

## Contribution of agroforestry trees to nutrient requirements of intercropped plants

C. A. PALM

*Tropical Soil Biology and Fertility Programme, P.O. Box 30592, Nairobi, Kenya*

**Key words:** lignin, nutrient content, nutrient release, polyphenols, prunings, synchrony

**Abstract.** A major tenet of agroforestry, that trees maintain soil fertility, is based primarily on observations of higher crop yields near trees or where trees were previously grown. Recently objective analyses and controlled experiments have addressed this topic. This paper examines the issues of tree prunings containing sufficient nutrients to meet crop demands, the timing of nutrient transfer from decomposition to intercrops, the percent of nutrients released that are taken up by the crop, and the fate of nutrients not taken up by the crop.

The amount of nutrients provided by prunings are determined by the production rate and nutrient concentrations, both depending on climate, soil type, tree species, plant part, tree density and tree pruning regime. A large number of screening and alley cropping trials in different climate-soil environments indicate that prunings of several tree species contain sufficient nutrients to meet crop demand, with the notable exception of phosphorus. Specific recommendations for the appropriate trees in a given environment await synthesis of existing data, currently only general guidelines can be provided.

Tree biomass containing sufficient nutrients to meet crop demand is not enough, the nutrients must be supplied in synchrony to crop needs. Nutrient release patterns from organic materials are, in part, determined by their chemical composition, or quality. Leguminous materials release nitrogen immediately, unless they contain high levels of lignin or polyphenols. Nonlegumes and litter of both legumes and nonlegumes generally immobilize N initially. There is little data on release patterns of other nutrients. Indices that predict nutrient release patterns will assist in the selection of species for synchronizing with crop demand and improve nutrient use-efficiency.

Field trials with agroforestry species ranging in quality show that as much as 80% of the nutrients are released during the course of annual crop growth but less than 20% is captured by the crop, a low nutrient-use efficiency. There are insufficient data to determine how much of the N not captured by the crop is captured by the trees or is in the soil organic matter, the availability of that N to subsequent crops, or how much of that N is lost through leaching, volatilization or denitrification. Longer term trials are needed.

## Introduction

One of the main tenets of agroforestry is that trees maintain soil fertility. This hypothesis is based partially on studies of the efficient transfer of nutrients from litter to trees in natural ecosystems [Vitousek and Sanford, 1986]. The assumption is that trees in agroforestry systems will likewise transfer nutrients to intercropped plants. Other support is based on observations of higher crop yields near trees, such as the famous case of *Faidherbia albida* [Vandenbelt, 1992], or where trees have been recently removed, as the case of bush and tree fallows [Nye and Greenland, 1960]. The effect of trees on

crop growth is actually due to a combination of factors such as water and temperature relations, soil structure, soil organic matter, in addition to recycling nutrients. Experiments with comparable treatments and proper controls have only recently been designed to determine the relative importance of the various contributions of trees in enhancing crop production [Coe, 1994].

Intercropping of agroforestry trees with crop plants includes sequential systems, where the trees and crops occupy the same piece of land at different times, and simultaneous systems, where the trees and crops are grown on the same piece of land at the same time. Simultaneous systems can vary greatly in the relative proportions of trees and crops and in their spatial arrangement [Young, 1989]. Spatially mixed systems such as coffee and cacao plantations include upper storey trees that provide nutrients, from litterfall and periodic prunings, and shade to the lower storey tree crops [Heuvelop et al., 1988]. Spatially zoned systems include alley cropping where annual crops are grown between hedges of trees that are pruned periodically to provide nutrients to the intercropped plants [Kang et al., 1981]. In both the spatially mixed and zoned systems the intercrops, whether they are annuals or perennials, receive nutrients from the agroforestry trees. This review will focus primarily on alley cropping and biomass transfer systems where trees are planted expressly to serve as a source of nutrients for the intercrops. The concepts and processes discussed, however, equally apply to other agroforestry systems.

Several issues related to the transfer of nutrients from agroforestry trees to intercropped plants are addressed. The first issue is a simple question: Do tree prunings and litter contain enough nutrients to meet crop demand? If yes, then one can ask several more questions. What proportion of the nutrients are released from the decomposing plant materials during the course of crop growth? What proportion of those nutrients are taken up by the crop and what proportion by the trees? What is the fate of the nutrients that were released but were not taken up by the crops? These questions are concerned with the efficiency of nutrient transfer from the tree prunings to the crops. This concept of supplying nutrients when demanded by the crop is now commonly referred to as synchrony [Swift, 1987]. In addition to the more direct, short term supply of nutrients from decomposing plant materials, nutrients can also be supplied indirectly from the mineralization of soil organic matter that is formed from the continued application of organic inputs. Another important issue to address is the relative importance of synchrony or soil organic matter for supplying nutrients to crops from the addition of tree prunings.

For most low-input systems that depend even partially on organic inputs as a source of nutrients, answers to such questions are crucial for making appropriate recommendations for the selection and management of organic inputs, including those from agroforestry trees, for improving crop production.

## Amount of nutrients

To answer the first question, do tree prunings contain enough nutrients to meet crop demand, it is necessary to know the amount of prunings produced and their nutrient concentration, as well as the nutrient requirements of specific crops. A large number of biomass production screening trials and alley cropping trials have been conducted in a range of climate and soil environments with a variety of leguminous trees, and even a few non-leguminous trees. Reviews indicate that leguminous trees in alley cropping systems produced up to  $20 \text{ t ha}^{-1} \text{ yr}^{-1}$  dry matter of prunings, containing as much as 358 kg N, 28 kg P, 232 kg K, 144 kg Ca, and 60 kg Mg [Young, 1989; Szott et al., 1991], more than enough to meet most crop requirements. In situations where trees are interplanted with crops, fine roots can also supply nutrients to crops through root turnover and root dieback, caused by pruning above-ground biomass. There is little data on the amount of nutrients supplied through roots in agroforestry systems so this study will focus on aboveground inputs. It is, however, important to note that fine root and mycorrhizal turnover in forest systems can contribute two to four times more nitrogen and six to ten times more phosphorus than aboveground litterfall [Bowen, 1984], so tree roots in agroforestry systems are likely to contribute a considerable amount of nutrients to intercropped plants.

Despite the large number of biomass screening trials, it is difficult to make recommendations for a given environment as to which trees produce sufficient pruning biomass. This difficulty results from poor documentation of site characteristics and research methodologies. Details of the climate and soils of the study area are frequently not provided. Trials are compared that have been conducted using different tree densities and pruning regimes. Prunings in one study may consist of leafy materials but a combination of woody and leafy components in another study. It is therefore important to assess data reported as tonnes of biomass per hectare per year taking these factors into account. In addition, often only pruning biomass is given and not the nutrient concentration or content of the prunings.

The nutrient content of the prunings depends on many factors, including tree species and the relative proportions of leaves and stems in the prunings and their respective nutrient concentrations. Even among leguminous trees the N concentration of the leaves varies from 1.5 to 3.4% [Young, 1989], or more. Within a species nutrient concentrations can vary by a factor of two or more as shown in Budelman's [1989] review of the information on nutrient content of leaves of *Leucaena leucocephala* and *Gliricidia sepium*. Despite the higher nutrient concentrations in *G. sepium*, *L. leucocephala* produced more pruning biomass and therefore served as a better source of nutrients for crops [Budelman, 1989], showing that the combination of factors is important.

Differences in nutrient concentrations within a species can be due to a number of factors, including differences in provenances, soil fertility, climate,

season, age of leaves or plant, frequency of pruning, or even differences in the laboratories or methodologies used to analyze nutrients. As with biomass production studies, many studies do not provide sufficient information to allow a cause and effect analysis and synthesis, although Budelman [1989] suggests that soil nutrient status is the most important factor influencing nutrient concentrations within a species. The magnitude of the effect, however, varies among species.

Thus, despite the considerable data on biomass and nutrient content of prunings which exist for several agroforestry species, data are often not comparable because of different methodologies or incomplete documentation. There is currently no way to predict the biomass and nutrient production for a particular species for a given soil, climate, and management practice, and there is not likely to be in the near future, except for a few well-documented species such as *L. leucocephala* and *G. sepium*. Fernandes et al. [1994] and Young [1989] have recommended several species with high biomass production and nutrient content for use in different environments. Databases such as ICRAF's multipurpose tree database [Von Carlowitz et al., 1991] and reference compilations such as TREE-CD [CABI, 1991] can be useful in selecting species but care must be taken in extrapolating information from one site to another when selecting tree species.

Given the constraints of the existing data for making recommendations, examples are given to illustrate the amount of nutrients provided in the leaves from tree prunings and other organic inputs compared with the nutrients required by a maize crop (Table 1). The nitrogen (N) content of 4 t ha<sup>-1</sup> of leaf material from a variety of agroforestry trees, except for the two non-leguminous species, is sufficient to meet the demands of 2 t of maize (plus 3 t stover). Whereas N was the focus of early studies in agroforestry and alley cropping in particular, in general tree prunings can meet crop N requirements, even though as little as 14% and often less than 50% of the N in prunings is from N fixation [Giller and Wilson, 1991].

Calcium demands were met by all the species and magnesium demands were close to being met. Potassium was not supplied in sufficient quantities by many of the species but if crop residues are recycled the nutrient balance is positive.

Phosphorus (P) was not provided in sufficient quantities to meet crop demand by any of the species. Even if crop residues are recycled there is still a negative P balance. Nutrient budgets accounting for the nutrients added in prunings and the nutrients removed in crop harvest from alley cropping systems on both fertile and infertile soils also show an insufficient amount of P in prunings [Palm et al., 1991; Salazari et al., 1993]. In order to meet P requirements, either more pruning biomass must be applied or the concentration of P in the prunings must be higher – both of these options are somewhat limited. Many of the soils in the tropics are P limited [Sanchez, 1976] so there is an obvious need to channel some research efforts to increasing P cycling and availability in intercropping systems.

Table 1. Nutrients required by a crop of maize compared to the nutrients contained in 4 t of organic inputs.

A. Nutrients required by a crop of maize

	Nutrients kg ha <sup>-1</sup>				
	N	P	K	Ca	Mg
Maize <sup>a</sup>					
Grain (2 t)	50	12	30	6	4
Stover (3 t)	30	6	36	9	6
Total	80	18	66	15	10

B. Nutrients added in 4 t of leaves of various organic inputs

Species	Nutrients kg ha <sup>-1</sup>				
	N	P	K	Ca	Mg
<i>Leucaena leucocephala</i> <sup>b</sup>	154	8	84	52	13
<i>Erythrina poeppigiana</i> <sup>c</sup>	132	7	46	61	—
<i>Inga edulis</i> (fertile soils) <sup>d</sup>	142	11	40	45	6
<i>Inga edulis</i> (infertile soils) <sup>e</sup>	127	9	50	30	7
<i>Senna siamea</i> <sup>f</sup>	105	6	44	110	7
<i>Dactyladenia barteri</i> <sup>f</sup>	60	4	31	40	8
<i>Grevillea robusta</i> <sup>g</sup>	52	2	24	60	7
Maize stover <sup>a</sup>	40	8	48	13	8

<sup>a</sup> Adapted from Sanchez (1976).

<sup>b</sup> Budelman (1989).

<sup>c</sup> Russo and Budowski (1986).

<sup>d</sup> Salazari et al. (1993).

<sup>e</sup> Palm and Sanchez (1990).

<sup>f</sup> Tian et al. (1992a).

<sup>g</sup> C.A. Palm (unpublished).

When discussing nutrient balances and nutrients applied via prunings of agroforestry trees, it is necessary to make an important distinction between nutrients recycled within a system and nutrients added to the system. Prunings added to intercropped plants are recycling nutrients within the soil-plant system, they are not a nutrient addition to the system. Some of the N may be added to the system by N fixation but the amount of N fixed varies greatly depending on the trees used and the environmental conditions [Giller and Wilson, 1991]. External inputs to the system from precipitation are small. Some nutrients, otherwise considered unavailable to crops because they are below the rooting zone of the crops, might be brought into the system from deeper layers in the soil by trees with deeper roots but the magnitude of this 'input' is not known. If crop products are harvested, then there is a net loss of nutrients from the system. Recycling of nutrients through prunings does

not offset those losses. Eventually a decline in productivity of the systems would be expected, unless external nutrient inputs are supplied in the form of inorganic fertilizers or organic amendments.

### **Release of nutrients**

Once it is established that prunings contain sufficient nutrients to meet crop requirements, those nutrients should be utilized efficiently and losses minimized by attempting to synchronize nutrient release with crop demands. Synchrony might be achieved by manipulating plant demands, through time of planting and crop selection, or by manipulating the nutrient release pattern of the inputs, through timing and placement of application or the resource quality of the organic input [Myers et al., 1994]. In this paper the emphasis will be on manipulating nutrient release patterns by the selection of agroforestry species based on their organic resource quality.

Resource quality generally refers to the relative rates of decomposition and nutrient release of organic materials, which is determined in large part by their chemical composition. Rapid decomposition and nutrient release are associated with high quality and conversely, immobilization or slow release refer to low quality [Swift et al., 1979]. Past decomposition and nutrient release studies focused on crop residues and cover crops in agricultural systems or leaf litter in natural ecosystems. These studies were concerned primarily with nitrogen dynamics. For agricultural crops, plant materials with %N greater than 1.73 or C:N ratio less than 20 mineralize N and other materials immobilize N [Iritani and Arnold, 1960; Frankenberger and Abdelmagid, 1985]. For natural ecosystems the lignin to N ratio,  $LIG/N$ , improved prediction of the percentage of initial N released from litter: the higher the  $LIG/N$  the slower the decomposition and N release [Melillo et al., 1982].

Recent studies focusing on the leaves of agroforestry trees indicate a wider range in the percent of initial N released and in the patterns of immobilization and mineralization than those described for crops and forest litters. The %N or  $LIG/N$  ratio of the materials also do not always serve as indices of release patterns for agroforestry materials. To facilitate the screening of agroforestry trees for their nutrient supplying capacity, better indices are needed that predict release or immobilization patterns. Until such indices, analogous to chemical formulations provided for inorganic fertilizers, are available for plant materials it will be difficult to recommend particular species for their fertilizer value.

Work by Constantinides and Fownes [1994] showed that it is first of all important to categorize materials into leguminous and nonleguminous plants and also to distinguish between nonsenesced leaves and litter, or senesced, leaves. The N release patterns of the categories are different; litters of legumes and nonlegumes immobilize N; fresh, nonlegume materials do not mineralize or immobilize N to a great extent; and fresh legumes mineralize N immedi-

ately. Percent N in the leaves serves as the best index of initial N released if all the materials are grouped together [Tian et al., 1992a; Constantinides and Fownes, 1994]. If legumes are considered as a separate category, %N does not serve as a good index of N release. There are enough cases where there is immobilization or N release is less than expected to merit attention.

Several laboratory incubation studies have followed the N release patterns from leaves of agroforestry legumes [Fox et al., 1990; Palm and Sanchez, 1991; Oglesby and Fownes, 1992; Tian et al., 1992a; Kachaka et al., 1993; Constantinides and Fownes, 1994; Handayanto et al., 1994]. Although the methods are not directly comparable (the length of the incubation varied and some studies included ground leaves while others used whole leaves), some interesting patterns still emerge (Table 2). Nonsenesced leaves, as opposed to litter, are compared unless otherwise specified. All comparisons here are based on cumulative N released at eight weeks, except for the study by Tian et al. [1992a] in which seven weeks was used.

*Gliricidia sepium* consistently released a higher percentage, 30–70%, of its N compared to other materials. *Leucaena leucocephala* leaves, with %N greater than 3.5 in all but one study, generally released less than 25% of its initial N. *Senna siamea*, a non N-fixing legume, released an intermediate percentage, 10–40%, of the N added. In all cases *S. siamea* showed initial immobilization that lasted up to six weeks before net mineralization occurred. Some of the studies have also shown temporary immobilization from other legumes. *Calliandra calothyrsus* and *Inga edulis* released less than 20% of the applied N. In contrast, *Dactyladenia barteri*, a nonlegume, showed net immobilization throughout the incubation.

The combined results from these studies provide preliminary indices for predicting relative amounts of initial N released or immobilized from the legume materials. Correlation analyses show that both polyphenol and lignin content are inversely related to the percent of N released. Both compounds lower the quality of the plant materials. Multiple regression analyses indicate that %N is the primary factor and %polyphenol the secondary factor in determining the percent of initial N released [Tian et al., 1992a; Constantinides and Fownes, 1994]. The polyphenol to N, PP/N, ratio may serve as an index for short term immobilization patterns observed for legumes with relatively high polyphenol content [Palm and Sanchez, 1991; Oglesby and Fownes, 1992]. The lignin plus polyphenol to nitrogen ratio (LIG + PP)/N may serve as an index for longer term release patterns [Fox et al., 1990; Handayanto et al., 1994; Constantinides and Fownes, 1994]. The legume materials with high polyphenol and lignin contents release more N than the nonlegume materials and as such would not necessarily be considered of low quality when compared to most crop residues.

Exact critical values at which N release is inhibited cannot yet be given because different methodologies have been used for measuring polyphenol content in the plant materials. Also, different types of polyphenolic are extracted together, some of which are quite reactive with N while others are

Table 2. Percent of added N released from leaves of agroforestry trees during eight weeks of incubation from various studies.

Material added	Oglesby and Fownes [1992] <sup>a</sup>	Constantinides and Fownes [1994]	Tian et al. [1992a]	Palm and Sanchez [1991]	Handayanto et al. [1994]	Kachaka et al. [1993]
<i>Gliricidia sepium</i>	60	70	42	46	31	
<i>Leucaena leucocephala</i>	35	25	23	2 <sup>b</sup>	16	58
<i>Calliandra calothyrsus</i>	11	28			18	
<i>Senna siamea</i>	30 <sup>b</sup>	38 <sup>b</sup>	10 <sup>b</sup>			40 <sup>b</sup>
<i>Inga edulis</i>	11	28		-4		
<i>Dactyladenia barteri</i>			-15			-54

<sup>a</sup> Used leaves and stems.<sup>b</sup> Denotes initial immobilization.



not [Swain, 1979]. The amount of N immobilized and the time before net mineralization occurs have not been thoroughly investigated but the model developed by Aber and Melillo [1982] could be applied to these plant materials.

Until more precise indices are available for selection of agroforestry materials, the following general guidelines will help in selecting organic inputs for their N release patterns. If %N in the organic material is less than 1.74, as is the case for most litters and many nonlegumes, net N immobilization will occur and will be relatively long term, perhaps beyond the length of a cropping season. If %N is greater than 1.74, then net mineralization will occur but will decrease as a function of the (LIG + PP)/N ratio. It is not yet possible to give details on the critical value at which immobilization will occur in plant materials with greater than 1.74% N and high polyphenol content, although the immobilization does appear to be short term in all cases. As rough estimates, if lignin concentrations are higher than 15% or soluble polyphenol concentrations are higher than 3%, there is likely to be reduced or delayed N release.

Most nutrient release work has focused on nitrogen. Once nitrogen requirements are met, phosphorus becomes limiting in many tropical soils and it may often be the primary limiting nutrient. Although release patterns of P generally follow that of biomass there can be periods of immobilization [Palm and Sanchez, 1990; Tian et al., 1992b; Thomas and Asakawa, 1993] that could exacerbate soil solution P deficiencies relative to crop demand. There is little understanding of controls on P release and immobilization patterns but combined with the net negative P balance reported for alley cropping systems, there is an obvious need for research similar to that conducted on N release patterns. In addition organic inputs can indirectly affect soil P availability by reducing the P fixation capacity of the soil [Singh and Jones, 1976]. The reduced P fixation capacity is temporary and probably depends on the resource quality of the inputs. The potential of plant materials to increase P availability either by release from decomposing materials or by reducing the P fixation capacity of the soil could be an important criterion for selecting agroforestry species.

Plant materials, once characterized for their nutrient release patterns, could be selected to match the nutrient demand pattern of a specified crop. Various scenarios have been proposed that illustrate attempts at synchronizing release and demand (Fig. 1). It is hypothesized that high quality materials will release nutrients too quickly, similar to the use of inorganic fertilizers, resulting in large losses and low nutrient use efficiency whereas low quality materials will release them too slowly or do not contain enough nutrients to meet crop demand. Based on this hypothesis materials of intermediate quality would be expected to show nutrient release patterns in closer synchrony with plant nutrient demand. This might be achieved with the use of specific plant materials or by a mixture of high and low quality materials with release of nutrients slowly at first, when crop demand is low, and providing an increasing

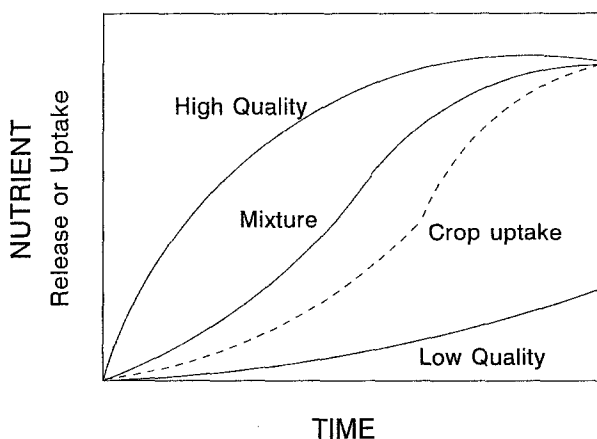


Fig. 1. Hypothetical nutrient release patterns of different quality plant materials compared with nutrient uptake patterns (adapted from Swift [1987]).

rate of release with time, as the crop grows and demands more [Swift, 1987].

There is no clear evidence that mixtures of high and low quality materials alter the patterns of nutrient release. In general, mixtures show release patterns that are parallel to those of the high quality materials rather than altered release patterns with an increase in release rates at later stages [Constantinides and Fownes, 1994; Handayanto et al., 1994]. A few studies cited by Myers et al. [1994] do show changes in release patterns with mixtures. More experimentation is needed in varying the proportions of high and low quality materials, to understand the relative importance of nutrient release versus immobilization in determining the combined pattern. Agroforestry species with high N content but with delayed release patterns or initial immobilization, caused by lignin and polyphenol contents, may provide release patterns more similar to crop demand and also provide sufficient N. Release patterns of *S. siamea*, that contains high N and high polyphenol contents, exhibit temporary immobilization followed by rapid net mineralization of N [Tian et al., 1992a; Constantinides and Fownes, 1994] and may come close to approximating crop demand.

### Fate of nutrients

Since the primary purpose of alley cropping and biomass transfer systems is to provide nutrients to the crop from tree prunings, it is important to ask: How much of the nutrients from the applied prunings are actually taken up by the crop? The amount of N added from the leaves or prunings of agroforestry species taken up by the crop is quite low. Recovery values are generally less than 20% and more frequently closer to 10% (Table 3). These recovery values

Table 3. The % N mineralized, % recovery of total N added, % recovery of the N mineralized, % remaining in undecomposed plant material, and the % of that is unaccounted for following the additions of the leaves of several agroforestry trees to crops. Values within a study are comparable but not among studies.

Source of N	% Mineralized	% Recovery of total N	% Recovery of mineralized N	% Remaining in mulch	% Lost or in SOM	References
<i>L. leucocephala</i>	76	4	5	24 <sup>b</sup>	71	1
<i>Sesbania sesban</i>	89	31	35	11 <sup>c</sup>	58	2
<i>L. leucocephala</i>	88	10	12	12 <sup>c</sup>	78	
<i>Calliandra calothyrsus</i>	40	-3	-	60 <sup>c</sup>	> 40	
<i>Acacia Cunninghamhamii</i>	66	2	3	34 <sup>c</sup>	64	
<i>L. leucocephala</i>	47	11	23	53 <sup>d</sup>	36	3
<i>G. sepium</i>	48	13	23	52 <sup>d</sup>	35	
<i>Peltophorum dasyrachis</i>	24	8	32	76 <sup>d</sup>	16	
<i>C. calothyrsus</i>	32	7	22	68 <sup>d</sup>	25	
<i>G. sepium</i>	100	21 <sup>a</sup>	21 <sup>a</sup>	0 <sup>c</sup>	79	4, 5
<i>L. leucocephala</i>	90	26 <sup>a</sup>	28 <sup>a</sup>	10 <sup>c</sup>	64	
<i>Inga edulis</i>	68	12	18	32 <sup>f</sup>	56	6
<i>Erythrina</i> sp.	94	21	22	6	73	
<i>Cajanus cajan</i>	73	20	27	27	53	

<sup>a</sup> Compared to fertilized control.

<sup>b</sup> 84 days.

<sup>c</sup> 70 days.

<sup>d</sup> 64 days.

<sup>e</sup> 100 days.

<sup>f</sup> 4 rice crops.

References: 1. Mulongoy and Van der Meersch (1988); 2. Gutteridge (1992); 3. Handayanto et al. (1994); 4. Tian et al. (1992b); 5. Tian et al. (1993); 6. Palm (1988).

are similar to those for crop legumes but less than those for inorganic fertilizers. The materials that released a higher percentage of initial N, such as *G. sepium* and *Sesbania sesban*, had higher percent recoveries than materials that released a smaller percent of N, such as *C. calothyrsus*. It is not clear what the implication of these results is with respect to the relative degree of synchrony attained by the different quality materials. Even though the materials that released a higher percentage of initial N also had higher percent recoveries, they may also have a greater percent loss of nutrients. So to assess synchrony it is important to know the potential loss of nutrients in addition to percent recovery of nutrients.

Why do the intercrops receive so little of the applied nutrients? What is the fate of the remaining 80–90% of the added N? Unfortunately, few agroforestry experiments have been designed to answer these questions or the data are not presented in sufficient detail to allow such an analysis. Using data presented in several key papers, an attempt is made here to try to answer some of the questions (Table 3). It is important to point out that some of the experiments are pot studies and others are field experiments, the time spans of the experiments are also different; nevertheless, some of the issues can be addressed. Most of these experiments do not include the competitive effect of intercropped trees, an important fact to keep in mind. Where possible results from trials with crop legumes are used to reinforce results or provide an indication if there are no data from tree legumes.

The amount of N released from the prunings during the course of crop growth is not always 100% of that added, and in many cases as much as 50% of the N may still be held in the undecomposed plant material (Table 3). Percent N recovery values improve to greater than 20% if they are calculated based on the N mineralized from the plant material, rather than the total N added in the plant material. The recovery values for the lower quality materials are more similar to those of the higher quality materials when calculated in this manner because a smaller percent of the N was mineralized. These modified recovery values are also more comparable to those obtained with inorganic fertilizer.

If the amounts of N taken up by the crop and remaining in the undecomposed plant material are summed, the amount of N unaccounted for ranges from 16 to 80%, the larger values corresponding to the higher quality materials. The N that is unaccounted for could be in the soil organic matter; in the soil as inorganic N, although much of it could have leached below the crop rooting zone; or have been lost by volatilization or denitrification. Nitrogen can also be taken up by the trees in intercropping situations, although trees were not included in these particular studies. Evidence for the relative importance of the different pools or loss pathways of N are presented below.

Haggar et al. [1993], based on a detailed labelling study of *Erythrina poeppigiana* and *G. sepium*, concluded that the majority of the N ends up in some readily mineralizable fraction of the soil organic matter. They also

showed that this fraction is not the microbial biomass because the biomass contained only 3–5% of the added N and there was no difference in microbial N among treatments despite different quantities of organic input. They speculated that it is a fraction with a longer turnover time. Ladd et al. [1981] found for a legume-wheat rotation that the first crop recovered 11–17% of the N added as legume and that 72–78% was found in the soil organic matter (SOM). They did not attempt to separate different SOM fractions. Both studies concluded that the benefit of legume inputs to crop production is through the long term buildup of soil organic N rather than the direct release of N from the decomposing legume.

Controlled experiments are needed that compare the effects of different quality materials on fractions of soil organic matter, and the relative N supplying capacity of those fractions. For example, plant material containing high N but also high polyphenol and lignin contents may result in the formation of different soil organic matter fractions, with differing N availability, compared with that formed from organic inputs with lower lignin and polyphenol contents. Size and density fractions of SOM, such as the Ludox fractions [Hassink, 1995] or particulate organic matter, POM [Cambardella and Elliott, 1992], would be good candidate measurements.

The N remaining in the soil organic matter and the undecomposed plant material should have a residual effect on subsequent crops. There are no agroforestry experiments yet that have looked specifically at the residual nitrogen effect, although some are currently underway (J. Henrot and M. van Noordwijk, pers. comm.). Studies with crop legumes provide an indication of the magnitude of the residual effect. Twenty-two percent of the N from labelled alfalfa was recovered by a first crop of wheat and an additional 4% by the second crop [Ladd et al., 1983]. Sisworo et al. [1990] followed the N added from a cowpea crop and found that more than 70% was recovered in six consecutive crops. There is no reason to believe the same would not hold for agroforestry systems with leguminous trees. The amounts of lignin and polyphenols in the prunings may influence the residual effect but it is not known if the residual effect would be enhanced or reduced.

Losses of N from leaching or gas emissions would depend on many soil and climatic factors and again few measurements are available. Volatilization only occurs if the prunings are surface applied, so the importance of this loss pathway will vary depending on management practice. Loss of N via volatilization from green manures measured in laboratory incubations ranges from 5 to 50% but it is usually less than 20% of the added N [Cornforth and Davis, 1968; Costa et al., 1990; Glasener, 1991; Janzen and McGinn, 1991]. Higher quality materials that release N rapidly tend to lose more N via volatilization [Glasener, 1991].

Leaching of nitrate is possible when there is a large pool of inorganic N in the soil, as could happen if there was asynchrony between release and demand. Leaching is only of concern, however, in more humid environments where the depth of wetting in the soil is deeper than the crop rooting zone.

This also implies that asynchrony is not an important issue in drier climates as proposed by Myers et al. [1994]. Even if leaching is a factor in humid environments, deep roots of trees might serve as a safety net for capturing N that leaches below the crop rooting zone [Van Noordwijk et al., 1995]. Again there are few field measurements to give an indication of the relative importance of N leaching in systems with or without agroforestry trees.

The biggest and perhaps the most important unknown is the amount of nutrients released from added plant material that is taken up by the intercropped trees, rather than the crop. Several studies have shown reduction in crop yield in the rows nearest to the trees [Rosecrance et al., 1992; Salazari et al., 1993; Fernandes et al., 1993]. The reduction may be due to shading, competition for nutrients or water, or a combination of these factors. Competition for nutrients, rather than water, between trees and crops would be likely on infertile soils of the humid tropics where water is usually not limiting to plant production. Although agroforestry trees have deeper rooting systems than crops, the majority of the roots are found in the topsoil and this proportion increases when the trees are pruned [Hairiah et al., 1992], increasing the likelihood of competition between trees and crops. Root pruning along the tree hedges has partially reduced the loss in crop yield near trees in some cases [Fernandes et al., 1994], suggesting there was in fact competition but root pruning has not helped in other cases [Sitompul et al., 1992].

The results above on the fate of N added from prunings indicate that as much as 80% is found in the soil, in SOM or inorganic form. The nutrient benefit to crops from tree prunings is more from longer term buildup of SOM rather than the short term release from decomposing prunings. Potential losses by volatilization and leaching are larger for higher quality materials. Scenarios for the fate of N from the prunings of two legumes, one with high N but low lignin and polyphenols concentrations and the other with high N and high lignin and polyphenol concentrations, are presented in Fig. 2. These scenarios are based on data from Table 3 and from estimates of volatilization cited above.

### **Crop response to different quality inputs**

This section is not intended to review crop production in agroforestry intercropping systems but to see if there are obvious effects of different quality inputs on crop yields. To make such comparisons it is best to have the inputs applied at equal N rates or the results expressed on an added N basis. In most agroforestry trials this is not the case so interpretations must be made with caution. One type of input may result in higher crop yields simply because it was applied at a higher rate, not because of increased synchrony or nutrient use efficiency.

Crop growth in pot experiments reflects the different qualities of the inputs. In an experiment by Fox et al. [1990], several legumes were added to sorghum-

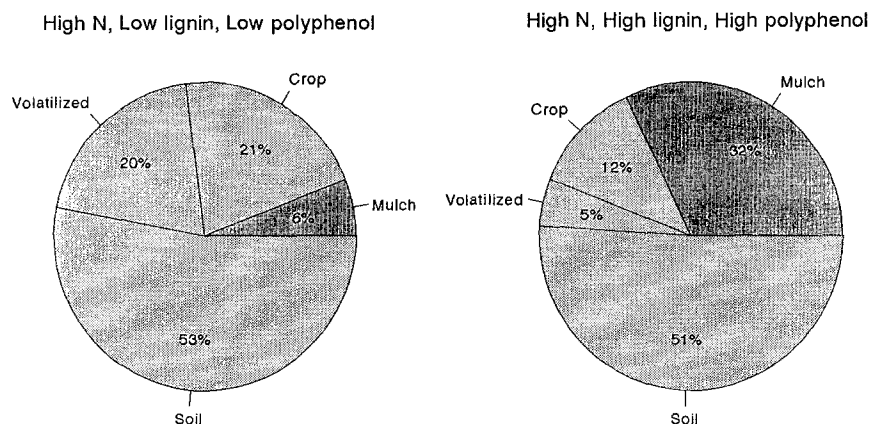


Fig. 2. The fate of N of prunings of different quality after a cropping season; in undecomposed mulch; in the crop; in the soil as SOM or inorganic N, or lost via volatilization (adapted from Palm [1988]). Dark shading represents the N not yet mineralized and light shading represents N mineralized during the cropping season.

sudan at equal N rates. Alfalfa released 47% of its N in 12 weeks and resulted in higher crop growth compared with *L. leucocephala* and *Cassia rotundifolia*, which released 29% and 11.2%, respectively, of their N in the same period (Fig. 3). Gutteridge [1992] applied a variety of tree legumes at equal biomass rates and compared the crop response at the rate of N applied. If compared at a rate equivalent to 100 N kg ha<sup>-1</sup>, *S. sesban* released 86% of its N and produced about 60 g of maize stover per pot compared with *L. leucocephala*, which also released 86%, but only produced 40 g of stover. *Calliandra calothyrsus* released 34% of its N and produced only 15 g of stover per pot. It is interesting to note that even though *S. sesban* and *L. leucocephala* released similar proportions of their N, the crops grown with *S. sesban* produced more mass. This difference could be a result of different N release patterns and different degrees of synchrony or that the N from *L. leucocephala* is somehow not available. Both these studies suggest that the higher quality material produced higher yields and higher %N recovery but the relative degree of synchrony is not known.

Many field experiments do not show differential response to the quality of inputs. Yamoah et al. [1986a,b] reported that maize yields were similar although 58% of *Senna siamea* prunings compared with 96% of *G. sepium* prunings decomposed during the cropping period. This lack of response to such different release patterns can be explained by two observations. More prunings of *S. siamea* were applied, resulting in twice the amount of N compared to that added in the *G. sepium* prunings. Even if only 58% of the N was released from *S. siamea*, it would be equal to the amount released by *G. sepium*. Other information suggests that the soil was not N limited, so a maize response to additional N would not be expected. Rosecrance et al.

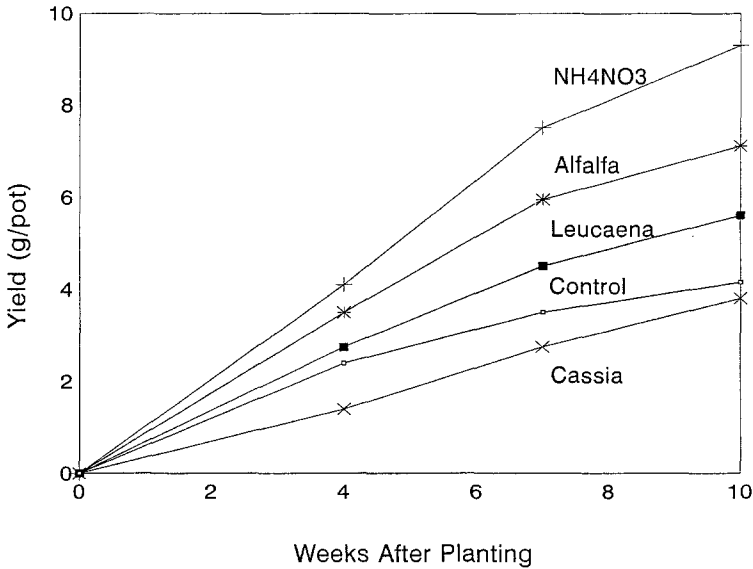


Fig. 3. Growth of sorghum-sudan in response to legume mulch inputs of different quality in a pot study [Fox et al., 1990].

[1992] found that maize yields were related to the amount of N added from the prunings of nine leguminous trees even though materials of strikingly different qualities, such as *Sesbania sesban* and *C. calothyrsus*, were used. Mulongoy et al. [1993] found no difference in maize yields when grown with 10 t ha<sup>-1</sup> prunings of *G. sepium*, *L. leucocephala*, and *Senna siamea*, materials with differing N release patterns. Only 70% of the N was added in *S. siamea* as compared with the other species. This soil was N limiting, so the results suggest that *S. siamea* has a higher N use efficiency, a possible indication of greater synchrony as speculated above. They also found that date of application of prunings relative to crop planting date affected maize growth: yields were higher when prunings were applied close to planting date, also an indication of better synchrony.

Tian et al. [1993] found interesting results when comparing maize response to different quality inputs. Although there were no significant differences in maize yields using the same quantity of different quality tree prunings, different trends were observed over two seasons. Yields in the first season, with abundant rainfall, were directly related to the amount of N released from the materials. Higher quality *L. leucocephala* and *G. sepium* produced higher yields than the nonlegume *Dactyladenia barteri*. In the second season, with insufficient rainfall, *L. leucocephala* produced the highest yields but yields in *D. barteri* plots were higher than those of *G. sepium*. The authors contend that high quality materials enhance crop production through the direct contribution of nutrients from decomposition and that lower quality materials enhance production through mulching effects on microclimate. In the dry



season, the temperature was lower and moisture higher in plots with *D. barteri* compared with plots where the mulches had already decomposed; these conditions are more favorable to maize growth and possibly enhance SOM mineralization.

The results of the pot and field studies give contradictory evidence on the effect of leguminous prunings of different quality on crop yields. Why? If only 10% of the N released from the decomposing material is recovered by the crop, that would be 20 kg of N from 100% decomposition of a material containing 200 kg N, or 10 kg N from a material that decomposed by only 50%. Significant responses to these small differences in inputs are difficult to detect in field studies but may be detectable in pot studies where conditions are more controlled and uniform. In addition, other factors, such as microclimate, can be affected by input quality and confound the interpretation of results.

The need for well-designed experiments that address these issues systematically should now be obvious. First of all, these types of experiments must be done in soils known to be N limiting, or limiting in the nutrient in question for each particular study. The amounts of N added should be within the responsive part of the curve, in order to detect differences. Including N response curves as part of the study would help in the interpretation of results. Equal rates of N should be applied, or the results expressed in terms of N added so as not to confound the amount of mulch added with the amount of nutrient added. Other factors that may also be affected by input quality and affect crop yields, independently of nutrients, must be monitored. These factors include soil temperature and moisture, pests, disease, and allelopathy.

## Conclusions

Many leguminous agroforestry trees produce sufficient pruning biomass and contain enough nutrients, except for P, to meet crop demand in intercropping systems. The nitrogen release patterns, or quality, of the prunings differs greatly, from 100% mineralization to net immobilization during the course of crop growth. These patterns are reflected in differential crop growth in pot studies but not in field studies. In general, only 10 to 20% of the N released is taken up by the first crop and a large portion is in the soil organic matter, indicating that the N benefit of the pruning additions is in the long term rather than immediate. The effect of different quality inputs on the various soil organic fractions and their N supplying capacity is not known.

## Acknowledgements

The author would like to thank Nancy Wangari for assistance in the review and synthesis of literature. Comments on an earlier draft of this paper by E.

Barrios, M. van Noordwijk, M. Swift, G. Tian, and two anonymous reviewers were very helpful.

## References

- Aber J and Melillo J (1982) Nitrogen mineralization in decaying hardwood leaf litter as a function of initial nitrogen and lignin content. *Canadian Journal of Botany* 60: 2263–2269
- Bowen GD (1984) Tree roots and the use of soil nutrients. In: Bowen GD and Nambiar EKS (eds) *Nutrition of Plantation Forests*, pp 147–179. Academic Press, London, UK
- Budelman A (1989) Nutrient composition of the leaf biomass of three selected woody leguminous species. *Agroforestry Systems* 8: 39–51
- CABI (1991) *TREE-CD*. CAB International, Wallingford, UK
- Cambardella CA and Elliott ET (1992) Particulate soil organic-matter changes across a grassland cultivation sequence. *Soil Science Society of America Journal* 56: 777–783
- Coe R (1994) Through the looking glass: 10 common problems in alley-cropping research. *Agroforestry Today* 6: 9–11
- Constantinides M and Fownes JH (1994) Nitrogen mineralization from leaves and litter of tropical plants: relationship to nitrogen, lignin and soluble polyphenol concentrations. *Soil Biology and Biochemistry* 26: 49–55
- Cornforth IS and Davis JB (1968) Nitrogen transformations in tropical soils. I. Mineralization of nitrogen-rich organic materials added to soil. *Tropical Agriculture* 45: 211–221
- Costa FJSA, Bouldin DR and Suhet AR (1990) Evaluation of N recovery from mucuna placed on the surface or incorporated in a Brazilian oxisol. *Plant and Soil* 124: 91–96
- Fernandes ECM, Davey CB and Nelson LA (1993) Alley cropping on an acid soil in the upper Amazon: mulch, fertilizer, and hedgerow root pruning effects. In: Ragland J and Lal R (eds) *Technologies for Sustainable Agriculture in the Tropics*. ASA Special Publication 56, pp 77–96. ASA, Madison, WI, USA
- Fernandes ECM, Garrity DP, Szott LT and Palm CA (1994) Use and potential of domesticated trees for soil improvement. In: Leakey RRB and Newton AC (eds) *Tropical Trees: The Potential for Domestication and the Rebuilding of Forest Resources*, pp 137–147. HMSO, London, UK
- Fox RH, Myers RJK and Vallis I (1990) The nitrogen mineralization rate of legume residues in soil as influenced by their polyphenol, lignin and nitrogen contents. *Plant and Soil* 129: 251–259
- Frankenberger WT and Abdelmagid HM (1985) Kinetic parameters of nitrogen mineralization rates of leguminous crops incorporated into soil. *Plant and Soil* 87: 257–271
- Giller KE and Wilson KJ (1991) *Nitrogen Fixation in Tropical Cropping Systems*. CAB International, Wallingford, UK
- Glasener KM (1991) Ammonia volatilization losses from tropical legume mulches. MSc thesis, North Carolina State University, Raleigh, NC, USA
- Gutteridge RC (1992) Evaluation of the leaf of a range of tree legumes as a source of nitrogen for crop growth. *Experimental Agriculture* 26: 195–202
- Haggar JP, Tanner EVJ, Beer JW and Kass DCL (1993) Nitrogen dynamics of tropical agroforestry and annual cropping systems. *Soil Biology and Biochemistry* 25: 1363–1378
- Hairiah K, Van Noordwijk M, Santoso B and Syekhfani MS (1992) Biomass production and root distribution of eight trees and their potential for hedgerow intercropping on an ultisol in southern Sumatra. *Agrivita* 15: 54–68
- Handayanto E, Cadisch G and Giller KE (1994) Nitrogen release from prunings of legume hedgerow trees in relation to quality of the prunings and incubation method. *Plant and Soil* 160: 237–248
- Hassink, J (1995) Density fraction of macro-organic matter and microbial biomass as predictors of C and N mineralization. *Soil Biology and Biochemistry* (in press)

- Heuvelop J, Fassbender HW, Alpizar L, Enriquez G and Folster H (1988) Modelling agroforestry systems of cacao (*Theobroma cacao*) in Costa Rica. II. Cacao and wood production, litter production and decomposition. *Agroforestry Systems* 6: 37–48
- Iritani WM and Arnold CY (1960) Nitrogen release of vegetable crop residues during incubation as related to their chemical composition. *Soil Science* 89: 74–82
- Janzen HH and McGinn SM (1991) Volatile loss of nitrogen during decomposition of legume green manure. *Soil Biology and Biochemistry* 23: 291–297
- Kachaka S, Vanlauwe B and Merckx R (1993) Decomposition and nitrogen mineralization of prunings of different quality. In: Mulongoy K and Merckx R (eds) *Soil Organic Matter Dynamics and Sustainability of Tropical Agriculture*, pp 199–208. John Wiley and Sons Ltd., West Sussex, UK
- Kang BT, Wilson GF, and Sipkens L (1981) Alley cropping maize (*Zea mays* L.) and leucaena (*Leucaena leucocephala* LAM) in Southern Nigeria. *Plant and Soil* 63: 165–179
- Ladd JN, Oades JM and Amato M (1981) Distribution and recovery of nitrogen from legume residue decomposing in soils sown to wheat in the field. *Soil Biology and Biochemistry* 13: 251–256
- Ladd JN, Amato M, Jackson RB and Butler JHA (1983) Utilization by wheat crops of nitrogen from legume residues decomposing in soils in the field. *Soil Biology and Biochemistry* 15: 231–238
- Melillo JM, Aber JD and Muratore JF (1982) Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. *Ecology* 63: 621–626
- Mulongoy K and Van der Meersch MK (1988) Nitrogen contribution by leucaena (*Leucaena leucocephala*) prunings to maize in an alley cropping system. *Biology and Fertility of Soils* 6: 282–285
- Mulongoy K, Ibewiro EB, Oseni N, Kilumba AO, Opara-Nadi and Osunubi O (1993) Effect of management practices on alley-cropped maize utilization of nitrogen derived from prunings on a degraded alfisol in south western Nigeria. In: Mulongoy K and Merckx R (eds) *Soil Organic Matter Dynamics and Sustainability of Tropical Agriculture*, pp 223–230. John Wiley and Sons Ltd, West Sussex, UK
- Myers RJK, Palm CA, Cuevas E, Gunatilleke IUN and Brossard M (1994) The synchronisation of nutrient mineralization and plant nutrient demand. In: Woomer PL and Swift MJ (eds) *The Biological Management of Tropical Soil Fertility*, pp 81–116. John Wiley and Sons, West Sussex, UK
- Nye PH and Greenland DJ (1960) The soil under shifting cultivation. Technical communication 51. Commonwealth Bureau of Soils, Harpenden, UK
- Oglesby KA and Fownes JH (1992) Effects of chemical composition on nitrogen mineralization from green manures of seven tropical leguminous trees. *Plant and Soil* 143: 127–132
- Palm CA (1988) Mulch quality and nitrogen dynamics in alley cropping system in the peruvian Amazon. PhD dissertation, North Carolina State University, Raleigh, NC, USA
- Palm CA and Sanchez PA (1990) Decomposition and nutrient release patterns of the leaves of three tropical legumes. *Biotropica* 22: 330–338
- Palm CA and Sanchez PA (1991) Nitrogen release from the leaves of some tropical legumes as affected by their lignin and polyphenolic contents. *Soil Biology and Biochemistry* 23: 83–88
- Palm CA, McKerrow AJ, Glasener KM and Szott LT (1991) Agroforestry systems in lowland tropics: is phosphorus important? In: Tiessen H, Lopez-Hernandez D and Salcedo IH (eds) *Phosphorus Cycles in Terrestrial and Aquatic Ecosystems. Regional Workshop 3: South and Central America*, pp 134–141. Saskatchewan Institute of Pedology, Saskatoon, Canada
- Rosecrance RC, Brewbaker JL and Fownes JH (1992) Alley cropping of maize with nine leguminous trees. *Agroforestry Systems* 17: 159–168
- Russo RO and Budowski G (1986) Effect of pollarding frequency on biomass of *Erythrina poeppigiana* as a coffee shade tree. *Agroforestry Systems* 4: 145–162
- Salazari A, Szott LT and Palm CA (1993) Crop-tree interactions in alley cropping systems on alluvial soils of the Upper Amazon Basin. *Agroforestry Systems* 22: 67–82

- Sanchez, PA (1976) Properties and Management of Soils in the Tropics. John Wiley and Sons, New York, NY, USA
- Singh BB and Jones JP (1976) Phosphorus sorption and desorption characteristics of soil as affected by organic residues. *Soil Science Society of America Journal* 40: 389–394
- Sisworo WH, Mitrosuhardjo MM, Rasjid H and Myers RJ (1990) The relative roles of N fixation, fertilizer, crop residues and soil in supplying N in multiple cropping systems in a humid, tropical upland cropping system. *Plant and Soil* 121: 73–82
- Sitompul SM, Syekhfani MS and Van der Heide J (1992) Yield of maize and soybean in a hedgerow intercropping system. *Agrivita* 15: 69–75
- Swain T (1979) Tannins and lignins. In: Rosenthal GA and Janzen DH (eds) *Herbivores; Their Interactions with Secondary Plant Metabolites*. Academic Press, New York, NY, USA
- Swift MJ, Heal OW and Anderson JM (1979) *Decomposition in Terrestrial Ecosystems*. Studies in Ecology. University of California Press, Berkeley, CA, USA
- Swift MJ (1987) Tropical Soil Biology and Fertility: Interregional Research Planning Workshop. *Biology International Special issue 13*. IUBS, Paris, France
- Szott LT, Fernandes ECM and Sanchez PA (1991) Soil-plant interactions in agroforestry systems. *Forest Ecology and Management* 45: 127–152
- Thomas RJ and Asakawa NM (1993) Decomposition of leaf litter from tropical forage grasses and legumes. *Soil Biology and Biochemistry* 25: 1351–1361
- Tian G, Kang BT and Brussaard L (1992a) Effects of chemical composition on N, Ca, and Mg release during incubation of leaves from selected agroforestry and fallow plant species. *Biogeochemistry* 16: 103–119
- Tian G, Kang BT and Brussaard L (1992b) Biological effects of plant residues with contrasting chemical compositions under humid tropical conditions – decomposition and nutrient release. *Soil Biology and Biochemistry* 24: 1051–1060
- Tian G, Kang BT and Brussaard L (1993) Mulching effect of plant residues with chemically contrasting compositions on maize growth and nutrients accumulation. *Plant and Soil* 153: 179–187
- Van Noordwijk M, Sitompul SM, Hairiah K, Listyarini E and Syekhfani MS (1995) Nitrogen supply from rotational or spatially zoned inclusion of Leguminosae for sustainable maize production on an acid soil in Indonesia. *Plant and Soil* (in press)
- Vandenbelt RJ (ed) (1992) *Faidherbia albida* in the West African Semi-Arid Tropics. ICRISAT, Patancheru, India
- Vitousek PM and Sanford Jr RL (1986) Nutrient cycling in moist tropical forest. *Annual Review of Ecology and Systematics* 17: 137–167
- Von Carlowitz PG, Wolf GV and Kemperman REM (1991) Multipurpose Tree Database: An Information and Decision Support System. ICRAF, Nairobi, Kenya
- Yamoah CF, Agboola AA and Mulongoy K (1986a) Decomposition, nitrogen release and weed control by prunings of selected alley cropping shrubs. *Agroforestry Systems* 4: 229–246
- Yamoah CF, Agboola AA and Wilson GF (1986b) Nutrient contribution and maize performance in alley cropping systems. *Agroforestry Systems* 4: 257–254
- Young, A (1989) *Agroforestry for Soil Conservation*. International Council for Research and Agroforestry and CAB International, Wallingford, UK