

Domestication of Trees for Agroforestry in Drylands

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Abstract: With regard to drylands, this paper reviews the recent increased interest in enhancing firstly the production of tree products (particularly non-wood products) through the domestication of indigenous trees, and secondly the environmental services arising from their cultivation. A consideration of the purpose of tree domestication looks at the possible benefits to farmers in terms of increasing farmer income and their food and nutritional security. It also examines the special requirements for tree domestication in drylands and the better use of natural resources through agroforestry. Currently, tree domestication in drylands is at an early stage. For example, in the Sahel, priority tree species have recently been identified and germplasm collection initiated. Similar steps have also been taken in southern Africa where some genetic selection has commenced in indigenous fruit trees. Elsewhere, notably in Kenya, studies have examined the tree-crop-soil interactions (especially the competition for water) in simple agroforestry systems. In recent years, agroforestry interest in drylands has shifted back towards the more traditional practice of integrating crops, shrubs and other trees within widely spaced mature trees producing fruits and other products, which form a mature stage agroecosystem or multistrata agroforest. Unlike modern intercropping systems, this appears to mimic natural ecosystems and may represent a more sustainable form of productive landuse than intensive tree cultivation, which is particularly detrimental to water resources. Tree domestication, therefore, has the potential to enhance the economic benefits of agroforestry for farmers, while at the same time, promoting an agroforestry strategy that optimizes the interactions between trees and crops.

Key words: Tree improvement, agroecosystems, sustainable production, rural livelihoods.

Agroforestry should be recognised as a landuse option in which trees provide both products and environmental services (ICRAF, 1997a). During the 1960-80s, most research on the tree component was focused on the environmental interactions (soil amelioration and tree compatibility with crops) and on biomass production. More recently, the focus of agroforestry research has shifted towards the production of non-wood tree products. These changes have been paralleled by developments in the concept of agroforestry, in which a rather

agronomically intensive approach to integrating trees with crops and livestock is now being enhanced by a more ecological approach. The density of this agroforest may need to be balanced according to the carrying capacity of the land, especially the availability of water resources. In this new ecological approach, trees grown for an array of products and services are more randomly integrated into the agricultural landscape in a way that produces a more complex vertical and horizontal structure. The resultant mosaic also has a temporal dimension that is akin

to ecological succession (Leahey, 1996). This complexity provides both, an opportunity for the domestication of the component species of such agroecosystems and a challenge, especially in harsh environments like the drylands, where resources such as water can be limiting.

The Concept of Domestication

The domestication of agroforestry trees as producers of non-timber forest products has become a worldwide initiative in recent years (Simons, 1996a; Maghembe *et al.*, 1998; Roshetko and Evans, 1999). The extension of the concept of domestication from farm/domestic animals and staple crops to trees only emerged in the 1970-80s (Libby, 1973; Leahey *et al.*, 1982), with the start of clonal approaches to forest tree improvement. Since then it has been the topic of several international conferences (Leahey and Newton, 1994a; Leahey *et al.*, 1996) and is growing in importance as a means of balancing food security with sustainable natural resource utilization (Sanchez and Leahey, 1997). Tree domestication has been hailed as the start of a "Woody Plant Revolution" to follow the Green Revolution (Leahey and Newton, 1994b).

Domestication has been defined as "human-induced change in the genetics of a plant to conform to human desires and agroecosystems, culminating in the plant's loss of its ability to survive in natural ecosystems" (Harlan, 1975). More recently, the concept has been broadened to embrace "the regeneration and sustainable management of a species" (Leahey and Newton, 1994a) and "the management and adoption of genetic resources by farmers"

(Leahey and Simons, 1998). Further, it has been suggested by Michon and de Foresta (1996), that the processes of species domestication should be modelled on those employed by indigenous farmers in SE Asia, who have domesticated trees within their natural habitat, and thus 'domesticated' an agroforest. Leahey and Simons (1998) have concluded that between the two extremes of farmer-driven domestication through cultivation on-farm, and market-driven domestication through genetic selection and breeding, there is a wide array of scenarios to suit the requirements of different species in different environments. This is evident in the drylands, where many agroforestry trees have been tested experimentally for soil amelioration and where there are examples of farmer-driven traditional agroforestry, such as the Sahelian Parklands, that have domesticated indigenous trees for their products and environmental services in a harsh and risk filled environment.

Purpose of Tree Domestication

Trees in the wild have traditionally provided mankind with both products and environmental services, although the importance of the latter has really only been appreciated in second half of the Twentieth Century. With increasing environmental pressures on the land arising from increasing human and domestic animal populations, and with the parallel consequences of overpopulation on natural resources, agroforestry is seen (ICRAF, 1997a) as a means of simultaneously:

- increasing farmer income;
- increasing the food and nutritional security of poor people; and

- enhancing the environment through the better management of natural resources in the agroecosystem.

The domestication of the tree components of agroforestry is aimed at further increasing these three benefits.

Wealth creation

There are a number of ways in which agroforestry can increase the well-being of farming households. Firstly, by restoring soil fertility, preventing erosion, etc., production of staple foods can be assured and even enhanced, so generating a surplus that can be sold or exchanged for other products. For example, systems like the *Sesbania sesban* improve fallows, very effectively increase maize yields, and substitute for the need for fertilizer applications (Cooper *et al.*, 1996; Kwesiga and Beniést, 1998). Perhaps even more importantly, if a *Sesbania* fallow can increase maize yield three to four fold, then the farmer can afford to decide not to plant such a large plot of maize. This will allow him/her to grow something else, like a cash crop (cotton, tobacco, fruits, etc.), or perhaps animal fodder, so allowing the expansion of another enterprise on the farm. Trees also provide a buffer against risk, providing products when crops fail. There are opportunities to domesticate short-lived species like *S. sesban*, through genetic improvement, both in terms of increased biomass production and resistance to defoliating insects like *Mesoplatys ochroptera*. However, it is not easy to maintain any improvements introduced into the population because of the high risk, from year one, of cross-pollination with wild unimproved material. A domestication strategy for an indigenous,

short-lived species like *Sesbania* is probably best based on introduction of superior seed (provenances, progenies, etc.) and its isolation from wild pollen sources. This will involve very well developed germplasm delivery pathways (Simons, 1996b).

Within agroforestry, the biggest opportunity for wealth creation probably arises from growing marketable products (Lamien *et al.*, 1996), such as those from many indigenous trees, e.g., *Vitellaria paradoxa* (Boffa *et al.*, 1996) and *Acacia senegal* (Seif el Din and Zarroug, 1996). As seen above, taking advantage of this opportunity may depend on prior satisfaction of the need to produce staple foods, and also on the identification and creation of niches on-farm for trees that will form an upper strata above the food crops. Because of their longevity, these trees will also move the agroecosystem towards a mature, or climax, phase. The domestication strategy most appropriate for these trees is probably the one being implemented by ICRAF in its Agroforestry Tree Domestication Programme (Simons, 1996a; Leakey and Simons, 1998), which includes work in the Semi-Arid Lowlands of West Africa - Agroforestry Research Networks in Africa (SALWA-AFRENA). The strategy involves farmer identification of priority species for domestication (Franzel *et al.*, 1996; Jaenicke *et al.*, 1995), germplasm collection (Ndungu and Boland, 1994; Tchoundjeu *et al.*, 1998), selection and vegetative propagation of plus-trees (Leakey and Jaenicke, 1995), on-farm testing of putative cultivars, development of village nurseries, the establishment of planting stock delivery pathways (Simons, 1996a), the commercialization of the tree products

(Leakey and Izac, 1996; Leakey, 1999a), and the development of appropriate policies (Leakey and Tomich, 1999). A similar program is also in progress in southern Africa (Maghembe *et al.*, 1998; Ngulube *et al.*, 1997, 1998)

Compared with the humid tropics, there is less published evidence in drylands of the value and economic benefits of tree products to local people, but this deficiency is probably more a reflection of the lack of data collection than a reality. Nevertheless, the economic importance of gum arabic is well known (Seif el Din and Zarroug, 1996), amounting to 62,000 t y⁻¹ from Sudan between 1968-69, but falling to 11,410 t in 1992-93 when the price was US\$ 4500 per tone. Not surprisingly, the value of tree products for local use is lower; for example shea nuts (*Vitellaria paradoxa*) which are a source of butter, were worth US\$ 150 per tone in Burkina Faso in 1994-95 (Lamien *et al.*, 1996). This equates to about US\$ 20-35 per household per year (Boffa *et al.*, 1996). The market price of locally processed shea butter was about five fold greater (Lamien *et al.*, 1996). In addition, shea nut oil and butter are both exported and traded internationally for cosmetics and pharmaceutical purposes, offering opportunities for greater income generation. For the farmer and his household, however, there are many other tree products (néré, *Parkia biglobosa*), baobab (*Adansonia digitata*) leaves and fruits, tamarind (*Tamarindus indica*), etc., valued individually at 2 to 10 times that of shea nuts, coming from the same hectare of land. According to ICRAF (1997b), the sale of nééré fruits can increase household income by US\$ 270 y⁻¹. Bonkounou (1995)

has reported that with eight *V. paradoxa* and *P. biglobosa* trees per hectare, the overall returns from farmland are increased by US\$ 55 ha⁻¹ y⁻¹. Thus the overall value of tree products to subsistence farmers, who may be earning less than US\$ 1 per day, is not insignificant.

In the Sahel, livestock contribute about 70% of farm cash income and have an important social value, as well as being an insurance against long periods of drought and famine. The availability of dry-season fodder is, however, the main constraint to livestock production. Vendors bring 40 to 70 kg bundles of *Pterocarpus erinaceus* fodder from 30 to 50 km into markets in Bamako, Mali and make a revenue of US\$ 6 to 12 day⁻¹ from this activity (ICRAF, 1997b). This laborious activity is the result of overexploitation of natural stands close to the city, making the establishment of fodder banks close to market an obvious agroforestry alternative. Trials suggest that such fodder banks produce 4.5 t ha⁻¹, which converts to gross income of US\$ 630 y⁻¹ on the basis of an average price of US\$ 0.14 kg⁻¹. This level of income should be attractive to periurban farmers where average annual per capita income is US\$ 270 (ICRAF, 1997b).

In southern Africa, there are many Miombo trees that produce edible fruits, some of which are already being commercially utilized for beer, wine and liquor production ("Amarula" made from the *Marula* plum). These alcoholic beverages are breaking onto the international market. At present, the fruits are from wild, unplanted trees, but research is in progress to improve the quality, size and flavour of the fruits and to promote their use in agroforestry to farmers for

integration into agroecosystems (Taylor *et al.*, 1995; 1996; Maghembe *et al.*, 1995; 1998). In the Transvaal, a conservative estimate of fruit yield as 50 kg tree⁻¹ and a density of 3 trees ha⁻¹, and a price of US\$ 1.4 kg⁻¹ results in an annual income of US\$ 210 ha⁻¹ (Shackleton, 1996). In this area 46% of all households surveyed cultivate indigenous fruits, mostly for domestic use, although trade generated income of US\$ 27 month⁻¹ (Shackleton *et al.*, in press). One household, also selling home-brewed beer, reported an income of US\$ 822 month⁻¹. Taylor *et al.* (1996) have reported the following per tree values for fruit of US\$ 70, 140, 80, and 60 y⁻¹ for *Sclerocarya birrea*, *Strychnos cocculoides*, *Azanza garckeana* and *Vangueria infausta*, respectively.

Agroforestry systems are appropriate not only for the production of staple foods and tree products, but also for new crops producing commercially viable products. In semi-arid regions of India, for example, the plant *Coleus forskholii* is grown for its medicinal properties. Since 1974, this species has been conserved and domesticated (Shah and Kalakoti, 1996). It is now amenable to cultivation, and the 'forskolin' content has been increased 8-fold by genetic selection. Development of this nature could further enhance the economic returns from small-scale farming/agroforestry. In South Africa, indigenous medicinal plants are widely used and marketed, but their cultivation is still in its infancy (Mander *et al.*, 1996).

In Australia, dryland agroforestry is practised on a large scale. In Western Australia, for example, the woody shrub *Tagasaste* (*Chaemaecytisus proliterus* subsp. *proliferus* var. *palmensis*) is grown in

managed hedgerows as a source of fodder for cattle (Lefroy, 1996). Between 1988 and 1993, some 50,000 ha were established and edible dry matter production in areas with rainfall of 450 mm y⁻¹ has been increased 4-fold. Consequently, it is possible to support a cow/calf unit per hectare, with the calf growing at 1 kg d⁻¹ for 8 months on a year round grazing system (Edwards *et al.*, 1996). Additionally, the establishment of these trees in areas with a rising water table, and consequent salinity problems, has resulted in a lowering of the water table and environmental benefits.

As seen earlier, people living in drylands have learnt to utilize the gums, resins, oils and fibres of their local trees. The existence of these tree products (gum arabic, myrrh, frankincense, sheanut oil) offers opportunities for their domestication and improvement by genetic selection and cultivation. These opportunities may be further increased in the future by the development of new polypropylene composites using raw materials produced by agroforestry, with industrial potential in car manufacture (Panik, 1998; Kübler, 1998). To maintain product prices, production should not exceed market demand. Farmers therefore require market information and market opportunities for the diversification into other products.

Food/nutritional security

Numerous non-timber forest products, especially wild fruits and nuts, are used by local people as a source of food on a daily basis (Lamien *et al.*, 1996), especially in periods of drought and famine. Many of these products are rich in minerals, vitamins, essential amino-acids, etc. (Leakey, 1999a), and have the potential to become

food crops through domestication. Several parts of the baobab are nutritionally valuable: the average vitamin C content of the fruits is ten times that of oranges (Booth and Wickens, 1988); the seed kernels contain 12 to 15% edible oils, more protein than groundnuts and are rich in lysine, thiamine, calcium and iron and the leaves are rich in vitamin A. A deficiency of this vitamin is severe in many African countries where baobab occurs. The World Health Organization recommends that children should have 400 mg of vitamin A per day, which can be provided by 15 g of shade-dried baobab leaf (Sidibé *et al.*, 1998) and the recommended daily dose of vitamin C for an adult is obtained from 23 g of dried fruit pulp (Sidibé *et al.*, 1996). In other words, people in much of dryland Africa can easily enhance their nutrition by including products that they already know and enjoy, such as these, in their diet. These benefits would be further enhanced if, through domestication and agroforestry, ways can be implemented to select those trees that have especially desirable quality or yield, for propagation, wider distribution and cultivation. There may also be possibilities of improving the management of such trees in cultivation. For example, it may be possible to manage young baobab trees like a hedge for regular plucking of leaves, as a source of leaf protein and vitamins.

Other trees also appear to have both local and regional market potential. For example, shea nut (*V. paradoxa*) is one of the most common trees of the Sahelian Parklands. One hundred kilograms of fruit give about 5 kg of shea butter, with an oil content of 46 to 52% (33% non-saturated and 67% saturated). Shea butter is used

as baking fat, margarine and is increasingly used in edible products, such as patisserie, confectionery and as a cocoa butter substitute in chocolate (Leakey, 1999a). The seeds of néré (*P. biglobosa*) are fermented to make Soumbala, a strong-smelling proteinaceous food, which is eaten with sorghum/millet dumplings throughout most of the year. It is rich in protein (40%), lipids (35%), linoleic acid and vitamin B₂, but is deficient in the amino acids, methionine, cystine and tryptophan. However, these are provided by the cereals with which it is customarily eaten. The yellow, floury pulp around the seeds in the pod is a high energy food with up to 60% sugar and also rich in vitamin C (Leakey, 1999a). This pulp can be eaten raw or made into a refreshing drink with water, or fermented into an alcoholic beverage. Likewise, tamarind products are highly developed and widely used in Asia, much more than in Africa. The fruit pulp is used in sauces, syrups, flavourings, etc., while tamarind gum (a polysaccharide polymer) is used as a thickening, stabilizing and gelling agent in foods (Leakey, 1999a). Both these products have entered international trade, although the main markets are domestic. In Thailand and India, tamarind cultivars have been developed to meet specific requirements with a range of nutritive values (Chauhan *et al.*, 1991; Suriyapan Anont *et al.*, 1995).

In contrast to the case of tamarind, little is known about the extent of intraspecific variation in nutritive value of most tree products, especially the extent to which variation is attributable to genetic and/or environmental factors. One other exception to the lack of reports about intraspecific variation in dryland trees is *Adansonia*

digitata (baobab). However, even this knowledge about a tree found throughout dry Africa, is limited to the geographic variation in rainfall and soil types within a single country (Mali). In this case, the vitamin C content of fruits varied more than three-fold (1505 to 4991 mg kg⁻¹) between trees (Sidibé *et al.*, 1996). Mean ascorbic acid (vitamin C) content in fruits from Nigeria has been reported to be higher than that from Malawi or Senegal (Leakey, 1999a), suggesting that a wider comparative study, which also takes the growing environment into account, is needed. Variation has also been recorded in the vitamin A content of baobab leaf, which is eaten as a vegetable, and is affected by the leaf size and method of drying (Sidibé *et al.*, 1998).

The relative lack of comparative technical information about geographic and genetic variation in nutritive value of tree products is currently a hindrance to any attempts to domesticate these species for agroforestry purposes, and to evaluations of the benefits of domestication. Rangewide collections are needed, in which collection, handling and analysis are done in a consistent manner. Ideally for each target species for domestication, these collections would sample variation at the level of individual trees and be linked to phytogeographical analysis using molecular markers. This systematic approach would allow the development of appropriate strategies for the wise conservation and use of the genetic resource.

Resource capture and environmental services

The domestication process must not overlook the biophysical interactions in tropical agroforestry systems, which are the

key to successful practice of agroforestry (Rao *et al.*, 1998). Trees can modify soil fertility and water status, as well as the above- and below-ground environment, both favorably and unfavorably according to site, species, age and stocking density. Most recent research has focused on the negative effects of growing trees with crops in simultaneous agroforestry practices in which fast growing species are planted at high density, such as intercropping systems. This reflects the fact that, in these practices, perennial trees dominate the small, short-lived, intercrops. In the dry tropics, where water is the limiting factor, trees are especially aggressive competitors because their large root systems are already deployed when annual crops are sown.

Interestingly, interplanted crops apparently suffer much more seriously from competition by the trees for water than the natural ground flora. This seems to be because, in the much-studied hedgerow intercropping, young fast-growing trees compete for water in the upper layers of soil where the crop roots are found. In contrast, the large, slower-growing, scattered mature savannah trees that exist in traditional parklands can additionally tap deeper water resources, especially in the dry season when the upper layers are dry. Additionally, there are many other ecological benefits of trees, e.g., carbon sequestration, which are strongly associated with mature agroecosystems (Ong and Leakey, 1999).

The evidence for ecological benefits from biological diversification through the practice of agroforestry is not well documented in dryland agroecosystems, although there is increasing evidence from the moist tropics, which illustrates the benefits of mature

agroecosystems (Michon and de Foresta, 1995; Leakey, 1999b). Soil microbial biomass and macrofauna are, however, often increased in systems containing trees (Rao *et al.*, 1998) and will play an important role in nutrient cycling and soil structure. There is, nevertheless, a problem which is perhaps particularly important in the drylands, and which is probably scale-related. Integrating trees within farm crops in dry areas is often criticised on the basis that they become perches for grain-eating birds that damage the crops. This problem probably represents the lack in small-scale farming systems of the next trophic level of predation. Stepping up to the next trophic level (i.e., the raptors that predate seed-eating birds) probably requires trees in a sufficiently large area that will sustain a viable population of raptors. Consequently, agroforestry is of little, or only negative, benefit to pest control if not implemented on a large enough scale to provide habitats and food for the top predators. Scale factors such as this may, however, be achieved by the creation of a landuse mosaic or corridors, in which trees provide sufficient habitat for top predators (Leakey, 1999b).

Diversification can be achieved by introducing both exotic and indigenous tree species into farming systems. As a result of the weediness of some introduced species, and the effects they can have on the incidence of damaging pests and diseases, there is growing international concern about the impacts of introducing species into areas outside their native range. The research agenda required to provide a good understanding of, and solution to this problem (Ewel *et al.*, in press) included an examination of the merits of domesticating indigenous

trees versus the introduction of exotic species. It is assumed that domesticated indigenous trees may not have so many negative impacts on the local ecology or environment, although (see later), they are not necessarily more water-use efficient.

Special Requirements of Drylands

The social and biophysical conditions of drylands have some special consequences for agroforestry tree domestication, which need to be taken into account.

Social environment

One of the critical factors affecting farmers' willingness to domesticate and establish trees through agroforestry are the rights that they have either on the land or the trees. In dryland areas of the tropics there are many different traditional rights and also some imposed by Government policy. Without some form of ownership, there is no incentive for farmers to commit time, effort or limited financial resources to establishing and tending trees, for someone else to lop, cut down, or harvest the fruits. In addition in drylands, where livestock are traditionally allowed to roam anywhere, at least in the dry season, there is even less incentive to try to establish young trees, which without elaborate protection, will be eaten to the ground by goats or cattle (Arnold and Dewees, 1997). In many areas of the Sahel, crops are protected during the growing season by temporary fences made from the stems of cereal plants or sticks, which are broken down by termites and animals to allow free access during the dry season. These fields are interspersed with mature trees of species providing useful products (*V. paradoxa*) as part of a traditional approach

to agroforestry, whereby farmers protect and retain saplings and young trees during the clearance of land for traditional shifting agriculture. Unfortunately, human and livestock populations have now reached a point where forest fallows are no longer managed to allow the regeneration of these trees.

To promote agroforestry, either through the establishment of fodder banks or fruit trees, ICRAF has been encouraging farmers to establish living hedges using thorny tree species (ICRAF, 1997b), including acacias and those like *Zizyphus mauritiana*, that produce edible fruits. These hedges, which are becoming popular in some places, are also suitable for the permanent protection of vegetable gardens close to irrigation points. Furthermore, when planted around fields, they will provide protection for seedlings of other trees, especially fruit trees. This promising change in land management is, however, not without its disadvantages, at least to the nomadic herdsman, as the proliferation of enclosed fields would greatly reduce the traditional grazing land available to their livestock. These hedges could even block the traditional routes that nomads follow. Both these consequences of field enclosure would cause serious social tension between the sedentary people and the nomads. It is clear, therefore, that there is a need for negotiation and planned development to avoid this conflict. Many dryland areas of Africa are plagued by wars and social unrest: the development of agroforestry must not be allowed to exacerbate the existing tensions.

It is interesting that in many parts of the tropics, contrary to common perception, growing population pressures have resulted not in further land degradation, but in

measures to reduce soil erosion (Tiffen *et al.*, 1994), and to increased establishment of trees on farmland (Sanchez *et al.*, in press). This has particularly occurred where farmers have secured land or tree tenure. The complex factors and interactions that are behind this important social behavior have been examined in detail in the area around Machakos in Kenya (Tiffen *et al.*, 1994).

The involvement of multinational industry, such as Daimler-Benz, in agroforestry and community-based, small-holder production of raw materials and processing for car manufacture (Panik, 1998; Kübler, 1998), provides hope that "big business" and subsistence farming may not always be on a collision course.

Biophysical environment

Dryland areas are notorious for their harsh environment, which places both people and trees in a situation where the requirements for life, especially water, are scarce and irregularly available. Trees have adapted to this environment and can exploit opportunities, while having fall back strategies to minimize risk. For many species this means having deep and spreading root systems, shedding their leaves when water is scarce, storing carbon in gums, resins and oil-rich seeds, producing fibrous bark, and having protective thorns. Deep root systems allow the tree to tap the water table in times of scarcity, while spreading surface roots allow the reciprocal strategy of water harvesting after rain. For agroforesters, these adaptations have negative and positive aspects. Deep roots ensure tree survival during drought, and also give access to nutrients below the soil depths exploited by annual crops. Opportunities

appear to exist for improving resource capture and reducing competition through careful selection, combination and management of species, and this is vital for the successful development of agroforestry systems in dry zones (Cannell *et al.*, 1998). Selection for more efficient water use and complementarity in water use are options which are related to phenology, root system architecture and function, and inherent physiological characteristics (water-use efficiency) should be considered at the same time as selecting for the added value of improved tree products.

Although trees can be very competitive, their longevity and ability to scavenge over large areas are assets, which contribute considerably to their service functions. Deep roots can bring up nutrients otherwise inaccessible to crops from great depths. In

general, soil nutrient concentrations tend to diminish with increasing soil depth but there is increasing evidence of a large reserve of $\text{NO}_3\text{-N}$ at depth in groundwaters in arid zones. Edmunds *et al.* (1992) found $\text{NO}_3\text{-N}$ concentrations as high as 2.8 g L^{-1} in interstitial waters of unsaturated sediments in Sudan. In northern Senegal $\text{NO}_3\text{-N}$ values are typically 100 mg L^{-1} (Edmunds and Gaye, 1997) but concentrations approaching 500 mg L^{-1} have been found in profiles beneath N_2 fixing trees. A typical profile of NO_3 concentrations beneath a young N_2 fixing *Acacia senegal* tree is presented in Fig. 1. There is a zone of large $\text{NO}_3\text{-N}$ concentration located about 15 to 22 m below ground where maxima are similar to those prevailing in the surface soil. The $\text{NO}_3\text{-N}$ is thought to derive from N_2 fixation and

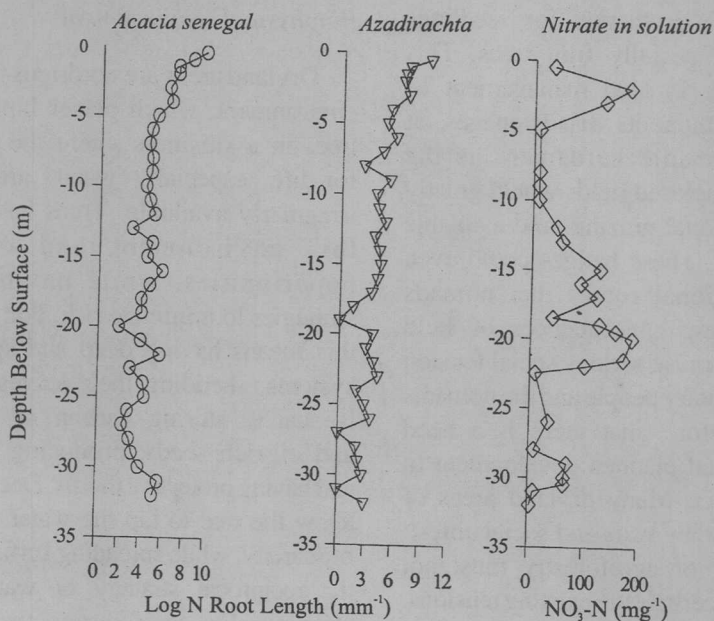


Fig. 1. Distribution of fine roots of *Acacia senegal* (O) and *Azadirachta indica* (▽) fine roots between the soil surface and 35 m depth in a sandy soil profile in northern Senegal and the nitrate-N under the *Acacia senegal* (◇).

to have been concentrated by evaporation (Edmunds, 1991). Although N_2 fixing bacteria are known to occur at the water table at 34 m depth in the western Sahel (Dupuy and Dreyfus, 1992), nodules have not been reported on such deeply located roots. The root distribution of five tree species have been found to be capable of rooting to water table depth and thus, theoretically, are capable of recycling the NO_3-N to surface horizons via root and leaf litter turnover. Mekonnen *et al.* (1997) and Jama *et al.* (1998) have reported that fast growing tree species with large root length densities can effectively recycle subsoil NO_3 . However, while this NO_3 could be effectively accessed by deep root systems, these would also exploit ground water reserves, and the implications of this need to be considered before embarking on such an approach.

On the negative side, however, the spreading surface roots enhance the trees' ability to compete with crops for recent rain, making simultaneous agroforestry practices very sensitive to water limitations in dry zones. Additionally, the use of ground water by trees can lower the water table with serious consequences for people dependent on wells for domestic use and for livestock. The carrying capacity of drylands in terms of trees and people is lower than moister parts of the tropics.

Current Status of Tree Domestication in Drylands

In the drylands, as in other parts of the tropics, there are many tree species with domestication potential for the production of fodder, fruits, extractives, fibres, medicines, etc., and the provision of environmental services.

Priority setting

To determine the priority species for the Sahel, ICRAF and partners have undertaken a priority setting exercise to identify those species that farmers consider most worthy of domestication, using the method developed by Franzel *et al.* (1996). The top five species in order of priority, were identified as *Adansonia digitata*, *Vitellaria paradoxa*, *Parkia biglobosa*, *Tamarindus indica* and *Zizyphus mauritiana*. These are all fruit trees, although most have other uses as well. In addition, other species are important for fodder (*Pterocarpus erinaceus*, *Bauhinia rufescens*, *Combretum aculeatum* and *Prosopis africana*). *C. aculeatum* also produces an edible nut, with almost continuous production throughout the year.

Germplasm collections and genetic conservation

To date, germplasm collections have been initiated by ICRAF for *Prosopis africana* (Tchoundjeu *et al.*, 1998) on account of its endangered status. In addition, collections were made in 1997 of *V. paradoxa* (6 populations: 1, 2, 3 from Senegal, Mali and Burkina Faso, respectively) and *Sclerocarya birrea* (1 population in Mali), as the first step towards a domestication program for species producing non-timber forest products for agroforestry purposes (Dawson, pers. comm.). These collections also form the basis of a genetic resource conservation strategy, but it is essential that this strategy encompasses other means of ensuring that the genetic base of a domestication program is expanded over time and wisely used to ensure that a diverse array of unrelated cultivars is developed. As described by Leakey (1991), a wise strategy involves a continuous program

of germplasm introduction and a rolling program of cultivar selection and deployment. Modern techniques of molecular ecology are particularly appropriate for the determination of patterns of intraspecific variation due to genetic drift, genetic erosion through deforestation, etc., as a basis for the formulation of genetic conservation and utilization strategies. Dendrograms of genetic distances between provenances in *Faidherbia albida* have revealed ecotypic differentiation between populations from western Africa and from southern/eastern Africa (Joly, 1992).

Systematic range-wide germplasm collections have also been made by other organizations for *Faidherbia albida* (Fagg, 1992), *Acacia karroo*, *A. nilotica*, *A. senegal*, and *A. tortilis* (OFI, 1999). Less complete collections have been made of a number of other species, (e.g., *Azadirachta indica* (Gupta *et al.*, 1996), *Prosopis cineraria* (Solanki, 1996)), leading to genetic improvement studies *via* provenance/progeny trials.

The process of tree domestication includes the conservation of tree germplasm, in some circumstances the process should also include the conservation of the associated microsymbionts (mycorrhizal fungi and rhizobium), and then the selection and use of the most appropriate isolates.

Tree improvement

To implement a single strategy for tree improvement and domestication of agroforestry trees would be unwise, as the required activities would differ for trees that were: (i) exotic or indigenous, (ii) new or an existing introduction, (iii) of low or high value, (iv) for domestic or international

markets, (v) sexually or vegetatively propagated (Simons, 1996a). In forestry, tree improvement has typically involved the selection of populations, either by provenance or by progeny (Gupta *et al.*, 1996). However, for long-lived trees producing valuable products, there is the opportunity to capture genotypic variation, and to produce genetically uniform copies of selected individual trees by the use of vegetative propagation. The decision as to when this is a wise strategy will depend on a number of single or simultaneous biological and economic issues (see Leakey and Simons, 2000). For example, vegetative propagation is appropriate when:

- rare individuals in a population combine 2-3 superior traits (precocity, and large sweet fruits);
- uniformity is required to meet market specifications;
- market size and product value justifies the extra expense;
- results are required on a timescale not practical through a breeding program;
- seed viability is low or of very short duration; and
- there is existing knowledge of proven traits from other research or from long term experiments.

The antithesis of this is that sexual propagation is preferable when the requirements are for large quantities of genetically diverse, low-value plants and non-limited seed supplies. Many other decisions also have to be made once the appropriate means of propagation has been decided (see Leakey and Simons, 1999).

Low-cost, simple techniques for the vegetative propagation of dryland species suitable for rural development projects exist (Leakey *et al.*, 1990; Longman, 1993) and are being implemented in many tropical countries, for example for *Terminalia spinosa* and 28 other species in Kenya (Milimo *et al.*, 1994; Newton *et al.*, 1992, 1996a), and *Prosopis africana* and *Bauhinia rufescens* in Mali (Tchoundjeu, 1996). Similar systems have been developed in the USA (Felker, 1994). These provide the means by which clonal propagation of cultivars can be achieved, even within rural communities. A simple manual and associated video programs provide training material

(Longman, 1993; ECTF, 1994) in the establishment and use of low-technology propagators. A number of species from drylands (*Dalbergia sissoo*) can be propagated under intermittent mist, while others (*Faidherbia albida*) can also be propagated by suckering from intact or severed root cuttings (Puri and Verma, 1996; Danthu, 1992). *In vitro* propagation systems have generally been found to have a low success rate with dryland species.

In an alternative approach, superior trees of *Sclerocarya birrea* with larger than average fruits have been identified and grafted in South Africa (Holtzhausen *et al.*, 1990) and Botswana (Taylor *et al.*, 1996), to form

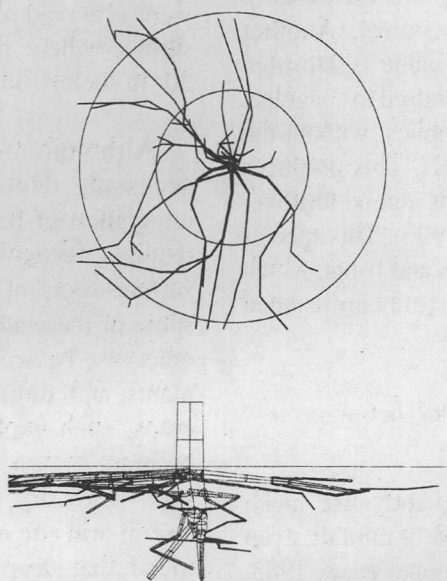


Fig. 2. Reconstruction of the root system of a 10-year-old *Acacia raddiana* viewed from directly above the stem, (upper) and from the side (lower). Circles (upper) are centred on the middle of the stem and have diameters of 5 and 2.5 m. The lower view contrasts the steeper rooting angles adopted by roots that originate immediately beneath the stem with those of the more horizontal first order lateral roots that have origins located closer to the soil surface. The line drawn at ground level extends about 1 m to the left and 1.5 m to the right of the stem centre.

cultivars that have started to be productive after 4 to 5 years, instead of 8 to 10 years from seed. Trials with this species are also in progress in Israel. Similar progress has been made with *Strychnos cocculoides*, *Azanza garckeana*, and *Vangueria infausta* in Botswana, as well as with *Zizyphus mauritiana* and *Tamarindus indica* in India.

The commercialization of products can sometimes stimulate domestication, first through cultivation and later through genetic selection. In Mali, the extraction and processing of *Jatropha* seed oil (*Jatropha curcas*) is stimulating the cultivation of the species as field hedges (Henning, 1998), such that there is a positive impact of the need for oil for energy on agricultural production and erosion control. Another species of great practical value is *Moringa oleifera*, whose seeds can be used to coagulate the impurities in water supplies, without the need to adjust the water pH. This produces a non-toxic sludge, which is a good fertilizer (Folkard and Sutherland, 1996). This species also produces edible leaves and fruits, which are widely traded and the fruits are canned and marketed worldwide.

Tree/Crop interactions and below-ground competition

Agricultural crops frequently use much less water than is deposited in rainfall, even in the semi-arid tropics (Cooper *et al.*, 1983; Ong *et al.*, 1991; Wallace, 1991). Consequently, the integration of trees with crops in agroforestry offers the opportunity to capture the unutilized water and hence increase overall productivity. Clearly, where top soils are dry and water tables exist deep below ground, plants with deep roots will have a better chance of surviving drought

than shallow rooted species such as annual crops. Where dryland soils are deeply rootable, tree root systems tend to be two tiered: they comprise a shallow network of widely spreading more or less horizontal lateral roots which exploit surface horizons and a few "tap" roots and sinkers which are capable of accessing resources located at greater depths, e.g., *Acacia raddiana* (Fig. 2). In sandy soils in Senegal, the "tap" roots are capable of achieving substantial depth. Roots of *Azadirachta indica* (neem), *Acacia senegal*, *A. tortilis*, and *Faidherbia albida* have all been observed at the water table, which varied between 16 and 35 m below ground. Similarly, in an incomplete profile, roots of *Eucalyptus camaldulensis* were observed about 20 m beneath the soil surface where the water table was about 30 m below ground.

Although tree roots are capable of accessing deeply located reserves, the integration of trees with crops in drylands requires recognition of the fact that the surface roots of trees will exploit at least some of the water and nutrients that would otherwise be accessible to the roots of crop plants, and, unlike the case with short lived crops, such exploitation of resources will be more or less continuous. When surface soils were dry during the dry season at a semi-arid site in Kenya, Ong *et al.* (1999) found that deep tree roots supplied most of the transpired water. However, as soon as surface soils rewetted at the start of the rains, pre-existing shallow lateral roots exploited this rainfall and supplied most of the water for transpiration. At the same site, Odhiambo *et al.* (1999) have found that, although there are interspecific differences in root length, tree roots are

concentrated in the same surface soil layers as crop roots, and differences in above-ground tree phenology in leafing do not appear to be translated into below-ground phenology in root development, hence opportunities for limiting tree-crop competition by selection for different phenologies appear limited. Furthermore, from two years after planting, Wilson *et al.* (unpublished) have noted considerable drying of the soil at this site on plots with trees, and there is insufficient input in most rainy seasons to replenish the soil. Likewise, at the end of the dry season in northern Senegal, the top 2 m of soil had been uniformly dried irrespective of distance to tree stems in linearly arranged agroforestry plantings of 10-year-old *Acacia senegal* (Sall and Diagne, 1997). However, at greater depths, soil profiles within 3 m of trees contained less water than those located further from trees and thus the trees dried the soil to a greater extent than the crops. At the cessation of the annual rains, only 60 to 80 mm of water had accumulated in the top 2 m of soil, the topsoil was driest within 3 m of trees and total soil moisture content to 5 m depth approximated only 250 mm. The implications of this for tree domestication are that unless tree species can be found which lack surface lateral roots, which is unlikely, competition between trees and crops for water and nutrients is inevitable whenever they occur in intimate mixture.

The substantial interspecific variation in water use by trees suggests that it should be possible to select species that use less water than others (Fig. 3). During moist conditions in the southern Sahel, *A. indica* uses much less water per unit leaf area

than many indigenous species and even although it tends to have a large leaf canopy, it uses only about 40% and 30% of the amounts of water used by *Acacia nilotica* and *Acacia seyal* trees of the same dbh. Because neem also grows faster than the two latter species, neem not only uses less water than them, but also uses its water more efficiently. Since there is also considerable intraspecific, tree-to-tree variation in water use it may be possible to seek and select water-use efficient individuals.

Although trees can increase the efficiency of water capture at a site, they (as C_3 plants) will convert light and water resources into dry matter less efficiently than potentially C_4 crops (Ong *et al.*, 1996). Tree stocking densities and the locations of trees in the landscape are issues requiring consideration at different scales – from the immediate impacts on adjacent crops, to the longterm impacts on local water resources. To put water use by trees into context, annually, a typical Sahelian village in northern Senegal consumes about $300 \text{ m}^3 \text{ km}^{-2}$ for domestic water supplies in an area where water table recharge varies between 1100 and 13000 $\text{m}^3 \text{ km}^{-2} \text{ y}^{-1}$ (Edmunds, 1991). These figures equate to 0.3, 1.1 and 13 mm y^{-1} and thus at current extraction rates, domestic water use is sustainable in terms of water table recharge. In stark contrast, at the end of the rainy season, water use by continuous blocks of trees spaced at $7 \times 7 \text{ m}$ approximates 3 to 7 mm d^{-1} . Thus, the entire annual water table recharge could be transpired within 5 days and the 250 mm of water stored in the top 5 m of soil could sustain transpiration for only about 50 days.

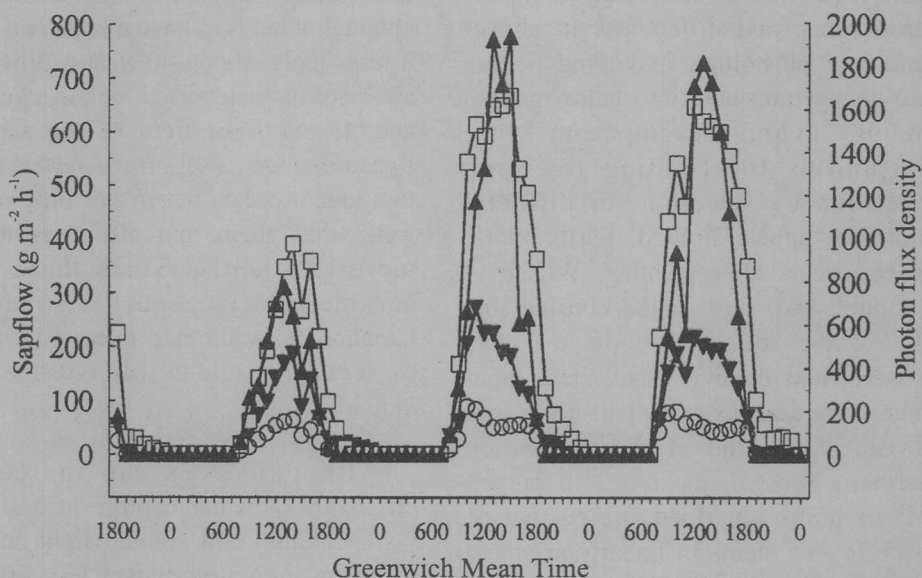


Fig. 3. Photon flux density ($\mu\text{E m}^{-2} \text{s}^{-1}$, $\blacktriangle$), and sapflow (g m^{-2} of leaf area h^{-1}) for neem (O) *Acacia nilotica* ($\blacktriangledown$), and *Acacia seyal* ($\square$) on three consecutive days at the end of the rainy season in the southern Sahel.

Because there are about 8 months between the finish of one rainy season and the start of the next one, in order to survive, the trees must either shed their leaves, or utilize deeper water resources. Tree water use on this scale is probably sustainable in the short term because of the great depth of the rootable soil volume, but in the longer term, water use by large continuous blocks of trees such as plantations appears unsustainable in dry areas. These figures probably help explain why the natural vegetation of many drylands is open savannah and why the spaced tree Parkland system of agricultural production in the Sahel is successful. They also clearly indicate that there is a maximum tree spacing density which should not be exceeded if long term sustainability of water supplies

is to be ensured. This has important implications for tree domestication, since in the past, the tendency has been to think of cultivating trees in densely planted blocks.

Rhizobial and mycorrhizal symbionts

The importance of fungal and bacterial root symbionts for nutrient and water cycling is well known, especially in crop plants (Sprent, 1994; Mason and Wilson, 1994; Lapeyrie and Högborg, 1994). While the roles of both types of symbiont have been intensively studied, the nitrogen fixing bacteria have been more effectively harnessed to produce practical benefits for farmers, than the mycorrhizal fungi. In agroforestry, there has been a long period of intensive research to try to capitalize on the ability of nodulating bacteria to fix atmospheric

nitrogen for the benefit of the host plant, and through indirect effects of incorporating host plant organic matter, to improve the fertility of the associated soil (Sanchez, 1976; Young, 1997).

Many dryland trees are nitrogen-fixing, with either rhizobial or actinorhizal bacterial symbioses. However, unlike crop plants, there has been relatively little work on the optimization of tree growth through the matching of selected host and symbiont genotypes (Sprent, 1994). What needs to be appreciated is that nodulation may not necessarily occur naturally at all sites. For instance, in Kenya, Odee *et al.* (1995) tested the ability of a range of native and non-native woody legumes to nodulate with indigenous rhizobia in soils from arid and semi-arid sites, and found that not only did species vary in their nodulating ability, but that there was large between-plant and site variability. Likewise Shepherd *et al.* (1996), found that nodulation of *Leucaena leucocephala* was poor or absent in a range of Kenyan farm soils. Hence successful cultivation of leguminous trees may require inoculation with appropriate rhizobial symbionts. Options exist for selecting particularly effective host x rhizobium symbiont combinations (to which a mycorrhizal component could also be added), but whether this will be a practical approach in the long term remains to be seen.

Mycorrhizal fungi are an integral part of practically all plant communities and have a fundamental role in plant growth and in the functioning of ecosystems (Mason and Wilson, 1994). The majority of tropical trees are arbuscular mycorrhizal, like herbaceous

plants. However, there are some notable exceptions which are ectomycorrhizal, or which form both types of mycorrhiza, particularly among the conifers, eucalypts, casuarina, dipterocarps and the caesalpinoid legumes, and it is among these ectomycorrhizal 'exceptions' that the best examples exist of the benefits of mycorrhizal inoculation (Garbaye, 1991), without which plantations can fail. Despite this, and a large body of research data, there are relatively few examples of their deliberate use by farmers or foresters to maximize productivity.

While many tree species respond positively to inoculation in controlled conditions, responses are often reduced in field situations against a background of indigenous inocula and over longer timescales. With both mycorrhizal and rhizobial symbioses, positive long term responses by trees to inoculation are only likely to occur in situations where appropriate indigenous inocula are absent or in short supply – when introducing ectomycorrhizal tree species to new sites, or when working on degraded land where vegetation cover is sparse. Selection for longterm improved performance in the field is a substantial challenge (Dommergues, 1995; Mason and Wilson, 1994) as inoculants must be competitive against indigenous species and have superior performance across a spectrum of environmental conditions and changes in the host's physiological state. Furthermore, because of strong host genotype x fungal genotype interactions, numerous selections would be needed to optimize systems while maintaining diversity of the tree host. Nevertheless, despite the inherent problems in selection for long term gain, the short

term gains on sites which are low in indigenous inocula should not be overlooked (Haselwandter and Bowen, 1996).

The role of arbuscular mycorrhizal fungi in dryland agroforestry was studied in Kenya, where the background inoculum potential of degraded land was found to be patchy. Samples taken at Olorgasailie, an alkaline site with about 475 mm rain y^{-1} indicated that arbuscular mycorrhizal spores declined rapidly with increasing distance from *Acacia tortilis* trees, from about 400 spores 50 g^{-1} soil close to the trunk to 100 spores outside the tree canopy. Although spore numbers declined with distance from trees, they were higher than have been reported from tree plots in Senegal (Ingleby *et al.*, 1997). A subsequent experiment indicated that the site generally contained sufficient inoculum for mycorrhizal formation on planted trees: when rooted cuttings of *A. tortilis*, *Prosopis juliflora* and *Terminalia spinosa* were planted into pots containing soil inoculum taken from close to the same *A. tortilis* trees, or from beneath other vegetation (*Sporobolus iocladius*, *Indigofera schimperi*), or from bare ground at the same site, plants generally became adequately mycorrhizal over a 9 week period. Acacias, which are native to the site became most heavily mycorrhizal (averaging 45% over the different soil treatments), and *Prosopis*, which is exotic to Kenya, formed least mycorrhizas (23%). Most mycorrhizas (47 to 62% of root length, depending upon tree species) were formed with soil from beneath the grass *S. iocladius*, however, even when bare soil was used as inoculum, plants still became 23 to 41% mycorrhizal. Although these studies suggest mycorrhizal formation when tree planting on these sites will be adequate, further benefits

can be conferred by 'low tech' inoculation procedures in nurseries prior to outplanting, as plants grown in nurseries can often be poorly mycorrhizal (Michelson, 1992).

Mixed mycorrhizal inocula produced by growing maize or cowpea plants in soil collected from around mature trees of *Acacia tortilis*, *Prosopis juliflora*, *Terminalia brownii* and *Terminalia spinosa* were used as inoculum for *Acacia tortilis* seedlings in the nursery. Plants grown in ordinary (unsterilized) nursery soil were significantly less mycorrhizal and smaller than those which were inoculated (Munro *et al.*, 1999). Inoculated seedlings survived better (up to 80%) after outplanting (Wilson *et al.*, 1991), and sometimes had higher water use efficiencies (Newton *et al.*, 1996b), but benefits to their subsequent growth were not clearly demonstrated. Unfortunately the project terminated before significant benefits of tree inoculation in the performance of interplanted crops were demonstrated, but there was a trend of improving crop yield with time up to the end of the project. The role of trees in maintaining mycorrhizal inoculum has been demonstrated by Mbuthia (1992) and McGreevy (1996), who found that maize grown in soil taken from close (0.5 m) to trees (*Senna siamea*) formed more mycorrhizas than when it was grown in soil collected at 2 m distance. Thus the use of microsymbionts can enhance the ability of trees to become established on degraded soils and, in turn, these trees can improve the soil inoculum potential in previously impoverished dryland sites, which can be of benefit to intercrops. In such environments, trees and other perennials will have an important role in maintaining populations of microsymbionts for short-lived crops.

A Strategy for Agroforestry in the Drylands

In conclusion, the competition for scarce water resources in upper horizons of the soil profile and the potential risks of overexploitation of the groundwater and consequent lowering of the water table, clearly suggest limits to the carrying capacity of drylands in terms of the number of trees. It has been suggested that the competition between trees and crops in intercropping systems with a more or less continuous tree canopy, restrict the sustainable use of such systems to areas with rainfall in excess of 800 mm y^{-1} (Cannell *et al.*, 1998). This suggests that the indigenous Sahelian Parklands System, described by Bonkougou (1995), in which there are scattered mature trees (40 to 80 trees ha^{-1}) within crop fields, represents a more appropriate approach to dryland agroforestry. To some extent, these parkland agroforests do equate to the late stage of an agroecological succession, as discussed earlier (see also Leakey, 1996). They integrate trees with crops in farmers' fields and are a better mimic of tree/grass interactions in natural semi-arid grasslands than hedgerow intercropping systems (Ong and Leakey, 1999). The combination of the lower level of competition with crops by these mature trees and the economic returns and social benefits from the use and sale of tree products, makes these systems more attractive to farmers. The current problem is how to regenerate these parklands now that pressures for land are making the traditional fallows impractical. As indicated earlier, one apparently viable option may be to re-establish the parkland

trees within living hedges around enclosed fields. However, as also indicated earlier, there could be consequent social conflicts between sedentary farmers and nomadic herdsman if this enclosure is not done with the needs of nomads in mind. Perhaps, the solution is to domesticate a wider range of trees for farmers in the Sahel, by improving the yields and quality of the fruits, fodder, etc., and to examine ways to integrate these into a mature parklands agroecosystem. For example, this could involve small blocks of fodder and widely spaced fruit trees, within living hedges. These, and similar enclosed areas for vegetables and other perennial or valuable crops, would neither block the routes of roaming livestock belonging to nomadic herdsman, nor would they be in direct competition with crops. Breman and Kessler (1995) in their authoritative book on woody plants in semi-arid agroecosystems conclude that in situations of nutrient-limited production, optimal woody plant cover is around 15 to 20%.

In his paper, "Has the Sahel a future?", Wickens (1997) states that far too little attention has been given to non-wood forest products and agroforestry in the Sahel. This review has indicated that there are many opportunities for more intensive and imaginative use of trees for both their non-timber forest products and their environmental services, and that both of these opportunities can be harnessed by agroforestry. How can the opportunities be turned into reality? We believe that the issues have to be tackled on three fronts, all of which have to be oriented towards the needs of the people:

- the social constraints (lack of property rights) that act as disincentives to farmers to grow trees for their products and services have to be overcome;
- the trees have to be domesticated to provide additional incentives (higher yields and quality) to farmers to plant them; and
- markets and processing have to be developed to support the domestication effort to provide further commercial incentives.

In effect, there is a need for policy and development activities on a large scale to allow progress and to show what needs to be done. As emphasised by Barrow (1996), these activities need to get away from the concept that the forest department and development project should adopt the "policeman" role in tree planting and management of forest resources. In parallel with a change in policy and an enhanced understanding of the role of trees in the community, there is a need for further applied and adaptive research to domesticate trees. This research effort needs to be directed towards the creation of cultivars of the indigenous species with agroforestry and market potential, which meet the needs of the people. Then, in the development of acceptable landuse practices, it is important to avoid the creation of conflict between sedentary farmers and nomadic herdsman. These landuse practices must take into account the low carrying capacity of semi-arid environments for young, fast-growing trees. Instead, they could be modelled on mature 'parkland' agroforests, which more closely mimic the tree/grass interactions of natural ecosystems, and provide annually harvested products for food, fodder, pharmaceutical

and extractive markets. It is encouraging that some industrial companies are seeing a future for novel products synthesised from gums, resins and fibres grown by subsistence farmers. This might provide the incentive for a "woody plant revolution" in the dry tropics. It is interesting that in Tanzania, it is the younger farmers who seem to be more interested in the opportunities to increase their income from growing indigenous fruit trees (Buwalda *et al.*, 1997).

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