

The Fate of Organic Matter and Nutrients in Agroforestry Systems

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Abstract

Agroforestry systems are intermediate between forest ecosystems and agricultural systems, and exhibit some of the nutrient cycling and environmental services of natural systems and a complementarity-competition balance between trees and crops. This paper reviews how the status of nutrients and organic matter are affected by the inclusion of trees in agricultural systems and indicates some focal points for needed research. Nutrient pumping from deeper soil layers, and scavenging leached nutrients through horizontal root development, may significantly increase the overall supply and efficiency of nutrients. But nutrient pumping is limited in humid, strongly acid soils, where the contribution of P by trees usually is far below crop P requirements. Selection of trees with a deep rooting pattern and limited horizontal root development will be enhanced by more convenient methods developed recently based on fractal analysis. Fallow-rotation hedgerow systems, a variant intermediate between a simultaneous and a sequential agroforestry, hold promise to overcome some of the limitations of continuous alley cropping. Expectations of an increase in soil organic matter content in agroforestry is dependent on the amount, source, and management of the pruning biomass. Crop performance in association with N-fixing tree species often is not superior to that with non-fixing species, suggesting that N-fixation should not be over-emphasized in relation to characters that reduce competition between trees and crops. On sloping land there is a dramatic redistribution of soil fertility across the alleyways in contour hedgerow systems. This is a serious challenge to the sustainability of yields in these systems. Little effort has been expended in understanding nutrient cycling in the many farmer-developed agroforestry systems employed on millions of hectares. The fate of nutrients and soil organic matter in them is poorly quantified. Recognizing the pathways of agroforestry systems evolution in response to the availability of external nutrients may be a useful point of departure for research on the fate of nutrients in a practical context.

Introduction

Agroforestry systems deliberately combine woody perennials with crops or animals in spatial or sequential arrangements. The tree and crop components experience significant ecological and economic interactions (Nair, 1993). Because the

ACIAR. 1995. Management of Soil Organic Matter for Sustainable Agricultures in Asia. Australian Centre for International Agricultural Research, Canberra (forthcoming)

structural characteristics of agroforestry systems are intermediate between forest ecosystems and agricultural systems, there are great expectations that they can replicate many of the nutrient cycling and environmental services of associated with natural forests, yet deliver exportable yields equivalent to or exceeding those of conventional agriculture. Testing the validity and limits of this premise is the driving force behind much current research.

Agroforestry encompasses a very wide range of land use systems. Examples of spatial associations of trees and crops include hedgerow intercropping (or alley cropping), trees on the boundaries of crop fields, trees managed in cropland, and mixed perennial systems as in complex agroforests and home gardens. Examples of sequential associations include fallow rotation systems with natural or improved tree components, as occur in shifting cultivation, and tree plantation establishment after cropping with annuals.

Conventionally, trees are viewed as helping to improve nutrient cycling and nutrient retention in agricultural ecosystems by performing a number of functions related to increased resource conservation (Buresh, 1994). Among the benefits relevant to the cycling of nutrients and the maintenance of organic matter are (Young, 1989):

- 1) nutrient pumping from the subsoil by deep-rooted perennials,
- 2) reduction in leaching losses through capture of mobile nutrients by capture of mobile nutrients by the well-developed rooting systems of perennials (ie. nutrient safety net),

- 3) addition of nitrogen through biological nitrogen fixation by perennials,
- 4) maintenance of soil organic matter through supply of above- and below-ground litter and prunings from the perennials,
- 5) better maintenance and improvement of soil physical properties and, 6) enhanced protection from soil erosion.

But there are also negative repercussions, and the forces that drive the complementarity-competition balance between trees and crops are complex. A recent approach (Ong and Huxley, 1995) is to quantify the overall tree-crop interaction (I) by:

$$I = F + P + L - C \pm M$$

where F is the benefit of the organic inputs contributed by the trees, P is the consequence of changes in soil proportion, L is the reduction of losses in nutrients or water on sloping land, C is the yield reduction due to interspecific competition between the trees and crops for nutrients, water and light. M is the consequence of changes in microclimate due to the presence of the trees. All terms are expressed in terms of changes in crop yield compared to open field controls (kg/ha or percentages).

F incorporates the first three benefits listed above: Nutrient pumping (1), the scavenging of leached nutrients (2), and N-fixation (3). P includes the benefits of increased organic matter(4) and improved soil physical properties (5), which are

also mediated partially by soil organic matter. L considers the positive effects of reduced erosion (6). F and C are usually the dominant counterbalancing factors, and their magnitude is often closely associated with each other. Although P, L, and M are sometimes large, their effects on crop yield are relatively unimportant in the short term (Akyeampong et al, 1992). The individual factors, particularly F and C, can be quantified in adequately designed experiments (Ong and Huxley, 1995).

This paper reviews how the status of nutrients and organic matter is affected by the inclusion of trees in agricultural systems. Emphasis is placed on the practical significance of these benefits, in light of the associated competitive effects (C) that tend to reduce or negate them. The paper concludes with a discussion of the pathways of agroforestry systems evolution in response to a fundamental soil fertility factor: Whether external nutrients are available to the farmer or not.

Nutrient pumping

Since trees have deeper root systems than annual crops, it has long been suspected that they absorb significant quantities of nutrients from the subsoil, which are deposited on the surface soil via litter, pruning production, or decay of shallow roots (Nair, 1984; Glover and Beer, 1986; Young, 1989). This translocation process will increase the stock of nutrients available to the shallower-rooted crops grown in association, thus increasing system yield. This "nutrient pumping" function is now frequently cited as a promising benefit of the tree

component in agroforestry systems (Buresh, 1994). The process would be particularly useful in concentrating at the soil surface more of the relatively immobile nutrients such as P and Ca. The cycling of P in organic forms would also be expected to increase its availability.

The practical question is whether nutrient pumping occurs to such an extent that it is economically important? Or is the effect masked by competition for nutrients or water between the deeper and shallower-rooted components?

The idealized system is conceived as a combination of tree and crop genotypes that exploit the growth resources of the soil volume fully, while minimizing competition (Figure 1). Complementarity exists if the trees and crops take up nutrients from different zones of the soil profile.

Trees do have a tendency to root more deeply into the soil profile, and to extract growth resources from below the maximum rooting depth of annual crops. Many tropical trees develop roots extending 4 m deep or more (Jenik, 1978). However, in the humid tropics most rooting depth studies (Szott, 1995) show relatively shallow rooting depths for the common multipurpose tree species, with a range frequently between 40 to 200 cm. In both agroforestry and natural ecosystems in the humid tropics the majority of tree roots in many cases are found in the top 30 cm of soil (Szott, 1995). Lateral root extension in younger trees was found frequently to be between 1 and 4 m.

There are only a few studies that have estimated the locus of nutrient uptake experimentally. Results of ^{32}P studies from various sites (IAEA, 1975) on cacao, coffee, and banana, a large proportion of the uptake of P (30-85%) originated from the superficial zone close to the stem (less than 30 cm depth and less than 100 cm laterally from the base). However, in the case of coconut and oil palm P uptake from this zone was less than 20%. The percentage of P uptake from points farthest from the stem (usually > 45 cm depth and > 1.5 m lateral distance from the stem) was less than 4 % for the majority of the tree crops. Such levels would not be of much practical contribution. Further, the proportion of nutrient uptake from zones in competition with crop roots may be reasonably assumed to be considerably higher than this.

There are several key factors working against effective nutrient pumping in humid, strongly acid soils:

- 1) There is a limited reservoir of nutrients in the subsoil. In the typical ultisol or oxisol, the concentration of nutrient cations and phosphorus below a 30 cm depth are often low or at trace levels (eg Evenson, 1989). Even considering the much larger volume of soil explored by the roots, the aggregate quantities of nutrients capable of being extracted are often insubstantial. A countervailing factor, however, is that roots may be capable of converting recalcitrant forms of P to extractable forms, and thus increasing the exploitable P reservoir.

2) There is a distinct tendency for tree roots to grow shallowly in strongly acid soils due to aluminum toxicity in the subsoil. caused by Al saturation of the exchange complex, less mechanical impedance in the topsoil compared to the subsoil, and a much greater pool of nutrient availability in topsoil.

3) Ecological theory suggests that below-ground competition tends to increase as soils become more infertile. This is due to a tendency toward increased in the root/shoot ratios, and to an increase in root length as macro-nutrients become limiting (Gillespie, 1989).

Alley cropping was envisioned as an agroforestry system particularly suited to capturing the benefits of deep-root nutrient pumping. The circumstantial evidence from studies on acidic soils in the humid tropics is that deep-root pumping does not provide major practical benefits. Phosphorus is usually the most limiting nutrient in these environments. Palm (1988) observed a negative P budget in most alley cropping systems studied, but did observe an increase in available P in the soil. They attributed this to either P pumping or conversion of P to more available forms.

A severe practical limitation is that the contribution of P in the prunings of the commonly used hedgerow tree species is usually in the range of only 4-10 kg/ha annually (Garrity et al, 1993). This is far below crop P requirements. When one considers that a large proportion of this modest amount of P is likely to be derived from the crop root zone, it is not likely that the amount of deep-soil pumped P exceeds that amount 'robbed' from the crop (Szott et al, 1991).

In alley cropping, reduced crop yields near the hedges are commonly observed (Garrity, 1995). Root barrier studies in alley cropping frequently show that about 50% or more of the yield reductions observed close to the hedges are due to below-ground competition, and that competition increases with tree age (Fernandez et al, 1993). This highlights the significant competitive effect of the tree shallow roots that appears to negate the pumping effect.

Nutrient pumping dynamics are significantly different in subhumid to semiarid situations. In these water-limited environments there is evidence of the extraction by trees of soil water deep in the profile (Stone and Kalisz, 1991). Tree rooting depth tends to be deeper, promoting the survival and resource competitiveness of the trees. During periods when the upper soil profile is dry, nutrient pumping may be more significant, since at such times the tree is totally dependent upon water (and nutrient) extraction from deeper layers. Unfortunately there are no data to confirm this, and the premise has been questioned (Comerford et al, 1984). Common soils of the drier regions (eg alfisols, inceptisols) tend to have higher cation exchange capacities at depth than the soils common to the humid tropics, indicating a greater reservoir of extractable nutrients. But as the trees display a major competitive advantage in water and nutrient competition in drought-prone environments, there is quite serious suppression of associated crops during water-limited seasons (Singh et al, 1989; Ong et al, 1991).

Tree-crop systems display varying tendencies for overlap of rooting zones. Trees are likely to effectively operate as nutrient pumps only in situations where they

produce deep root systems, and there are substantial nutrient quantities at depth. These conditions are most likely on deep, high base-status soils with good moisture. Care must be taken in selecting the specific tree genotype and crop genotype that exhibit suitable compatibility. Van Noordwijk (1989) has emphasized the selection of trees with a deep rooting pattern and limited horizontal root development. But much more work to document rooting depth profiles and nutrient cycling in agroforestry systems is needed. This may best proceed by quantitative study of the indigenous farmer-developed systems in current use. It will provide more evidence for the robustness of the nutrient pumping phenomenon.

Trees as Nutrient Safety Nets

One of the serious deficiencies of conventional annual cropping systems, particularly in humid environments, is their tendency to exhibit high leaching losses of the mobile nutrients such as nitrogen and potassium. This results in both short-term financial losses to the farmer, and serious off-site environmental nutrient pollution effects. In contrast, forest and perennial-crop systems are known to exhibit more closed nutrient cycles. Table 1 compares leaching losses for four nutrients between a monoculture maize system and a mixed perennial system. Nutrient losses from the root zone varied from three to fifty-one times more for the maize system.

This has led to the concept that in mixed annual-perennial systems the trees may behave as nutrient safety nets (van Noordwijk and de Willigen, 1991), reducing leaching losses and recycling the re-captured nutrients. Van Noordwijk (1991) has also posited that tree roots may play another indirect role in reducing leaching losses: the presence of old root channels may tend to increase the amount of soil water that infiltrates through by-pass flow.

Experimental evidence quantifying the safety-net hypothesis is scarce. Horst et al (1991) has shown that the presence of *Leucaena leucocephala* hedgerows reduced leaching losses in a hedgerow intercropping system, and attributed this to *Leucaena*'s high root density in the subsoil of the alley-cropped plots.

The safety-net feature of trees is a function of their lateral rooting behavior. It may be accomplished efficiently without deep rooting, in contrast to nutrient pumping. Lateral rooting strength, however, may increase the tendency for tree-crop root competition. There is evidence, however, of large species differences in rooting patterns, suggesting the utility of selecting species with naturally deep rooting systems. Van Noordwijk et al (1994) have proposed a method for characterizing tree root systems based on fractal analysis that simplifies the effort of determining total root length, root diameter distribution, and root length per unit dry weight. A proportionality factor, or 'index of root competitiveness' can be calculated based on the sums of root diameter squares for roots with a horizontal versus vertical orientation, and used to compare trees growing on the same soil (van Noordwijk and Garrity, 1995).

The research and extension work on alley cropping during the past 20 years was based on the premise that the pruned hedgerows would enable continuous cropping without additional fertilizer. They were conceived as "simultaneous fallows", constantly producing nutrient supplies for annual crops. In most cases, however, this has proved unrealistic. Yields usually cannot be maintained without supplemental chemical fertilizers (National Research Council, 1993). Many farmers practicing hedgerow intercropping eventually discontinue cropping, a realistic reaction to the inability of the hedgerow fields to sustain yields.

Fallowed tree hedgerow systems can rapidly accumulate nutrients in the woody biomass, compared with the performance of the conventional grass fallow succession obtained in many areas. This has stimulated interest in the concept of fallow-rotation hedgerow systems as a variant intermediate between a simultaneous and a sequential agroforestry system. Although little experimental evidence has yet been generated, it is an alternative that deserves serious investigation, as it may fit the practical realities of low-cash flow farmers better than continuously cropped (and fertilized) hedgerow systems.

Trees as N-fixers and providers

The contribution of biologically fixed nitrogen by the tree component is substantial in many agroforestry systems. Since N is often strongly limiting, the capacity of trees to supplement the supply of N is a highly valued characteristic. Not many measurements exist of the amounts of fixed N actually contributed. Ladha et al

(1993) found 30-60% of the N in the hedgerow prunings of *Gliricidia sepium* was biologically fixed N. The percentage of atmospherically derived N varied seasonally and tended to be higher in the wet season.

Recently, attention has been drawn to the fact that crop performance in association with N-fixing species often is not superior to that with non-fixing species (Garrity and Mercado, 1995). In the Philippines, *Senna (Cassia) spectabilis* (non-nodulating legume) supplied 20-30% more N to associated annual crops over a four-year period than *Gliricidia sepium*, with similar yields. *Senna* also exhibited major advantages over *Leucaena leucocephala* in Machakos, Kenya, due primarily to reduced competition for water (Ong, C K, pers comm, 1994). Van Noordwijk et al, 1995 reported that the non-fixing *Peltophorum dasyrachis Kurz. (pterocarpa)* outperformed three other leguminous species in stimulating maize performance in Indonesia, with a similar N content in its prunings (Figure 2). They concluded that reduced canopy shading per unit biomass produced (due to a more compact branching pattern), and the strikingly deep root system of *Pelthophorum* were major contributing characteristics. The causes for the superiority of the non-fixing trees clearly varied among these studies. This emphasizes that N-fixation is only one of a number of critical characters affecting the optimum fit of a tree species in an agroforestry system, and should perhaps not be over-overemphasized in place of a more holistic comparison among prospective species.

The synchrony of plant demand with nutrient release from tree litter and prunings is a major issue in current research. The range of pruning-derived N that is utilized

by annual crops is usually quite low, varying from 5-30% (Kang and Atta-Krah, 1990). Pruning N from some sources may be mineralized rapidly, and leached or volatilized before crop roots gain access to it during crop establishment. Or it may be mineralized slowly and remain unavailable during the peak demand phase of crop growth. The lignin/N ratio has been considered an important predictor of mineralization rates, but the content of polyphenolics may also explain part of the variation in N mineralization rates. Handayanto *et al.* (1994) has shown that the importance of polyphenolic content decreases with higher leaching rates.

In an analysis of alley cropping trials at several locations in Africa, Akyeampong *et al.* (1992) found a low correlation between relative maize yields and the amount of N applied as prunings. In Maseno, Kenya, for example, leafy biomass production by *Calliandra* (50 t/ha in 40 months) exceeded that from *Leucaena* (33 t/ha) and *Gliricidia* (21.6 t/ha) but resulted in the same accumulated maize yield over six seasons. This corroborates the growing body of evidence indicating that maximum hedgerow leafy biomass, once considered a prime factor in sustainably productive alley cropping, may not be as important as characters that reduce competition between trees and crops. Competitiveness is often best achieved with trees having low biomass production to decrease pressure on below-ground resource pools.

The critical balance between F (pruning effects) and C (tree-crop competition for nutrients, water and light) is highlighted by the relative values calculated from alley cropping studies at six sites in Africa varying in tree species, management, soils

an climate (Figure 3). F ranged from 12 to 60%. Increasing F was closely associated with higher levels of C. These tradeoffs make it particularly difficult to make the response to organic inputs in agroforestry systems as predictable as that for inorganic inputs such as fertilizers and lime.

Soil Organic Matter Enhancement

In their review of tree crops as soil improvers in the humid tropics, Sanchez et al (1985) examined trends in soil properties when tree crops and fast-growing tree plantations are established. Lundgren's (1978) model hypothesizes that soil organic matter levels will decline substantially after forest clearing and plantation development, recover partially during maximum growth, and then decline again upon felling, and establishment of the second rotation.

Available data sets from Southeast Asia, Africa and Latin America indicated, however, that during the years after forest clearing and establishment of rubber, oil palm, and *Gmelina arborea* or *Pinus caribaea* plantations, soil organic matter and nutrient levels did not tend to decrease significantly, and in some cases increased (Sanchez et al, 1985). Toward the end of the productive period, however, there was a declining trend in soil organic carbon in some of the perennial crops.

The relatively small and gradual changes in soil organic carbon in tree crops contrast with the rapid and dramatic reduction in soil organic carbon usually observed when cleared forests are cultivated with annual crops. Do agroforestry

tems tend to moderate or reverse the adverse effects of annual cropping systems on soil organic matter? The answer depends on the particular components, environmental conditions, and the management regime.

Tropical home gardens and complex agroforests often resemble natural secondary forest systems in structure and ecology. In Torquebiau's (1992) review of the sustainability indicators of tropical home gardens, he found many indirect sources of evidence that soil fertility levels were maintained over long periods, and hypothesized that organic matter levels generally increase. Unfortunately, datasets are not available to test this contention.

In sequential agroforestry systems, such as shifting cultivation, the land is fallowed after a period of annual cropping. There are numerous beneficial effects attributed to such fallows, whether they are natural or improved fallows. Rebuilding soil organic matter levels is a frequently cited effect.

The case for increased soil organic carbon contents is not so clear-cut with simultaneous agroforestry systems. In parkland systems, where trees are maintained at a low density in the fields (Belsky et al, 1993), or when native forest trees are retained on paddy bunds, as in northeast Thailand (Vityakon, 1993), there is clear evidence that the presence of the trees has a positive influence on soil organic matter levels, at least in the vicinity of the trees.

Hedgerow intercropping systems, several studies have reported increases in soil organic matter (eg Yamoah *et al.*, 1986) as a consequence of continuous pruning application in such systems. The degree of positive benefits varies with the tree species (in this case the ranking of positive effects was *Cassia (Senna) spectabilis* > *Gliricidia sepium* > *Flamengia congesta*). The decomposition literature has elucidated quite dramatic differences among species in the rate at which litter decomposition and nutrient release occurs (Palm and Sanchez, 1990; Miah, 1993)

Expectations of an increase in soil organic matter content are dependent on the amount, source, and management of the pruning biomass. Kang et al (1990) reported a nonsignificant increase in soil organic matter in a *Leucaena* hedgerow system that produced large amounts of prunings, but had a very rapid litter decomposition rate. Considering the modest hedgerow biomass yields often obtained with practical alley widths and environmental constraints, it is more likely that the presence of hedgerows will decrease the rate of carbon depletion, rather than actually increase organic matter levels.

Many studies have reported that more favorable carbon levels were maintained with hedgerows than in open field systems (Kang et al, 1984; Atta-Krah et al, 1986; Lal, 1989; Evenson, 1989). But exceptions are observed: On a strongly acid (ph 4.2) steeply sloping ultisol, Samsuzzaman (1993) found that in the absence of external fertilizer inputs, soil organic matter declined more rapidly in hedgerow treatments than in with open field cropping.

Since the soil organic matter benefits of agroforestry accrue gradually, system viability will be strongly dependent on a favorable F/C balance in the short run. In analyzing and recommending the use of on-farm organic matter sources, the analysis of yield and income per unit of labor expended is often a key, but very neglected, aspect.

Spatial Fertility Redistribution in Developing Terraces

The dramatic reduction in soil loss from sloping fields upon installation of contour hedgerow systems has now been well-documented for a wide range of slopes, soils, and systems (Sajjapongse, 1992; Garrity, 1995). Contour hedgerows typically reduce soil losses by 50 to 95%. Consequently, they have been promoted as a major option in conservation farming systems in many tropical countries.

Rapid terrace development occurs behind vegetative barriers, particularly when tillage is practiced frequently in the alleyways. Although soil movement off-field is minimized, redistribution downslope within the alleyway is promoted. This removes or 'scours' the topsoil in the upper alley, with sediment accumulation in the lower alley and in the hedgerow. This results in quite striking gradients in soil fertility across the alleys (Garrity et al, 1994; Samsuzzaman, 1993; Agus. 1994). Organic C and N levels, available P, and exchangeable Ca and K are reduced upslope and enriched downslope in a linear pattern, resulting in dramatically lower

crop biomass the upper alley. Thus, 'scouring' presents a serious challenge to the sustainability of yields in these systems.

There are three ways to cope with this fertility redistribution problem: Apply the crop residues, hedgerow prunings, and inorganic fertilizers differentially by zone to alleviate the upper alley depletion; reduce the frequency of tillage to decrease the rate of scouring; or switch to perennials better adapted to scavenging nutrients in the degraded upper alley zone. Unfortunately, there has been almost no research on this problem, although it looms as one of the key nutrient-related issues in the sustainability of contour hedgerow systems.

Smallholder System Pathways

The limitations of pruned tree hedgerows have prompted interest in a wide range of other alternative hedgerow components that perform the same soil conservation functions with less labor and greater economic benefits. The options include fodder grass strips and cash perennials such as coffee, fruit trees, and many others. Although these alternatives are often very effective in erosion control, they do not solve the problem of maintaining soil nutrient balances. Fertilization with manure, fertilizers, and/or additional plant residues is still required.

Figure 4 illustrates the major pathways available to smallholders to meet their production and income sustainability objectives, particularly on sloping lands. The

the dichotomy of system choice depends fundamentally on whether an external nutrient supply is available to the farmer.

Farmers without access to nutrient inputs must depend on some form of fallowing. To increase productivity they need better ways of accelerating the accumulation of nutrients in the fallow vegetation. The viable options are improved fallows (A1 in Figure 4), fallow-rotation hedgerow systems (A2), and agroforests containing cash-generating perennials (A3).

Farmers begin using external nutrient inputs as markets develop for commodities with a substantial return to fertilizer investment--vegetables, horticultural crops, or cash perennial crops. Credit mechanisms appear as these enterprises develop.

When continuous cropping becomes feasible (B) further evolution is needed to protect investments in soil fertility through some form of conservation farming. Options range from natural vegetative strips (B1), that may be enhanced by value-added perennials (B2), to pruned leguminous tree hedgerows. Further transformation may lead to commercial perennial crops or tree horticulture (B4).

There is a correspondence between the options appearing opposite each other on the left and right pathways in Figure 1. This reflects the potential for a parallel transfer from left-to-right, or right-to-left, depending on changing nutrient availability. Different parcels on the same farm may be managed simultaneously in separate categories on both sides of the diagram.

Conclusion

Although trees possess the potential for deep rooting and nutrient pumping, they also tend to form extensive lateral roots in the topsoil which, although capturing and recycling leached nutrients, also compete with associated crops for nutrients. This competition may often outweigh the benefits due to deep rooting, except perhaps on the more fertile and deep soils. The prospects for exploiting these rooting mechanisms are least in humid, infertile tropical soils.

Because of the strong tradeoff between the fertility enhancement (F) functions of trees and competition with crops (C) in simultaneous agroforestry systems, the use of pruned tree hedgerows may often be more suitable in a fallow-rotation mode than in continuous cropping situations. More attention should be given to this and other practices intermediate between simultaneous and sequential systems. The inherent opportunities of agroforests or mixed perennial systems as a basis for sustainable low-input farming should also be given much more attention.

There are many agroforestry systems developed by farmers and employed on millions of hectares in the tropics. Unfortunately, little effort has been expended in understanding them as the basis of building improved systems. The fate of nutrients and soil organic matter is poorly quantified in these systems. This presents a major current challenge for agroforestry research and development.

Table 1. A comparison of nutrient leaching losses between an annual crop and a mixed perennial system (cacao, plantain, and *C alliodora*) during a 242 day period. Source: Adapted from Seyfried and Rao, 1991.

Nutrient	Monocrop Maize	Mixed Perennials
----- kg/ha -----		
Nitrogen	51	1
Potassium	3	1
Magnesium	21	3
Calcium	43	3
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Figure Captions

- Figure 1. Contrasting tree phenotypes in agroforestry systems: (A) deep roots that complement the crop rooting zone, or (B) shallow, spreading roots that compete for growth resources.
- Figure 2. Maize performance in association with hedgerows of the non-N fixing species *Peltophorum dasyrachis* Kurz. (*pterocarpa*) consistently exceeded that with the N-fixing species *Gliricidium sepium* on an acidic soil in Lampung, Indonesia (adapted from Van Noordwijk et al, 1995).
- Figure 3. The balance between F (positive fertility effects of pruning application in increasing crop yields) and C (negative effects of tree-crop competition for nutrients, water and light) in alley cropping studies at six sites in Africa varying in tree species, management, soils and climate (Ong and Huxley, 1992).
- Figure 4. Pathways in smallholder farming systems evolution on sloping lands as mediated by the availability of external nutrients.

Nutrient Pumping:-

* deep root complementarity or shallow root competition

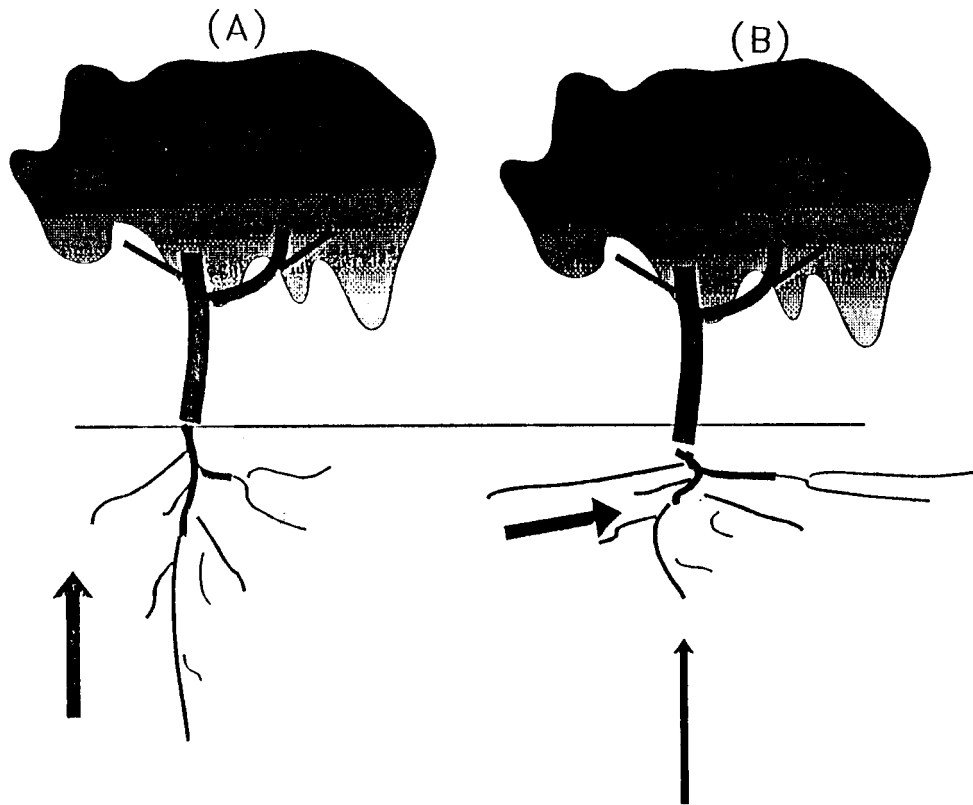


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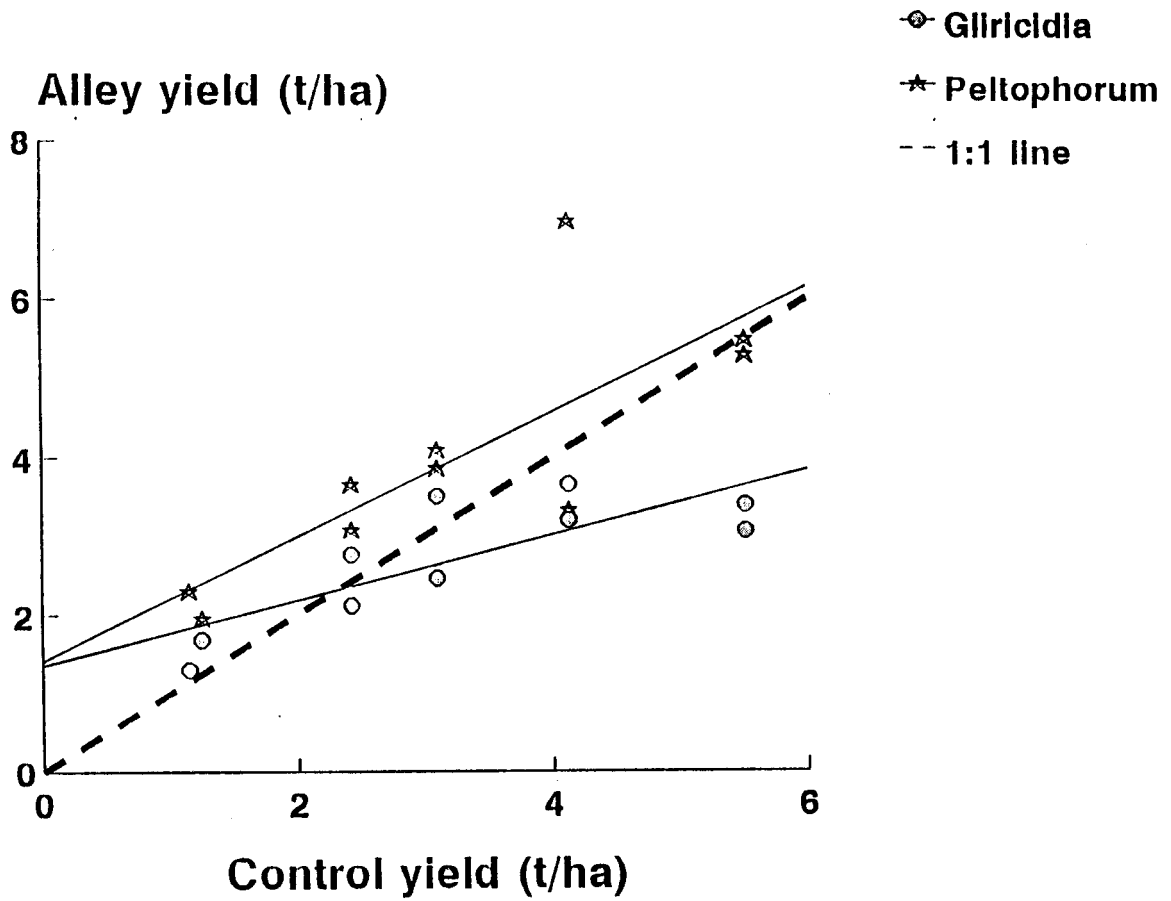


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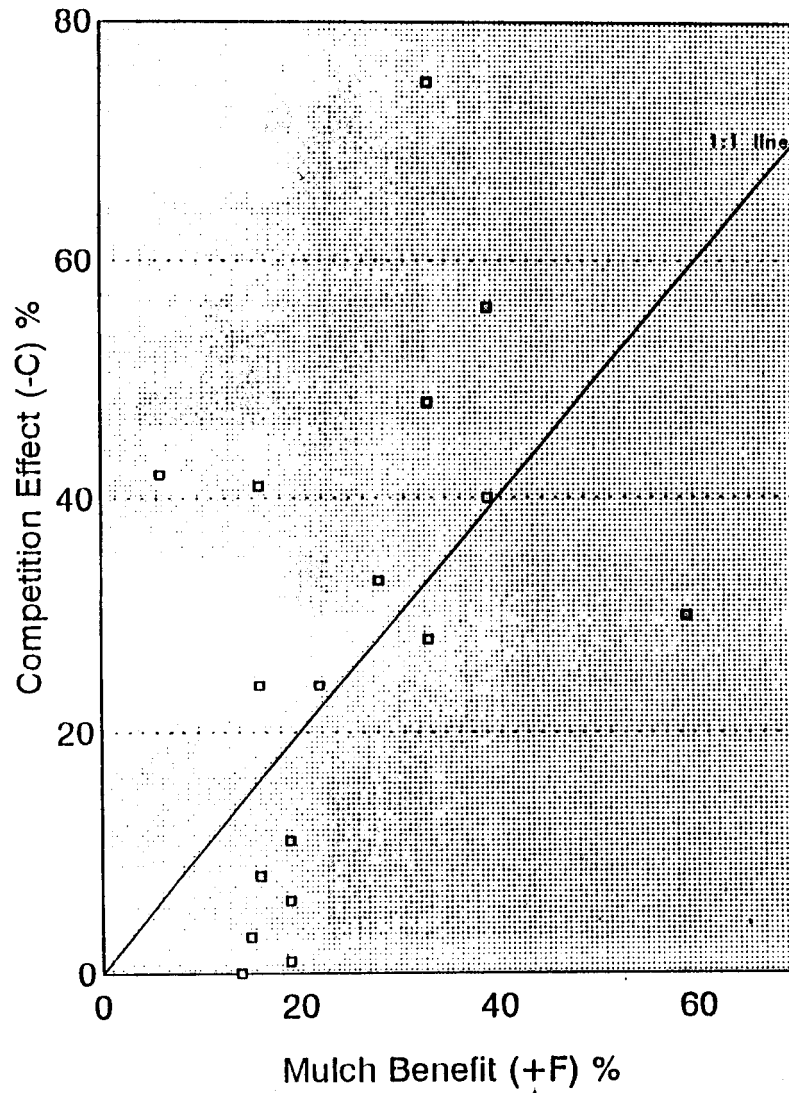
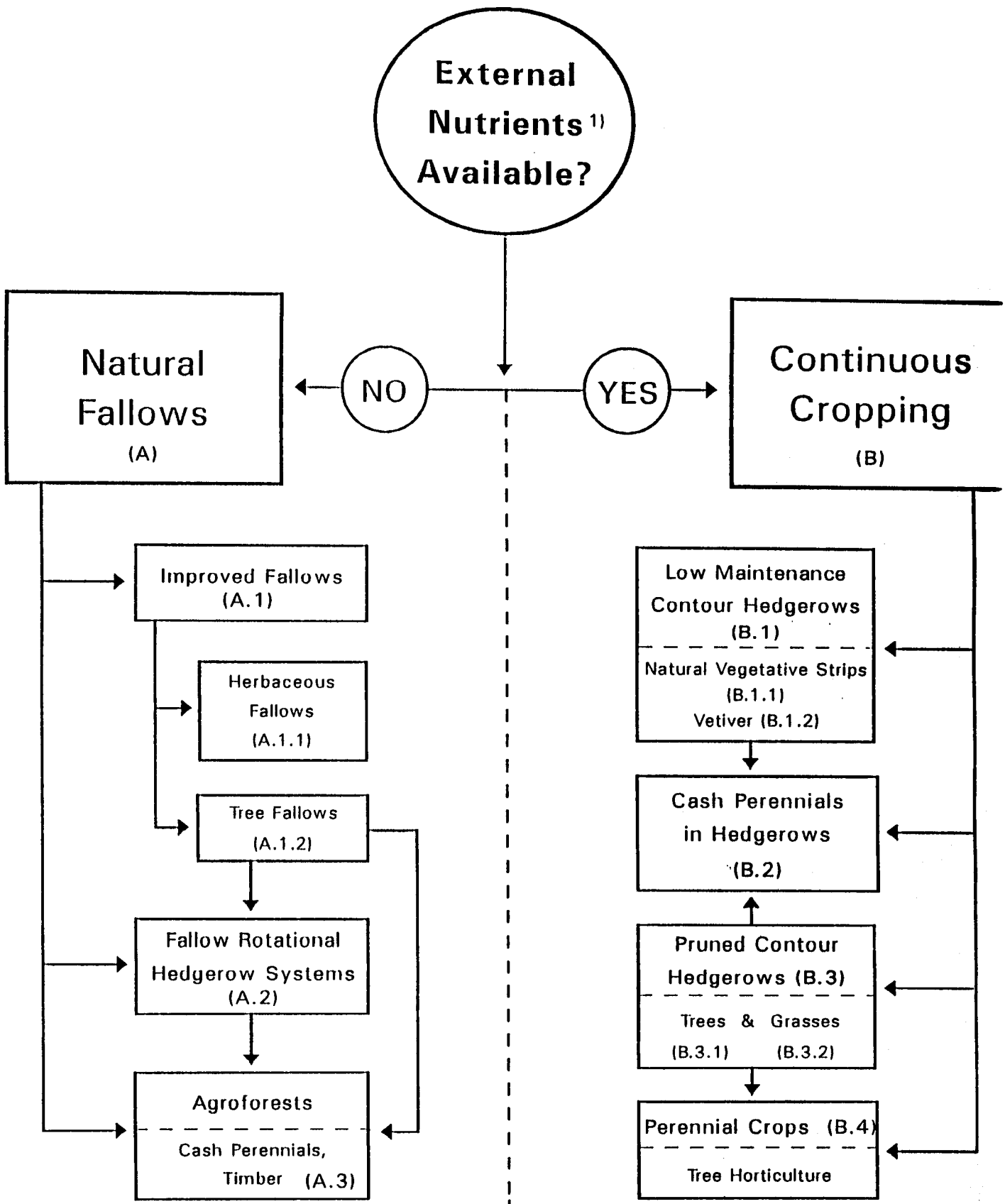


Figure 3. The balance between F (positive fertility effects of pruning application in increasing crop yields) and C (negative effects of tree-crop competition for nutrients, water and light) in alley cropping studies at six sites in Africa varying in tree species, management, soils and climate (Ong and Huxley, 1992).



1) Manure, fertilizer or off-field plant residues

D. Garrit

Figure 4. Pathways in smallholder farming systems evolution on sloping lands as mediated by the availability of external nutrients.