TREES, SOILS AND FOOD SECURITY

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INTRODUCTION

The continuing threat to the world's land resources is exacerbated by protracted rural poverty and food insecurity in the Third World and wider climatic variations resulting from global warming. During the last decade food security was not a aglobal priority, but studies such as the 2020 Vision (IFPRI 1996) show that rural poverty in the Third World is one of the main global concerns of our time, and that food insecurity is a major factor in rural poverty. Access for all to sufficient and nutritious food is the key to poverty alleviation -this was one of the main aoutcomes of the 1996 World Food Summit (FAO 1996). Food security encompasses both food production and the ability to purchase food. But calories and protein are not the only factors¿ nutritional security includes overcoming deficiencies of vitamin A, iron, zinc, iodine and selenium (IFPRI 1996).

Therefore, the three interlinked factors for reversing rural poverty are: income generation, increasing food and nutritional security and protecting the environment.

Although food insecurity occurs thoughout the developing world, it is most acute in sub-Saharan Africa -hereinafter referred to as Africa- where per-capita food production continues to decrease, in contrast with increases in other parts of the developing world (FAO 1996). Africa has the highest rate of population growht of any region in the world (2.9 % per year) and the highest rate (30%) of degradation of usable land (Cleaver & Schreiber 1994). Deficiencies in vitamin A and micronutrients are also acute on this continent (IFPRI 1996). The Malthusian nightmare, although unrealistic at the global scale, could become a reality in Africa.

The bulk of food in Africa is produced on small-scale farms by women. The three main determinants for overcoming rural poverty under these conditions are 1) and enabling policy environment for the smallholder farming sector; 2) reversing soil fertility depletion and 3) intensifying and diversifying land use with high-value products (Sanchez & Leakey 1997).

Attaining these three goals can only be achieved in Africa with modern agricultural practices bases on tradiitional green-revolution approaches (Borlaug & Dowswell 1994; Borlaug 1996) if fertilizers and other farming inputs are available at a price affordable by resource poor farmers. They can also be achieved with agroforestry -the deliberate use of trees on farms as a low input system- a common feature of small-scale farming throughout the tropics. The purpose of this contribution is to discuss the added value of tree-based agricultural systems and link them to the three determinants for poverty alleviation.

IMPACT OF TREES ON SOIL FUNCTIONS

Trees have different impacts from annual crops on soil properties, because of their longer residenc e time, larger biomass accumulation and continuous and more extensive root systems. In natural forest stand, nutrients are efficiently cycled with very small inputs and outputs from the systems, the opposite happens; nutrient cycling is limited, while inputs and outputs are large, and hte soil is not continuously protected by a plant canopy. Agroforestry encompasses the continuum between these two extremes and emerging hard data show that specific agroforestry systems provide added value to soil processes when the competition for growth resources between the tree and the crop component is adequately managed (Ong & Huxley 1996). Before considering the effects of agroforestry trees on soil properties it is imperative to deal with agronomically successfuk agroforestry systems.

There are fopur ways which trees can have benficial effects on soil properties, crop production and environmental protection. Trees in effective agroforestry systems 1) increase nitrient inputs to the soil; 2) enhance internal cycling, 3) decrease nutrient losses from the soil and 4) provide environmental benefits, these ways are summairzed below, bases largely on reviews by the authors (Sanchez et al. 1985; Leakey & Newton 1994b; Sanchez 1995; Leakey et al. 1996; Buresh & Tian 1997; Sánchez & Leakey 1997; Sánchez et al. 1997). We focus on nitrogen (N) and phosphorus (P), because these are the main limiting nutrients in smallholder farms in Africa. In contrast to other continents, soil acidity and aluminum toxicity are not widespread constraints in cultivated areas of Africa (Sánchez & Leakey 1997).

a) Increased nutrient inputs

Trees can provide nutrient inputs to crops in agroforestry systems by capturing nutrients from atmospheric deposition, biological nitrogen fixation (BNF) and deep in the subsoil, and storing them in their biomass. Biomass transfers from one site to another also provide nutrient inputs. These nutrients become inputs to the soil when the tree biomass is added to and is decomposed in the soil. the main processes are BNF, deep nitrate capture and biomass transfer .

(i) Biological nitrogen fixation

Although the magnitude of BNF is meth9odologically difficult to quantify, overall annual estimates are in the order of 25 to 280 kg N ha^{-1} yr^{-1} for leguminous trees (Giller & Wilson 1991). Woody and herbaceous legumes can provide practical means of capturing nitrogen via BNF when grown as fallows in rotation with annual crops, taking advantage of the dry season in subhumid environments when no crops can be grown. Two years of Sesbania sesban fallows in Zambia overcome nitrogen deficiencies for three subsequent maize crops (Kwesig & Coe 1994).

There is high genetic variability within tree species in their effectiveness of BNF (Sanginga et al. 1990; 1991; 1994). Phosphorus deficiencies can limit N_2 fixation and growth of N_2-fixing trees. Sanginga et al. (1994, 1995) found large differences in early growth and P-use efficienct among and within N_2 fixing tree species. These results highlight the merit of selecting provenances of N -fixing trees that are tolerant to low available P at an early growth stage.

(ii) Deep nitrate capture

The uptake of nutrients by tree roots are not present can be considered an additional nutrient input in agroforestry systems. suich nutrients become an input upon being transferred to the topsoil via tree litter decomposition. Tree roots frequently extend beyond the rooting depth of crops. an exciting dimension has recently been discovered in nitrogen-deficient Nitisols of western Kenya, where mean nitrate levels in six farmers' fields ranged from 70 to 315 kg N ha^{-1} at 0.5- to 2.0-m depth (Buresh & Tian 1997). The accumulation of subsoil nitrate is attributed to greater formation of nitrate by soil organic matter (SOM) mineralization in the topsoil than the crop can absorbe (Mekonnen et al. 1997). The excess nitrate then leaches to the subsoil where it is sorbed on positively charged clay surfaces, retarding the downward movement and leaching loss of nitrate (Hartemink et al. 1996). Nitrate sorption is well documented in subsoils rich in iron oxides (Kinjo & Pratt 1971). Sesbania sesban fallows deplete this pool, thus capturing a resorce that was unavailable to the maize crop (Mekonnen et al. 1997).

In soils with high quantities of subsoil nitrate, a N_2 -fixing tree should ideally be able to rapidly take up the subsoil nitrate before it can be leached. When the tree has depleted subsoil nitrate, it should then ideally meet a substantital proportions of its N_2 requirements thorugh biological N fixation.

Under such conditions, agroforestry trees become a biological safety net. How extensive are these soils? There are 260 million hectares of Nitisols (oxic or rhodic Alfisols and Oxisols) and similar soils in Africa that have anion-exchange capacity in the subsoil, where roots of sesbania and similar agroforestry trees can penetrate (Sánchez et al. 1997). Assuming that one thent of them are under cultivation, the magnitude of this resource could be in the order of 3 million tons of nitrate nitrogen, much more than the annual nitrogen fertilizaer consumption rate 0.8 million tons of nitrogen in sub-Saharan Africa, excluding South Africa (FAO 1995). We do not yet know the extent to which this resource is renewable. Nevertheless, the utilization of this hitherto unrecognized nitrogen source via its capture by deep rooted trees is an exciting area of research in Africa, as well as in other regions with similar oxidic subsoils.

(iii) Biomass transfer

The leafy biomass of trees is frequently cut from hedges or uncultivated areas and incroporated to crop fields as a source of nutrients in Africa. While the quantities of biomass farmers are able to apply are often sufficient to supply N to a maize crop with a moderate grain yield of 4 tons ha^{-1}, they seldom can supply sufficient P to that crop (Palm 1995). Leguminous trees are most frequently used as biomass transfer systems but there is increasing evidence that some non-leguminous shrubs may also accumulAte high concentrations of nutrients in their biomass. Tithonia diversifolia, a common hedge species found at middle elevations throughout East Afriuca and Southeast Asia has unusually high nutrient concentrations (3.5% N; 0.38% P and 4% K) in its leaf biomass (Gachengo 1996; Niang et al. 1996). These P and K levels are higher than those of commonly used legumes in agroforestry (Palm 1995). Reasons for such high concentrations remain speculative but members of the Compositae family, to which Tithonia belongs, have a reputation of being nutrient scavengers.

The processes involved are not presently identified, but may involve the dissolution of inorganic phosphours, desorption of fixed soil phosphorus by root exudates, organic acids and/or extremely effective mycorrhizal associations. Woody species grown in hedges outside the cultivated fields, therefore, may be able to transform less available organic forms, as well as supply significant quantities of N and K, when their leaves are incorporated into the soil as biomass transfers.

b) Enhanced nutrient cycling

Trees in agroforestry systems can increase the availability of nutrients in the soil through the conversion of nutrients to more labile forms of soil organic matter (SOM). Plants convert inorganic forms of N and P in the soil solution into organic forms in their tissues. The addition of in situ-grown plant material to the soil as litter fall, root decay, green manures, crop residue returns (or animal manures in grazing systems), and its subsequent decomposition results in the formation of organic forms of soil N and P. Mineralization of soil organic N or P converts them once again to nitrates and orthophosphate ions in the soil solution which are readily available to plants. This is the process of cycling.

It is important to distinguish organic cycling from organic inputs. Cycling involves organic materials grown in situ, such as those described in the previous paragraph. They do not add N or P to the soil-plant system, except for additional giological N_2 fixation and capture from below the crop rooting depth, and therefore do not constitute inputs from outside the system. Biomass transfers, composts and manures produced outside the field are the true organic inputs.

Total SOM generally does not relate to crop yields (Sánchez & Miller 1986). Nutrient release from SOM is normally more dependent on its biologically active fractions than on total SOM quantity. Microbial biomass P, light fraction organic N and P and NaOH-extractable organic P appear to be relevant fractions in agroforestry systems (Buresh & Tian 1997).

(i) Soil organic nitrogen

Agroforestry tree species vary greatly in their quality, usually measured by the (lignin + phenolics)/N ratio of their leaves (Palm & Sánchez 1991; Constantinides & Fownes 1994; Schroty et al. 1995; Tian et al. 1995; Jonsson et al. 1996). High-quality materials are readily mineralized while low-quality ones decompose slowly and may eventually form part of soil organic pools. For example, Barrios et al. (1997) found that N availability, as determined by inorganic soil N, N in light fraction SOM, and N mineralization in topsoil was ligher in maize plots following improved fallow species with the lowest (lignin + polyphenoll)/N ratios in leaf litter in an N-deficient Alfisol in eastern Zambia. Sesbania sesban fallows and fertilized maize monoculture resulted in similar inorganic soil N levels, but N mineralization and light fraction N were greateer after S. sesban. the amount of light fraction N appears to be a sensitive measure of SOM differences among cropping systems and is correlated with N mineralization of the whole soil (Barrios etr al. 1996ab). Light fraction SOM can be increased by addition of tree biomass to maize (Barrios et al. 1996a) and by rotation of maize with planted tree fallows (Barrios et al. 1997). Appropriate agroforestry systems, therefore seem to enhance internal N flows.

(ii) Soil organic phosphorus

Most studies have found little or no benefit of trees in agroforestry systems on inorganic soil P tests (Drechsel et al. 1991; Siaw et al. 1991; Kang et al. 1994; 1997). Methods related to labile soil organic P fractions seem more ppropriate for agroforestry systems with little or no inorganic P inputs. For example, S. sesban fallows, as compared to continuous unfertilized maize, increased soil P availability, measured by chloroform extractable P and P in light fraction SOM, but had no effect on extractable inorganic soil P (Maroko et al. 1997). Sesbania sesban fallows, as compared to continuous unfertilized maize, increases maize yields when P was the limiting nutrient, but they did not eliminate the need for external P inputs to completely overcome the P deficiency.

Som e trees and shrubs, but apparently few crop species, have the ability to exude organic acids form its roots or mycorrhizal associations and dissolve inorgacnic soil phosphates notr otherwise avaiulable to rroots of crop plants (Lajtha & Harrison 1995). Pigeon pea (Cajanus cajan) secretes pisidic acid in calcareous soils (Ae et al. 1990; Otani et al. 1996) increasing the plant's phosphorus uptake, while Inga edulis is believed to have access to phosphorus not available to maize and beans (Hands et al. 1995). Both these species are legumes, which are known to acidify their rhizosphere in the process on nitrogen fixation. In such cases, organic cycling has the advantage of transforming otherwise unavailable inorganic soil phosphorus into more available organic forms.

Agroforestry will not eliminate the need for P fertilizers on P-deficient soils (Buresh et al. 1997). The integration of organic materials with inorganic P fertilizers, is likely to enhance the availability of P added from inorganic fertilizers (Palm et al. 1997).

There are at present no methods for quantifying nutrient cycling efficiency in agroecosystems and its effects on productivity and sustainability. This is an area that requires further conceptualization, and a start has been made by van Noordwijk (1997) who describes possibilities at various spatial and temporal scales.

c) Decreased nutrient losses from the soil

Losses by runoff, erosion and leaching account for about half of the N, P and K depletion in Africa (Smaling 1993). Agroforestry systems have been found to decrease nutrient losses by runoff and erosion to minimal amounts (Lal 1989a; Young 1989).

The evidence for decreased leaching losses is less comprehensive. Horst et al. (1995) reported that Leucaena leucocephala hedgerows reduc ed nitrate leaching as compared to a no tree control on a sandy Ultisol in Benin. Lower subsoil water provided indirect evidence of reduced leaching loss of nutrients under trees in agroforestry systems of western Kenya (ICRAF 1996). Subsoil water in S. sesban fallows seldom exceeded field capacity in a clayey Oxisol despite a mean annual rainfall of about 1800 mm. Subsoil water in the natural uncultivated fallow and maize monoculture at the same site occasionally exceeded field capacity; indicating that mobile water was present to transport nitrate downward. Low subsoil water and nitrate content under S. sesban were attributed to high water and N demand by the fast-growing tree.

d) Environmental benefits

Trees protect the soil surface via two canopies: the litter layer and the leaf canopy, thereby decreasing runoff and erosion losses, dampening temperature and moisture fluctuations and in most cases, maintaining or improving soil physical properties (Sánchez et al. 1985; Lal 1989bc; Hulugalle & Kang 1990; Hulugalle & Ndi 1993; Rao et al. 1997). In agroforestry systems, the beneficial effects of protecting the soil surface depend on the spatial and temporal coverage of the tree component. Also, tree roots can loosen the topsoil by radial growth and improve porosity in the subsoil when roots decompose. The perennial nature of tree root systems provides a dependable source of carbon substrate for microorganisms in the rhizosphere; microbial mucilage binds soil particles into stable aggregates, which results in improved soil structure (Tisdall & Oades 1982). These two processes, surface soil protection and root penetration take place continually in agroforestry systems instead of temnporarily, as in agricultural systems. Out of them, three major kinds of environmental benefits ensue: soil conservation, biodiversity conservation and carbon sequestration.

(i) Soil conservation

Many agroforestry systems help keep the soil resource in place by biological instead of engineering measn (Young 1989; Lal 1989a; Kiepe & Rao 1994; Juo et al. 1995; Rao et al. 1997). While contour hedges do require mangement, although certainly less than earth terraces, they also become a productive niche on the farm while conserving the soil Controlling soil erosion biologically has an additional advantage: the slope between the hedges becomes less steep and even flat in some cases (Garrity 1996; Kiepe & Rao 1994). These "biological terraces" are produced by taking advantage of the erosion process within the contour hedges, with the vegetative growth keeping up with the higher soil surface at the lower end, something nonbiological terraces cannot do. Trees, however, do not conserve the soil until they are well established and have developed a littter layer (Sánchez et al. 1985). Once established, most trees protect the soil constantly, provided they are healthy and the litter layer is not removed. Biomass transfer of tree leaf litter to cropped fields undermines this process (Nyathi & Campbell 1993).

(ii) Enhancing biodiversity

All agroforestry systems are more diverse than crop or forest plantation monocultures, while some such as the complex agroforests of Southeast Asia are nearly as diverse as natural forests (Thiollay 1995). But importantly, groforestry also helps to conserve plant and animal biodiversity by reducing the further clearance of tropical forests by providing viable alterantives to slash-and-burn agriculture (Sánchez 1994; Schroeder 1994). Precise estimates of these substitution values do not exist for agroforestry systems, although figures of 7.1 and 11.5 hectares saved for each hectare put in successful agroforestry have been reported (Schroeder 1993).

Multistrata or complex agroforests are one such alternative to slash-and-burn. in these systems, annual food crops are planted along with trees and cover the ground quickly until they are shaded out by these trees that eventually occuypy different strata and produce high-value products such as fruits, resins, medicinals and high-grade timber (de Foresta & Michon 1994; Michon & de Foresta 1996). Plant diversity is in the order of 300 species ha^{-1} in the mature complex rubber agroforests of Sumatra, Indonesia. This level of plant biodiversity by far exceeds that of rubber plantations (5 species ha^{-1}) and approximates than that of adjacent undisturbed forests with 420 plant species ha . The richness of bird species in mature damar (Shorea javanica) -bases agroforests is approximately 50% that of the original rainforest (Thiollay 1995) and almost all mammal species are present in the agroforest (Sibuea & Herdimansyah 1993). This is possible because such agroforests, composed of hundreds of small plots managed by individual families, occupy contiguous areas of several thousand hectares in sumatra. Tracks of the rare Sumatran rhino (Dicerorhinus sumatrensis) were recently discovered in one of these rubber agroforests, implying that they may provide a habitat similar to the natural rainforest (Sibuea 1995). such high biodiversity levels, however, cannot be expected of shorter duration agroforestry systems, such as improved fallows, or in systems that are less geographically extensive.

Agroforestry plays a major role in the reclamation of degraded and abandoned lands and is genrally considered the most workable approach to mimic natural forest succession and increase biodiversity (Anderson 1990). Hard data on increasing biodiversity in degraded lands through agroforestry, however, are practically non-existent (Sánchez et al. 1994).

Below-ground biodiversity is also higher in agroforestry systems than in crop monocultures, approximating the levels of the natural forest in the Amazon (Lavelle & Pashanasi 1989). Soil macrofauna and microflora are key regulators of the basic decomposition processes that provide nutrients to higher plants and animals. While not as attractive as "furry and feathered creatures", soil communities are a major component of biodiversity conservation and ecosystem functioning.

(iii) Carbon sequestratrion

Agroforestry systems help keep carbon in the terrestrial ecosystem and out of the atmosphere by preventing further deforestation and by accumulating biomass and soil carbon (Schroeder 1994). As in the case of biodiversity conservation, the main contribution of improved agroforestry systems to terrestrial carbon conservation, comes from its preventive effect, that is, the area of natural forests that will not ve cleared because farmers can make continuous use of already cleared land through improved agroforestry systems (Schroeder 1993; Unruh et al. 1993; Sánchez 1994). One hectare of humid tropical forests contains on average 160 t C ha^{-1} in the above-ground biomass (Houghton et al. 1987). When it is slashed and burned, most of it is emitted to the atmosphere either inmmediately during the burn or gradually through the decomposition of unburned logs and branches. Keeping this carbon resource (some 96 billion tons of C in the remaining humid tropical forest biomass) in situ is of critical importance.

Complex agroforestry systems of long duration such as jungle rubber and damar agroforests of Sumatra and multistrata systems throughout the humid tropics can sequester carbon in its tree biomass, where it remains sequestered for decades. In addition, complex agroforests act as sinks for methane emitted by adjacent paddy fields, thereby neutralizing these greenhouse gas emissions at the landscape scale (Murdiyarso et al. 1996).

The greatest potential for carbon seuestration is probably in soils that have been depleted of carbon and nutrients adn have the potential to regain their original SOM levels. Woomer et al. (1997) estimate that 66 tons ha^{-1} of carbon can be sequestered in woody biomass and nutrient-depleted soils in Africa over a 20 year period by a combination of nutrient recapitalization, erosion control, boundary tree plantings and woodlot or orchard establishment.

The overall magnitude of carbon sequestration by agroforestry is considered among the highest among land-use systems by climate change researchers. Unruh et al. (1993) performed complex calculations of agroforestry systems in Africa, their biomass accumulation and their potential distribution using GIS ttechniques. Their results suggest a huge amount of carbon can be sequestered, ranging from 8 to 54 Gt (billion tons) of C in a total of 1.55 billion hectares where agroforestry could potentially be practiced. This figure represents the theoretical upper limit. Above-and bellow-ground carbon sequestration values, however, need to be genrated locally, taking into account the duration of each agroforestry system, and extrapolated geographically in a realistic fashion, bases on actual rates of agroforestry adoption.

TREES AND OVERCOMING RURAL POVERTY IN AFRICA

While agroforestry trees may improve soil fertility, nutrient use efficiency and provide major environmental benefits, they are not likely to have a significant impact on food security or alleviating poverty by themselves. Successful agroforestry can contribute to 1) food security from the production point of view through soil fertility replenishment, along with fertilizers, and 2) povertly alleviation and access to enough and nutritious food through the domestication of indigenous trees and enabling policies. This section examines such possibilities.

a) Soil fertility replenishment

Soil fertility depletion in smallholder farms of Africa is beginning to be recognized as the fundamental biophysical limiting factor responsible for the declining per capita food production of the continent (Sánchez et al. 1996; 1997; IFPRI 1996). The magnitude of nutrient mining is huge, as evidenced by nurient balance studies. An verage of 660 kg of N, 75 kg P and 450 kg K per ha has been lost during the last 30 years from about 200 million ha of cultivated land in 37 African countries. The total annual nutrient depletion in sub-Saharan Africa is equivalent to 7.9 million tons of NPK per year, six times the amount of annual fertilizer consumption to the region, excluding South Africa (Sánchez et al. 1997). Nutrient capital has gradually been depleted by crop harvest removals, leaching and soil erosion, because farmers did not sufficiently compensate these losses by returning nutrients to the soil via crop residues, manures and inorganic gertilizers. The consequences of nutrient depletion are felt at the farm, watershed, national and global scales and include major economic, social and environmental externalities. Sánchez et al. (1997) suggested that soil fertility replenishment should be considered as an investment in natural resource capital.

Phosphorus replenishment strategies are mainly fertilizer-based with biological supplementation, while nitrogen replenishment strategies are mainly biological, with chemical supplementation. Replenishing phosphorus capital can be accomplished by large applications of phosphorus fertilizers in high P-fixing soils. Africa has ample rock phosphate deposits that could be used directly or as superphosphates to reverse phosphorus depletion.

One of the problems is the need to add acidifying agents to rock phosphates in order to facilitate their dissolution in many phosphorus-depleted African soils that have pH values above 6.0, which are too high for acification to occur at a rapid rate. Decomposing organic materials produce organic acids that may help acidify rock phosphate. Mixing rock phosphates with compost has shown promise in increasing the availability of rock phosphate in Burkina Faso (Lompo 1993) and in Tanzania (Ikerra et al. 1994). Organic acids produced during the decomposition of plant materials may temporarily reduce the P-fixation capacity of the soils by binding to the oxides and hydroxide surfaces of clay particles (Iyamuremye & Dick 1996). Through this process phosphorus availability and nutrient use efficiency are temporarily increased. Research in western Kenya with Minjingu rock phosphate and triple superphosphate indicates higher maize yields following incorporation of P with T. diversifolia, rather tan urea at an equivalent N rate. The benfit from T. diversifolia was partially attributed to addition of K and about 5 kg P ha^{-1} (Buresh et al. 1997). Subsequent research confirmed higher maize production with sole application of T. diversifolia biomass than with an equivalent rate of NPK mineral fertilizer on a P and K deficient soil (Bashir Jama et al. unpublished data). The integration of available organic resources, such as T. diversifolia, with commercial phosphorus fertilizers may be important to increase and sustain soil phosphorus capital (Palm et al. 1997).

Given the largely biological nature of the nitrogen cycle, the use of organic inputs as a source of biologically-fixed nitrogen and deep nitrate capture play a crucial role in nitrogen replenishment. Agroforestry trees and herbaceous leguminous green manures play a major role in internal cycling. Organic inputs have an important advantage over inorganic fertilizers with regard to fertility replenishment; they provide a carbon source for microbial utilization resulting in the formation of soil organic nitrogen. Inorganic fertilizers do not contain such carbon sources; therefore, most of the fertilizer nitrogen not used by crops is subject to leaching and denitrification losses, while much of the nitrogen released from organic inputs and not utilized by crops could build soil organic nitrogen capital (Sánchez & Palm 1996). Nitrogen fertilizers will likely to be needed to achieve high crop yields on top of the nutrient contributions of agroforestry (Sánchez et al. 1996).

Accompanying technologies and enabling policies are needed to make recapitalization operational. Soil conservation technologies must be present in order to keep the nutrient capital investment in place, and to avoid polluting rivers and groundwaters. Policy improvements are needed to provide the timely access to markets, adaptive research and extension education-particularly in the combined use of organic and inorganic sources of nutrients. The issue of who should pay for this recapitalization is based on the principle that those who benefit from a course of action should incur the costs of its implementation. On-farm, maintenance costs should be borne by farmers, whereas the national and global societies should share the more substantial costs of actual phosphorus applications. This sharing should reflect the ratio of national to global benefits (Sánchez et al. 1997).

b) Intensifying and diversifying land use though tree domestication

Soil fertility replenishement can go a long way in boosting agricultural production in Africa but it is a necessary and not sufficient condition for attaining food secruty and eliminating rural poverty -particularly considering the economic constraint on farmers' affording fertilizers. Numerous other factors have to come together as well, such as post-harvest losses, pests and disease attacks, the declining size of land holdings and declining human health. The last two have an impact on the availability of field labor that is also a consequence of family memebers moving to the town to secure off-farm income. What is needed is a paradigm shift from policies directed only at increasing yields of the few staple food crops to one geared at "putting money in farmer's pockets". This Green Revolution approach has played, and will continue to play, an important part in meeting the needs of the rural poor, but addictional steps also must be taken. It is in this vein that Sánchez & Leakey (1997) suggest that a further transformation is needed in the long run: intensifying land of smallholder farms in Africa in ways that generate income for farmers so that they have the option to invest in farm inputs.

President Yoweri Museveni of Uganda, in his opening address to a SPAAR (Special Program for African Agricultural Research) meeting in Kampala, 6 February 1996 articulated this idea very clearly. He stated that "it does not make sense to grow low-value products (maize and beans) at a small-cale; intead high-value products should be grown at a small-scale, while low value products should be grown on a large-scale".

The obvious implication is that small-scale farming in Africa must diversify by producing a combination of high-value, porfitable crops along with the basic food crops. Examples of this strategy occur in western Kenya, where small patches -in the order of 100 m^2 -of French beans are grown by smallholders contracted by an exporting company for fresh consumption in Europe. The market is assured and farmers intensively water, fertilize and weed these inslands of wealth among their lower value crops. But the largest opportunities for farm diversification come from trees producing an array of marketable products.

Traditionally people throughout the tropics have depended on indegenous plants for fruits and everyday household products, from medicines to fibres. These products have also provided the essential vitamins and minerals for family health, and through local and regional trading have generated cash to meet household needs for purchased products and services. Maybe it is here, in peoples' own backyard,m that the solution lies. But sadly, through deforestation, the forest or woodland that used to be in the farmers' backyard has now all but disappeared for the vast majority of people in Africa. This is where tree domestication as part of agroforestry becomes so important. Already there is a body of biophysical information on the techniques available to domesticate a wide range of wild tree species (Leakey & Newton 1994a; 1994b; Newton et al. 1994; Leakey et al. 1996; Franzel et al. 1995). Furthermore, guidelines have been developed for determining the species priorities of farmers (Franzel et al. 1996; Jaenicke et al. 1996).

These "Cinderella" species -so called because their value has been largelky overlooked by science although appreciated b y local people-include indigenous fruit trees and other plants that provide medicinal products, ornamentals or high-grade timber. Some examples are shown in Table 1.

Techniques being developed to convert some of these wild species into domesticated crops in agroforestry sustems include vegetative propagation and clonal slection designed to caputre genetic diversity (Leakey & Jaenicke 1995). Domestication involves the formulation of a genetic improvement strategy for agroforestry trees and a strategy on the use of vegetative propagation to capture the additive and non-additive variation of individual trees in tree populations (Simons 1996). The domestication strategy for these indigenous fruit tree species, as well as for Prunus africana and Pausinystalia johimbe, two priority trees for medicinal products, is to conserve their genetic resource in living-germplasm banks and subsequently to develop cultivars for incorporation into multistrata agroforests (Leakey & Simons 1997).

High-value trees can fit in specific niches on farms making the system ecologically stable and more rewarding economically, thus

Table 1. Examples of "Cinderella" tree species with high potential for domestication (Leakey *el al.* 1996)

Species	Common Names	Ecoregion	Products
Irvingia gabonensis	Bush mango, mango de souvage	Humid West Africa	Fruit, kernels
Uapaca kirkiana		Miombo of Southern Africa	Fruit
Sclerocarya birrea		Miombo of Southern Africa	Fruit, beverage
Bactris gasipaes	Peach palm, pejibaye, pupunha, pijuayo. chontaduro	Western Amazonia	Fruit, heart of palm, parquet floors, fibres
Viterallia paradoxa	Karité, shea nut	Sahel	Cosmetics, oils
Prunus africana	Pigeum	Montane tropical Africa	Medicinal
Pausinystalia johimbe	Johimbe	Humid West Africa	Medicinal

diversifying and increasing rural incomes and improving food security. Timber trees can also be grown on farm boundaries with legiminous fodder trees under them. Similarly, fuelwood trees can be grown on field boundaries or as contour hedges on sloping lands. In such a scheme, improved fallows become a crucial part of the crop rotation. The result is that farm income is increased and diversified, providing resiliency against weather or price disruptions, soil erosion is minimized, nutrient cycling maximized and above- and below-ground biodiversity enhanced. The farm truly approximates a functioning ecosystem. The latest definition of agroforestry summarizes this approach: a dynamic, ecologically-based, natural resource management system that, through the integration of trees in farm and in the landscape, diversifies and sustains smallholder production for increased social, economic and environmental benefits (Leakey 1996).

Through domestication these tree crops could become higher yielding, produce higher quality products, be more attractive comercially and diversify diets (Leakey et al. 1996). Such progress could improve household welfare by providing traditional food and health products, boosting trade, generating income and diversifying farming systems, both biologically and economically, beyond the production of basic food crops. Generally tree crops have lower labor requirements than basic food crops and could thus allow farmers time for off-farm income generation. A new paradigm for smallholder farming in Africa emerges: one that instead of being based on a limited number of highly domestical crops, often grown in monoculture, is based on a much greater divesity of commercially important plants that together produce food and high-value products (Leakey & Izac 1996).

c) Enabling policies

Current policy recommendations place a high priority on the revitalization of the agricultural sector in Africa (IFPRI 1996; FAO 1996) and some success stories are beginning to emerge (Cleaver & Schreiber 1994). The fact that most food in Africa is produced by smallholders, often female farmers, is frequently considered a major constraint to agricultural development. In contrast, the authors of this paper believe that small-scale farms can be an asset rather than a liability when supported by appropriate policies. The agricultural production boom in Asia is a product of smallholder farms and not of a shift from samll -to large-scale farming. The policies include improvements in land tenure, infrastructure, marketing information, credit, research, extension and access to inputs and markets at reasonable prices (Place 1996). Public investment to increase access to education by girls and improve public health services in rural areas also plays an important role in this transformation process. Policy reform to seize opportunities for smallholder development and to eliminate policies that discriminate against the smallholder agricultural sector therefore remains a top priority. Indeed, policy reform is a necessary but not a sufficient condition for food security and environmental conservation. In order for enabling opolicies to work in most of Afriuca the twin issues of soil fertility depletion and land-use intensification and diversification have to be tackled.

Thus the vision now is of agroforestry as an integrated land use policy that combines increases in productivity and income generation, with environmental rehabilitation and the diversification of agro-ecosystems. such a vision can be fitted to the range of situations found in the major ecoregions of Africa. According to Cooper et al. (1996) and Sánchez et al. (1997), the rrealization of this vision, however, is going to be dependent on:

– the appreciation by the international community of the importance of soil fertility replenishment and high-value indigenous species in the lives and welfare of local people, as well as incentives (or the removal of disincentives) for local people to plant trees on their farms,

– replenishment of plant nutrients that can alkso be viewed as an investment in natural resource capital, just like investments in dams and irrigation

– the domestication of commercially-important indigenous tree species producing high-value products

– the development of processing infrastructure at the rural scale and a dynamic market perspective at natural and global scales.

Commercialization is both necessary and potentially harmful. It is necessary because without it the market for products is small, and the opportunity for rural people to make the money would not exist. A degree of product domestication is therefore essential. On the other hand commercialization is potentitally harmful to rural people, if it expands to the point that outsiders with capital to invest, come in and develop large-scale monocultural plantations. however, from the experience of the complex agroforests in southeast Asia (de Foresta & Michon 1994; Michon & de Foresta 1996),m smallholder units producing non-timber forest products that are also biologically-diverse and economically viable, indicating that the intensification and divesification of land use is not a pipe-dreams.

THE WAY FORWARD

While land use intensification caused by demographic pressure is generally associated with environmental degradation, the long-term relationship between land resource degradation and demographic pressure is not ncessarily negative and linear (Harwood 1994; Scherr & Hazel 1994). With further increases in population pressure, however, a point is reached where degradation is reversed with further land intensification and incorporation of trees within the farm. This has happened in the semiarid Machakos District of Kenia, where despite increasing population pressure since the 1930s farmer were able to reverse land degradation through an indigenour soil conservation technology that improved both crop and livestock productivity (Tiffen et al. 1994; Pagiola 1994). This technology did not have a major agroforstry component, but recent evidence in Eastern Africa indicates that the same is true with agroforestry. In the more heavily populated areas of Burundi (Place 1995), Kenya (Holmgren et al. 1994; Bradley et al. 1995; Patel et al. 1995) and Uganda (Place & Otsuka 1997) where farm size is extremely small, the number of trees on farms is also expanding as farmers increasingly recognize their value . In fact, much of the reforestation in the tropics is taking place on farm, though agroforestry, and not as plantations (John Spears, personal communication). Most of the planted trees are generally of low value and used for fodder, fuelwood, boundary delineation and exotic fruits

like avocado and mango. The next step is to incorporate high-value domesticated trees into these farms. If the three determinants are realized -replenished soils, high value trees and enabling policies- Africa will be facing a win-win situation (socially, economically and ecologically) where poverty alleviation, food security and environmental protection go hand in hand.

REFERENCES

AE, N., AKIHARA, J. OKADA, K. YOSHINARA, T.& JOHANSEN, C. 1990. Phosphorus uptake by pigeon pea and its role in cropping systems in the Indian subcontinent. *Science* 248, 477-480.

ANDERSON, A.B. (ed.) 1990 *Alternatives to deforestation: steps toward sustainable use of the Amazopn rainforest.* New York: Columbia University Press.

BARRIOS, E., BURESH, R.J. & SPRENT, J.I. 1996a Organic matter in soil particle size and density fractions from maize and legume cropping systems. *Soil Biology and Biochemistry* 28, 185-193.

BARRIOS, E., BURESH, R.J. & SPRENT, J.I. 1996b Nitrogen mineralization in density fractions of soil organic matter from maize and legume cropping systems. *Soil Biology and Biochemistry* 28, 1549-1465.

BARRIOS, E., KWESIGA F. BURESH, R.J. & SPRENT, J.I. 1997 Light fraction soil organic matter and available nitrogen following trees and mazie. *Soil Science Society of Marica Journal* (In press).

BORLAUG, N. & DOWSWELL, C.R. 1994 Feeding a human population that increasingly crowds a fragile planet. *Supplement to Transactions 15th World Congress of Soil Science, Acapulco, Mexico.* Chapingo, Mexico: Internationall Society of Soil Science.

BORLAUG, N., 1996 Mobilizing science and technology for a green revolution in African agriculture. In *Achieving greater impact from research investments in Africa* (ED. S.A. BRETH), PP. 209-217. México city: Sasakawa Africa Association.

BRADLEY, P.N. CHAVANGI, N. & VAN GELDER, A. 1995 Development research and energy planning in Kenya. *Ambio* 14, 228-236.

BURESH, R.J. SMITHSON, P.C. & HELLUMS, D. 1997 building up soil P capital in sub-Saharan Africa. In *Replenishing soil fertility in Africa* ASA-SSSA Special Publication (forthcoming).

BURESH, R.J. & TIAN, G. 1997 soil improvement by trees in sub-Saharan Africa. *Agroforestry Systems* (forthcoming).

CLEAVER, K.M. & SCHREIBER, G.A. 1994 *Reversing the spiral; the population, agriculture and environment nexus in sub-Saharan Africa* Washington, D.C: World Bank.

CONSTANTINIDES, M. & FOWNES, J.H. 1994 Nitrogen mineralization from leaves and litter of tropical plants: relationships to nitrogen, lignin and soluble polyphenol concentrations. *Soil Biology and Biochemistry* 26, 49-55.

COOPER, P.J.M. LEAKEY, R.R.B.; RAO, M.R. & REYNOLDS, L. 1996 Agroforestry and the mitigation of land degradation in the humid and sub-humid tropics of Africa. *Experimental Agriculture* 32,. 235-290.

DE FORESTA, H. & MICHON, G. 1994 Agroforests in Sumatra: Where ecology meets economy. *Agroforestry Today* 6. 12-13.

DRECHSEL, P. GLASER, B. & ZECH, W. 1991 Effect of four multipurpose tree species on soil amelioration during tree fallow in Central Togo. *Agroforestry Systems* 16, 193-202.

FAO 1995 *FAO Fertilizer yearbook volume 44-1994* Rome: FAO

FAO 1996 *World food summit: Synthesis of the technical background documents* Rome: FAO.

FRANZEL, S., JAENICKE, J. & JANSSEN, W. 1996 *Choosing the right trees: Setting priorities for multipurpose tree improvement. ISNAR Research Report No 8* The Hague, Netherlands: ISNAR.

GACHENGO, C.N. 1996 *Phosphorus release and availability on addition of organic materials to phosphorus fixing soils.* MSc. Thesis, Moi University, Eldoret, Kenya.

GARRITY, D.P. 1996 Tree-soil-crop interactions on slopes., In *Tree-crop interactions, a physiological approach* (ed. C.K. Ong & P. A. Huxley), pp. 299-318. Wallingford, U.K. CAB International.

GILLER, K.E. & WILSON, K.J. 1991 *Nitrogen fixation in tropical cropping systems.* Wallingford, UK:CAB International.

HANDS, M.R. HARRISON, A.F. & BAYLISS-SMITH, T. 1995 Phosphorus dynamics in slash-and-burn and alley cropping systems of the humid tropics. In *Phosphorus in the global environment* (ed. J.Tiessen) pp. 155-170. Chichester, UK: Wiley.

HARTEMINK, A.E. BURESH, R.J., JAMA, B. & JANSSEN, B.H. 1996 Soil nitrate and water dynamics in sesbania fallow, weed fallows, and maize. *Soil Science Society of America Journal* 60, 568-574.

HARWOOD, R.R. 1994 Agronomic alternatives to slash-and-burn in the humid tropics. In *Alternatives to slash-and-burn agriculture. Symposium ID-6, 15th World Congress of Soil Science Acapulco, Mexico* (ed. P. A. Sánchez & H. van Houten), pp. 93-106. Chapingo, Mexico: International Society of Soil Science.

HOLMGREN, P. MASAKHA, E.J. & SJÖHOLM, H. 1994 Not all African land is being degraded: a recent survey of trees on farms in Kenya reveals rapidly increasing forest resources. *Ambio* 23, 390-395.

HORST, W.J. KÜHNE, R. & KANG, B.T. 1995 Nutrient use in Leucaena leucocephala and Cajanus cajan in maize/cassava alley cropping on Terre de Barre, Benin Republic. In *Alley farming research and development* (ed. B.T. Kang, A.O. Osiname & Larbi) pp. 122-136. Ibadan, Nigeria: Alley Farming Network for Tropical Africa.

HOUGHTON, R.A. BOONE R.D., FRUCI, J.R., HOBBIE, J.E. MELILLO, J.M. PALM, C.A. PETERSON, B.J. SHAVER, G.R. WOODWELL, G.M. MOORE, B. SKOLE, D.L. & MYERS, N. 1978 The flux of carbon from terrestrial ecosystems to the atmosphere in 1980 due to changes in land use: geographic distribution of the global flux. *Tellus* 39B, 122-139.

HULUGALLE, N.R.. & KANG, B.T., 1990 Effect of hedgerow species in alley cropping systems on surface soil physical properties of an oxic paleustalf in southwestern Nigeria. *Journal of Agricultural Science* (Cambridge,UK) 114, 301-307.

HULUGALLE, NR & NDI, JN , 1993 Effects of no-tillage and alley cropping on soil properties and crop yields in a typic kandiudult of southern Cameroon. *Agroforestry Systems* 22, 207- 220.

ICRAF 1996 *1995 annual report.* Nairobi, Kenya: International Centre for Research in Agroforestry.

IFPRI 1996 *Feeding the world, preventing poverty and protecting the earth: A 2020 vision.* Washington: International Food Policy Research Institute.

IKERRA, T.W.D., MNEKENI, P.N.S. & SINGH B.R. 1994 Effects of added compost and farmyard manure on P release from Minjingu phosphate rock and its uptake by maize. *Norwegian Journal of Agricultural Sciences* 8, 13- 23.

IYAMUREMYE, F & DICK, R.P 1996 Organic amendments and phosphorus sorption by soils. *Advances in Agronomy* 56, 139-185.

JAENICKE, H., FRANZEL S & BOLAND D.J 1996 Towards a method to set priorities among species for tree improvement research: a case study from west Africa. *Journal of Tropical Forest Science* 7, 490-506.

JONSSON, K, STAHL, L & HOGBERG, P. 1996 Tree fallows: A comparison between five tropical species. *Biology and Fertility of soils* 23, 50- 56.

JUO, A.S.R. et al 1995 Changes in soil properties during longterm fallows and continuous cultivation after forest clearing in Nigeria. *Agriculture, Ecosystems and Environment* 56, 9- 18.

KANG, B.T., AKINNIFESI,F.K. & LADIPO D.O. 1994 Performance of selected woody agroforestry species grown on Alfisol and Ultisol in the humid lowland of West Africa, and their effects on soil properties. *Journal Tropical Forest Science* 7, 303- 312.

KANG, B.T. et al 1997 Role of some perennial leguminous and natural fallows species in the amelioration of a degraded oxic paleustalf. Effect on soil properties and crop performance. *Land Use Management.* (In Press).

KIEPE, P & RAO M.R. 1994 Management of agroforestry for the conservation and utilization of land and water resources. *Outlook in Agriculture* 23 (1), 17- 25.

KINJO T. & PRATT P.F. 1971 Nitrate adsorption. *Soil Science Society of America Proceedings* 35, 722- 732.

KWESIGA, F. & COE R 1994 The effect of short rotation Sesbania sesban planted fallown on maize yields. *Forest Ecology and Mangement* 64, 199-208.

LAJTHA, K. & HARRISON, A.F. 1995 Strategies of phosphorus acquisition and conservation by plant species and communities. In *Phosphorus in the global environment* (ed. H. Tiessen), pp. 139-148. Chichester, UK: Willey.

LAL, R. 1989a Agroforestry systems and soil surface management of a tropical alfisol: II. Water runoff, soil erosion, and nutrient loss., *Agroforestry Systems* 8, 97-238.

LAL, R. 1989b Agroforestry systems and soil surface management of a tropical Alfisol: IV. Effect on soil physical and mechanical properties. *Agroforestry Systems* 8: 197-215.

LAL, R. 1989c Agroforestry systems and soil surface management on a tropical Alfisol: V. Water infiltrability, tranmsmissivity and soil water sorptivity. *Agroforestry Systems* 8: 217-238.

LAVELLE, P. & PASHANASI, B. 1989 Soil macrofauna and land management in Peruvian Amazonia. *Pedobiologia* 33: 283-291.

LEAKEY, R.R.B. & NEWTON, A.C. 19944a Domestication of "Cinderella" species as a start of a woody plant revolution. In *Tropical trees: Potentital for domestication and the rebuilding of forest resources* (ed. R.R.B. Leakey & A.C. Newton) pp. 3-6. London: HMSO.

LEAKEY, R.R.B. & A.C. NEWTON (ed.) 1994b *Domestication of Timber and Non-timber Forest Products MAB Digest 17.* París. France. UNESCO.

LEAKEY, R.R.B. & JAENICKE, H. 1995 The domestication of indigenous fruit trees: opportunities and challenges for agroforestry. *In Proc. 4th International BIO-REFOR Workshop* (ed. K. Suzuki, S. Sakurai, K. Ishii & M. Norisada), pp. 15-26. Tokyo. Japn. BIO-REFOR.

LEAKEY, R.R.B. 1996 Definition of agroforestry revisited. *Agroforestry Today* 8 (1) 5-7.

LEAKEY, R.R.B. & IZAC, A.M.N. 1996 Linkages between domestication and commercialization of non-timber forest products: *implications for agroforestry.*

Non-wood forest products 9 (ed. R.R.B. Leakey, A.B. Temu, & M.Melnyk), pp. 1-8. Rome. FAO.

LEAKEY, R.R.B. & SIMONS, A.J. 1997 The domestication and commercialization of indigenous trees in agroforestry for the alleviation of poverty. *Agroforestry Systems* (forthcoming).

LEAKEY, R.R.B.; TEMU, A.B., & MELNYK, M. (ed.) 1996 *Domestication and commercialization of non-timber forest products for agroforestry. Non-wood forest products 9.* Rome: FAO.

LOMPO, F. 1993 *Contribution a la valorisation des phosphates natureles du Burkina Faso: Etudes des effets de l'interaction phosphates natureles-materies organiques* These Docteur Ingenieur, Faculte des Sciences et Techniques de L'Université Nationale de Cote d' Ivoire. Abidjan.

MAROKO, J. BURESH, R.J. & SMITHSON, P.C. 1997 Soil phosphorus pools in unfertilized fallow-maize systems and relationships to maize yield. Soil Science *Society of America Journal (*Submitted).

MEKONNEN, K. BURESH, R.J. & JAMA, B. 1997 Root and inorganic nitrogen distributions in sesbania fallow, natural fallow and maize. *Plant and Soil* (In press).

MICHON, G. & DE FORESTA, H. 1996 Agroforests as an alternative to pure plantations for the domestication and commercialization of NTFPS. *In Domestication and commercialization of non-timber forest products for agroforestry. Non-wood forest products 9* (ed. R.R.B. Leakey, A.B. Temu, & M. Melnyk), pp. 160-175. Rome. FAO.

MURDIYARSO, D.; HARIAH, K.; HUSIN, Y.A. & WASRIN U.R,. 1996 Greenhouse gas emisions and carbon balance in slash and burn practices. In *Alternatives to slash-burn in Indonesia* (ed. M. van Noordwijk, T.P. Tomich, D.P. Garrity, d.P. & Fagi A.M.), pp. 15-38. Bogor, Indonesia: AARD.

NEWTON, A.C., MOSS, R.& LEAKEY, R.R.B. 1994 The hidden harvest of tropical forests¿ domestication of non-timber products. *Ecodecision* 13, 48-52.

NIANG, A. AMADALO, B. & GATHUMBI, S. 1996 Green manure from the readside. *Miti Ni Maendeleo* 2, 10. Kisumu, Kenya: Maseno Agroforestry Research Centre.

NYATHI, P. & CAMPBELL, M.B. 1993 the acquisition and use of miombo litterby small-scale farmers in Masvingo, Zimbabwe. *Agroforestry Systems* 22: 43-48.

ONG, C.K. & HUXLEY, P.A. (ed.) 1996 *Tree-crop interactions, a physiological approach.* Wallingford, UK. CAB International.

OTANI, T., AE, N. & TANAKA, J. 1996 Phosphorus (P) uptake mechanisms of crops grown in soils with low P status. II. Significance of organic acids in root exudates of pigeonpea. *Soil Science and Plant Nutrition* 42, 553-560.

PAGIOLA, S. 1994 Soil conservation in a semi-arid rgion of Kenya: rates of return and adoption by farmers. In *Adopting conservation on the farm* (ed. T.L. Napier, S.M. Camboni & S.a. El-Swaify), pp. 171-187. Alkeny, Iowa: Soil and Water Conservation Society.

PALM, C.A. & SÁNCHEZ, P.A. 1991 Nitrogen release from the leaves of some tropical legumes as affected by their lignin and polyphenolic conttents. *Soil Biology and Biochemistry* 23, 83-88.

PALM, C.A. 1995 Contribution of agroforestry rees to nutrient requeriments of intercropped plants. *Agroforestry Systems* 30, 105-124.

PALM, C.A., MYERS, R.J.K. & NANDWA, S. 1997 Organic-inorganic nutrient interactions in soil fertility replenishment. In *Replenishing soil fertility in Africa. ASA-SSSA* Special Publication (forthcoming).

PATEL, S.H.; PINCKNEY, T.C. & JAEGER, W.K. 1995 Smalholder wood production and population pressure in East Africa: Evidence of an environmental kuznets curve? *Land Economics* 71, 516-530.

PLACE, F. 1995 *The role of land and tree tenure on the adoption of agroforestry technologies in Zambia, Burundi, Uganda and Malawi: A summary and synthesis* University of Wisconsin, Madison: Land Tenure Center.

PLACE, F. (ed). 1996 *Towards improved policy making for natural resources and ecosystem management in Sub-Saharan Africa.* Nairobi, Kenya: ICRAF.

PLACE, F. & OTSUKA, K. 1997 *Population density, land tenure and resource management in Uganda* Manuscript. Nairobi, Kenya: ICRAF and IFPRI.

RAO, M.R., NAIR, P.K.R. & ONG, C.K. 1997 Biophysical interactions in tropical agroforestry. *Agroforestry Systems* (forthcoming).

SANCHEZ, P. A.; PALM, C.A.; DAVEY, C.B. ; SZOTT, L.T. & RUSSSELL, C.E. 1985 Trees as soil improvers in the humid tropics? In *Trees as crop plants* (ed. M.G.R. Cannell & J.E. Jackson), pp. 327-358. Huntingdon, UK: Institute of Terrestrial Ecology.

SANCHEZ, P.A. & MILLER, R.H. 1986 Organic matter and soil fertility management in acid soils of the tropics. In *Transactions 13th International Congress Soil Science, Hamburg* 6, 609-625.

SANCHEZ, P.A. 1994 Alterantives to slash-and-burn: a pragmatic approach for mitigating tropical deforestation. In *Agricultural technology, policy issues for the international community* (ed. J.R. Anderson), pp. 451-480. Wallingford, UK: CAB International.

SANCHEZ, P.A.; WOOMER, P.L. & PALM, C.A. 1994 Agroforestry approaches for rehabiliting degraded lands after tropical deforestation. In *Rehabilitation of degraded forest lands in the tropics-technical approach. JIRCAS International Symposium Series* 1, pp. 108-119. Tsukuba, Japan: JIRCAS.

SANCHEZ, P.A. 1995 Science in agroforestry. *Agroforestry Systems* 30, 5-55.

SANCHEZ, P.A., IZAC, A.M., VALENCIA, I.M. & PIERI, C. 1996 Soil fertility replenishment in Africa. In *Achieving greater impact from research investments in Africa* (ed. S.A. Breth), pp. 200-208. Mexico City: Sasakawa Africa Association.

SANCHEZ, P. A. & PAL, C.A. 1996 Nutrient cycling and agroforestry in Africa. *Unasaylva* 185 (47), 24-28.

SANCHEZ, P.A. & LEAKEY, R.R.B. 1997 Land-use transformation in Africa: Three determinants for balancing food security with anutral resource conservation. *Fourth Congress, European Society of Agronomy* (in press).

SANCHEZ, P.A., IZAC, A.-M.N. BURESH, R.J., SHEPHERD, K.D., SOULE, M., MOKWUNNYE, A.U., PALM, C. A., WOOMER, P.L. & NDERITU, C.G. 1997 Soil fertility replenishment in Africa as an investment in natural resource capital. In *Replenishing soil fertility in Arica.* ASA-SSSA Special Publication (forhcoming).

SANGINGA, N., BOWEN, G.D. & DANSO S.K.A. 1990 Assessment of genetic variability for N_2 fixation between and within provenances of Leucaena leococephala and Acacia albida estimated by ^{15}N labelling techniques. *Plant and Soil* 127, 169-178.

SANGINGA, N., et al 1994 Field validation of intraspecific variation in phosphorus use efficiency and nitrogen fixation by provenances of *Gliricidia sepium* grown in low P soils. *Applied soil Ecology* 1, 127-138

SANGINGA, N., VANLAUWE B & DANSKO S.K.A. 1995 Management of biological nitrogen fixation in alley cropping systems: Estimation and contribution to N balance. *Plant and Soil* 174, 119-141.

SCHERR, S.J. & HAZELL, P.A. 1994 Sustainable agricultural development strategies in fragile lands. *Environment and production technology division discussion paper 1.* Washington D.C : IFPRI