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Trees, soils, and food security

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SUMMARY

Trees have a different impact on soil properties than annual crops, because of their longer residence time, larger biomass accumulation, and longer-lasting, more extensive root systems. In natural forests nutrients are efficiently cycled with very small inputs and outputs from the system. In most agricultural systems the opposite happens. Agroforestry encompasses the continuum between these extremes, and emerging hard data is showing that successful agroforestry systems increase nutrient inputs, enhance internal flows, decrease nutrient losses and provide environmental benefits—when the competition for growth resources between the tree and the crop component is well managed. The three main determinants for overcoming rural poverty in Africa are (i) reversing soil fertility depletion, (ii) intensifying and diversifying land use with high-value products, and (iii) providing an enabling policy environment for the smallholder farming sector. Agroforestry practices can improve food production in a sustainable way through their contribution to soil fertility replenishment. The use of organic inputs as a source of biologically-fixed nitrogen, together with deep nitrate that is captured by trees, plays a major role in nitrogen replenishment. The combination of commercial phosphorus fertilizers with available organic resources may be the key to increasing and sustaining phosphorus capital. High-value trees—'Cinderella' species—can fit in specific niches on farms, thereby making the system ecologically stable and more rewarding economically, in addition to diversifying and increasing rural incomes and improving food security. In the most heavily populated areas of East Africa, where farm size is extremely small, the number of trees on farms is increasing as farmers seek to reduce labour demands, compatible with the drift of some members of the family into the towns to earn off-farm income. Contrary to the concept that population pressure promotes deforestation, there is evidence that demonstrates that there are conditions under which increasing tree planting is occurring on farms in the tropics through successful agroforestry as human population density increases.

1. 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 global 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 for all is the key to poverty alleviation—this was one of the main outcomes of the 1996 World Food Summit (FAO 1996). Food security encompasses both food production and the ability to purchase food. However, calories and protein are not the only factors: nutritional security includes overcoming deficiencies of vitamin A, iron, zinc, iodine and selenium (IFPRI 1996). It is also recognized that the attainment of food security is intrinsically linked with safeguarding the natural resource base (IFPRI 1996). Therefore, the three interlinked factors for reversing rural poverty are (i) income generation, (ii) increasing food and nutritional security and (iii) protecting the environment.

Although food insecurity occurs throughout 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 growth 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 (i) an enabling policy environment for the smallholder farming sector; (ii) reversing soil fertility depletion and (iii) 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 based on traditional rock-phosphate 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 to link them to the three determinants for poverty alleviation.

2. IMPACT OF TREES ON SOIL FUNCTIONS

Trees have different impacts than annual crops on soil properties, because of their longer residence time, larger biomass accumulation and continuous and more extensive root systems. In natural forest stands, nutrients are efficiently cycled with very small inputs and outputs from the system, and the soil surface is continuously protected by one or more plant canopies. In most agricultural systems, the opposite happens; nutrient cycling is limited, while inputs and outputs are large, and the 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). Such added value occurs more commonly in sequential, as opposed to simultaneous, agroforestry systems, because the competition for water, nutrients and light between the crop and tree component is separated over time (Sanchez 1995). While the effects of trees on soil functions in agroforestry systems are generally positive, the effects on crop production are often negative. This happens when the competition for light, water or nutrients is intense (Sanchez 1995). In such cases, trees decrease crop yields (van Noordwijk *et al*. 1996). Before considering the effects of agroforestry trees on soil properties it is imperative to deal with agronomically successful agroforestry systems.

There are four ways in which trees can have beneficial effects on soil properties, crop production, and environmental protection. Trees in effective agroforestry systems (*a*) increase nutrient inputs to the soil, (*b*) enhance internal cycling, (*c*) decrease nutrient losses from the soil, and (*d*) provide environmental benefits. These ways are summarized below, based largely on reviews by the authors (Sanchez *et al*. 1985, 1997; Leakey & Newton 1994*b*; Sanchez 1995; Leakey *et al*. 1996; Buresh & Tian 1997; Sanchez & Leakey 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 (Sanchez & 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 methodologically difficult to quantify, overall annual estimates are in the order of 25–280 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 overcame nitrogen deficiencies for three subsequent maize crops (Kwesiga & Coe 1994).

There is high genetic variability within tree species in their effectiveness at 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 efficiency among and within N_2-fixing tree species. These results highlight the merit of selecting provenances of N_2-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 at depths where crop roots are not present can be considered an additional nutrient input in agroforestry systems. Such 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 0.5–2.0 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 absorb (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 resource that was unavailable to the maize crop (Mekonnen *et al*. 1997). These relationships are shown in figure 1.

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 substantial proportion of its N requirements through BNF.

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

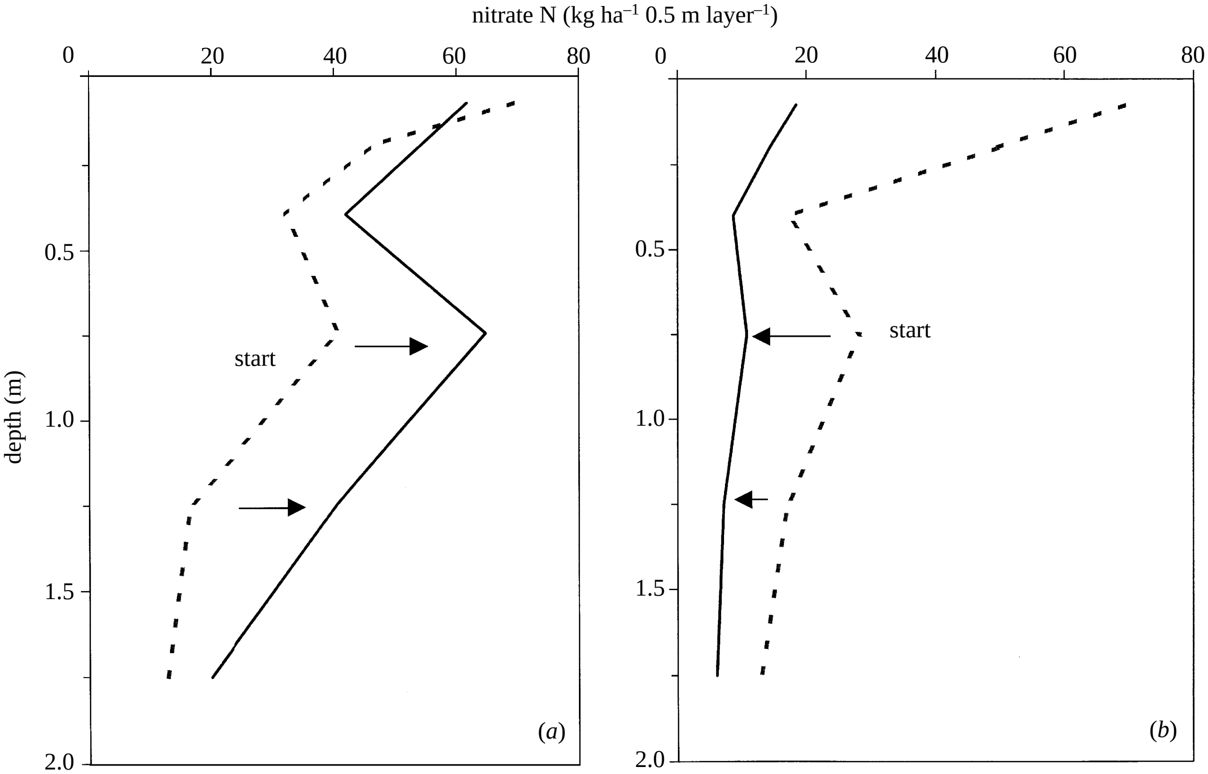

Figure 1. Nitrate accumulates in the subsoil of this Oxisol, near Maseno, Western Kenya. (*a*) Maize is unable to access this pool, while *Sesbania sesban* (*b*) depletes it. (Adapted from Hartemink *et al.* and Buresh, unpublished data.)

that have anion exchange capacity in the subsoil, where roots of *Sesbania* and similar agroforestry trees can penetrate (Sanchez *et al.* 1997). Assuming that one-tenth of them are under cultivation, the magnitude of this resource could be in the order of 3 million tonnes (Mt) of nitrate nitrogen, much more than the annual nitrogen fertilizer consumption rate, 0.8 Mt 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 incorporated into 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 t 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 Africa and South-East 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 (potassium) 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 for being nutrient scavengers.

The processes involved are not presently identified, but may involve the dissolution of inorganic phosphorus, 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 inorganic forms of phosphorus into more 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 litterfall, 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 biological 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 (Sanchez & 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 & Sanchez 1991; Constantinides & Fownes 1994; Schroth *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 higher in maize plots following improved fallow species with the lowest (lignin + polyphenol)/N ratios in leaf litter in an N-deficient Alfisol in eastern Zambia. *Sesbania sesban* fallows and fertilized maize monocultures resulted in similar inorganic soil N levels, but N mineralization and light fraction N were greater 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 *et al*. 1996*a*, *b*). Light fraction SOM can be increased by addition of tree biomass to maize (Barrios *et al*. 1996*a*) 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 appropriate 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, compared with continuous unfertilized maize, increased 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.

Some trees and shrubs, but apparently few crop species, have the ability to exude organic acids from their roots or mycorrhizal associations and dissolve inorganic soil phosphates not otherwise available to roots 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 of 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 caused 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 1989*a*; Young 1989).

The evidence for decreased leaching losses is less comprehensive. Horst *et al*. (1995) reported that *Leucaena leucocephala* hedgerows reduced nitrate leaching as compared with a no-tree control on a sandy Ultisol in the Benin Republic. 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 (Sanchez *et al*. 1985; Lal 1989*b*, *c*; 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 temporarily, as in agricultural systems. Due to these, three major kinds of environmental benefits ensue: soil conservation, biodiversity conservation, and carbon sequestration.

(i) *Soil conservation*

Many agroforestry systems help keep the soil in place by biological instead of engineering means (Lal 1989*a*; Young 1989; Kiepe & Rao 1994; Juo *et al*. 1995; Rao *et al*. 1997). While contour hedges do require management, 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 (Kiepe & Rao 1994; Garrity 1996). 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 non-biological terraces cannot do. Trees, however, do not conserve the soil until they are well established and have developed a litter layer (Sanchez *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) *Biodiversity conservation*

All agroforestry systems are more diverse than crop or forest plantation monocultures, while some, such as the complex agroforests of South-East Asia, are nearly as diverse as natural forests (Thiollay 1995). But, importantly, agroforestry also helps to conserve plant and animal biodiversity by reducing the further clearance of tropical forests through viable alternatives to slash-and-burn agriculture (Sanchez 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 into 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, which in turn eventually occupy 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 to that of adjacent undisturbed forests with 420 plant species ha^{-1}. The richness of bird species in mature damar (*Shorea javanica*)-based 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 generally 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 (Sanchez *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 they are not as attractive as 'furry and feathered creatures', soil communities are a major component of biodiversity conservation and ecosystem functioning.

(iii) *Carbon sequestration*

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 with biodiversity conservation, the main contribution of improved agroforestry systems to terrestrial carbon conservation comes from its preventive effect, i.e. the area of natural forests that will not be cleared because farmers can make continuous use of already cleared land through improved agroforestry systems (Schroeder 1993; Unruh *et al*. 1993; Sanchez 1994). One hectare of humid tropical forests contains on average 160 t C (carbon) 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 immediately during the burn, or gradually through the decomposition of unburned logs and branches. Keeping this carbon resource (some 96 billion tonnes of C in the remaining humid tropical forest biomass) *in situ* is of critical importance.

Complex agroforestry systems of long duration, such as the jungle rubber and damar agroforests of Sumatra and multistrata systems throughout the humid tropics, can sequester carbon in their tree biomass, where it remains 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 sequestration is probably in soils that have been depleted of carbon and nutrients and have the potential to regain their original SOM levels. Woomer *et al.* (1997) estimate that 66 tonnes 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 compared with other 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 techniques. Their results suggest that a huge amount of carbon can be sequestered, ranging from 8–54 Gt (billion tonnes) of C in a total of 1.55 billion hectares where agroforestry could potentially be practised. This represents the theoretical upper limit. Above- and below-ground carbon sequestration values, however, need to be generated locally, taking into account the duration of each agroforestry system, and extrapolated geographically in a realistic fashion, based on actual rates of agroforestry adoption.

3. 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 alleviate poverty by themselves. Successful agroforestry can contribute to (*a*) food security from the production point of view through soil fertility replenishment, along with fertilizers, and (*b*) poverty alleviation and access to enough and nutritious food through the domestication of indigenous trees, and (*c*) enabling policies. This section examines these possibilities.

(*a*) *Soil fertility replenishment*

Soil fertility depletion in smallholder farms in Africa is beginning to be recognized as the fundamental biophysical limiting factor responsible for the declining per capita food production of the continent (IFPRI 1996; Sanchez *et al.* 1996, 1997). The magnitude of nutrient mining is huge, as evidenced by nutrient balance studies. An average of 660 kg of N, 75 kg of P and 450 kg of K ha^{-1} 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 Mt yr^{-1} of N, P and K, six times the amount of annual fertilizer consumption to the region, excluding South Africa (Sanchez *et al.* 1997). Nutrient capital has gradually been depleted by crop harvest removals, leaching and soil erosion. This is because farmers did not sufficiently compensate these losses by returning nutrients to the soil via crop residues, manures and inorganic fertilizers. The consequences of nutrient depletion are felt at the farm, watershed, national and global scales, and include major economic, social and environmental externalities. Sanchez *et al.* (1996, 1997) suggested that soil fertility replenishment should be considered as an investment in natural resource capital.

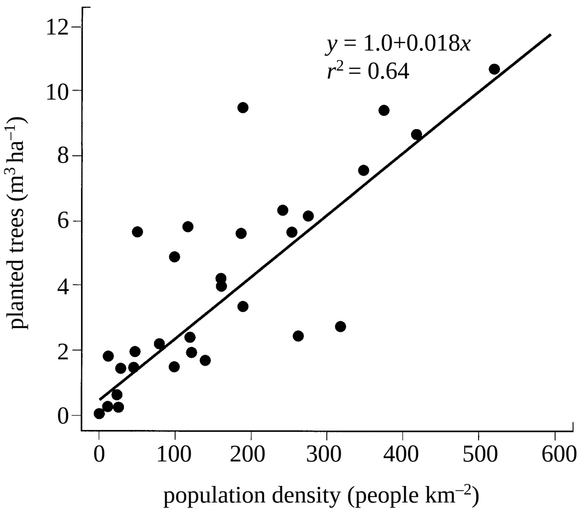

Figure 2. The effect of nitrogen source, as either urea or *Tithonia diversifolia* biomass transfer (1.8 t ha^{-1} of dry mass), with Minjingu rock-phosphate (RP) and triple superphosphate (TSP). Both applied at a recapitalization rate of 250 kg ha^{-1} of P, on maize grain yield on an acid soil near Maseno, Kenya. The amounts of N supplied by urea and *T. diversifolia* were the same, 60 kg ha^{-1} of N. (Adapted from Buresh *et al.* 1997.)

Phosphorus replenishment strategies are mainly fertilizer-based, with biological supplementation, while N-replenishment strategies are mainly biological, with chemical supplementation. Replenishing phosphorus capital can be accomplished by large applications of P 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 P-depleted African soils that have pH values above 6.0, which are too high for acidification 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 at sites in Burkina Faso (Lompo 1993) and 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 P 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 than urea, at an equivalent N rate (figure 2). The benefit from *T. diversifolia* was partially attributed to the addition of K and about 5 kg of 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 P fertilizers may be important in increasing and sustaining 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, plays a crucial role in N 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 N. Inorganic fertilizers do not contain such carbon sources; therefore, most of the fertilizer N not used by crops is subject to leaching and denitrification losses, while much of the N released from organic inputs and not utilized by crops could build soil organic N capital (Sanchez & Palm 1996). Nitrogen fertilizers are likely to be needed to achieve high crop yields on top of the nutrient contributions of agroforestry (Sanchez *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 availability of the right types of fertilizers at reasonable cost, better infrastructure, credit, 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 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 (Sanchez *et al*. 1997).

(*b*) *Intensifying and diversifying land use though tree domestication*

Soil fertility replenishment can go a long way in boosting agricultural production in Africa. However, although it is necessary it is not sufficient for attaining food security 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 factors have an impact on the availability of field labour that is also a consequence of family members 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 farmers' pockets'. This rock-phosphate approach has played, and will continue to play, an important part in meeting the needs of the rural poor, but additional steps must also be taken. It is in this vein that Sanchez & Leakey (1997) suggest that a further transformation is needed in the long run: intensifying and diversifying 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: 'It does not make sense to grow low-value products (maize and beans) at a small-scale; instead, 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, profitable 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 islands 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 indigenous 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, 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 1994*a*, *b*; Newton *et al*. 1994; Franzel *et al*. 1995; Leakey *et al*. 1996). 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 largely overlooked by science although appreciated by 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 systems include vegetative propagation and clonal selection designed to capture genetic diversity (Leakey & Jaenicke 1995). Domestication involves the formulation of a genetic improvement strategy for agroforestry trees and a strategy for the use of vegetative propagation to capture the additive and non-additive variation of individual trees in tree populations (Simons 1996). The domestication strategy

Table 1. *Examples of 'Cinderella' tree species with high potential for domestication* (*Leakey et 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

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 diversifying and increasing rural incomes and improving food security. Timber trees can also be grown on farm boundaries with leguminous 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 resilience against weather or price disruptions, soil erosion is minimized, nutrient cycling is maximized and above- and below-ground biodiversity is 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 farms 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 commercially, 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 labour 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 domesticated crops, often grown in monoculture, is based on a much greater diversity 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 (FAO 1996; IFPRI 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, we 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 small- 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 of 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 policies to work in most of Africa, the twin issues of soil fertility depletion and land-use intensification and diversification have to be tackled.

Therefore, 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 agroecosystems. 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 Sanchez *et al*. (1997), the realization of this vision, however, is going to be dependent on (i) 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; (ii) replenishment of plant nutrients, that can also be viewed as an investment in natural resource capital, similar to investments in dams and irrigation; (iii) the domestication of commercially-important indigenous tree species producing high-value products; and (iv) the development of processing infrastructure at the rural scale and a dynamic market perspective at the national 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 money would not exist. A degree of product domestication is therefore essential. On the other hand, commercialization is potentially harmful to rural people if it expands to the point where outsiders with capital to invest come in and develop large-scale monocultural plantations. However, from the experience of the complex agroforests in South-East Asia (de Foresta & Michon 1994; Michon & de Foresta 1996), smallholder units producing non-timber forest products that are also biologically diverse and economically viable, indicate that the intensification and diversification of land use is not a pipe-dream.

4. 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 necessarily 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 semi-arid Machakos District of Kenya, where despite increasing population pressure since the 1930s, farmers were able to reverse land degradation through an indigenous soil conservation technology that improved both crop and livestock productivity (Pagiola 1994; Tiffen *et al.* 1994). This technology did not have a major agroforestry 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 (figure 3). In fact, much of the reforestation in the tropics is taking place on farms, though agroforestry, and not as plantations (J. 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-win situation (socially, economically and ecologically) where poverty alleviation, food security and environmental protection go hand in hand.

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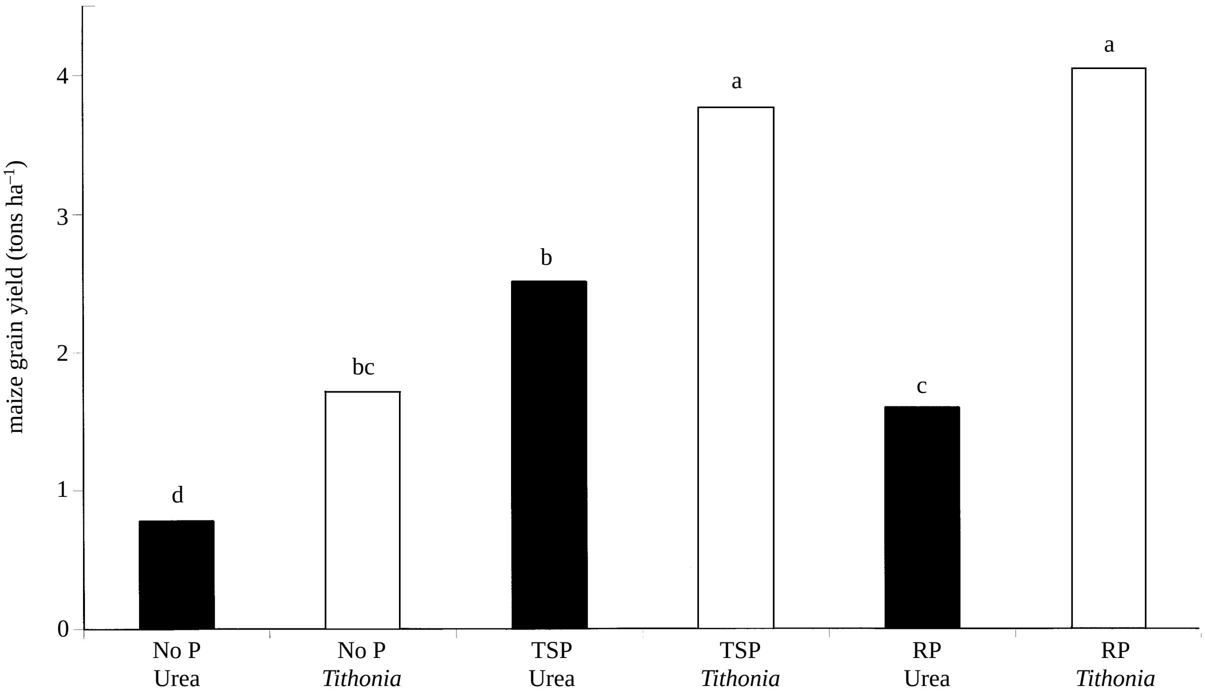

Figure 3. Correlation between high population density and planted woody biomass for districts in high potential areas of Kenya (Holmgren *et al.* 1994).

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Discussion

L. T. Evans (*CSIRO Division of Plant Industry, Australia*). I agree with your emphasis on the crucial need to raise the available soil phosphorus level in Africa, especially given their high capacity. But I missed one key word in your presentation, namely tenure of land. Small farmers can hardly be expected to invest in fertilizers unless they have security of tenure to guarantee the return on their investment, and small farmers in Africa often lack that essential ingredient.

P. A. Sanchez. Land tenure, according to ICRAF research in several African countries (Kenya, Uganda, Burundi, Zambia, Malawi), is less of a constraint in smallholder farms than previously thought, because most farmers have either formal land tenure or customary rights, which are well respected. The key tenure-related issues are women's access to land and trees even though the husband owns them, and land fragmentation. Therefore, effective tenure in many smallholders in Eastern and Southern Africa paves the way for a fertility replenishment strategy.

G. D. Anderson. Is there a function for lime in releasing P from organic form in the high altitude forested or former forested soils in Africa?

P. A. Sanchez. Aluminium toxicity is not an extensive soil constraint in subhumid and semi-arid Africa, where most of the soil fertility depletion takes place; therefore, there is seldom a need to apply lime to correct soil acidity. There will be little advantage in applying lime to increase P availability.

P. Wood (*Commonwealth Forestry Association, Oxford, UK*). (1) How far do you see farmers' decisions based on financial profit (for cash crops, for example) likely to favour practices that *do not* improve the soil? (2) Farm sizes in sub-Saharan Africa are small and decreasing. How far to you think privatization, development of 'free' markets and structural adjustment may lead to *increases* in farm size, as has happened in the capitalist West?

P. A. Sanchez. (1) Farmers everywhere base most of their decisions on economic considerations. African farmers are no exception. (2) I think farm size will not increase with improvements in privatization and structural adjustments programmes. Smallholder areas in Africa are likely to follow the pattern in Asia, where the impact of the Green Revolution did not appreciably change farm size, but it sure alleviated poverty and improved the standard of living of smallholder farmers. There are many social considerations that will likely maintain farm size pretty much as is.

P. Vlek (*Institute of Agriculture in the Tropics*, *University of Goettingen*, *Germany*). When you advocate recapitalization of soils with P in Africa, do you believe the infrastructure/marketing system can be put in place in time to avoid a calamity?

P. A. Sanchez. Good question. Fertility replenishment must be accompanied by improved road and marketing infrastructure. The answer depends on the degree of commitment governments have to liberalizing their markets and providing an enabling policy environment to smallholder farmers who produce most of the food in the countries. In some countries, it is likely to happen, but not so in others. The point is that soil fertility replenishment is a necessary, but it is not sufficient condition for Africa's food security.

D. S. Powlson (*Institute of Arable Crops Research–Rothamsted*, *Harpenden*, *UK*). What is the mechanism for the increased availability of P to crops relative to the use of organic inputs? Is it that more inorganic P is made soluble, or are organic forms of P that are less readily fixed put into solution?

P. A. Sanchez. The mechanisms involved are (i) the mineralization of organically bound P in the organic inputs; (ii) the transformation of less available pools of inorganic P into more readily available organic P that is mineralized, when plants convert inorganic P in their tissues, and those are cycled back to the soil; and (iii) organic C radicals can block P-sorption sites. The relative importance of these three processes has not been quantitatively determined in inorganic–organic nutrient interaction studies.

E. B. Barbier (*University of York*, *UK*). (1) Comment on the role of land and tree tenure on the farmers' decisions and (2) the role of risk in influencing farmers' decisions to invest in agroforestry systems.

P. A. Sanchez. (1) Land and tree tenure are critical prerequisites for soil fertility replenishment. (See my comments in response to Lloyd Evans's question, which are relevant to this one.) (2) Risk is also a key determinant; therefore, agroforestry decisions must entail relatively low risk. The time lag until an agroforestry intervention begins to produce results is perhaps a more important consideration; policies must address this issue of short-term gains versus a delayed return. Some of our farmer surveys, however, indicate that African farmers are very aware of the time lag and are willing to wait. In other cultures this is not the case.

M. Wood (*University of Reading*, *UK*). Could I offer some of our own evidence in support of Dr Sanchez's strategy for soil fertility replenishment in Africa. Our detailed ^{15}N studies on the recovery of nitrogen fertilizer in maize in central Kenya have shown that the recovery of fertilizer in the crop is very low (20%), and indicate that a significant proportion of the fertilizer is leached below the rooting zone. This may contribute to the pool of nitrate at depth, which, as described by Dr Sanchez and others, may be captured by deeper rooting plants such as trees.

P. A. Sanchez. Thank you. Could you send me the data?