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Use and potential of domesticated trees for soil improvement

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ABSTRACT

The ancient and widespread use of tree and bush fallows to recuperate soil productivity following several years of cropping, has resulted in research aimed at identifying, planting and managing trees for soil improvement. The goal is either to reduce the traditional fallow periods (normally between 4 and 25 years) or to eliminate the fallow period by introducing systems in which "soil-improving" trees are managed together with crops or pasture species (agroforestry). Trees commonly used by farmers for soil improvement include *Acioa barteri*, *Calliandra calothyrsus*, *Erythrina berteroana*, *E. poeppigiana*, *Faidherbia albida*, *Gliricidia sepium*, *Inga edulis*, *Leucaena leucocephala*, *Prosopis cineraria*, *Samanea saman* and *Sesbania sesban*. Although many of these species are largely undomesticated, a number of them are currently the focus of genetic improvement programmes (see papers by Brewbaker & Sorrensen, Simons *et al.*, Owino *et al.*, Milimo *et al.*, and Felker, this volume). The possibility exists that in such programmes selections could be made for tree characteristics to significantly improve soils. A synthesis of the research data from work on acid and high base status soils in the humid, sub-humid, and semi-arid regions of Central and Latin America, Africa and Asia is used to critically evaluate "tree-soil improvement" hypotheses related to nutrient cycling, organic matter additions, and nitrogen fixation. These hypotheses are discussed in the context of developing domestication strategies for multipurpose species, taking account of the influence of the species on the soil environment.

INTRODUCTION

The claimed potential of trees to improve soils probably originates from the fact that forest fallows have been used to restore soil productivity in the traditional and widespread practice of shifting cultivation (Greenland and Nye, 1959). In addition, there exist several traditional land use systems in which farmers retain trees on farmland. The recognition of the importance of the existing, but little studied, integration of trees in tropical land use systems led to the coining of the term agroforestry (Bene *et al.*, 1977).

Increased yields have been reported for crops and forage grasses in close proximity to trees and this has been partly attributed to better soil chemical and physical properties as a result of tree growth (Nair, 1984). Several hundred semi-domesticated tree species are currently being used by farmers in the tropics. If these species can be further domesticated and utilized to counteract the soil degrading effects of cropping and animal husbandry, small farmers in the tropics who are currently practicing shifting cultivation may not need to slash and burn additional forests every 2-4 years. The objective of this paper is to critically examine "tree-soil improvement" hypotheses in relation to some of the semi-domesticated tree species that have not yet been used to a significant degree in plantation forestry. Since multipurpose tree species with potential for soil improvement are currently the focus of considerable scientific research in the context of agroforestry (Young, 1989), we will evaluate primarily agroforestry data sets in evaluating the key tree-soil improvement hypotheses related to nutrient cycling, organic matter additions, and nitrogen fixation. This will lead to a consideration of the ways in which the domesticated tropical tree species can enhance soil improvement.

TREE-BASED CROPPING SYSTEMS IN THE TROPICS

Trees in rotation with crops (forest fallows)

Shifting or slash and burn cultivation is a major form of land use in the tropics (Greenland, 1974). Farmers typically clear about a hectare of primary or secondary forest, burn it and then plant crops for one or more years taking advantage of the nutrients released in the ash. Once yields decline or

the weeds are no longer easily controlled and the site is abandoned. The nutrient accumulation by the forest fallow, shading out of weeds, and the action of tree roots and associated microorganisms and fauna are the processes by which the potential soil productivity is gradually improved to a state approaching that of a primary rainforest.

In areas of high population pressure such as Nigeria, farmers are no longer able to leave the land fallow for a long period and resort to "accelerated or biologically enriched fallows" involving tree species such as *Acioa barterii*, *Alchornea cordifolia*, *Anthonota macrophylla*, *Crestis ferugina*, *Dialium guineense*, *Gliricidia sepium*, and *Harungana madagascariensis* (Okafor, 1982; Okigbo, 1983). In S.E. Asia, farmers use *Calliandra calothyrsus* (NRC, 1983) and *Leucaena leucocephala* (NRC, 1984) as fallow species.

Trees in association with crops

In the Sahelian and Sudanian zones of Western Africa, farmers maintain and manage around 20 different tree species on crop lands. Of these species, *Faidherbia albida* (Charreau and Vidal, 1965) and *Parkia biglobosa* (Kessler, 1992) have been reported to improve soils. Farmers in the semi-arid zones of India commonly retain and manage tree species such as *Prosopis cineraria* (Aggarwal *et al.*, 1976), *P. juliflora* and *Delonix elata* (Jambulingam and Fernandes, 1986) for soil improvement, fuel wood, and fodder. In northeastern Thailand, where multipurpose trees are maintained or planted on paddy fields, significantly higher organic matter and soil macronutrients were found in fields with the nitrogen-fixing *Samanea saman* than in fields with non-leguminous trees (Sae-Lee *et al.*, 1992). Other tree species used to improve soils include *Sesbania sesban* (Evans and Rotar, 1987), *Erythrina berteroana* and *E. poeppigiana* (Ramírez *et al.*, 1990).

TREE CHARACTERISTICS FOR SOIL IMPROVEMENT IN THE TROPICS

Fast-growing tree species are major components of agroforestry technologies (Nair *et al.*, 1984). With the exception of *Leucaena leucocephala* (Brewbaker, 1987), the great majority of tree species have only just begun to be scientifically tested for their biological potential, adaptability to site

conditions and responses to management factors such as pruning, fertilization, and competition with agronomic crops.

On the more fertile soils the presence of apparently sustainable, age-old agroforestry systems and experimental evidence indicate that the tree component of agroforestry systems contributes to reduced erosion and efficient cycling (Alpizar *et al.*, 1988). On acid, infertile soils the potential of trees to increase nutrient inputs or reduce losses is limited by chemical constraints to root expansion. High aluminium (Al) saturation in the subsoil, low levels of calcium (Ca) and phosphorus (P), and a lack of weatherable minerals can severely limit plant productivity and thereby reduce nutrient capture and recycling as compared to more fertile sites (Szott *et al.*, 1991). Adaptability to soil chemical and physical conditions is an obvious but vital requirement for any tree species to contribute to soil improvement. Desirable characteristics for soil-improving trees include the following:

- (i) *Moderate to high leafy biomass production:* around 2 Mg ha⁻¹ yr⁻¹ for semi-arid regions, 4 Mg ha⁻¹ yr⁻¹ for sub-humid regions and 8 to 10 Mg ha⁻¹ yr⁻¹ for the humid tropics (Table 1). These values are based on estimates by Young (1989), of organic residues required to maintain soil organic carbon at 7.5, 15 and 30 Mg ha⁻¹ for each region respectively.
- (ii) *Nitrogen fixation potential* (10 to 200 kg N ha⁻¹ yr⁻¹ based on estimates from various species in the tropics (Peoples and Herridge, 1990). The lower values are likely to be encountered for trees in the semi-arid tropics where moisture stress is frequent, and also in the humid tropics where acid soils with low P availability predominate.
- (iii) *Low fine root (< 2mm diameter) density in the top soil.* For example, no more than 30% of fine roots in the top 15 cm of the soil, and these preferably to be concentrated close to the stem (e.g. *Acioa barteri* as described by Ruhigwa *et al.*, 1992).

- (iv) *Capacity to form effective mycorrhizal associations with native populations of Vesicular-Arbuscular (VA) mycorrhizal fungi or ectomycorrhizal fungi (see papers by Lapeyrie & Högberg and Mason & Wilson, this volume)*
- (v) *Moderate to high nutrient concentrations in leafy biomass (e.g. 2.0-3.5% N, 0.2-0.3% P, 1-3% K and 0.5-1.5% Ca). Interpreting data for micronutrient concentrations in tree and shrub biomass is still difficult.*
- (vi) *Appreciable nutrient concentrations in the root systems.* For comparison, fine and coarse roots from two rainforest sites in Asia (Andriessse, 1987) had the following mean concentrations: 0.66% N, 0.04% P, 0.55% K, 0.85% Ca, and 0.18% Mg. These values will vary with soil type, vegetation and root sizes.
- (vii) *Different rates of leaf litter decay.* Rapid litter decay (1 to 3 weeks) where tree biomass is used to provide nutrients to associated crops or slow decay (2 to 6 months) when tree biomass is used as mulch for weed suppression and soil protection. Slow turnover of leaf and root litter rich in N, for example, may actually be beneficial for N-fixation.
- (viii) *Absence of toxic substances in the foliage or root exudates.* For example, in the acid savannas (*cerrado*) of Brazil some species have been shown to accumulate from 4,000 to 14,000 mg kg⁻¹ of Al in the foliage (Haridasan, 1982). Non-accumulator species typically have Al concentrations < 200 mg kg⁻¹.

Other desirable characteristics of soil-improving trees remain to be identified and there is considerable potential for the exploitation of the intraspecific genetic variation in the characteristics listed. Several tree species with soil-improving characteristics can be identified:

- (i) *Acid soils - humid tropics: *I. edulis*, *Cassia reticulata*, *Cassia spectabilis*, *Erythrina berteroana*, *G. sepium* (OFI 14/84) & *Paraserianthes falcataria*.*

- (ii) Non-acid soils - humid & sub-humid tropics: *C. calothyrsus*, *Erythrina fusca*, *E. poeppigiana*, *G. sepium* & *Leucaena leucocephala*.

- (iii) Non-acid soils - semi-arid tropics: *F. albida*, *Cassia siamea*, *Prosopis cineraria*, *P. juliflora*, & *Sesbania sesban*.

TREE-SOIL IMPROVEMENT HYPOTHESES

Sanchez (1987) formulated the agroforestry hypothesis "appropriate agroforestry systems have the potential to control erosion, maintain soil organic matter and soil physical properties, augment nitrogen fixation, and promote efficient nutrient cycling". What distinguishes agroforestry from other cropping systems is the presence of trees either in association, or in rotation with annual crops and/or animals. The hypothesized benefits of agroforestry are thus directly related to the presence, function, and management of the tree component and the interactions with the crop and/or animal components (Lundgren and Raintree, 1983).

The rationale for supposing soil improvement in agroforestry relative to other cropping systems is that the nutrient exports via the harvest of crop and animal products, erosion, leaching, volatilization, and the deterioration in soil physical properties due to cropping or grazing can be counteracted by the tree component. This may occur via:

- (i) nutrient uptake by deep rooted trees allowing for capture and surface deposition via tree litter, of nutrients beyond the reach of crop roots (more efficient nutrient cycling);

- (ii) increased amounts of organic (shoot and root) inputs to the soil help to maintain soil organic matter and thus improve soil structure and nutrient status; and

- (iii) increased nutrient additions to the soil via nitrogen fixation and dust or aerosol interception by tree canopies. These hypotheses are examined below.

Nutrient cycling and nutrient pumping

According to the "nutrient pumping" hypothesis, nutrients absorbed from the subsoil are used in tree growth and eventually deposited in or on the surface soil via root and leaf litter production, nutrient leaching from foliage, and pruning of leaves or branches (Nair, 1984; Young, 1989).

Nutrient pumping is one of the most frequently cited potential benefits of incorporating trees into cropping systems (agroforestry) and is based on the general belief that trees have deep spreading root systems capable of exploiting a greater soil volume and more nutrients than those of annual crop plants. Careful combination of trees and crops with different rooting characteristics offers the possibility of increasing productivity of admixtures by optimizing the complementarity of soil nutrient exploitation. Factors such as the spatial distribution and temporal patterns of root growth are clearly important, and should influence the choice of species or genotypes to be used.

Research on a variety of soil types and in different climates has involved the injection of ^{32}P at different soil depths and varying distances from the stems of banana (*Musa* spp.), Cacao (*Theobroma cacao*), coffee (*Coffea arabica*), coconut (*Cocos nucifera*), and oil palm (*Elaeis guineensis*) showed that 30-85% of P uptake occurred within a depth of 30 cm and a distance of up to 1 m from the stems of banana, cacao, and coffee. In the case of coconut and oil palm, however, P uptake from similar zones comprised less than 20% of the total applied. The uptake of P from a depth of 45 cm or greater and 1.5 m or further from the stem was less than 4% for the majority of tree crops, but up to 15% for coconut (IAEA, 1975). Indirect evidence of nutrient uptake by trees from the subsoil is provided by studies on *Eucalyptus* and *Prosopis* that showed water uptake from soil depths of 5 m or greater (Stone and Kalisz, 1991). *Leucaena leucocephala* in an alley cropping system depleted soil moisture to a depth of 60 cm (Singh *et al.*, 1989).

In spite of the potential for deep rooting possessed by many tree species, most roots do not reach very deep due to the presence of physical or chemical barriers in the soil. Barriers to root expansion would restrict the absorption of nutrients such as P and K; that diffuse slowly in the soil and are depleted rapidly from localized pockets around roots, or those, such as Ca; which is absorbed mainly through unsubsized root apices. However, root penetration of these barriers does occur. Adaptations to high soil Al levels exist in many plants (Marschner, 1986). Furthermore, localized

discontinuities in these barriers caused by changes in soil texture, mineralogy, or biotic factors such as soil macrofauna may permit roots of non-tolerant plants to grow through these barriers. The importance of these factors to nutrient uptake and cycling on infertile soils deserves further attention. In summary, the greatest possibility for nutrient pumping by deep-rooted trees exists on relatively fertile soils where physical barriers to root penetration are absent.

Organic inputs and soil organic matter

It has been hypothesized that the presence of trees in agroforestry systems results in levels of soil organic matter (SOM) that are adequate for maintaining soil fertility and productivity (Young, 1989). Organic inputs to the soil consist of the above- and below ground litter, crop residues, mulches, green manures and animal manures. Soil organic matter is the result of the partial or complete transformation in the soil of these inputs. Trees may be managed to provide large quantities of biomass for use as organic inputs. Furthermore, considerable scope exists for selecting among and within tree species for different chemical compositions and decomposition rates of the biomass produced. This offers a means of manipulating nutrient release from biomass inputs, soil microbial activity, and the rate of conversion of these organic inputs to SOM.

The quality of organic inputs is one of the factors that influences the rate of decomposition and release of nutrients from organic residues. The use of different tree species with litter of different qualities could be used to manipulate the short- and long-term storage and mineralization of carbon and nutrients. Research on tropical plant species has shown that indices of quality (e.g. C/N or lignin/nitrogen ratios) which are adequate for temperate zones (Melillo *et al.*, 1982) may not be the best predictors of nitrogen mineralization from leguminous materials in the tropics. Nitrogen release patterns may be more closely related to tissue polyphenolic contents than to lignin or nitrogen contents or lignin/nitrogen ratios (Palm, 1988). In general, on fertile soils, leaf litter quality is higher and decomposition faster than on acid, infertile soils (Vitousek and Sanford, 1987). Very little is known about the quality of root litter. Root litter from trees may differ from that of annual crops in proportions of fine to coarse roots, the amount of lignins and polyphenols present, quantities of secondary or allelopathic compounds, and nutrient concentrations. Conventional indices of quality may therefore not be good predictors of tree root decomposition.

Organic phosphorus is the most important source of phosphorus in highly weathered tropical soils (Tiessen et al., 1984). Incorporation of fast-growing trees into tropical farming systems offers the potential to increase this organic P pool. Tiessen et al., (1992) found a 28% increase of organic P in the soil but only a 9% increase in total P during a 10 year bush fallow. There is even some evidence that some species are able to utilize insoluble forms of soil P not utilized by crop species (Ae et al., 1990).

The role of soil organic matter (SOM) in contributing to soil fertility and productivity were summarized by Alison (1973) as described below: SOM is:

- (i) a source of inorganic nutrients to plants;
- (ii) a substrate for microorganisms;
- (iii) an ion exchange material;
- (iv) a factor in soil aggregation and root development; and consequently
- (v) a factor in soil and water conservation.

Despite these potential benefits of SOM, there exist several cases where no consistent correlation has been found between total SOM and existing or potential soil productivity (Sanchez and Miller, 1986). As a result, research has focused on several conceptual fractions of SOM based on different turnover times in the soil as a function of chemical structure and association with soil particles (Parton *et al.*, 1987).

A key issue involves the possibility of influencing soil improvement via the selection and management of tree species with differing litter qualities. Litter that decomposes at a slow rate (low quality) is likely to lead to the formation of slow and passive fractions of SOM which are less important in short-term nutrient availability but play an important role in maintaining soil structure.

In managed fallow or plantation systems where trees are used to regenerate soil productivity, the use of domesticated species with low quality, slowly decomposing materials would build up the organic pools of nutrients and buffer long-term nutrient availability and release. In systems where trees and crops are grown simultaneously (e.g. alley cropping), the use of a mixture of species or genotypes with different litter qualities may be advisable.

N-FIXATION BY TREES

There are around 650 species of nitrogen-fixing trees and shrubs (see Sprent, this volume). Some tree species appear to have a higher capacity for nitrogen fixation than others. Published estimates of the amount of nitrogen fixed by N-fixing trees are in the range 10-500 kg N ha⁻¹ yr⁻¹. The proportion of tissue nitrogen in trees derived from fixation can vary between 4-80% (Peoples and Herridge, 1990; Danso *et al.*, 1992). In addition to differences in N-fixation among tree species, large differences exist among genotypes within a species. Sanginga *et al.*, (1990) reported 2-3 fold differences in N-fixation among genotypes of *F. albida* and *L. leucocephala* after 12 weeks and 70% differences after 36 weeks.

The potential nitrogen contributions of leguminous tree species to the soil may not be realized, however, due to high soil acidity, low soil nutrients (Szott *et al.*, 1991), and low soil moisture contents (Venkateswarlu *et al.*, 1990). Studies of leguminous annuals, have shown that low levels of P in acid soils can severely limit nitrogen fixation (Barea and Azcon-Aguilar, 1983). There is, however, a lack of experimental data for leguminous tree species. In P-deficient soils, the planting of nitrogen-fixing tree species with crops may actually result in competition for P between the trees and associated crops. Addition of moderate amounts of P fertilizer to the trees could alleviate the competition for phosphorus. Effective symbiosis with compatible vesicular-arbuscular (VA) mycorrhizal fungi (see Mason & Wilson, this volume) will also be important.

Nitrogen-fixing trees probably contribute little nitrogen directly to the soil environment in excess of their own nitrogen requirements for growth. This can be overcome by shoot pruning and the application of this biomass to associated crops (e.g. alley cropping). In addition to the release of N

and other nutrients from the decomposing biomass, shoot pruning brings about an additional contribution of N to the soil via the death of fine roots and nodules. In a pot experiment with *L. edulis*, shoot pruning resulted in significant reductions in fine root biomass, total root length infected with VA mycorrhizal fungi, and numbers of active nodules relative to non-pruned control plants (Fernandes, 1990). The renewal of nodulation and nodule function may be further suppressed by the release of N from the decomposing prunings, fine roots and nodules (Danso *et al.*, 1992).

In summary, a number of factors can affect N-fixation in trees. These include soil acidity, low soil P, vesicular-arbuscular (VA) mycorrhizal fungi, high soil N, rhizobial strains, soil moisture and temperature, tree age, shoot pruning, and tree genotype. Optimization of nitrogen fixation by tree species will require not only selections among and within tree species for adaptability to soil factors adversely affecting N-fixation, but also selections for enhanced efficiency of tree-rhizobial-VA mycorrhizal associations.

SIGNIFICANCE OF TREES AS NUTRIENT EXPORTERS

While trees may contribute significantly to soil improvement, they can also have adverse effects on soils and associated crops or pasture species. These potential negative effects include: biomass and nutrient export from the site via tree harvests, as well as competition for nutrients and moisture between the trees and associated crop species. We review these issues through discussion of three types of agroforestry systems: domesticated timber tree-based systems, tree/perennial crop systems, and pruned hedgerow intercropping systems.

Timber-based systems

Tabora (1991) compared three perennial agroforestry species in terms of their impact on annual nutrient removal: a abaca-based (Manila hemp, *Musa* sp.) system, a coconut-based system (*Cocos nucifera*), and a *Paraserianthes falcataria* pulpwood production system. The abaca system was found to sustain the least nutrient exportation, with only 4 kg of macro-nutrients (sum of elemental N,P, and K) removed per year in the fiber harvest. Abaca fiber is a highly cellulosic material

composed of only 1.0% ash. The coconut based system removed double this quantity of nutrients while macronutrient export from the *Albizia* wood production system was an order of magnitude higher (Table 2). In a 6.8 year-old plantation, Halenda (1989) estimated that harvesting of *A. mangium* stems alone would have resulted in the export from the site of 284 kg N, 15 kg P, 225 kg Ca and 24 kg Mg/ha respectively. Clearly although the trees accumulated considerable biomass and nutrients, tree harvesting for 2 or 3 rotations would result in a nutrient depleted site.

Tree/perennial intercropping

Alpizar et al (1986) and Fassbender et al (1988) inventoried the nutrient uptake and flows in two agroforestry systems composed of cacao (*Theobroma cacao* planted at 1111 trees ha⁻¹), in association with either *Erythrina poeppigiana* or *Cordia alliodora*, serving as shade and timber trees spaced at 278 trees ha⁻¹. Biomass accumulation in stems of *C. alliodora* was 2.5 times higher than in *E. poeppigiana*. *Erythrina* accumulated the majority of its biomass in branches and leaves, which recycled in the system through pruning and litter fall. The total annual net primary productivity of the two systems, however, was fairly high and similar (21.6 versus 21.3 t ha⁻¹).

Nutrient accumulation in the standing biomass was much higher for the timber trees than for the cacao. This may have induced serious competition for nutrients, were it not for the relatively limited nutrient offtake demands of the system, in comparison to the abundant nutrient cycling occurring within it. Annual nutrient extraction from the system through the harvest of cacao pods and husks was relatively low (compared to annual crop systems) at 19-25 kg N, 4.0-4.3 kg P, and 28-27 kg K. There was also a low proportion of nutrient exportation compared with the total nutrient content in the standing biomass (5% N, 8% P, and 8% K). The recycling of nutrients through residues returning back to the soil system exceeded off-take by 5.9-6.8 times in the case of nitrogen, 3.8-4.8 times for P, and was about double for K. Only one of the over-storey trees was a nitrogen-fixing species (*E. poeppigiana*). The cacao/*E. poeppigiana* combination registered a total increase of 80 kg N ha⁻¹ in the soil-plant system over a five year period, indicating an annual contribution due to fixation equivalent of 18 kg N ha⁻¹.

Pruned tree hedgerows

Direct nutrient exportation in alley cropping or hedgerow intercropping systems may occur by the use of leaves and green stem prunings as animal fodder, or by the harvest of poles, fuel wood, or fruits. Indirect export occurs through the harvest of annual crops obtaining nutrients from hedgerow litter fall and prunings. The harvest of economic products results in direct nutrient exports but contributes to the productivity and profitability of the system. Farmers practicing alley cropping often find that the economic value of hedgerow prunings when used as animal fodder exceeded their value as green manure (Kang et al, 1990). This practice may, however, result in accelerated decline in soil fertility. The increased quantity of animal manure that results from greater fodder production can be returned to the field, along with additional inorganic fertilizer, to at least partially balance the losses. Unless this is done, the increased rate of soil nutrient removal may jeopardize the long-term sustainability of the system.

SIGNIFICANCE OF TREES AS COMPETITORS FOR RESOURCES IN AGROFORESTRY SYSTEMS

The very nature of agroforestry dictates that resource competition largely controls system viability and productivity. The development of prospective systems involves the search for tree domesticates to fill complementary or synergistic niches that minimize resource competition. Limited research during the past decade has begun to explore the nature of tree-crop interactions (Ong et al, 1991). The concepts of resource sharing in agroforestry systems were reviewed by Buck (1986).

The tree component of agroforestry tends to have a competitive advantage over an annual crop, owing to its dominant stature, both above- and below-ground. As in any intercropping system, competition may increase production of the systems as a whole, or help stabilize outputs when resource supply is erratic (Monteith et al, 1991).

Below-ground competition

In water-limited environments, the potential of agroforestry is strongly influenced by the major tree-crop differential in ability to capture soil moisture. Severe reductions in crop yields in alley cropping

are often observed in the semi-arid tropics, drawing the viability of these systems into question. In India, for example, studies with root barriers have indicated that these reductions are mainly due to competition for water (Singh et al, 1989). The presence of a shallow root barrier (to 0.5 m depth) was sufficient to eliminate a yield reduction in cowpea and sorghum yield. Ong et al (1991) found that root barriers eliminated crop yield reductions in tree-annual crop associations, and concluded that competition for water was the driving factor. Roots of *L. leucocephala* were abundant in the top 30 cm of soil in adjacent alleys, contrary to the assumption that tree roots do not compete with crops.

Malik and Sharma (1990) observed that *Eucalyptus tereticornis* extracted five times more water than mustard from a 150 cm soil profile at the tree-crop interface when grown in a hedgerow cropping system in a semi-arid environment. Mustard and wheat yields were reduced 47 and 34% in adjoining 10 m wide strips. Likewise, boundary plantings of *L. leucocephala*, *Eucalyptus camaldulensis*, *Albizia procera*, and *Morus alba* reduced yields of wheat 15-70% up to 4 m in adjoining fields (Akbar et al, 1990). These results emphasize the importance of taking water-use characteristics into account during any domestication programme.

Since uptake of N, P, and K is most strongly regulated by plant demand and plant demand is strongly related to growth, it follows that competition between soil-improving trees and associated crop or pasture species may be minimized if the tree and associated species differ in phenology. In many tropical tree species rapid growth and high nutrient demand occur during the rainy season. An exception to this pattern is provided by *F. albida* which loses its leaves at the beginning of the wet season. Presumably, this would result in less nutrient demand and less nutrient competition with annual crops during the wet season.

Demand for nutrients is generally highest during the period of growth in foliage and fine roots. This usually occurs within the first ten to twenty years of tree growth, although root accumulation may continue to occur for longer periods of time. Since internal re-translocation is limited in young trees, high demand is placed on soil stocks (Miller, 1984). The implication is that competition for nutrients and water is likely to be most severe during the early stages of tree growth and continues to

decrease as the trees get older due to increasing importance of internal re-translocation and the expansion of the tree roots into previously unexplored soil. If tree products are being harvested, however, the nutrient exports in the harvested fraction will reduce internal re-translocation and may increase competition between trees and associated vegetation as the trees seek to compensate for the exported nutrients (Atkinson, 1986).

Although the soil volume explored by tree roots might be expected to increase as the trees age, differences in rooting volume will vary among species, provenances and individuals of a species (Jenik, 1978), and may therefore be the subject of selection during tree improvement. More equitable sharing of below-ground resources between trees and associated vegetation could be accomplished by: selection of appropriate genotypes or ideotypes, varying plant spacing and time of planting; and the use of shade, liming, and above- or below-ground pruning. In an alley cropping experiment on acid soils (Fernandes, 1990), root pruning of hedgerow roots significantly increased crop yields in the second year of tree-crop interaction (Figure 1).

Perhaps the most cost-effective technique would be to use species and provenances that have complementary patterns of nutrient uptake. This presupposes knowledge regarding the spatial and temporal patterns of nutrient uptake and/or rooting patterns. While data on rooting patterns of the more recently domesticated trees are very scarce, genetically-based differences in rooting patterns exist even among provenances (Vandenbelt, 1991). In a study of 15 provenances of *G. sepium*, there were significantly different patterns of vertical root distribution among provenances 20 months after growth in the field (Fernandes, 1990). Such differences offer the potential of selecting adapted germplasm for optimizing the desired effects of trees on soils.

Trees species used in agroforestry systems are commonly selected for their ease of establishment, fast growth, ability to coppice vigorously, high foliage production, N-fixing ability, and high rates of production of useful products such as wood or fruits (Kang *et al.*, 1990). These trees are typical of the "competitive" ideotype as described by Donald and Hamblin (1976). Invariably, high tree productivity is associated with high nutrient demand and high nutrient uptake efficiency. On infertile soils, however, these tree characteristics will increase competition for nutrients and water

between trees and associated crops thereby negating any beneficial effects that the trees have on soil chemical or physical properties. Trees of the "crop" ideotype, however, are not strong competitors, and make efficient use of those site resources to which they have access (Cannell, 1978). Selection for trees with a crop ideotype are likely to be more suitable than trees with a competitive ideotype for agroforestry systems in which trees and crops are present simultaneously.

Above-ground competition

Theoretical aspects of above-ground interactions in agroforestry systems were reviewed by Monteith et al (1991). The taller statured tree component tends to exert four types of microclimatic effects on an associated annual crop: Changes in light interception, rainfall interception, saturation vapour pressure in the canopy, and crop temperature. The effect upon the crop may be negative or positive, depending on the environment, and particularly the degree of water deficit.

Shading effects tend to be particularly pronounced on short statured crops grown in association with tree hedgerows, such as upland rice. Solera (1992) inserted root barriers next to hedgerows of *G. sepium* and *C. spectabilis* in the southern Philippines, and observed that the large rice grain and dry matter yield reduction that occurred in the rows nearest to the trees was not due to below-ground competition. The 50-cm tall hedges apparently resulted in a substantial deleterious shading effect on the rice, even though the trees were pruned frequently during the growing season. These results contrast starkly with observations from semi-arid areas where above-ground interactions were found to be of minor importance compared with below-ground competition for soil moisture (Ong *et al*, 1991). The importance of tree architecture, and of matching trees to their light environments, are discussed elsewhere in this volume (see papers by Oldeman & Binnekamp, and Fasehun & Grace).

Allelopathy

There is evidence that at least some tree species observed in agroforestry systems produce phytotoxins that can directly affect germination and growth of common agricultural crops (Bhatt and Todaria, 1990). The species include *Adina cordifolia*, *Alnus nepalensis*, *Celtis australis*, and

Prunus cersoides. The significance of this allelopathy at the field level, however, is not yet known, and there is little information concerning intra-specific variation in this characteristic.

CONCLUSIONS

The mechanisms by which trees may improve soils are now reasonably well understood. That certain tree species can improve soils is shown by regeneration of soil productivity in fallows. Pioneer species that possess adaptive characteristics to overcome soil constraints play a key role in modifying the site for late successional species. The time frame for this modification is usually long (10-20 years). It is hypothesized that it is possible to combine trees and crops in certain proportions so that crop yield is increased by soil-improving trees. Evidence has so far shown that on fertile soils where nutrients are not limiting, this may indeed be possible. On nutrient limited soils, however, tree-crop competition is usually so severe that intensive management of the components is required before any soil improvement benefits are obtained from the associated trees. The use of well adapted tree domesticates in managed fallows together with minimum levels of inorganic inputs could significantly shorten the time for regenerating soil productivity on acid soils.

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Table 1. Biomass production by tree species in alley cropping on fertile and infertile soils in the humid, sub-humid, and semi-arid zones of the tropics

Species	Trees/ha	Tree Age (mo)	Prunings (No/yr)	Dry Matter (Mg/ha/yr)	Ref.
Hyderabad, India; rainfall 750 mm/yr; Alfisol, pH 7.0; P = 8 ppm (Olsen)					
<i>Leucaena leucocephala</i>	2000	48	n.d.	01.4 l*	1
	833	48	n.d.	07.4 l+w	2
Ibadan, S.W. Nigeria; rainfall 1280 mm/yr; Alfisol, pH 6.2, P = 25 ppm					
<i>Leucaena leucocephala</i>	10000	36	6	06.5 l	3
Yurimaguas, Peru; rainfall 2200 mm/yr; Ultisol, pH 4.2-4.6, P = 8 ppm (Olsen)					
<i>Inga edulis</i>	8888	11	3	09.6 l+w	4
<i>Gliricidia sepium</i> 14/84	5000	11	3	08.1 l+w	
<i>Gliricidia sepium</i> 34/85	5000	11	3	01.8 l+w	
Onne, S.E. Nigeria; rainfall 2400 mm/yr; Ultisol, pH 4.0, P = 50 ppm (Bray-1)					
<i>Acacia barteri</i>	2500	48	n.d.	13.8 l+w	5
<i>Alchornea cordifolia</i>	2500	48	n.d.	14.9 l+w	
<i>Cassia siamea</i>	2500	48	n.d.	12.2 l+w	
<i>Gmelina arborea</i>	2500	48	n.d.	12.3 l+w	
Sumatra, rainfall 2575 mm/yr; Oxisol, pH 4.1, P = 4.8-6.8 mg/kg (Melich I)					
<i>Paraserianthes falcataria</i>	19900	09	4	04.9 l+w	6
		21	4	09.7 l+w	
<i>Calliandra calothyrsus</i>	19900	09	4	06.8 l+w	
		21	4	10.7 l+w	
<i>Gliricidia sepium</i>	10000	09	4	00.6 l+w	
		21	4	01.4 l+w	
Costa Rica, rainfall 2640 mm/yr; Inceptisol, pH 4.3-4.8, P = 8-15 ppm (Olsen)					
<i>Gliricidia sepium</i>	6666	24	2	09.6 l+w	7
		60	2	15.2 l+w	
<i>Erythrina poeppigiana</i>	555	24	2	07.4 l+w	
		60	2	11.1 l+w	
Western Samoa, rainfall 3000 mm/yr; mod. fertile Inceptisol, no soil data					
<i>Calliandra calothyrsus</i>	5000	48	3	12.1 l+w	8
	3333	48	3	07.6 l+w	
<i>Gliricidia sepium</i>	5000	48	3	10.7 l+w	
	3333	48	3	06.5 l+w	

* l = leaves and green shoots, w = woody material.

1. Singh *et al.*, 1989; 2. Hocking & Rao, 1990; 3. Kang *et al.*, 1981;

4. Fernandes, 1990; 5. Ruhigwa *et al.*, 1992; 6. Evensen, 1989

7. Kass *et al.*, 1989; 8. Rosecrance *et al.*, 1992;

Table 2. Estimated nutrient export per hectare per year of three agroforestry systems.

Component	Biomass (t ha⁻¹)	N content (kg)	P content (kg)	K content (kg)
Coconut kernel removed	1.4-1.9	00.87	04.46	03.34
Abaca fiber removed	1.1	01.38	00.05	02.76
Albizia wood removed	12.0	n.a	42.00	18.00
Albizia litter recycled	4.8-6.2	99.36	03.12	31.08

Source: Tabora (1991).

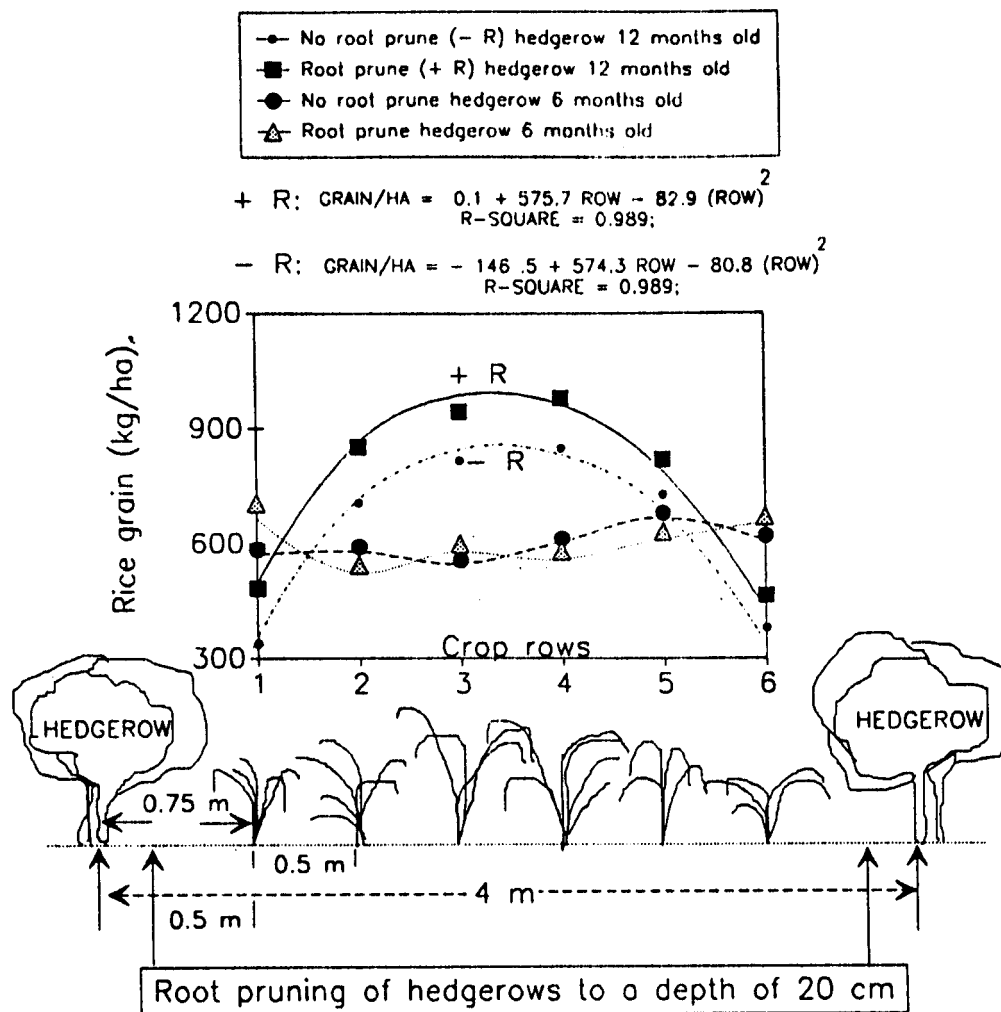


Figure 1. Rice grain yield with distance from hedgerows of *Inga edulis* as affected by age of hedgerow and pruning of hedgerow roots (Fernandes, 1990).