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Fertilizers in agroforestry systems

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Abstract. This review encompasses results of fertilization experiments on several agroforestry systems — alley cropping, perennial shade systems, home gardens — in which fertilizer use is a likely management alternative. Fertilizer response was found to be most common in alley cropping, variable in perennial shade systems, and rarely reported in home gardens. Level of nutrient removal in harvested products is probably the overriding factor in determining fertilizer response; greater accumulation of organic residues, slower growth under shade, and longer periods of nutrient uptake probably also contribute to the relatively smaller fertilizer response of the perennial shade systems and home gardens. Considerable knowledge gaps exist regarding the breakdown of organic residues, and interactions between mineral and organic amendments. Systems based on annual crops (e.g., alley cropping) are likely to be less nutrient-efficient and sustainable than systems based on perennial crops, due to reduced fixation and transfer of N to the crops, the tendency of the trees to compete for and sequester nutrients, relatively high P requirements of the crops, and the high labor cost of tree management. The possible benefits of fertilization of specific components in home gardens, and relative advantages of including low-value tree legumes, high-value shade trees, and fertilization in shaded perennial systems are only beginning to receive research attention.

Introduction

Agroforestry systems in which large quantities of nutrients are removed in harvested products are unlikely to be sustainable without fertilization. This is especially true on acidic, infertile tropical soils where system performance has often been less successful than expected. On these soils, the ability of agroforestry systems to significantly increase nutrients through enhanced nutrient recycling or nitrogen fixation appears to be limited, mainly due to the low levels of available nutrients and high levels of elements toxic to plant growth [Sanchez, 1987; Hawkins et al., 1990; Palm et al., 1991; Szott et al., 1991b]. On fertile soils, nutrient deficiencies may also occur under high levels of nutrient removal. A balance between nutrient removals and additions can be achieved by reducing the quantity of nutrients (and products) exported or, as is more likely, by increasing nutrient inputs via fertilization. This paper focuses on the latter. We intend to indicate the types of agroforestry systems in which fertilizers might be, or are, used and review the results of fertilizer use in these systems. We discuss the management of organic and inorganic fertilizers in tree-based systems, and finally, we examine some economic considerations of fertilizer use in agroforestry.

Relevance of fertilizers in agroforestry

Fertilizers are defined as any organic or inorganic material which is added to a soil to supply certain elements essential to the growth of plants [Soil Science Society of America, 1987]. Although fertilizer use is theoretically possible in almost all agroforestry systems, the greater labor or capital costs associated with fertilizer application would tend to limit its use to systems where cash cropping is an important feature [Raintree, 1987]. These systems would likely include alley cropping and mixed tree-crop systems (e.g., home gardens and shaded perennial crops) due to the high level of nutrient removal and the high value of products produced in these systems. The use of organic fertilizers would likely predominate where agricultural and market infrastructure are less developed; the use of organic fertilizers, inorganic fertilizers, or mixtures of the two types would predominate where relatively low-cost commercial fertilizers are available, and where a high return is expected from fertilizer applications.

Review of results

Alley cropping

In alley cropping, the annual removal of nutrients is usually greater than in most perennial tree-crop systems [Szott et al., 1991b; Palm et al., 1991; Wood and Lass, 1985], resulting in greater demand on the system to supply and/or recycle nutrients. Much of the research on alley cropping during the past decade has addressed the ability of this system to maintain productivity with or without mineral fertilizers [Hawkins et al., 1990; Kang et al., 1985; Kass et al., 1989; Salazar, 1990, 1991; Sanchez, 1987]. In many studies, however, interpretation of the response of alley cropping to fertilization is difficult due to: (1) a lack of a true control treatment in which trees and prunings are absent; (2) the importation of mulch from off-site; (3) fertilization of plots with P and K, effectively limiting the scope of many studies to examinations of the effect of nitrogen; and (4) the relatively short duration of the studies [Hawkins et al., 1990].

Crop and tree yields

Most studies address the ability of leguminous species to substitute for nitrogen fertilization. The results usually show that the application of inorganic nitrogen fertilizers considerably increases (up to 1000 kg ha^{-1})

yields of maize alley cropped with *Leucaena leucocephala*, but gives much smaller increases with *Gliricidia sepium*, *Flemingia macrophylla*, or other alley cropping species. A more limited database suggests that additions of inorganic N also increase grain legume yields in these systems (Table 1).

Levels of other nutrients are rarely varied in alley cropping studies but here, too, responses are apparent. Yamoah and Burleigh [1990] reported a considerable increase in pole bean (*Phaseolus vulgaris*) production when 30 and 60 kg ha^{-1} of P were applied to N-fertilized *Sesbania sesban* alley cropping systems, but results of only one harvest were presented. Other studies have shown that beneficial effects of fertilization are often delayed. Salazar [1991] observed a response to low levels of P (25 kg ha^{-1} $year^{-1}$) — in otherwise unfertilized *Inga edulis*, *Cassia reticulata*, or *G. sepium* alley cropping systems on an Ultisol (Acrisol) — only in the seventh (cowpea), tenth (cowpea), and eleventh (rice) crops of an eleven-crop-long sequence (Fig. 1). Fertilizer additions (50 kg N, 25 kg P, 20 kg K, 35 kg Ca, and 16 kg Mg ha^{-1} $crop^{-1}$) to rice and cowpeas alley cropped with *I. edulis* on an Ultisol resulted in significantly greater grain yields in the fertilized, as compared to the unfertilized, treatment in the fourth through the seventh crops of a seven-crop-long sequence [Fernandes, 1990]. Balances of P additions and removals in alley cropping systems on infertile and acidic, or fertile (but low in P) soils suggest that P may eventually limit the productivity of these systems [Salazar, 1990, 1991; Palm et al., 1991]. This would tend to support the argument that prunings alone, especially on infertile soils, cannot sustain the productivity of continuous alley cropping [Palm et al., 1991; Szott et al., 1991a, b].

Although few studies report the effect of direct fertilization on pruning production by alley cropping species, limited results suggest that many respond to nitrogen. It should be noted, however, that nitrogen fertilization may decrease N_2 fixation, as observed by Sanginga et al. [1989] for *L. leucocephala*. Hill [1970] and Stewart and Gwaze [1988] observed that *L. leucocephala* and *Faidherbia albida* (syn. *Acacia albida*), respectively, respond to nitrogen. On an acidic soil in Rwanda, Yamoah et al. [1989] observed that, in the first four months after transplanting, growth of *S. sesban*, *Calliandra calothyrsus*, *L. leucocephala*, and *Markhamia lutea* increased with manure additions of up to 5 Mg ha^{-1}, but that by eight months, there was no response to manure. They also noted that lime increased the growth of all trees. On an acidic, infertile Ultisol, Szott [1987] found little response in pruning production of *I. edulis*, *Erythrina* sp., or *Codariocalyx gyroides* to lime or lime + P applied to the hedges at transplanting, but production of *Cajanus cajan* responded to lime. Tissue P contents of these species, however, did increase with P addition, and the Ca and Mg contents of *C. cajan* increased with lime. Responses of *C. cajan* to K and P additions to an Oxisol (Ferralsol) were also noted by De Lucena-Costa and Paulino [1992] and De Lucena-Costa et al. [1992]. Netera et al. [1992]

Table 1. Cases of fertilizer response in alley farming systems [after Hawkins et al., 1990].

Site	Soil type	Crop	Hedgerow species	Years hedge	Fertilizer N; P; K (kg ha^{-1})	Grain yield (kg ha^{-1})	Ref.
Nigeria	Infertile Alfisol	Maize	Leucaena	4	0; 13; 25	3228	1
〃	〃	〃	〃	〃	60; 13; 25	4075	
Nigeria	?	Maize	Leucaena	6	0; 0; 0	1366	2
〃	〃	〃	〃	〃	90; 20; 38	2223	
Nigeria	Infertile Alfisol	Maize	Leucaena	6	0; 13; 25	3200	3
〃	〃	〃	〃	〃	45; 13; 25	3536	
Nigeria	?	Maize	Leucaena	2	0; 0; 0	820	4
〃	〃	〃	〃	〃	45; 20; 38	1450	
Philippines	?	Maize	Leucaena	3	0; 0; 0	845	5
〃	〃	〃	〃	〃	100; 18; 0	1817	
Costa Rica	High organic matter Inceptisol	Maize	Gliricidia	6	0; 39; 108	2007	6
〃	〃	〃	〃	〃	150; 39; 108	2101	
Nigeria	Infertile Alfisol	Maize	Gliricidia	2	0; 62; 58	2360	7
〃	〃	〃	〃	〃	30; 62; 58	2610	
Nigeria	Infertile Alfisol	Maize	Flemingia	2	0; 62; 58	2240	7
〃	〃	〃	〃	〃	30; 62; 58	2553	
Nigeria	Infertile Alfisol	Maize	Acioa	4	0; 13; 25	3228	1
〃	〃	〃	〃	〃	60; 13; 25	3900	
Nigeria	?	Cowpea	Leucaena	2	0; 0; 0	580	4
〃	〃	〃	〃	〃	45; 20; 38	760	
Costa Rica	High organic matter Inceptisol	Beans	Gliricidia	6	0; 39; 108	1019	6
〃	〃	〃	〃	〃	0; 39; 108	1114	

References: 1. Kang and Osinubi [cited in IITA, 1989]; 2. Osinubi and Kang [cited in IITA, 1989]; 3. Kang and Gichuru [cited in IITA, 1989]; 4. Gichuru, Palada and Kang [cited in IITA, 1989]; 5. O'Sullivan [1985]; 6. Kass et al. [1989]; 7. Yamoah et al. [1986].

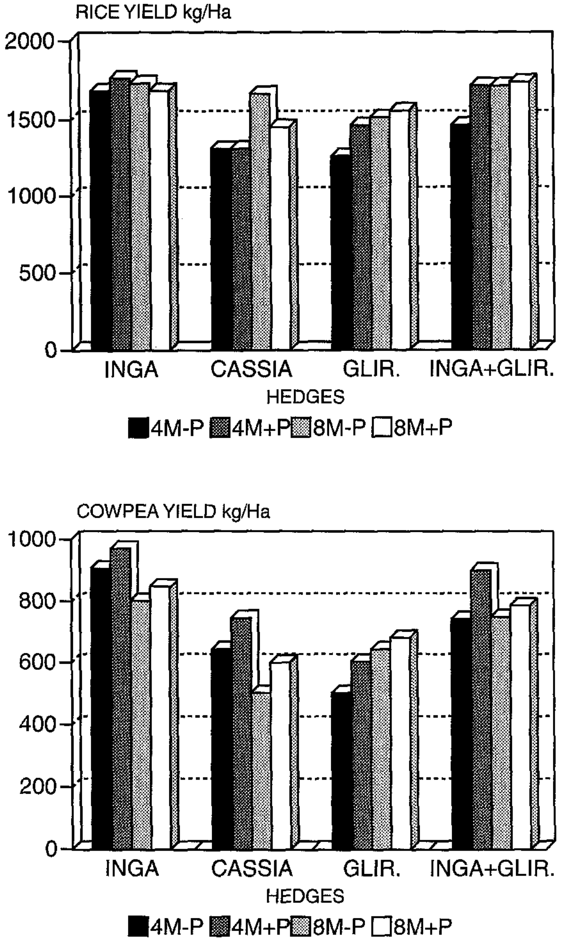

Fig. 1. Mean response of crops to P (25 kg P ha^{-1} $crop^{-1}$) in three cropping cycles with different hedgerow species and alley widths (4 m and 8 m) on an Ultisol (Acrisol) in Yurimaguas, Peru (initial modified Olsen P = 4.9 ppm). INGA = *Inga edulis*, CASSIA = *Cassia reticulata*, GLIR = *Gliricidia sepium*. *Source*: Salazar [1991].

observed that the response of *C. calothyrsus* to lime and P was genotype-dependent.

Indirect evidence of tree response to fertilizers is provided by alley cropping studies where the productivity of hedges adjacent to fertilized cropped areas (from which hedgerow trees could presumably tap nutrients) is compared to trees associated with unfertilized areas. Kang et al. [1981, 1985, 1990] observed increased pruning production and N yield of *L. leucocephala* and *Alchornea cordifolia* with increasing N additions to a sandy Entisol (Arenosol). However, no responses were observed for *L. leucocephala* or *Acioa barteri* on an infertile Alfisol (Lixisol) [Siaw et al., 1991], or for *G. sepium* or *A. barteri* on a sandy Entisol [Kang et al., 1990]. On a high organic matter Inceptisol (Cambisol), Kass et al. [1989] showed that *G. sepium*, but not *Erythrina poeppigiana*, responded to N fertilization of the cropped areas. Fernandes [1990] noted that pruning biomass and macronutrient contents were greater in *I. edulis* hedgerows bordering plots fertilized with N, P, K, Ca, and Mg than in those bordering unfertilized plots. However, Salazar [1991] did not observe differences in production or P concentration of prunings for *I. edulis*, *G. sepium*, or *C. reticulata* bordering P-fertilized or unfertilized cropped areas. The lack of tree response to fertilization, based on comparisons of fertilized vs. unfertilized plots, should not be taken as clear evidence of the inability to respond to fertilization; trees bordering unfertilized plots may take up nutrients from nearby, fertilized plots [Rao and Roger, 1990].

Perennial crop/shade tree systems

The most extensively studied fertilized, perennial crop/shade tree system is cacao (*Theobroma cacao* L.). In contrast to alley cropping, there are a number of long-term experiments with published and reasonably consistent results [Akenorah et al., 1974; Cabala-Rosand et al., 1972; Byrne, 1972]. Benefits and disadvantages of shade trees over coffee and cacao have been reviewed by several authors [Willey, 1975; Budowski et al., 1984; Wood and Lass, 1985; Beer, 1987].

Cacao fertilization experiments have been conducted on a wide range of soil types. In almost all of these studies, yields of shaded cacao increased when fertilizer was applied. However, shade removal in the absence of fertilization generally produced greater yield increases than fertilization of shaded trees, and the highest yields were obtained in fertilized, nonshaded treatments (Fig. 2). Under non-shaded conditions, nitrogen fertilization was particularly important since overbearing and subsequent dieback often occurred in the absence of N [De Geus, 1973]. Yields from unshaded treatments were also generally more variable, and increased yields could not be maintained over more than ten years [Wood and Lass, 1985]. As a result, maintenance of shade trees was generally recommended.

There are fewer long-term fertilization experiments with shaded coffee. For this species, removal of shade is generally recommended [Franco and Inforzato, 1951], at least on large plantations, since yield is more or less determined by the amount of light received, independent of the amount of fertilizers applied [De Geus, 1973]. However, high light intensities in the presence of limited N can cause dieback, which can be reduced by either providing shade or adding N. As with cacao, shaded systems usually produce more stable yields over time [Beer, 1987; Willey, 1975]. A long-term experiment on a fertile alluvial Entisol (Fluvisol) in Costa Rica showed that shaded coffee required lower fertilization levels than non-shaded coffee to obtain the

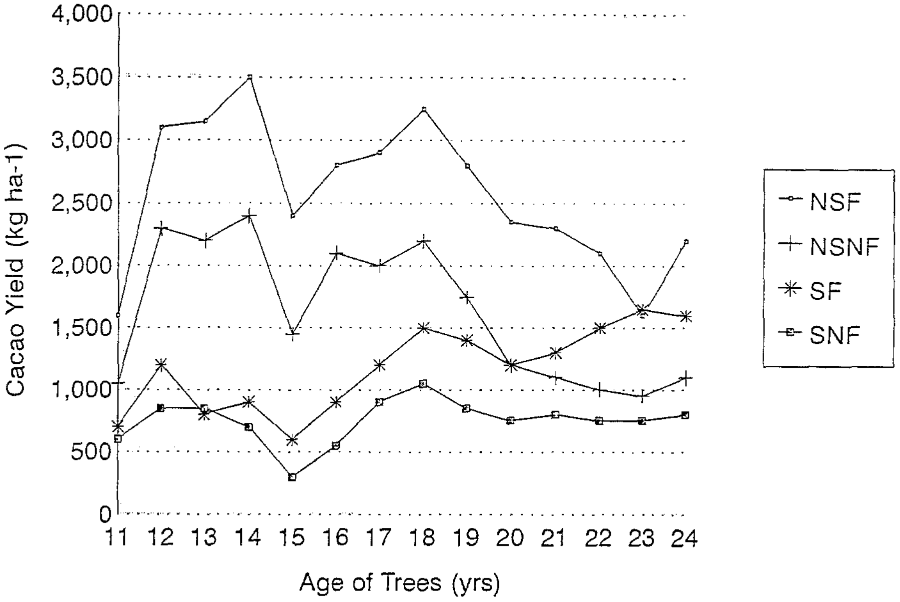

Fig. 2. Effect of shade removal and fertilizer applications on yield of Amelondo cacao in Ghana. Shade removed and fertilizer applied in Year 10. NSF = no shade, fertilized; NSNF = no shade, no fertilizer; SF = shaded, fertilized; SNF = shaded, no fertilizer. *Source*: Akenorah et al. [1974].

same yields. Response to fertilization was more linear in non-shaded coffee [CATIE, 1992]. In addition to N, K is an important nutrient for high coffee yields [De Geus, 1973].

Tea responds to nitrogen and light in a manner similar to cacao and coffee. Yields under full light are often linear with the quantity of N applied, but the relationship is more complex under shade [De Geus, 1973]. The full effect of N application may not be observed in the year after fertilization because some of the N will be taken up by the shade trees and subsequently recycled to the associated crop following pruning; responses to N application are cumulative during various pruning cycles.

Studies of nutrient cycling in crop/shade tree systems suggest that fertilization and/or periodic pruning of leguminous shade trees leads to increased crop production, greater quantities of nutrients recycled, and a greater proportional export of nutrients with respect to the amount recirculated, compared to unfertilized and/or unpruned systems [Herrera et al., 1987; Fassbender, 1987; Fassbender et al., 1988; Beer et al., 1990]. The importance of pruned leguminous shade trees to nutrient circulation in these systems is noteworthy. Escalante et al. [1984] estimated that approximately 60 kg N ha^{-1} $year^{-1}$ were recycled from nodules in a cacao/*E. poeppigiana* plantation.

Glover and Beer [1986] found that the amount of P and K contributed by prunings and litterfall of *Erythrina*, alone, was greater than that of *Erythrina* combined with *C. alliodora*; the amount of N circulated by the two shade systems was about equal; and the quantities of Ca and Mg recycled were greater in the *C. alliodora/Erythrina* combination than with *Erythrina* alone. Beer [1988] suggests that the partial replacement of leguminous trees by a non-leguminous timber species may reduce the amount of nutrients recycled, warranting supplemental mineral fertilization, at least for shaded coffee.

Home gardens

There are few studies of fertilizer use in home gardens. It is sometimes maintained that such systems are chiefly found on soils of relatively high native fertility [Szott et al., 1991a], but this does not preclude the possibility that they may respond to fertilizer additions. Indeed, it is usually mentioned that most home gardens are fertilized with household wastes, crop residues, litterfall, human or animal manure, or ant or termite nests, but quantification of these inputs is lacking [Posey, 1985; Fernandes et al., 1989]. In the Kandyan home gardens of Sri Lanka, 85% of the home gardens never received inorganic fertilizers [Perera and Rajapakse, 1991]. Only 5.9% of the cash required to manage the gardens was spent on inorganic fertilizers, compared to 87.8% for hired labor; most of the fertilizer use was on a few high-value crops [Jacob and Alles, 1989]. However, fertilizer use in such systems is reportedly increasing [Soemarwoto, 1987].

The components of home gardens are varied, but fruit trees are a constant and conspicuous component [Fernandes and Nair, 1987]. Many fruit trees respond to inorganic or organic fertilization, and may have special nutritional requirements. Often, they have complex response patterns because nutrient supply in one year may have a major effect on tree nutrition and crop production in subsequent years [Atkinson, 1986]. A review of the nutrient requirements of many tropical crops common to home gardens is provided by De Geus [1973]. Many palms — such as coconut (*Coco nucifera*), peach palm (*Bactris gasipaes*), and oil palm (*Elaeis guieensis*) — respond to early applications of N and P with improved vegetative growth and earlier bearing; K application at bearing results in higher yields [Hartley, 1970; De Geus, 1973; Perez et al., 1993]. Arecanut (*Areca catechu*), a home garden component common in Southeast Asia, is often fertilized with manure. Regular and high yields of black pepper (*Piper nigrum*) require additions of N, K, and Mg after about the second year, when plants start to bear; N is usually required throughout the season, but K and Mg are especially critical during pepper ripening. Bananas (*Musa* spp.) have high N and K requirements but relatively low P requirements. Other fruits, such as avocado (*Persea americana*), mango (*Mangifera indica*), papaya (*Carica papaya*), and cashew (*Anacardium occidentale*) require N and P during early stages to produce rapid vegetative growth and early fruiting. During fruiting, avocado requires

N, K, and Zn; mango needs N, K, and Ca; papaya, especially, needs high rates of N; and cashew has responded to N and P. Pineapple (*Ananas comosus*) growth is mainly determined by the amount of N, which in turn determines the amount of K required; P requirements are relatively low. Most of the above knowledge comes from studies of pure stands. There are virtually no studies that have examined how tropical fruits common to home gardens respond to shade combined with nutrient additions.

Organic and inorganic fertilizers and their interactions

Given the prevalence, importance, and potential of organic fertilizer use in agroforestry systems, further examination is needed of how these sources, alone or in combination with inorganic fertilizers, affect nutrient availability and product yield. Since there have been few studies of organic fertilizers in agroforestry systems, we have had to rely chiefly on literature developed in annual-cropping or forestry systems. Agroforestry systems, however, are structurally and functionally more complex than annual crops or forest monocultures; this makes fertilizer management more difficult. The advantages of organic vs. inorganic fertilizers have long been debated and we will not recount these arguments in detail, except to note that in some cases organic fertilizers may offer advantages. However, prediction of the quantity and timing of nutrients supplied by organic sources is difficult. In contrast, inorganic fertilizers offer the significant advantage of accurate control of the rates, placements, sources, and timing of fertilizer applications.

Quantities of nutrients in organic residues

Considerable quantities of nutrients in organic forms can be applied through litterfall and prunings in agroforestry systems [Budelman, 1989; Hawkins et al., 1990; Szott et al., 1991a]. The actual quantities can vary greatly depending on climate, soil type, tree species, spacing, and management techniques. For example, fertilization is apt to increase the amount of nutrients contained in pruned material or in litter [Szott et al., 1991a], and frequent pruning — a common management technique in alley cropping and shade tree systems — reduces biomass production, nitrogen fixation [Duguma et al., 1988; Fernandes, 1990; Rogers and Rosecrance, 1992], and the production of Ca- and Mg-rich woody tissue in the pruned tree. It should be recognized, however, that nutrients in litterfall and prunings, unless added from off-site, are merely recycled and are not true additions to the system. The application of inorganic fertilizer, on the other hand, represents a true addition.

Nutrient release from organic residues

The effective use of organic fertilizers in agroforestry requires an understanding of controls on nutrient release from these sources. The controls that regulate the decomposition and release of nutrients from organic residues and soil organic matter include climate (temperature and moisture), soil texture, the quantity and chemical composition of the material, and placement. Decomposition usually proceeds faster in warmer and more humid locations [Anderson and Swift, 1983], in sandy vs. clayey soils [Amato et al., 1987], and when material is incorporated rather than applied to the soil surface [Holland and Coleman, 1987]. However, Meentemeyer [1978] suggests that, in the tropics, the rate of decomposition is controlled more by the quality of plant material than by climate. Organic residue decomposition and N mineralization in short-term (<6 month-long) studies have been negatively correlated with the C:N ratio, the polyphenol concentration, and the initial (lignin + cellulose) concentration of the material [Aber et al., 1990; Fox et al., 1990; Palm and Sanchez, 1990, 1991]. This suggests that many leguminous plants used in agroforestry systems may not be good sources of available N, despite high N contents, because of high polyphenol:N or (lignin + polyphenol):N ratios [Fox et al., 1990; Palm and Sanchez, 1991]. The wide range in decomposition constants of pruned materials from agroforestry systems (see Budelman [1988] and Palm and Sanchez [1990]) tends to support this argument, although differences in methodology or climate may partially contribute to the observed variability. In contrast to differences in short-term decomposition patterns, Aber et al. [1990] suggest that decomposition of different materials in the long term (once the original mass is reduced to about 20%) will be similar, due to similarity in C chemistry of the remaining material.

The mineralization of nutrients, other than C and N, from organic materials in agroforestry systems has been less studied. In the humid tropics in general, 50% or more of K is released in less than one month, whereas Ca loss is slow, with turnover times often longer than one year [Palm and Sanchez, 1990; Swift et al., 1981]. Release of P is difficult to predict since C, P, and N may interact to determine patterns of mineralization and immobilization. Clearly, much further research is required to develop information that can serve as a base for providing usable recommendations at the farm level.

Fertilizer recovery

There is little information regarding the recovery of nutrients from organic or inorganic sources by trees in agroforestry systems. In alley cropping, usually less than 20% of the N, about 40 kg N ha^{-1} or less, in surface-applied prunings ends up in the immediately succeeding crop [Guevara, 1976; Haggar, 1990; Kang et al., 1990; Mulongoy and Sanginga, 1990]. Somewhat greater utilization of N has been observed when prunings are buried or incorporated [Kang et al., 1984, 1985], but this increases the labor requirement of the system. The remainder of the organic N is either not released

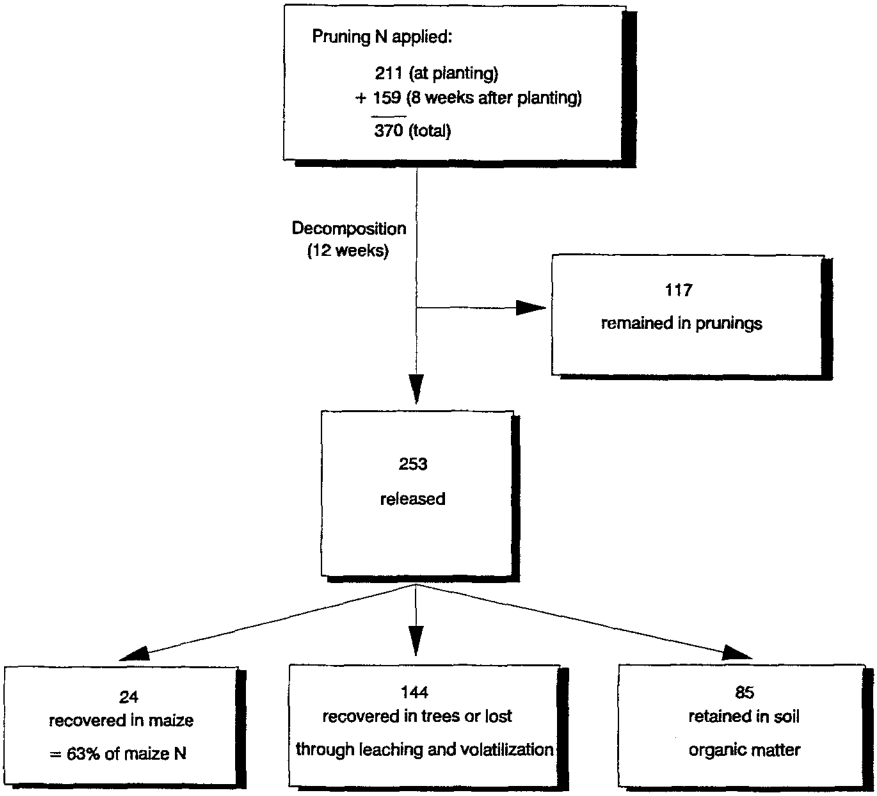

Fig. 3. Fate of nitrogen from prunings of *Leucaena leucocephala* applied to a maize crop. All data expressed in kg ha^{-1}. *Source*: Mulongoy and Sanginga [1990].

(31%), is lost or taken up by the trees (39%), or incorporated into the soil organic matter (23%) (Mulongoy and Sanginga 1990) (Fig. 3).

Undoubtedly, greater efficiencies of nutrient recovery from organic sources in these systems would be noted if residual effects are considered. Compared to inorganic fertilizers, many organic materials have a greater residual effect on soil fertility because of the slow-release characteristics of their N and P components [Doran and Smith, 1987]. Sisworo et al. [1990] noted that around 70% of the N applied in legume residues was recovered within two years of application. In comparison, the recovery of inorganic N fertilizers by annual crops in the tropics is seldom over 30 to 40% [Baligar and Bennett, 1986; Sisworo et al., 1990]; uptake efficiencies of trees are largely unknown. It is expected that recoveries are likely to vary with climate, type of nutrient applied, the timing and frequency of application, and placement. Efficiencies are lowest in high rainfall environments and highest in semiarid zones [Myers, 1988], mainly due to greater leaching and denitrification losses in more humid areas.

Timing and frequency of fertilization

The timing and frequency with which nutrients are made available to plants affect nutrient recovery. In alley cropping systems, attempts have been made to synchronize organic or inorganic fertilizer application with crop nutrient demand. While some information exists to guide the application of inorganic fertilizers, there is much less information for organic sources. In the case of organic residues, nutrient release and availability are apt to be much more complicated for the reasons mentioned above.

In shaded perennial crops or home gardens, the question of nutrient synchrony during a given season may not be as important as in alley cropping, since perennial-crop root systems are likely to be active for a greater part of the year. Certain fruit species, however, may require specific nutrients at certain times in order to ensure high levels of fruit production, as noted previously. In perennial-crop systems, it may be most important to consider nutrient synchrony as related to the developmental stage of the individual plants or of the stand. The first year after planting is often a critical time for many fruit and timber species, and delays of more than a year in P application often result in loss of productivity, which is seldom recovered by later fertilization [Ballard, 1984]. Nutrient deficiency is also apt to occur around the time of canopy closure, when tree growth and nutrient demand are high, internal nutrient retranslocation is low, and nutrient quantities supplied by soil and recycling mechanisms may be low [Miller, 1984]. Even after this stage, deficiencies may persist if nutrient removal in harvested products is high.

Based on studies of forest fertilization in temperate climates (see Ballard [1984] and Binkley [1988] for reviews), it may be predicted that the response of agroforestry systems in the humid tropics to fertilization with inorganic N would be shorter (on the order of three years or less) than that observed for P. For N, most recovery and response would be expected to occur in the first year or two after application. This is due to immobilization of N and/or the large N losses that may occur under humid conditions if the uptake capacities of trees are saturated by large fertilizer doses. Reduced losses, greater responses, and more efficient fertilizer use may be obtained with frequent, low-level, but more costly, fertilizer applications. Under these conditions, slow ammonium-release fertilizers (e.g. organic residues or sulfur-coated urea) may be recommended over those which release nitrate, which is easily leached or denitrified. In wet/dry climates, gaseous losses of urea could occur during dry periods.

In contrast to N, the response to P should be longer lasting, since additions of P are usually large relative to the capital of available P in the soil and, hence, should be able to sustain a prolonged increase in P availability. However, the duration of the response would depend greatly on the P-fixing capacity of the soil. Slow release forms of P (e.g., organic residues or rock phosphate) would be recommended for acidic soils with a high P-retention capacity.

Organic/inorganic combinations

Due to the nature of agroforestry systems, we need to address the question of how combinations of organic and inorganic fertilizers will affect nutrient supply needs. The effects of such combinations can vary due to changes in the energy status of the soil and in the biological processes that determine nutrient availability. The immediate plant response to the addition of inorganic or organic fertilizers may be less than expected. Inorganic N or P added to systems where residues are concentrated at the soil surface may be immobilized or, in the case of urea N, volatilized. Similarly, additions of organic residues with high C contents can result in immobilization and the lowering of inorganic N and P in the soil solution, resulting in lower nutrient availability. In some cases, however, addition of organic residues can result in the complexation of organic material with Al and Fe, resulting in greater availability of inorganic forms of P.

Long-term nutrient use may be improved by organic-inorganic fertilizer combinations. Additions of inorganic N or P can result in greater immediate availability as well as longer-term increases in the organic forms of these elements, as greater amounts of C and organic N or P are returned to the soil in more abundant plant residues. Immobilization of inorganic P or N in organic form may reduce nitrogen losses by leaching, and buffer nutrient release [Doran and Smith, 1987; Stewart and Sharpley, 1987]. On high P-fixing or weathered soils, the conversion of P to organic forms may sustain plant-available P [Acquaye, 1963; Adepetu and Corey, 1976; Stewart and Sharpley, 1987; Haggar et al., 1991]. Additions of inorganic P to P-limited soil may also stimulate the mineralization of N [Munevar and Wollum, 1977].

Economic considerations

Fertilizer use in agroforestry will depend on fertilizer availability, cost, the cost/benefit relationship, and the interplay of socio-cultural values. Given the complexity of these interactions and the uncertainty regarding the effects of organic or inorganic fertilizers on the productivity of agroforestry components, economic analyses are difficult.

The economic utility of fertilization is a principal question and the outcome will depend on trade-offs among the biological response observed, the value of the products, the cost of fertilization, the length of the productive cycle, the timing and frequency of fertilization, and the discount rate. Generally, investment in fertilization can be most easily justified if a large increase in economically valuable products is quickly obtained. When the production cycle is long, early fertilization is usually justified only if a strong and prolonged response in productivity occurs and if the increase in productivity exceeds the discount rate. This occurs with P fertilization of many timber species [Binkley, 1988] and may occur with some tropical perennial crops, as already noted. Early fertilization would also be advantageous if it shortened the time to production, as might occur with many fruits.

In alley cropping, the economic benefit of using legumes vs. inorganic fertilizers as an N source rests chiefly upon the trade-offs between labor and inorganic fertilizer costs. For example, in Costa Rica, fertilizer prices would have to increase about six times in order to balance the extra labor costs involved in alley cropping [Hernandez et al., 1992]. One factor which might affect this conclusion is the value of other products or services (e.g., reduction of erosion and nutrient losses) produced by the leguminous hedges. If hedge products are valuable (e.g., for stakes, firewood, or fodder), then the response of both the crops and the trees must be considered. Mittal and Singh [1989] present an example in which alley cropping with *L. leucocephala* was uneconomical when only crop yields were considered, but which economically out-performed monocultures of annual crops when the value of staking material provided by the hedges was included in the economic calculations.

We have seen that trade-offs between shade and fertilizers can affect the production of perennial crops such as coffee and cacao. In these cases, the main economic issues include: the marginal utility of the use of shade and fertilizer or their combination, and their effect on the productive life of the plantation. An additional question is the utility of replacing woody legumes, used for shade and nitrogen additions, with non-leguminous, economically valuable species. It has been shown, for example, that the economic return of fertilized cacao is slightly higher with shade of *C. alliodora* than with *E. poeppigiana*, a legume, despite higher cacao yields under the latter [Von Platen, 1992]. This author suggested that fertilization, pruning regime, and high site fertility hid any possible positive effects of *E. poeppigiana*. These results in favor of the non-leguminous system, however, would be reversed at higher discount rates, higher cacao prices, lower timber prices, or lower labor costs [Von Platen, 1992]. It would be worthwhile to investigate the economic performance and trade-offs between shade/organically fertilized (via prunings) systems and non-shade, inorganically fertilized systems, especially in light of fluctuating prices for major perennial crops such as coffee and cacao.

Conclusions

In agroforestry systems, application of fertilizers would appear to be appropriate for cash crops having a high nutrient demand. Systems which meet these criteria are: alley cropping, shaded perennial crops, and home gardens.

In alley cropping, it is unlikely that high demand for nutrients, especially N, will be met solely by the prunings of the hedges, since nutrient demand appears to exceed the capacity of the trees to provide nitrogen and other elements, and labor costs of frequent hedgerow pruning are high. However, positive effects of fertilization may be less than expected due to the negative relationship between nitrogen fixation and quantity of inorganic N applied, the increased probability of N loss through leaching and volatilization, and the tendency of the trees to compete for and sequester nutrients such as P.

In contrast to alley cropping, there is a better possibility that, in the absence of fertilization, tree-based inputs and nutrient cycling may sustain the productivity of low-nutrient-demanding agroforestry systems, such as shaded perennial crops and home gardens. However, changes in species composition or management in order to increase economic yields (e.g., the substitution of timber or fruit trees for leguminous shade trees) may decrease the quantities of nutrients recycled and increase nutrient removal, resulting in subsequent increased fertilizer requirements. To achieve efficient fertilizer use, more studies are needed of the response of various species and agroforestry systems to inorganic and organic fertilizer additions. It seems that home gardens offer good prospects for increased fertilizer use, if only to specific crops within the garden, especially as land availability becomes more limited. Improved timing of application of specific nutrients in order to increase fruit production is likely to be a promising approach in such systems.

Phosphorus is the element that theoretically should be most limiting in agroforestry systems when woody legumes are used as a nitrogen source and/or when the amounts of P removed are relatively high or cycling is low. Responses to P applied to agroforestry systems, however, have been infrequently studied. Further research is needed on how interactions between inorganic and organic nutrient sources can be managed to sustain P availability in both the short and long terms.

Organic fertilizers appear to have longer residual effects on nutrient availability than inorganic fertilizers, but much more research is needed in order to develop a predictive understanding of how organic sources can be managed in order to provide the same advantages presently offered by inorganic fertilizers. Given the importance and prevalence of organic fertilizer use in many agroforestry systems, a greater understanding of how trees respond to fertilizers — organic, inorganic, or organic-inorganic combinations — needs to be developed.

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