alley-cropping/clear-cropping trials in the humid tropical lowlands of Costa Rica. Principal NFT species in the alleys were *Erythrina fusca* and *Gliricidia sepium*; a choice of species which was based upon published knowledge which was current at the time of planning the experiments. Supplementary experimental plots were added as a means of gaining experience with *Inga* and, based on earlier observations, as a first-order screening of *Inga* types. In total some eight *Inga* species were planted and monitored in alley-cropping configuration, mainly at the San Juan site. Reference is also made below to a number of other trials, notably at Yurimaguas, Peruvian Amazonia.

The two Costa Rican sites are:

1) **Finca La Conquista** (La C), Sarapiqui. Costa Rica.

TOPOGRAPHY: 40 m. above sea level; uplifted former alluvial terrace; topographically flat and uniform. Rainfall infiltration and percolation rates are very rapid; no surface-flow (or erosion) was observed over the 3 years' trials.

RAINFALL; VEGETATION: 4,200 mm; Lowland wet tropical forest (Holdridge).

SOIL: Ultisol (pH in $CaCl_2$, 3.9). Very marked stratification of upper organic layers (0–2 cm; 2–10 cm; 10–20 cm, etc.) over orange/yellow mineral subsoil.

SITE HISTORY: Lowland wet tropical rainforest until logging in the 1950s; then remnant and secondary forest interspersed with subsistence agriculture and clearance for cattle. Secondary forest cover on the site was slashed-and-burned in approximately 1985, followed by sporadic cropping. Reslashed-and-burned by the Cambridge project 1989. Remnant trunks were reduced by chainsaw and removed by hand. Alley plots, clear plots and the first maize

crop were established immediately after this burn. Based on observations of its performance locally, identical alleys of *Inga edulis* were established between two of the main experimental blocks (see Plates 2B–D).

2) **Co-operativa San Juan** (Co-operativa San Juan or San Juan). San Carlos. Costa Rica. (Northern plains bordering the San Juan river).

TOPOGRAPHY: Virtually identical to the La Conquista site; uniformly flat uplifted former alluvial terrace.

RAINFALL: Approximately 4,000 mm; no surface flow was observed during the entire 7-year duration of the trials.

SOIL: pH 4.1; slightly less deeply-weathered than La Conquista.

SITE HISTORY: Approximately 25-year-old secondary forest cover slashed and burned April/May 1989; all trunks reduced by chainsaw and removed by hand (Plate 1C). Experimental layout identical to La Conquista; later supplemented by alleys of 8 *Inga* species.

EXPERIMENTAL DESIGN (common to both sites): Large experimental plots (400 m²), set out on flat terrain, and comprising four each of the following four treatments: Alley-cropping or Clear-cropping; both with and without applications of phosphorus (P) as rock phosphate. At La Conquista, 80 kg P per ha (40 + 40). At Co-operativa San Juan, 100 kg P per ha (in 3 applications 40 + 40 + 20, in the Decembers of 1989, 1990, 1991).

Associated Crops: Maize sown immediately post-burn (June 1989) and every subsequent June (Plate 1D); beans sown each mid-December (La Conquista; 3 years'; Co-operativa San Juan; 6 years' continuous monitoring).

Alley Alignment and Configuration: both sites: East–West alleys; 2.5 m wide; 0.4 m within-row spacing (10,000 tree stems per ha).

Tree species:

La Conquista: *Erythrina fusca* and *Gliricidia sepium* in alternating rows. *Inga edulis* in pure stand; identical configuration. (10,000 trees per ha).

San Juan: As above; 2.5 m. alleys *Erythrina fusca/Gliricidia sepium*, same configuration. 8 *Inga* species (*I. edulis*; *I. oerstediana*; *I. goldmanii*; *I. punctata* (added later); *I. spectabilis*; *I. densiflora*; *I. marginata*; *I. samanensis*); 4.0 m alley width; 0.5 m within-rows (5,000 tree stems per ha); alleys aligned East–West, arranged around main experiment. Identical soil and management (Plate 3A–C).

PRUNING REGIME AND MANAGEMENT (common to both sites). The trials were intended to investigate the cycling and ecology of critical nutrients, especially phosphorus. Very heavy potential weed growth was controlled by slashing 5–6 times per year, followed, at least twice per year, by the spraying of Paraquat to control regrowth immediately before crop sowing. This was carried out for experimental reasons, to remove weed competition as a factor in crop performance and in the hope of highlighting differences in nutrient ecology. In this respect, the experiments were not a strict replica of local farming practice. Deliberate year-by-year repetition of the cropping regime was maintained in order to impose a steadily increasing nutrient stress on the system.

Pruning Height: 1.5 m.

Pruning frequency: Determined by crop requirements; 1 major pruning, following weeding, 1 week before crop sowing; followed by one light pruning 5–6 weeks later into crop-growth. i.e. 2 major and 2 minor, prunings per year.

Timing: June; December.

Manner of pruning: Care was taken to minimise ripping damage; clean cuts were made with a very sharp machete or pruning shears. Approximately 5–10% of foliage was left on the stem at each pruning, mainly as short sprigs. No pruning cuts were made close to the main stem(s); thus leaving short spurs (10–20 cm) to facilitate regrowth. The aim was to ensure minimal cambium exposure or damage; regrowth often occurred from the node below the cut.

<div align="center">RESULTS</div>

All plots started each cropping episode from the same weed-free condition. Without the paraquat, the clear plots would rapidly have been overwhelmed by weed-growth, whereas the alley plots maintained a degree of weed control for the first (2–3) years. The *Inga* alleys, once fully established, achieved a virtually complete weed-suppression.

Data available: Net Primary Production (NPP) of entire agro-ecosystems, including estimates of below-ground (b-g) production and estimates of weed components.

La Conquista: 3-years' data. San Juan: 6-years' data. Both sites, all above-ground (a-g) NPP in *Inga* alleys for comparison with the same components of the *E/G* system.

The distribution of fine roots within the systems

A number of corings were made with a saw-tooth corer (100 mm internal diameter) in order, firstly, to obtain a first estimation of the dieback which had been observed to occur in the finest tree roots and associated nodules following pruning; and, secondly, to compare vertical distribution patterns between soil layers and between species. A second set of corings was carried out at the La Conquista site shortly before abandonment and 5-months after pruning (Table 4).

1) *Grain Yields: Erythrina fusca/Gliricidia sepium (E/G) alleys versus clear plots; Inga alley plots.*

Because of the longer-term nature of the trials at Co-operativa San Juan, most of the data cited here derives from that site. The patterns at La Conquista were essentially similar, but all yields were at a lower level than those from the freshly-burned swidden at Co-operativa San Juan; differentials in biomass production between the *Inga edulis* and *Erythrina fusca/Gliricidia sepium* alleys were virtually identical between sites (see Table 5, below). All data from the main experiments are in preparation for publication elsewhere (Hands & Bayliss-Smith, in prep.); the main trends and findings are summarised here. Fig. 1 & 2 show the basic grain yields as a percentage of the first postburn crop.
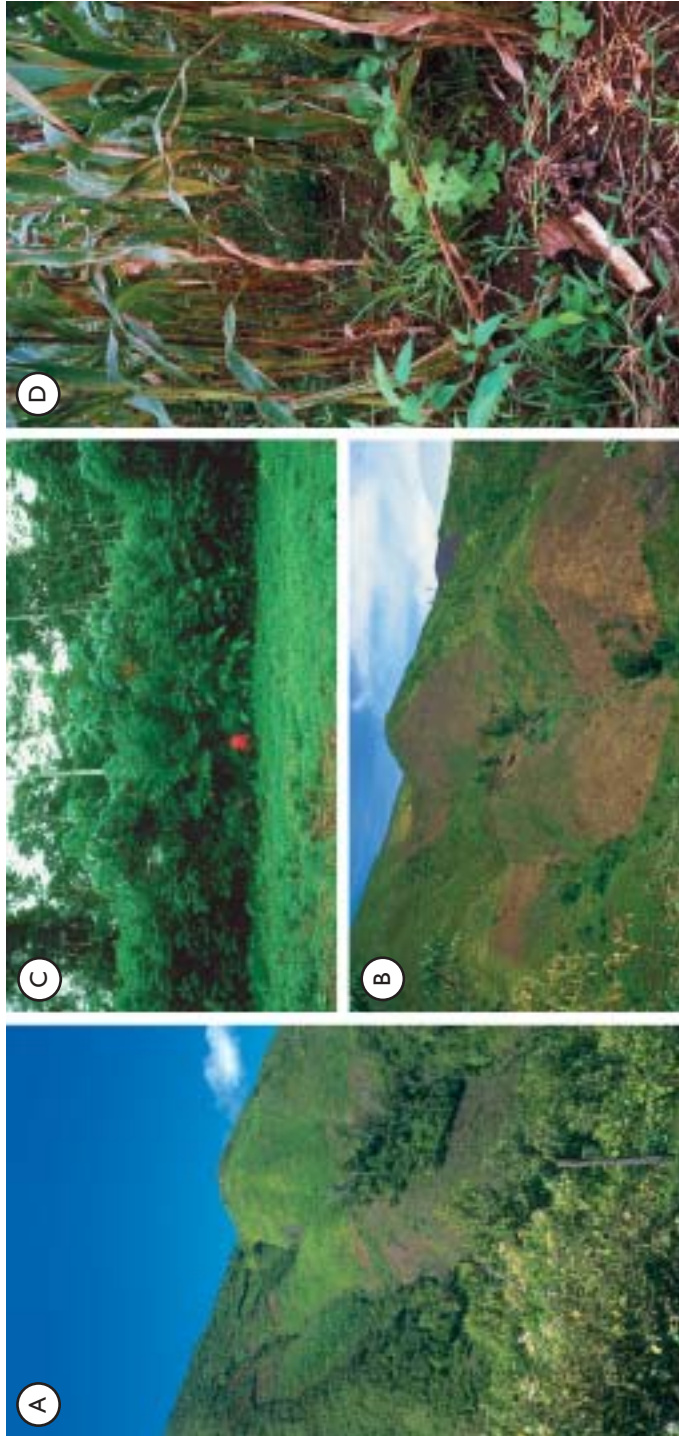
PLATE. 1. **A** Slash-and-burn on marginal hillslope land in Central America; near Montaña del Carbon. Olancho. Northern Honduras. Young maize, upper right. Few trees of the original rain-forest cover remain; with most of the vegetation into the scrub or perennial grass cover resulting from two, or more, burning cycles. **B** The same hillside 18-months later; the consumptive process further-advanced. The erosion potential is obvious. **C** The San Juan site; 1-year post-burn. In the foreground is an experimental clear plot with a light weed-cover. The ground immediately behind our field assistant was slashed-and-burned, but never used; in this picture it holds one year's "weed" growth. **D** The first maize crop following the burn at the San Juan site; the crop has completely dominated both the weeds and the developing *Gliricidia sepium* (right).

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PLATE. 2. **A** Soil profile in a road cutting near La Conquista; formed under tropical rain-forest and cleared a few years before this picture was taken. A virtually structureless acid, leached latosol of the utisol/oxisol type. Current estimates of tectonic uplift rates, and other evidence, indicate that this soil would have been laid down as alluvium in a fluvio-lacustrine environment, controlled by interglacial sea-levels, some 80–100 thousand years ago. Major tree-roots are seldom encountered at more than a few decimetres depth; the topsoil organic matter has largely disappeared. Landless subsistence farmers are increasingly attempting to settle marginal soils of this type which are widespread in the humid neotropics. **B** The La Conquista site. Seedlings of *Inga edulis* recently-established in 2.5 m alleys. **C** The same hedgerows of *I. edulis*, 3-months after transplanting; paraquat was used on the grasses. **D** The same hedgerows; 9-months after transplanting and undergoing their first pruning. The longest branches had reached 4.3 m and the canopy had completely closed.
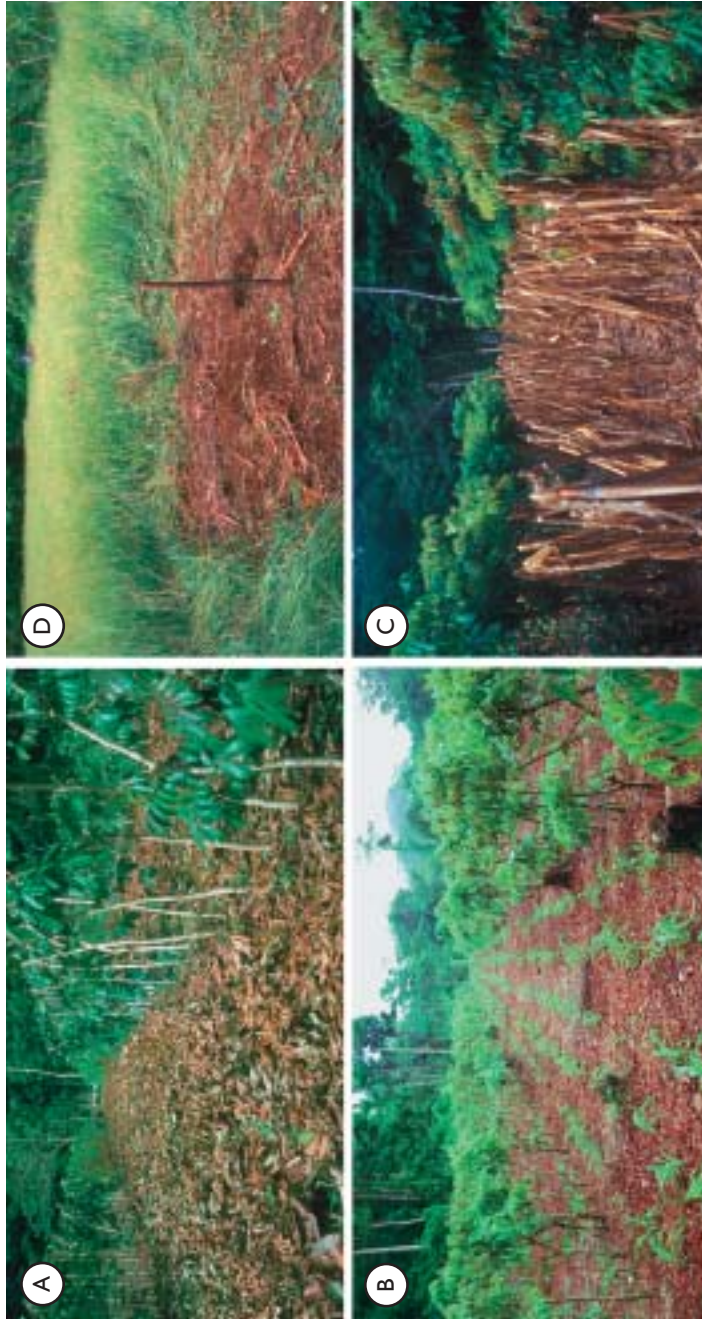
PLATE. 3. **A** San Juan site: 4-metre alleys of *I. densiflora* (foreground); *I. marginata* and *I. samanensis* (background). 16 months after transplanting and shortly after the first pruning. Mulch cover and weed-control are virtually complete; 5–8% of foliage left on the trees. Hedgerow height 1.5 m. **B** 4-metre alleys of *I. marginata*. Maize newly-emerged through the mulch, approximately 3 weeks after sowing and some 2–3 weeks before the second of the two prunings. Weed-control is virtually 100%. **C** The same alleys of *I marginata*; the maize doubled-over at the point-of-harvest. Weed-growth is almost zero; no herbicides were used. The hedgerows have begun a 3-month period of regrowth before the next cropping cycle. **D** A weed-sampling quadrat at the San Juan site; May 1996. Experimental clear-cropping plots showing 2–3 months weed-growth, dominated by perennial grasses. Previous weed-control was by slashing, followed by a spraying of paraquat on the regrowth.
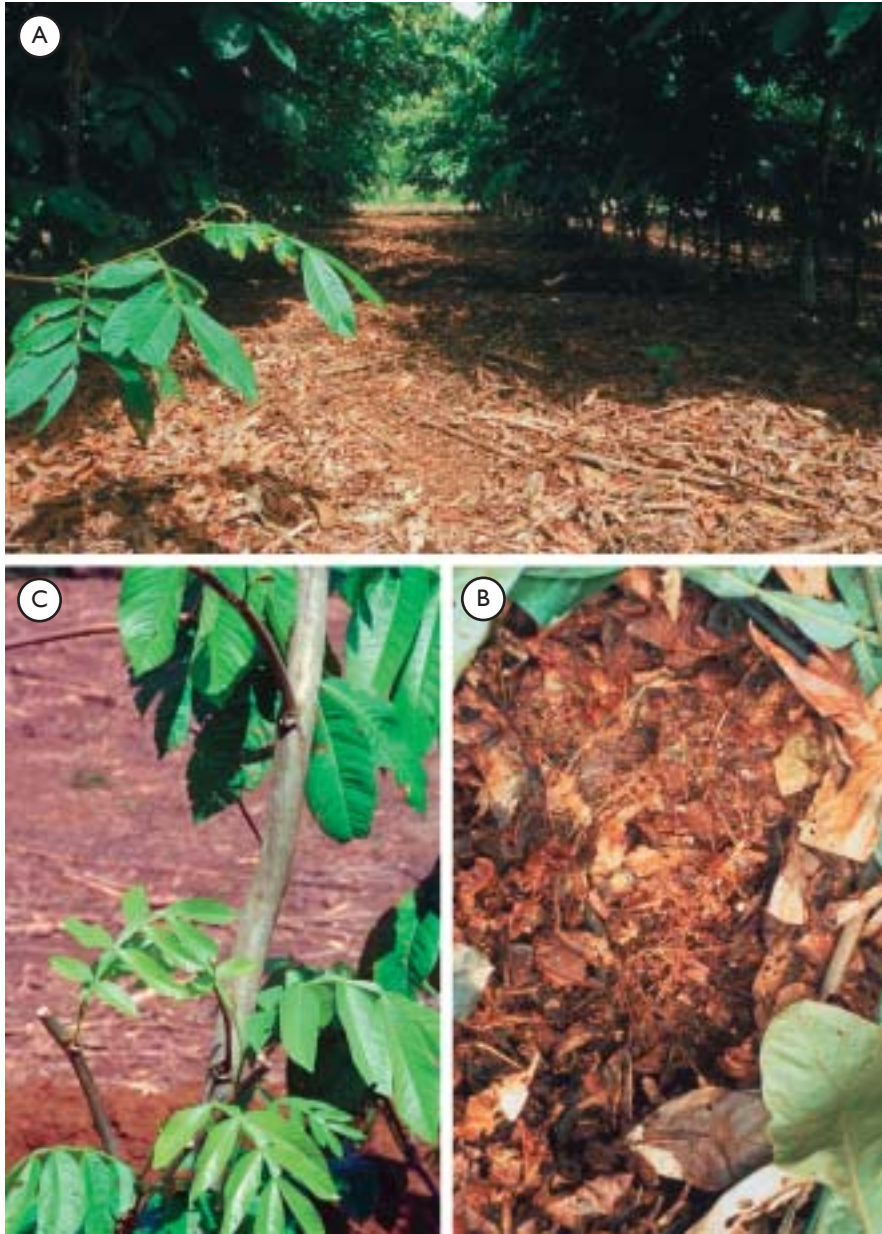
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PLATE. 4. **A** The San Juan site; May 1996. 4-metre alleys of *I. edulis*, 2 months after the removal of the previous bean-crop. No herbicides were used on any *Inga* plot at this site. The sampling quadrats contained no weed-biomass to sample. **B** Mulch of *I. edulis* scraped aside (recent and older prunings) to show fine-roots and nodules clear of the mineral soil and suffusing the mulch. **C** Management of *Inga* hedgerows: *I. edulis* 3–4 weeks post-pruning, showing older unpruned foliage (above) and the fresh regrowth from clean-cut spurs (below).
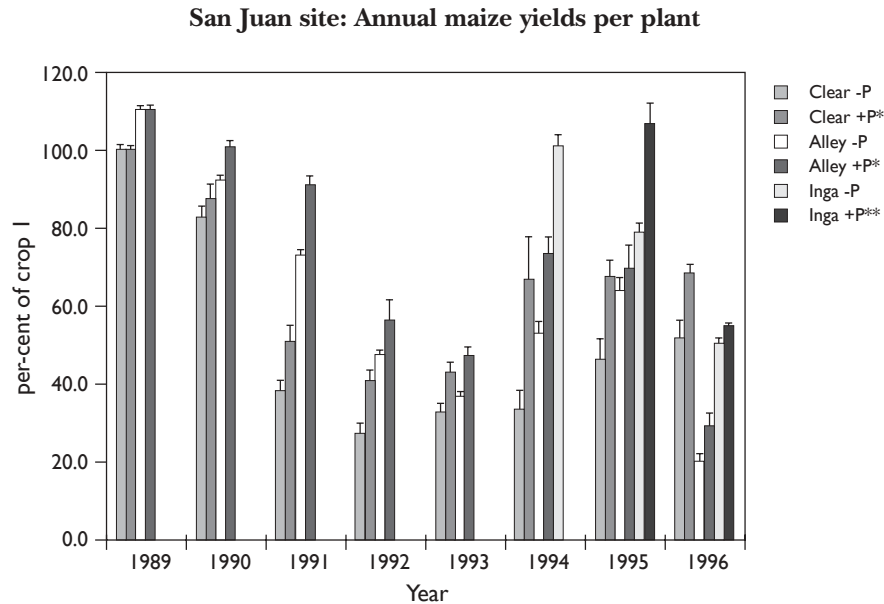
San Juan site: Annual maize yields per plant

Fig. 1. The San Juan site: **Maize** grain production under clear-cropping and alley-cropping with various hedgerow species. Annual dry-weight grain yields per plant, expressed as a percentage of the first post-burn crop. The years 1994 and 1995 included very intense dry periods followed by unusually heavy rainfall during the wetter season. It is assumed that these contrasts have produced a 'Birch effect' (Birch, 1960) on yields.

E/G Alley and clear plots; + and − rock P.

Maize grain is taken to be the critical indicator; data refer to yield per plant (strictly speaking: per "sowing-point"; usual practice is to sow 2–3 seeds at each point):

Maize (Fig. 1)
  i)   Maize yields declined in all experimental plots from the level of the immediate post-burn crop.
 ii)   Control (clear, -P) plots showed the classic post-burn decline in yields to a low steady-state in years 3–4.
iii)   Yields per maize plant responded strongly to rock P in both alley and clear treatments.
 iv)   Yields per plant in the alley +P treatment exceeded those in the clear +P plots for the first 3 years; equalled or exceeded them in years 4, 5, 6 and 7; and were significantly lower in year 8.
  v)   Sub-plot experiments within the main plots showed no yield or biomass responses to lime + cation (Mg, K) additions in year 4 following the burn. The only responses in any plot have been to rock P.
 vi)   The *E/G* alleys held 3 rows of maize at 0.75 m spacings. Depending on management, the two outer rows tended to be more or less suppressed by proximity to the tree-lines. Any yield differences were mainly provided by an enhanced performance in the centre row. The questions raised by this are examined below under "Management Options".

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Beans (Fig. 2)
  i) Bean yields were variable year-by-year, appearing to be strongly affected by seasonal factors (rainfall at a critical growth stage?). They showed positive responses to a-c in the first 5 years but dropped below their respective clear-plot yields in years 6 and 7.
  ii) As with maize, beans responded strongly to rock P applications and, for 5 years, most strongly to the alley +P treatment.

2) *Net Primary Production*
  i) All ecosystem components, except *Gliricidia sepium* in the alley plots, responded strongly to rock P.
  ii) Weed biomass production proved to be potentially the largest system component, partially replaced by the trees in the alley plots.
  iii) Weed biomass showed a strong response to rock P.
  iv) NPP was sustained at a higher level, and for longer, in the *E/G* alley + P plots, but all systems showed a decline from year 2.
  v) Prunings production in the *E/G* alleys was never sufficient to provide permanent mulch cover and declined from year 2. *Erythrina fusca* responded strongly to the rock P and came closest to providing complete cover. *Gliricidia sepium* did not respond to the rock P applications.
  vi) 5 years after the last application of rock P (Dec. 1991), most system components were still showing a residual P response.
Complete NPP data, over 6 years, are to be published separately (Hands & Bayliss-Smith, in prep.)

3) *Weeds*
  i) Weed growth, in spite of a rigorous weeding regime, was the largest system component in the clear plots.
  ii) Weed growth, without rigorous slashing and spraying, would rapidly have overwhelmed the clear plots by the end of year 1.
  iii) If the cropping and pruning regime had been reduced to one episode per year, weed growth in the alleys would have been suppressed by a combination of mulch and shading.
  iv) Weed growth responded strongly to rock P additions.
  v) Weeds in the clear plots were comprised of almost 100% grass species (*Paspalum sp.*; *Panicum sp.*); whereas weeds in the alleys were comprised of more herbaceous species (which are easier to control with a machete).
  vi) Weed-growth in the alleys was significantly suppressed by the more recalcitrant *Erythrina fusca* mulch during the first (2–3) years; thereafter increasing as mulch production declined in the *E/G* alleys.

Inga edulis alleys at the La Conquista site (Plates 2B–D)
  i) At La Conquista, the 2.5 m alley width with *I. edulis* proved too narrow for maize.
  ii) The highest bean yields were in these alleys.
  iii) Beans in the *I. edulis* alleys showed no signs of root-knot nematode (*Meloidygone sp.*) infection, whereas bean roots in all other treatments were commonly infected. Root knots were present in *Erythrina fusca*, but were absent in *Gliricidia sepium* and *I. edulis.*

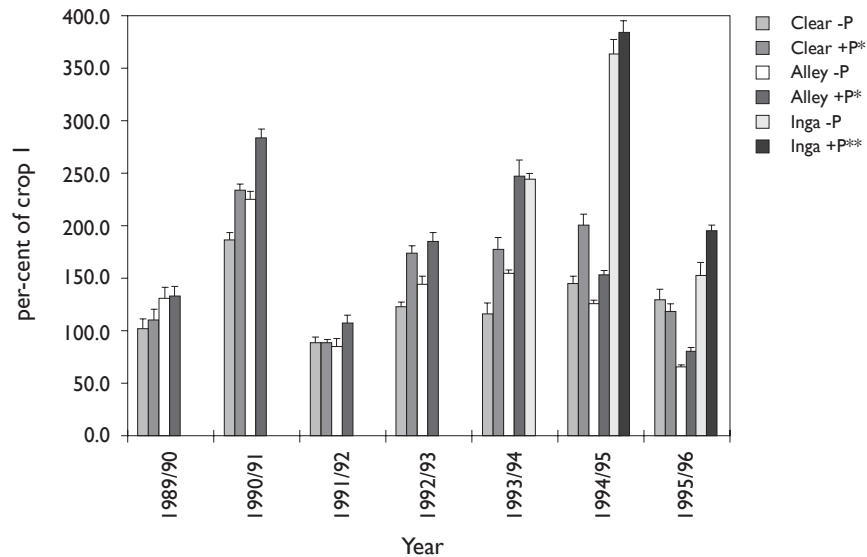**San Juan site: Annual bean yields per plant**

FIG. 2. The San Juan site: Bean grain production under clear-cropping and alley-cropping with various hedgerow species. Annual dry-weight grain yields per plant, expressed as a percentage of the first post-burn crop. Bean yields appear to highly variable year-to-year; probably due to seasonal factors such as rainfall or insolation at a critical time in the growth period. No long-term trend is discernible in these data, but yields have responded strongly to both alley-cropping, especially with *Inga*, and to rock phosphate. This is a very important and valuable basic grain crop in Central America.

iv)   Weed biomass was virtually zero in the *I. edulis* alleys; the soil was permanently covered by mulch.

v)   Those few weeds that were able to establish through the *I. edulis* mulch shared the same shallow-rooting characteristic as the trees and crops; because of this they were easily hand-pulled.

vi)   Data for total biomass production in the tree components of the *E/G* and *I. edulis* alleys (excluding fine roots) showed great differences between the two alley types; NPP in the *Inga* for year 3 was approximately 25 tonnes per ha compared to 5.1 for the *E/G* alleys (data in Hands *et al.*, 1995).

Inga alleys at the San Juan site

Alleys 4 m wide; inter-tree spacing 0.5 m, 8 *Inga* species tested. Sub-plot treatments established in *I. edulis* alleys: with and without phosphate; 100 kg P per ha, as rock P.

i)   Both maize and beans grown in *I. edulis* +P sub-plots maintained variable, but acceptable, grain yields for the 3 years which were monitored before the site was abandoned.

ii) *Inga edulis* foliage (leaf and stem prunings) responded to rock P applications both in biomass produced and in P content (Hands, unpublished data). Significant additional quantities of P were thus recycled through the mulch (see Table 6).

iii) Weed-control was virtually 100% in all *Inga* plots (see Plates 3B–D, 4A).

iv) Biomass production of prunings was maintained at a high and sustainable level over the 4 years of monitoring; some species were exceptionally productive (see data below) and all *Inga* species were significantly more productive than the *E/G* alleys.

v) As at the La Conquista site, beans responded particularly well to being grown in the *Inga* alleys.

vi) Informal observations indicate that a much higher biomass and diversity of invertebrates are to be found beneath the permanent mulch of the *Inga* alleys compared to the transient mulch cover of the *E/G* alleys. This could be an advantage or a disadvantage, but could be a factor in the mortality of weed seeds beneath the mulch.

vii) The 1991/92 bean sowing was virtually destroyed by slugs in the main *E/G* and clear plots. Beans growing in the only extant *Inga* alleys (*I. edulis*) were not attacked.
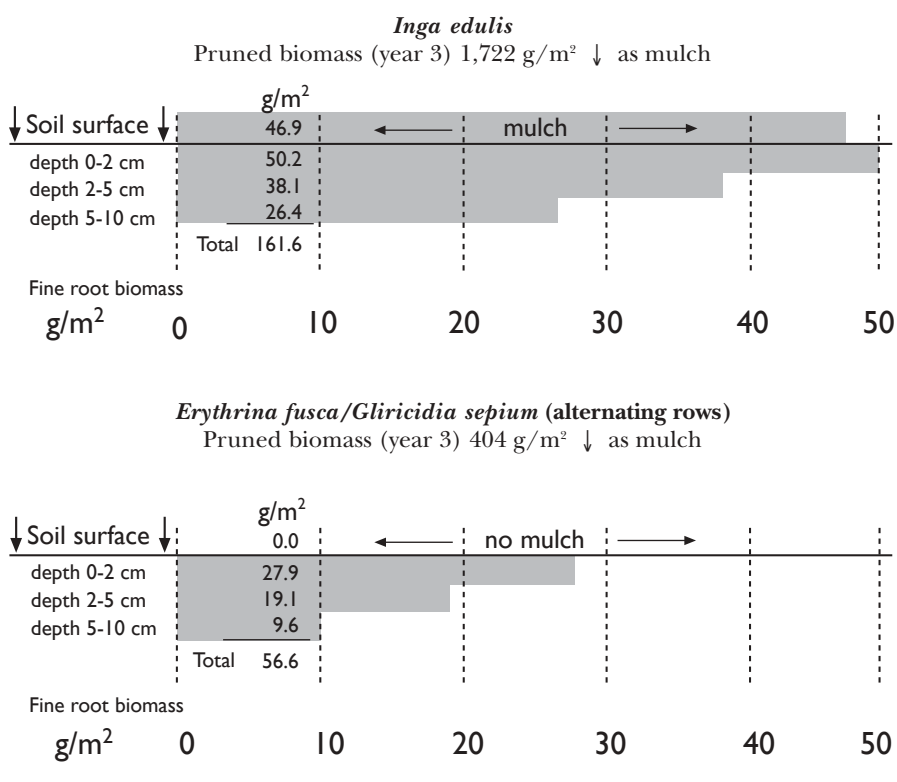
Fine root distribution and die back

In the *Erythrina fusca/Gliricidia sepium* alleys, corings taken before and after pruning showed that dieback resulting from pruning in the finest roots amounted to almost 100% in the uppermost layers (Hands, unpubl. data). As a first approximation, relating this input to foliage accumulated over the same period between prunings, gave a figure for below ground inputs as some 12% of leaf biomass. More data would obviously be desirable, but little information has hitherto been available, and serves as a best estimate for the time-being. As a high proportion of this input is comprised of nodules, it could represent an important source of readily-decomposed nutrients. Similar information relating to inputs in the *Inga* alleys is lacking. Corings taken at the La Conquista site shortly before the experiments were abandoned, yielded an interesting picture of the differences in fine root distribution between the *E/G* and *I. edulis* alleys under identical configuration and management (Table 4; Plate 4B)

DISCUSSION

These basic experiments took the form of a comparison between clear-cropping and alley-cropping within alternating rows of the legumes *Erythrina fusca* and *Gliricidia sepium*. The distinction between these two systems was somewhat artificial insofar as rigorous weed control was imposed upon all plots in order to allow differences in nutrient-supply to become expressed in crop yields. Because of very intensive weed-slashing, the comparison is actually that between two high OM-input systems; one based upon the slash-and-mulch of weed biomass; and the other based upon the prune-and-mulch of NFT foliage. In this sense, the hedgerow trees may be viewed as woody "weeds" under the farmer's control. Given the high levels of OM inputs in both systems, it is surprising that any yield differences were observed at all.

TABLE 4. Nitrogen-fixing Trees in Alley-cropping configuration. La Conquista. Sarapiqui. Costa Rica. (2.5 m alleys; 0.4 m within-row spacing (10,000 trees per ha); year 3). Distribution of fine root biomass between mulch and soil layers. Grams (dry-weight)/m². Species differences: *Inga edulis* and *Erythrina fusca/Gliricidia sepium.*

Inga edulis
Pruned biomass (year 3) 1,722 g/m² ↓ as mulch

	g/m²					
↓Soil surface ↓	46.9	← mulch →				
depth 0-2 cm	50.2					
depth 2-5 cm	38.1					
depth 5-10 cm	26.4					
Total	161.6					

Fine root biomass

g/m²   0   10   20   30   40   50

***Erythrina fusca/Gliricidia sepium* (alternating rows)**
Pruned biomass (year 3) 404 g/m² ↓ as mulch

	g/m²					
↓Soil surface ↓	0.0	← no mulch →				
depth 0-2 cm	27.9					
depth 2-5 cm	19.1					
depth 5-10 cm	9.6					
Total	56.6					

Fine root biomass

g/m²   0   10   20   30   40   50

*Core-sampled Oct. 1992; 5 months' regrowth since pruning

Those differences that were actually observed seem to have been due to an enhanced P nutrition in the alley system (Hands *et al.*, 1995), coupled with the likelihood that the *E/G* foliage, and accompanying fine root dieback, contained more nitrogen.

The real-life situation is very different. Few, if any, farmers would sustain weed-slashing, without herbicides, in the open plots, beyond the end of the first year. Common practice, in the absence of fresh forest fallow in which to "shift", would be to leave the weeds and second-growth for 2 or 3 years, if space allowed; then to reslash-and-burn. This would probably provide a crop, albeit a reduced crop, to satisfy the urgent short-term need; but it is an essentially consumptive strategy which is seen widely to fail in the long-term. The *E/G* hedgerows, at 2.5 m alley width, were unable to maintain a mulch cover beyond a few weeks, whereas the *Inga* hedgerows, at 4.0 m width were able to maintain a permanent cover within 12–16 months of transplanting from the nursery.

Trials on farmers' fields; early impressions

Trials of *Inga* A-C with farmers, as a follow-up to the more scientific phase described here, are (1997) only at a developing stage, but farmers have seen a number of demonstrations in the experimental plots which are now mature and fully-functioning. The indigenous farmers with whom the trials (40) have begun, appear to regard a fairly wide spectrum of yields as acceptable, but the factor that does appear important is the virtual elimination of weeds in the *Inga* alleys. At demonstrations in the San Juan site, the health, appearance and pod-loading of the individual bean plants interested them greatly, but they were unconcerned with the fact that the space occupied by the tree lines would inevitably reduce yields *per hectare* of whole system. Compared to the problems of access to forest fallows, the inclusion of perhaps an additional 10–20% of land in order to accommodate the same number of maize plants in an alley system appears not to concern them. Yield-per-plant or, more precisely, yield-for-effort appears to be the important criterion with them. It does seem clear that, although questions of sustainability must inevitably hinge upon nutrient retention and cycling, the most immediate concern of farmers, and their proximal reason for shifting, lies in the intolerable burgeoning of weeds in their swiddens.

One unexpected comment came from some collaborating indigenous farmers in Honduras, to the effect that a-c might constitute a "mejora", under Honduran law, this is a legal instrument which could strengthen their claim to tenure-of-use of the land they occupy.

Crop pests

In the main San Juan trial plots, the 1991 (Dec.) bean crop was destroyed, shortly after germination, by slugs. However, beans sown in the *Inga* alleys were unaffected. The immediate solution was to deploy metaldehyde, protected within short lengths of bamboo, and to resow the beans. The key difference between the plots appeared to be that the slugs had been able to subsist throughout the previous year on weeds in both the open and *E/G* alley plots; whereas the *Inga* plots were both weed-free and slug-free. The slugs had been, if anything, favoured by the temporary protection of the sporadic *Erythrina* mulch during the occasional dry spells which are normally experienced earlier in the year during the period February to May.

The importance of surface-rooting in Inga

The paramount importance of surface-rooting to *Inga* was illustrated by two occurrences in the La Conquista site. As part of an investigation into VA mycorrhizal spore density and distribution, surface soil was removed to a depth of 5 cm only, and for a distance of 5 m along one side only, of one of the *I. edulis* hedgerows. The result was a severe (75%) reduction in foliage production, during the ensuing weeks, of all the 10 tree stems affected, and the deaths of 3 of those trees. This occurred even though the trees were able to continue normally on the unsampled side. A later soil-sampling alongside another section of hedgerow produced an identical suppression of foliage regrowth.

Care in pruning

Reports from CATIE (Sanchez, pers comm.) and elsewhere (Cochabamba, Bolivia), suggested that *Inga* species are unsuitable for use in a-c as they cannot withstand coppicing. This was not found to be the case in these trials, provided that care is taken to minimise the impact of the pruning and that no attempt is made to remove 100% of the foliage at any one time (Plate 4C). As far as is known, the energy-drain on an individual *Inga* tree can be high; not only does the tree have to support its own metabolism and regrowth, but also, the symbiotic load of the nodules, VA mycorrhizae and nectar production. It was found not to be necessary to strip the tree completely.

Connected with this, an investigation in the *E/G* alleys into fine root densities and distribution in surface-soil layers, revealed a high mortality, approaching 100%, of the finest roots (< 1 mm approximately) following pruning. Slightly coarser roots (> 2 mm diam. approx.), rising from the main laterals at approx. 10 cm depth and which appear to be conducting tissue, survived intact. It may be that the energy-drain on the tree following pruning is too great to support the VAM and that the only way of reducing that drain, once the fine roots are VAM-infected, is by dieback. Without exhaustive experiments, the measure adopted during these projects, i.e. the leaving of 5–10% of foliage at each pruning, appeared to work.

Sustainability in pruned biomass production

Trees grown in the stressful, and relatively exposed, conditions of the alley system are likely to be more subject to variations in climate than those in the protected and more-constant forest environment; also, the timing and frequency of pruning will affect annual NPP (see below under "Management Options"). The NPP data given here (Table 5) result from a somewhat intense, but consistent, pruning regime; and, although it would be desirable to continue the monitoring over as long a period as possible, these pruning data from 7 *Inga* species, over 4 years, shows no apparent diminution in annual productivity and far exceed those of the *Erythrina* and *Gliricidia* from the main plots. This, at least, is one indicator of sustainability

Alleys of *I. punctata* were established later than the others at San Juan and data derived from them are thus not strictly comparable, but this species required a long period for establishment at the San Juan site. It may be that provenance is important with *I. punctata*, as other trials (not reported here) in Honduras are showing that seedlings grown from riparian sources (richer soils) are failing to establish well in more-acid upland soils nearby.

Ability to export Phosphorus in the form of grain

In soil conditions and ecosystems which are P-limited, one possibly useful criterion for the evaluation of any agricultural system is its ability to export that limiting nutrient as grain. Similarly, efficiency of retrieval and recycling could be a useful criterion for forestry sytems which do not export P in such an immediate way. A long series of P content and biomass determinations on material from the San Juan site is still underway (1997), and will be the subject of a separate publication (Hands, in prep.). However, some provisional data are included here which lend support to these ideas (Tables 6 and 7).

TABLE 5. Alley-cropping; La Conquista and San Juan sites. Lowland Humid Tropics, Costa Rica. Accumulated biomass of prunings (Branch + foliage) over 4 years: g (DW) per metre of hedgerow. Growth periods from transplanting date. * Mean value of two species in alternating rows. s.e. = standard error.

| SPECIES | CONFIGURATION | SITE | g (dry weight) of prunings (branch + foliage) per m of hedgerow | | | | | | | | | |
			12 months' growth	s.e.	20 months' growth	s.e.	24 months' growth	s.e.	36 months' growth	s.e.	48 months' growth	s.e.
I. edulis	4.0 m alley width × 0.5 m (5,000 trees/ha)	San Juan	2,290	88	6,773	381	7,869	386	11,108	430	14,632	462
I. oerstediana	"	"	4,486	750			10,742	938	16,012	967	21,192	995
I. goldmanii	"	"	2,074	152			4,151	265	6,950	309	9,060	332
I. spectabilis	"	"	1,690	105			3,973	242	7,054	336	11,534	376
I. densiflora	"	"	728	84			3,702	247	9,878	485	13,344	524
I. marginata	"	"	3,520	295			6,158	400	10,188	515	13,572	532
I. samanensis	"	"	2,507	127			4,864	325	8,304	395	11,576	432
Erythrina fusca	2.5 m alley width × 0.4 m (10,000 trees/ha)	"	1,190	42	2,370	54	2,735	63	4,022	74	4,915	81
Gliricidia sepium	"	"	770	25	1,934	41	2,720	60	4,837	76	6,290	88
Erythrina/Gliricidia*	"	La Conquista	n.a.		2,150	75	n.a.		3,436	72		
I. edulis	"	"	n.a.		5,925	260	n.a.		10,275	356		

TABLE 6. San Juan site 1995; Phosphorus (P) returned to the soil as prunings or slashed material: Selected *Inga* alleys compared to clear control plots; with and without added rock phosphate. Kg/ha/yr.

TREATMENT		MATERIAL	Kg P/ha/yr	s.e.
			Returned to the soil 1995 ↓	
Control plots	-P	Weed a-g biomass *	3.32	(0.12)
Control plots**	+P	" "	7.97	(0.33)
Inga alleys; 4.0 m				
I. edulis	-P	Leaf + branch prunings	27.66	(1.50)
I. edulis***	+P	" "	37.30	(0.77)
I. oerstediana	-P	" "	41.43	(1.56)
I. marginata	-P	" "	27.97	(1.72)

*above-ground biomass. ** 100 kg P ha^{-1} added as rock phosphate. *** 100 kg P ha^{-1} added; Dec. 1994, as rock phosphate.

TABLE 7. Alley-cropping with *Inga* versus Clear-cropping in P-deficient soils; with and without additions of rock phosphate. The ability of the systems to export phosphorus in the form of grain.

San Juan site; 1995; Kg P/ha/year

Plot Type	Control (clear-cropping)		*Inga edulis* Alleys (4 m width)	
Treatment: + or - rock P →	-P	+P	-P	+P
Plants/ha				
Maize*	21,333	21,333	13,333	13,333
Beans*	60,000	60,000	56,250	56,250
P exported in grain; Kg/ha:				
Maize	3.30 (0.80)	6.62 (0.78)	3.85 (0.22)	6.54 (0.73)
Beans	2.42 (0.26)	3.13 (0.34)	4.55 (0.32)	6.18 (0.37)
Total	5.72 (0.84)	9.75 (0.85)	8.40 (0.39)	12.72 (0.82)
	↓	↓		
Total P exported in grain per unit of cropped area alone: Kg/ha	5.72 (0.84)	9.75 (0.85)	11.01 (0.49)	17.06 (1.23)

Standard errors in parentheses.

* Spacing within and between rows of crop plants: Maize: 0.75 m; Beans: 0.4 m. In the alley system, the 4.0 m alleys contain 5 rows of maize (sown in June) or 9 rows of beans (December).

In leached, P-deficient soils, both grain yield and Phosphorus content of the grain vary according to treatment. The ability of the system to export P in the form of grain is thus a more useful index of performance than yield alone. In this example (San Juan site; 1995), the phosphorus economy of the *Inga* alley system is clearly superior to that of clear-cropping, in spite of the fact that the latter is recycling significant quantitites of P through the weed component.

In the alley plots, one row of crop is substituted by one row of trees. Judging by the biomass production of the *Inga*, this, if anything, would appear strongly to bias the data in favour of the control plots, as it is likely that the crop rows adjoining the hedgerow will experience higher levels of below-ground competition in addition to shading. On the basis of cropped area alone, the *Inga* system is exporting significantly more P as grain than either control treatments (Table 7). In all the *Inga* alleys, the amounts of P returned to the soil as mulch (Table 6), and released by decomposition during the 3-month growth period of the maize, are commensurate with the amounts exported in a normally acceptable maize crop; this ignores the possibly significant amounts returned in fine root dieback. Whether such P is truly available to the crop is, of course, not proved by the data; but, at least, by this criterion, the *Inga* alley system possesses the fundamentals of sustainability.

THE DESIGN AND MANAGEMENT OF ALLEY CROPPING SYSTEMS USING *INGA*

System variables within the control of the farmer
1) Choice of species: As argued above, more-durable mulch species are desirable; but mixtures are feasible and might include a proportion of readily decomposable foliage species such as *Gliricidia sepium*, which is very well-known throughout Central and South America. The research project reported here has trials of pepper (*Piper nigrum*) grown on living supports of this species, between hedgerows of *Inga*. The pepper receives no agro-chemical inputs whatsoever and, in a weed-free environment, appears to be thriving.

The first choice *Inga* is likely to be the commonest local provenance; and commonly, the *Inga* species grown for shade over coffee or cacao. However, *I. edulis* is not endemic to Central America, yet appears to have undergone a widespread and spontaneous local adoption as an easily-established shade species.

There exists a wide spectrum of choice within which to choose, and alley-cropping systems with *Inga* appear to be rather forgiving, provided they are pruned with care.

2) Within-row density: Although more detailed work is needed, the indications are that, above a certain planting density, foliage production in an alley hedgerow tends to stabilise at a certain level per metre of hedgerow, while decreasing per tree stem. A useful spacing in the La Conquista and San Juan sites appeared to be about 0.5 m, which allows for some sporadic mortality without compromising mulch production; however, this was a somewhat intuitive choice.

3) Alley width: A balance needs to be struck between a wider spacing to minimise competition between the trees and crops and a narrower spacing to maximise weed-control; the working assumption being that the latter is the dominant factor. A general rule-of-thumb would then be: "As wide as is compatible with sufficient mulch production for permanent cover". Any over-dominance by the tree component can be controlled by varying other management practices, such as pruning height or frequency.

The 4.0 m alley width for the *Inga* at the San Juan site was also an intuitive choice based upon experiences at La Conquista. The most productive species of the San Juan trials (*I. edulis*; *I. oerstediana*) should be able to achieve permanent mulch cover at 5 m alley width.

4) Alley alignment: It can be argued that, in equatorial regions, an ideal alley alignment would be East-West, because this is likely to impose more competition for sunlight within tree rows than between the trees and the crops which will be in sunlight for most of the day. This could be important for maize, but beans at both the La Conquista and San Juan sites appeared little affected by a degree of shading, as the sun, in the Northern winter, swung to the southward of the hedgerows.

However, the need for a contouring alignment to counter the risk of erosion on slopes may override this ideal; and this factor, in turn, implies that greater care needs to be taken to reduce shading. It seems, therefore that decisions of this nature need to be integrated with other management variables; such as: "If there is a risk of shading from contoured tree lines, then reduce stem-height or increase pruning frequency".

5) Hedgerow height: The higher the stem, the greater and more rapid will be the recovery of foliage; and, probably, the more resilient the tree; whereas, the lower the stem is pruned, the fewer the available nodes for regrowth. *Inga* appears to require a moderate-to-high stem. Pruning-height and frequency are probably the easiest ways of altering the dominance or "presence" of the tree component in an alley system. The height options thus fall within the range: a) to favour the trees and mulch production, as high as is feasible (say up to 1.75 m); b) to disfavour the trees, coppiced low to the ground (but the suggested minimum with *Inga* would be about 1 m).

6) Pruning regime (Table 8): In practice, the timing and frequency of pruning are likely to reflect cropping needs, rather than any agenda set by the trees themselves; but there are some exceptions. For example, if experience shows that an alley system may only sustain one crop per annum, then tree growth in the period between crops may, in the case of some *Inga* species, be very vigorous, leaving few branches and little foliage on the lower stem. This, in turn, may leave the stem bereft of foliage when pruned back to the working height. (*I. edulis* at the La Conquista site grew to over 4 m in 9 months from transplanting). In this instance, it is advisable to carry out the pruning in two phases. It may be preferable to cut out the leading central stem, reducing shading and allowing the lower stem to resprout before pruning back the side branches. However, this may not permit enough light to strike low enough on the stem for this to happen. Alternatively, it may be better to cut out all the side branches over the final pruning height, thus leaving the central leader to maintain the tree whilst the lower stem resprouts. When this is clearly under way, the leader (called a "chimenea" in Costa Rican cafetales) can be taken out. The aim would be to time the second pruning for a week or two before the planned crop-sowing; this, in turn, implies a first-phase pruning some month to six weeks earlier. All this would have to harmonise with local

TABLE 8. Pruning frequency in alley-cropping; a spectrum of effects.

Frequency of pruning	
Low	**High**
Greater dominance of the system by the tree component	Lesser role of the tree component
Greater shading of weeds Less smothering of weeds by mulch	Lesser shading of weed More smothering of weeds by mulch
The greater overall production of pruned biomass	Less overall production of pruned biomass
Greater proportion of woody biomass in the prunings	Greater proportion of leaf biomass in the prunings
Greater likelihood that 2-phase pruning will be necessary	Little likelihood that a 2-phase pruning will be needed
The possibility that the system will produce firewood	The probability that the system will not produce firewood

perceptions as to what are, or are not, good pruning and sowing times. In any case, a light pruning will be needed to reduce competition perhaps some 4–6 weeks into crop growth.

As outlined above, manner of pruning is very important to the survival of the trees and any attempt at a 100% foliage removal will involve the risk of killing the tree. Similarly, the damage and ripping associated with pruning too close to the main stem must be avoided. Clean cuts with sharp tools, together with the leaving of short spurs, with some foliage, minimises this risk; also, the branches of some *Inga* species (e.g. *I. marginata*; *I. samanensis*) are characteristically more slender and appear to suffer much less setback as a result of pruning. It is hoped that more detailed knowledge of the pruning-tolerance of the species groups may be gained in the future.

7) Soil supplements

Rock Phosphate. As argued above and elsewhere (Palm *et al.,* 1991; Hands *et al.,* 1995), the minimum condition for any low-input, sustainable agricultural system, as a stable, alternative subsistence strategy to shifting cultivation, will be that maintenance supplies of phosphorus will have to be made cheaply available. For a number of reasons, the obvious source of this phosphorus input is rock phosphate; and it is suggested that this is more efficiently applied to the mulch in an alley system, rather than to the soil itself. At a national or regional scale, the logistical difficulties of this are clearly very great and involve social, political and economic issues which go far beyond the scope of this text; the condition itself is, however, ecological in nature (i.e. pertaining to plant ecology) and non-negotiable.

Lime. In addition to rock phosphate, one further long-term ecological condition which may have to be fulfilled on an acid soil relates to slash-and-burn agriculture itself.

One aspect of the short-term success of a slash-and-burn operation in a rain-forest swidden lies in the effect of the ash upon the accumulated organic reserves of the soil (SOM). In short, SOM that may be turning over very slowly may undergo an accelerated decomposition due to a temporary change in the pH of the immediate surface soil (Hands, 1988; Hands *et al.*, 1995). It is the release of N and P associated with these reserves that may be the key process in swidden agriculture. In a green mulch system such as A-C with *Inga*, it is likely that, over time, the soil will accumulate a wide range of SOM types with many differing decomposition characteristics. It could prove to be necessary for well-sustained maize yields, for example, that this pH-effect of the ash will have to be simulated, not by burning, but by lime or dolomitic lime (for the magnesium); and, possibly, by some source of potassium. The expectation is that A-C will retain and recycle these supplements better than any bare-soil alternative.

There is wide scope for experiment with all these options and experiences with *Inga* in alley-cropping indicate that these systems are rather flexible, resilient and forgiving. Supplements, as described above, are, of course necessary for long-term sustainability; but the system does not appear to collapse if they are witheld for a year.

The uses of *Inga* in the reclamation of degraded soils; abandoned pasture; etc.

The need to rehabilitate soils that were formerly under forest, and that have since degraded as a result of exposure and use as cattle rangeland, appears poised to become one of the priorities of the future. In this case, the hope would be that nitrogen-fixing tree species, whether planted in alleys or at "nurse tree" spacing for reforestation, can begin the process by which the soil's condition and OM-content can be returned to a state more closely resembling that of the original forest. *Inga* are light-demanding forest gap species (Pennington, this volume) and, although not pioneer colonisers of open-ground, they can function as such, once they are established as seedlings; some species do this very effectively. However, the system cannot fulfill the functions that are ascribed to it here unless its roots can encounter nutrients for retrieval and recycling. It thus appears very likely that the use of *Inga* in this remedial role, and with cropping as a desired goal, will require the help of soil supplements; a conclusion also reached, in the more general context of managed fallows, by Sanchez (1987) and Palm *et al.* (1991).

The project of which the Co-operativa San Juan and La Conquista trials comprised an early phase has begun a trial on a soil which has been exposed for 12 years since burning and which now appears to consist of bare, red sub-soil. The initiative for this came from the farmer himself who considers that he now has no other option than to give alley-cropping a trial. Given the long fallows which would be considered normal in indigenous shifting agriculture, the *Inga* alleys will face a protracted struggle, even to establish themselves, and leaving aside, for the moment, thoughts of crop production.

Also, a number of A-C experiments, reported in the literature, on open, but much less degraded soil contexts, have been maintained for some years before showing any yield response.

In this extreme, but nevertheless increasingly widespread, example, the addition of cheap sources of P, Ca, etc., could be enough to stimulate foliage production to a level capable of providing adequate mulch; which, in turn, would raise the fine root system; which, in turn, would use the supplements with increasing efficiency. Eventually, gradually increasing influence of the mulch should begin the replenishment of the soil's OM-content and quality to the state in which it had originally been 12 years before. This is the theory behind the trial.

The species in question here are *I. oerstediana* and *I. marginata*, in alternating rows; and both of local provenance. Both are readily available as seedlings taken from beneath the parent trees for transplanting into forestry bags, and later into the hedgerows. In common with the experiences outlined above at the San Juan site, and also elsewhere (Pennington, this volume), *I. oerstediana* has proved itself a very aggressive pioneer of open ground and seemingly outstandingly tolerant of soil acidity. *I. marginata* appears to need a little more help in early weed control, but once established, also appears excellent as a less aggressive A-C species; its root nodules are larger than those of *I. edulis* or *I. oerstediana*; moreover, its finer branching habit renders it more tolerant of pruning than most *Inga* species under trial at San Juan (see also Neill & Revelo, this volume, on the use of *Inga* for the control of old pasture).

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