AGRISILVICULTURE SYSTEMS: TIMBER – FOOD CROP SYSTEMS IN THE HUMID TROPICS

Lindsey Norgrove
BP2008 (Messa) Yaoundé
Cameroon
Email Norgrove@usitmail.com

Abstract

In this article, I describe agrisilviculture with examples of both indigenous and experimental systems. Methodological aspects of assessing systems productivity are outlined. Perspectives on improving the existing systems and to develop new ones for smallholder farmers are given.

Keywords: Complementarity, deforestation, facilitation, taungya.

INTRODUCTION

In many parts of the humid tropics, forest cover has been drastically reduced. In Latin America, the estimated deforestation rate for 1990-1995 was 7.7 million hectares per year (Palo et al. 1996a). Deforestation rates in Asia during the same period were 3.9 million hectares per year (Palo et al. 1996b). In Africa estimated losses for 1990-1995 were 1.1 million hectares per year (FAO 1997). In the long term, it is expected that timber supplies will fall short of demand. For example, Lawson et al. (1993) predict a one million m^3 gap by 2020 between the annual yield from Cameroon's permanent forests and the local demand for timber. In addition, the timber demand for export cannot be covered from natural forests due to rapidly progressing deforestation.

A 'forestry solution' to meet the future local demand for timber and fuelwood would be to establish new timber plantations, as it is difficult to encourage natural regeneration of existing timber species in logged-over forests and on deforested land. Plantations, when adequately managed, typically yield up to ten times more timber volume than natural forest (Evans 1992). However, plantations in the humid tropics are often ineffectively managed when they are controlled by state departments and loggers are unlikely to invest in plantations if they still have the option to move to new concessions. Smallholder farmers might be unlikely to plant timber trees unless they get title to the land and to the tree and are also unwilling to wait at least thirty years for the revenue from their investment. Furthermore, smallholder farmers need the land to meet their immediate need: food production. So if plantation establishment does occur, it often results in conflict between the authorities who establish and smallholder farmers who encroach on forest or plantations, fell the trees and crop the land, to which they may hold customary rights.

One compromise to avoid this conflict, that could provide food and timber, is combining silviculture with agriculture: growing food crops or perennial crops such as cacao in combination with timber trees. In this way, farmers might obtain sufficient income from the understorey crops that they would be prepared to wait for the revenue from the timber trees. This system, known as agrisilviculture (synonyms 'agrosilviculture', 'sylvoagriculture'), is not new but has received less research attention than other agroforestry systems. For example, in an assessment of papers published in 'Agroforestry Systems' from 1995 – 1997, excluding a special issue, only five out of 67 papers reporting from the humid tropics referred to agrisilvicultural systems (Figure 1). Of those, only one paper was experimental; the rest described existing systems. In the period 2000-2002, there was an increase in the number of agrisilvicultural papers, with the majority being experimental, suggesting increasing interest in this field.

Agrisilvicultural systems can be classified into two main groups:

- 'taungya': food crop production during the first few years of establishing timber plantations, (synonyms 'shamba', 'tumpangsari' and 'yakihata ringyo').
- long-term associations of timber trees, usually with perennial crops, particularly cacao or coffee, or growing of food crops after routine thinning of the timber plantation.

Some examples of systems, their locations and components are given in table 1.

Taungya is one of the oldest known agrisilvicultural systems. In Burma, the taungya system was suggested by Brandis, chief forestry officer in the British Colonial Service, as a method to produce teak (Blanford 1958; Bryant 1994). The first system was implemented in 1856 by the U Pan Lee. They planted sweet potatoes, cotton and chillies between the tree seedlings (Blanford 1958). Use of the taungya system spread worldwide, both through British colonial expansion and through its adoption by national forestry services (Table 1). Usually the system was instigated by forestry departments who permitted farmers to crop between trees and thereby did not need to pay for weeding the plantation. Consequently, the only data of interest to the foresters were comparisons of tree survival, growth and maintenance costs with and without crops. Thus, data on crop yields in taungya systems compared to growing crops alone are rare. Usually the tree seedlings grew better when combined with food crops because of the better weed control (e.g. Chamshama et al. 1992; Peñafiel 1987).

While the taungya system has been criticised because of its apparent colonial, exploitational origins, according to Xu Guangyi (1639), quoted in Menzies (1988), an identical system was first used by the Miao and Yao peoples of Jiangnan, southern China, in the cultivation of a subtropical conifer. More recently it has been used by small-scale farmers in Luang-Prabang province in Laos to produce teak (Roder et al. 1995). Such systems include mango, coconut palm and banana. Teak plantings increased five-fold between 1977 and 1992 and it was predicted that this trend would continue (Roder et al. 1995).

Longer term agrisilvicultural systems are relatively rare. One of the best known is the *'damar'* system of Indonesia, in which damar, a dipterocarpaceae, is planted for timber and resin production and combined with food crops and fruit trees (Torquebaiu 1984). There is anecdotal evidence that such systems are '*sustainable*[1]' as they have existed for a long time.

---

[1] An agroecosystem will be considered sustainable if it fulfils the following criteria; after Schaller (1993):
Ecologically,

i. maintains or improves soil properties,
ii. has an input: output (harvest) ratio greater than one for all macronutrients,
iii. uses inputs, whether fertilizer, or pesticides, that seek to complement natural nutrient cycling or pest- and disease-regulating mechanisms
iv. seeks to use inputs from renewable rather than non-renewable resources
v. is able to recover from the disturbances caused by cultivation and harvest

Economically,

vi. outputs (harvests) have to be large enough and stable enough to provide sufficient yearly profits, while maintaining (i).
vii. where commodities traded have fluctuating market prices (which cannot be influenced by an individual farmer), income sources have to be sufficiently diversified to reduce the chance of years with shortfalls and to reduce investment risk.

Socially,

However, no work has been done on assessing their nutrient budgets and impact on soil properties or on quantifying their outputs. Usually, farmers possessing such systems also manage annual cropping systems so it is difficult to estimate the profitability of an individual field.

The most extensively documented experimental system to date has been the use of *Cordia alliodora* and *Erythrina poeppigiana* as a shade crop for cacao in Costa Rica (Beer 1988, Beer et al. 1990, Heuveldop et al. 1988, Fassbender et al. 1988, Imbach et al. 1989).

Cropping phases can also be reintroduced at each routine thinning of the timber stand after its establishment with a taungya system. The post-thinning periods have reduced competition and greater light availability to the understorey and thus may provide suitable conditions for shade-tolerant crops. Medium rotation timber species require three or four thinnings and final harvest is taken at 22-37 years of age, depending on the site class (Dupuy 1993). This would permit up to five food crop phases per timber cycle.

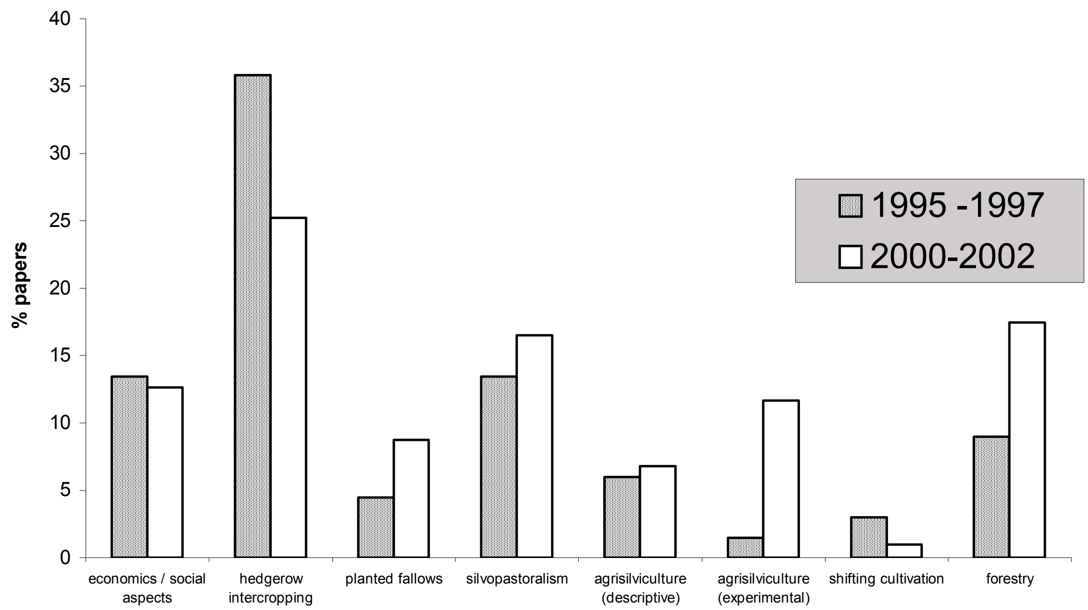

Figure 1 Assessment of papers published in Agroforestry Systems from 1995-1997 and from 2000-2002. Papers were allocated into one category only.

---

viii. systems should have secure land-tenure to permit long-term planning.
ix. production should not lead to conflict between different groups within a society.

Table 1 Agrisilviculture systems with classes or individual components either named, or classified as present (X) or absent (-). S - managed by small-scale farmers, L - institutionalised or large-scale commercial systems, E = experimental systems

Place	planted timber trees	fruit trees	tree cash crops (not timber)	starchy food crops	other	refs
***Agrisilvicultural systems :* ‘taungya’**						
S Laos	Teak (*Tectona grandis)*	*mango (Mangifera indica)*		banana (*Musa* spp. AAA)	Coconut (*Cocos nucifera*)	1
E Costa Rica	tropical laurel (*Cordia alliodora*) & *Acacia mangium*	*Eugenia stipitata*	-	maize (*Zea mays)*	ginger (*Zingiber officinale*)	2
E Costa Rica	Terminalia ivorensis	-	-	X	-	3
L Thailand	teak (*Tectona grandis*), *Eucalyptus camaldulensis,* chinaberry (*Melia azedarach*)	-	-	upland rice (*Oryza sativa*), maize, sorghum (*Sorghum bicolor*)	-	4
L Indonesia	teak	-	-	X	-	5
L India	sal (*Shorea robusta*)	-	-	-	cotton, jute	6, 7
L Nigeria	teak, sapele (*Entandrophragma cylindricum*), African mahogany (*Khaya ivorensis*), bibolo (*Lovoa trichilioides)*	-	-	X	-	8

E	Nigeria	*Gmelina arborea* (pulp wood)	-	-	maize, yams (*Dioscorea spp.)*, cassava (*Manihot esculenta*)	-	9
L	Kenya	cypress (*Cupressus lusitanica*), pines (*Pinus patula, P. radiata), Eucalyptus* spp., *Araucaria* spp., *Acacia* spp.,	-	robusta coffee (*C. canephora*), cashew (*Anacardium occidentale*)	X	-	10

continued…

	Name / Place	planted timber trees	non-planted timber trees	fruit trees	tree cash crops (not timber)	other trees (N-fixing or shade)	Palms	starchy food crops	vegetables	other	refs
Agrisilvicultural systems: long-term											
S	damar agroforests, Sumatra, Indonesia	damar (*Shorea javanica*)	-	durian (*Durio zibethinus*), rambutan	-	-	-	-	-	pepper, *Piper nigrum*	11
E	cacao plantation, Ghana	*Terminalia ivorensis*	-	-	cacao	-	-	-	-	-	12
E	cacao plantation, CATIE, Costa Rica	tropical laurel	-	-	cacao	*Erythrina poeppigiana*	-	-	-	-	13-17
E	Terminalia - plantain	*Terminalia ivorensis*	*Lophira alata*					Plantain			18-19

[1] Roder et al. 1995 [2]Kapp and Beer 1995, [3]Castaneda-Amaya 1981, [4]Watanabe et al. 1988, [5]van der Hout 1984, [6]Lahiri 1989, [7]Shankar et al. 1998, [8]Lowe 1987, [9]Ojeniyi and Agbede 1980, [10]Oduol 1986, [11]Torquebaiu 1984, [12]Ahenkorah et al. 1987, [13]Beer 1988, [14]Beer et al. 1990, [15]Heuveldop et al. 1988, [16]Fassbender et al. 1988, [17]Imbach et al. 1989, [18]Norgrove and Hauser 2002a, [19]Norgrove and Hauser 2002b

MECHANISMS BY WHICH HIGHER YIELDS CAN BE OBTAINED IN AGRISILVICULTURAL SYSTEMS

So why should an agrisilvicultural system be used rather than an agriculture plus forestry mosaic? Why and when does integration of trees and crops have benefits for the farmer and what are those benefits? Benefits to farmers in the short term are manifested as either reduced input for the same output, increased yield for the same input, or higher quality outputs permitting a higher price. There may be lower labour demands for planting and/or weeding and/or pest and disease control, lower fertilizer or pesticide requirements, and reduced pest and disease pressure. Longer term benefits include soil improvements, stability of production or income and improved soil properties. The following section outlines some mechanisms by which yields can be higher in agrisilvicultural systems compared with agriculture and forestry. Some examples are borrowed from other tree crop systems.

The land equivalent ratio (LER) (after Mead and Willey 1980; Willey 1979a,b) compares the yields obtained in a particular time when a tree and crop are grown separately with the yields obtained when they are grown together[2]. Where yields are greater in the mixture than in the monocrops, the LER exceeds one and a mixture is recommended. For example, farmers in Bangladesh maintaining mango and jackfruit trees in their fields were aware of yield declines in understorey rice and wheat occurring up to 7 m from the trunk. However, these losses were acceptable because of the valuable fruit and timber supplied by the trees (Hocking et al. 1997).

In market orientated economies, farmers are more concerned with the monetary value of the crops rather than their area-based yields. Here, the 'relative value total' (RVT) (after Schultz et al. 1982) is used and the value of the mixture is compared to that of the more valuable of the monocrops[3].

Whether agrisilviculture is successful, relative to growing trees and crops separately, will depend on the species' combination selected, actual and relative strata densities and the limiting factors and pressures of the selected environment. The crux is that the benefits of combination, the processes of 'complementarity' and 'facilitation' must outweigh the costs of combination, the interspecific competition for space, light, water and nutrients such that long term productivity is higher and the LER exceeds one. Given that the understorey crop is subjected to a competitor with an established network of roots for water and nutrient uptake

---

[2] $$LER = \frac{Mt + Mf}{Yt + Yf}$$

Where Yt= yield per hectare of tree crop per unit time in monoculture at optimum density*
Yf = yield per hectare of food crop per unit time in monoculture at optimum density*
Mt and Mf = yields per hectare of tree and food crops, respectively, per unit time in mixture

If LER = 1 either both t and f are unchanged or decrease in one = increase in other
If LER > 1 either both t and f increase or increase in one > decrease in other
If LER < 1 either both t and f decrease or increase in one < decrease in other

[3] $$RVT = \frac{aM_f + bM_t}{aY_f}$$
where a = price of f
b = price of t

imposing shade that cannot be escaped by upward growth, it bears most of these interspecific competition costs.

Trees and crops are complementary if they exploit a greater amount of limited growth factors when grown together than when apart (Willey et al. 1987). Complementarity mechanisms include capturing more light per unit land area in a multilayered canopy, extracting water and nutrients from different depths in the soil or that demands for these growth factors are at different times in the growing season (Willey et al. 1987; Fukai and Trenbath 1993). However, complementarity excludes any modification to the environment by one partner that inadvertently benefits the other, known as 'facilitation' (Vandermeer, 1984). As well as affecting the availability of growth factors, trees will modify the environment of the understorey crop through, for example, shading which causes changes in the microclimate and these changes may have benefits.

If crops are planted in a timber plantation at optimum tree density (similar to the tree density found in timber plantation in monoculture), then any crop planted between the trees would be a net benefit compared to a timber plantation in monoculture[4]. However, clearly the yield of the crop has to exceed in energy or cash value the investment of seed, planting and maintenance and this demonstrates the drawback of the LER approach.

COMPLEMENTARITY OR COMPETITION?

Light

By combining trees and crops, light resources may be used more efficiently. This may be by capturing more light per land area or that plants have adaptations that allow them to grow under lower light conditions. Trees and crops may form two distinctive canopies. This may increase the amount of light interception and overall canopy cover may be higher (Gay et al. 1971; Nelliat et al. 1974). For this to happen, the tree and the crop have to fit well together. For example, it is usually practical to plant trees in a square pattern. As individual tree canopies, when viewed from the top, tend to be circular, there are unshaded areas in the mid-point between four trees making a square, permitting a shade-intolerant understorey species to be grown without compromising on its light requirement. Other trees form diffuse canopies that permit much photosynthetically active radiation to penetrate through to the understorey. Therefore a crop tolerant of the lower light levels, such as tannia, could be grown directly under the tree canopy. Crops can also adapt their leaves to lower light levels by having thinner, larger leaves, larger chloroplasts and higher chlorophyll concentrations than illuminated plants (Boardman 1977), cacao (Galyuon et al. 1996a,b), and bananas (Balasimha 1989). As well as tolerating low light levels, some crops, such as banana, plantain, cacao and coffee can have higher photosynthetic rates and therefore higher growth rates at these low levels. So, the spatial arrangement of the crops may permit a greater use of the total light resource, some crops can adapt and cope with the low light levels and some crops actually perform better under shade.

Low light levels may have other effects by altering the way a plant allocates biomass between different plant organs and this can directly affect the yield. For example, for bananas, Stolar (1962) found that banana bunch mass was greatest when the temperature of the banana trunk or pseudostem was between 21-24^{0}C. As shaded plots in the tropics have lower temperatures, bigger bunches may be obtained under shade. The reduction in radiation to the lower storey may also improve product quality. Bananas grown under shade are less

[4] If M_t / Y_t = 1, then any crop yield greater than 0 would produce an LER > 1.

likely to have necrotic scorching of peel (Wade et al. 1993) which reduces marketable value. However, in coffee, while reduced light flux density may cause changes in leaf morphology, it has little effect on the quality (chemical constituents) of the fruits (Willey 1975).

There are, however, many negative effects of low light levels. One is that some crops can become etiolated, with thinner, taller stems. This increases the risk of plant toppling and has been demonstrated in plantain resulting in yields much lower than in less shaded plots (Norgrove and Hauser 2002a).

Water and nutrients

Many reviews on agroforestry have assumed that trees preferably are accessing water and nutrients from soil layers below the rooting zone of annual crops. Nutrients are taken up to produce biomass, as well as partially being recycled through litterfall and deposited on the soil surface. So competition between trees and crops is avoided. This is the 'nutrient pump' hypothesis (Cannell et al. 1996). However, there is little empirical evidence for this process occurring. In an experiment, looking at competition between trees grown in rows and groundnut, Rowe et al. (1999) used labelled nitrogen applied at various soil depths. They found that the groundnut crop took up a larger proportion of the recovered nitrogen than the trees at all the depths therefore the trees and crops were competing for limited resources. Norgrove (unpubl) measured soil water content down to 1.6 m depth in systems of 17 year old timber trees and plantain at different tree densities and found that water contents in the topsoil were reduced in the high tree densities whereas there were no significant differences at deeper layers. Thus the trees were taking up water and most likely nutrients from the topsoil, where the plantains were also taking up nutrients. Deans et al (1996) also found that such trees do have a high percentage of their fine roots in the topsoil, where most nutrients are located. Also, Norgrove (1999) showed that nutrient inputs through litterfall in this system were less than those from periodically slashed arable weeds. Thus, if both trees and weeds are taking up nutrients from the same area, then there is no water and nutrient advantage to having a tree companion. And trees and crops might as well be grown in separate stands rather than together.

FACILITATION

Trees affect the environment of the understorey crop, usually lowering light levels, reducing air and soil temperature, altering soil moisture and rain and dew deposition (Thurston 1992). These changes in light and microclimate can be of benefit or detriment to the understorey crop, by altering weed, pest and disease dynamics and nutrient cycling of the system.

Loss of water through crop transpiration and stomatal conductance may be reduced under tree cover. Where this gain is greater than any soil water competition from the trees, yield may increase. Conversely, competition for water from trees may inhibit the growth of other crop plant parts which compete internally with the harvested organ thereby increasing the harvest index. This was demonstrated in cassava by Connor et al. (1981) who found higher tuber yields at lower soil water levels.

Shade from trees may change the degree of damage caused by leaf diseases. Brown leaf spot of coffee is reduced in shaded coffee plantations, compared with unshaded ones (Nataraj and Subramanian 1975, quoted in Thurston 1992). However, in contrast, damage from the leaf disease 'tea blister blight' was more severe under shade (Visser et al. 1961).

Shade also reduces damage to bananas and plantains caused by black and yellow sigatoka leaf fungal diseases. Stover (1987) noted less black sigatoka damage on plantains shaded by coconuts than on plantains in full sunlight. Shaded bananas had less damage from yellow sigatoka than bananas in full sunlight (Thurston 1992). According to Karani (1986), for centuries in Uganda, bananas were grown in association with large *Ficus* that provided shade. During the last 40 years, most of the trees have been eliminated, and the importance of yellow sigatoka has increased. But how important are these diseases? Yield loss of plantain to black sigatoka can reach 39% (Mobambo et al. 1993). It is very expensive to control by chemical methods: in Central America, the chemical control of black sigatoka is up to 27% of fruit production costs (Gauhl 1993). It can be reduced by tree shade. Norgrove (1999) showed that under high tree density plantain had nearly twice as much leaf area near harvest than plantains grown under low tree density because of higher leaf area losses to black sigatoka under low density.

Crop and tree losses to weed competition are often very high in the humid tropics. Shading can reduce weed biomass and reduce the possibility of the succession of weed communities toward one which is dominated by grasses and more difficult to control (Vernon 1967, Trenbath 1985). Work by Ng et al. (1997) showed that shading not only reduced the weed biomass, but had the most severe impact on the high biomass grasses, which would be most likely to affect negatively the growth of any understorey crop. So, not only are crop losses reduced, but weeding labour requirements may be reduced, too.

THE FACILITATION FUNCTION OF TREES

A central tenet in agroforestry research in the humid tropics is that trees improve or maintain soil fertility and 'ecosystem function' (Sanchez et al. 1985). Brown et al. (1994) hypothesised that soil fertility in tropical, derived systems is maintained by '*mimicking a forest ecosystem with perennials or perennial and annual mixtures'*. There are many proposed mechanisms: litter fall (Zinke, 1962; Leite and Valle 1990); root decomposition (Singh and Singh, 1993); maintaining soil organic matter levels; deep nutrient capture from subsoil layers; tighter nutrient cycling; reduction of topsoil acidity through base cycling, stem and through-flow (Gersper and Holowaychuk 1971); improved soil biological activity (as trees do not incorporate nutrients and organic carbon into the soil: they just drop in on the surface and it is the action of soil organisms that forms stable organic molecules and soil aggregates). However, these have not all been proven or only so under limited circumstances (Sanchez 1995). Also, many data on the effects of trees on soil have been collected from natural tree systems, rather than from planted systems. Therefore it is not possible to separate cause and effect. Is the soil better because it has been improved by the tree or did a tree successfully establish and grow there because the soil was better?

RESULTS TO DATE

Research on agrisilvicultural systems to date has demonstrated that it can be a successful <u>entreprise</u>. Compared with unweeded tree plantations, trees usually have higher growth rates when combined with crops, as they benefit from the weeding necessary to establish the crop. This was shown for *Terminalia ivorensis* trees grown with plantain (Norgrove and Hauser (2002b) and also for *Cordia alliodora* grown with maize and a fruit tree (Kapp and Beer 1995). Norgrove and Hauser (2002a) also showed that yields of plantain, grown under a low tree density are comparable to an open-light plantain-only system (Hauser 2000), so there is no yield loss by combining with trees at a low density.

DEVELOPMENT OF AGRISILVICULTURAL SYSTEMS

Innovative systems of any kind are most likely to be adopted by smallholder farmers if it is clearly demonstrated that (1) they produce something in short or decreasing supply, or (2) they can produce higher, sustained yields at similar or lower input levels than existing systems, or (3) that they can target land that farmers currently consider to be degraded and therefore out of production. These conditions need to be satisfied although adoption rates will depend upon issues such as security of land tenure, levels of land scarcity, contact with extension services, market access, sex and age of the farmer.

There are three major pathways for establishing agrisilvicultural systems. Agrisilvicultural systems could be developed by converting existing timber plantations, with farmers permitted to crop as instigated by the forestry authorities after thinning the plantations to the density recommended for the age of the plantation. This situation may be mutually beneficial as farmers receive access to additional land and the forestry authorities save money on underbrushing while potentially realizing larger timber growth increments.

A second method to establish agrisilvicultural systems is the traditional '*taungya*', used by farmers on land already used for food production and to be reverted to forestry, with crop production later in the silvicultural cycle after thinning the plantations to the density recommended for the age of the plantation. In 2000, the Lao government reported that it was encouraging the development of long term agrisilvicultural systems, using *Terminalia* spp., rubber and teak, from the smallholder taungya systems described earlier in this paper (Anon 2000).

In addition to land use opportunities for food production in timber plantations established on productive land, there may be opportunities to recover unproductive land through first introducing multipurpose trees to shade timber tree seedlings and then to add shade tolerant food crops, similar to the other two systems. Such an initiative was started in southern Cameroon after a local farmer group approached researchers and requested assistance in developing agrisilvicultural systems on land dominated by *Imperata cylindrica* grass that they classified as unsuitable for food crop production. They selected a mixture of timber and fruit tree species, including cacao, with plantain, cooking banana and a nitrogen-fixing tree. The effects of fertilizer regimes and shade crop regimes are being tested.

Existing agrisilvicultural systems can also be optimised by selecting the appropriate tree density. Clearly there should be some effort to document fully, together with the land users, the systems that are available, with respect to the tree density, crop combination and assessing which factors are considered limiting in the system. One recommended method to do this was developed by Herzog and Gotsch (1998) for assessing cacao agroforests. They propose selecting 10 m x 10 m areas within agroforests with differing upper canopy cover and then assessing understorey production and soil properties to determine optimum densities.

The adoption of agrisilvicultural systems by smallholder farmers should give them the opportunity to gain from such sales of timber and fuelwood and increase their cash income. In many tropical countries, governments gain much revenue from the sale of timber concessions, however, this is not always channelled back into the infrastructure of the region from which timber is extracted. So promoting such systems should also lead to greater income equity.

References

Ahenkorah Y., Halm B. J., Appiah M. R., Akrofi G. S., Yirenkyi J. E. K. (1987), Twenty years' results from a shade and fertilizer trial on amazon cocoa (*Theobroma cacao*) in Ghana. Experimental Agriculture, 23, 31-39;

Anon (2000), Country Progress Report, Lao People's Democratic Republic, Prime Minister's Office, Vientaine, Lao. 19pp;

Balasimha D. (1989), Light penetration patterns through arecanut canopy and leaf physiological characteristics of intercrops. Journal of Plantation Crops, 16, 61-67;

Beer J. (1988), Litter production and nutrient cycling in coffee (*Coffea arabica*) or cacao (*Theobroma cacao*) plantations with shade trees. Agroforestry Systems, 7, 103-114;.

Beer J., Bonnemann A., Chavez W., Fassbender H. W., Imbach A. C., Martel I. (1990), Modelling agroforestry systems of cacao (*Theobroma cacao*) with laurel (*Cordia alliodora*) or poró (*Erythrina poeppigiana*) in Costa Rica. Agroforestry Systems, 12, 229-249;

Beer J., Muschler R., Kass D., Somarriba E. (1998), Shade management in coffee and cacao plantations. Agroforestry Systems, 38, 139-164;

Blanford H. R. (1958), Highlights of one hundred years of forestry in Burma. Empire Forestry Review, 371, 33-42;

Boardman N. K. (1977), Comparative photosynthesis of sun and shade plants. Annual Review of Plant Physiology, 28, 355-377;

Brown S., Anderson J. M., Woomer P. L., Swift M. J., Barrios E. (1994), Soil biological processes in tropical ecosystems. In: Woomer P. L., Swift M. J. (eds) The biological management of tropical soil fertility. pp 15-46. Wiley and Sons, Chichester, UK;

Bryant R. L. (1994), The rise and fall of taungya forestry. Social forestry in defence of the Empire. The Ecologist, 24, 21-26;

Cannell M. G. R., van Noordwijk M., Ong C. K. (1996), The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. Agroforestry Systems, 34, 27-31;

Castaneda Amaya L. A. (1981), Comportamiento de *Terminalia ivorensis* A. Chev. asociada con cultivos anuales y perennes en su segundo ano de crecimiento. Universidad de Costa Rica/Centro Agronomico Tropical de Investigación y Enseñanza (CATIE), Costa Rica;

Chamshama S. A. O., Monela G, C., Sekiete K. E. A., Persson A. (1992), Suitability of the taungya system at North Kilimanjaro Forest Plantation, Tanzania. Agroforestry Systems, 17, 1-11;

Connor D. J., Cock J. H., Parra G. H. (1981), Response of cassava to water shortage. 1. Growth and yield. Field Crops Research, 4, 181-200;

Deans J. D., Moran J., Grace J. (1996), Biomass relationships for tree species in regenerating semi-deciduous tropical moist forest in Cameroon. Forest Ecology and Management, 88, 215-225;

Dupuy B. (1993), Timber plantations in the humid tropics of Africa. FAO Forestry Paper 98, FAO Rome, Italy;

Evans J (1992) Plantation forestry in the tropics. 2nd edition. Oxford University Press, Oxford, UK;

FAO (1997), State of the World's Forests. Words and Publications, Oxford, UK;
Fassbender H. W., Alpízar L., Heuveldop J., Fölster H., Enríquez G. (1988), Modelling agroforestry systems of cacao (*Theobroma cacao*) with laurel (*Cordia alliodora*) and poró (*Erythrina poeppigiana*) in Costa Rica III Cycles of organic matter and nutrients. Agroforestry Systems, 6, 49-62;

Fukai S., Trenbath B. F. (1993), Processes determining intercrop productivity and yields of component crops. Field Crops Research, 34, 247-271;

Galyuon I. K. A., McDavid C. R., Lopez F. B., Spence J. A. (1996a), The effect of irradiance level on cocoa (*Theobroma cacao* L.): I. Growth and leaf adaptations. Tropical Agriculture Trinidad, 73, 23-28;

Galyuon I. K. A., McDavid C. R., Lopez F. B., Spence J. A. (1996b), The effect of irradiance level on cocoa (*Theobroma cacao* L.): II. Gas exchange and chlorophyll fluorescence. Tropical Agriculture Trinidad, 73, 29-33;

Gauhl F. (1993), Some aspects of black sigatoka epidemiology in Central America and outlook for future research in subSaharan Africa. In: Gold C C, Gemmill B (eds) Biological and integrated control of Highland banana and plantain pests and diseases. Proceedings of a Research Coordination Meeting. International Institute of Tropical Agriculture, Ibadan, Nigeria. pp 276-289;

Gay L W, Knörr K. R., Braaten M. O. (1971), Solar radiation variability on the floor of a pine plantation. Agricultural Meteorology 8, 39-50;

Gersper P. L., Holowaychuk N. (1971), Some effects of stem flow from forest canopy trees on chemical properties of soils. Ecology, 52, 691–702.

Hauser, S. (2000), Effects of fertilizer and hot-water treatment upon establishment, survival and yield of plantain (Musa spp., AAB, French). Field Crops Research, 66, 213-223;

Herzog, F., Gotsch N. (1998), Assessing the sustainability of smallholder tree crop production in the tropics: a methodological outline. Journal of Sustainable Agriculture, 11,(4), 13-37;

Hocking D., Sarwar G., Yousuf S. A. (1997), Trees on farms in Bangladesh. 4 Crop yields underneath traditionally managed mature trees. Agroforestry Systems, 35, 1-13;

Imbach A. C., Fassbender H. W., Borel R., Beer J., Bonnemann A. (1989), Modelling agroforestry systems of cacao (*Theobroma cacao*) with laurel (*Cordia alliodora*) and poró (*Erythrina poeppigiana*) in Costa Rica IV Water balances, nutrient inputs and leaching. Agroforestry Systems 8, 267-287;

Kapp G. B., Beer J. (1995), A comparison of agrisilvicultural systems with plantation forestry in the Atlantic Lowlands of Costa Rica. Agroforestry Systems, 32, 207-223;

Karani P. K. (1986), Observations on the productivity of matoke (bananas) (*Musa* spp.) under agroforestry at Entebbe, Uganda. Commonwealth Forestry Review, 65, 241-250;

Lahiri A. K. (1989), Taungya-based agro-forestry trials in West Bengal. Indian Forester, 115, 127-132;

Lawson G. J., Mahamat A., Hockey H. (1993) Forest plantations in Cameroon. In: Protecting and regenerating the forests of Cameroon. Proceedings of the 2nd meeting of the Professional Forestry Association of Cameroon, 16 – 19 November 1993. pp89-102;

Leite J. O., Valle R. R. (1990), Nutrient cycling in the cacao ecosystem: rain and throughfall as nutrient sources for the soil and the cacao tree. Agriculture Ecosystems and Environment, 32, 143–154;

Lowe R. G. (1987), Development of taungya in Nigeria. In: Gholz H G (ed) Agroforestry: realities, possibilities and potentials. pp137-154. Martinus Nijhoff, Dordrecht, The Netherlands;

Mead R., Willey R. W. (1980), The concept of a 'land equivalent ratio' and advantages in yields from intercropping. Experimental Agriculture, 16, 217-228;

Menzies N. (1988), Three hundred years of taungya: a sustainable system of forestry in south China. Human Ecology, 16, 361-376;

Mobambo K. N., Gauhl F., Vuylsteke D., Ortiz R., Pasberg-Gauhl C., Swennen R. (1993), Yield loss in plantain from black sigatoka leaf spot and field performance of resistant hybrids. Field Crops Research, 35, 35-42;

Nataraj T., Subramanian S. (1975), Effect of shade and exposure on the incidence of brown-eye-spot of coffee. Indian Coffee, 39(6), 179-180;

Nelliat E. V., Bavappa K. V., Nair P. K. R. (1974), Multi-storeyed cropping: A new dimension in multiple cropping for coconut plantations. World Crops, 26, 262-266;

Ng K. F., Stür W. W., Shelton H. M. (1997), New forage species for integration of sheep in rubber plantations. Journal of Agricultural Science, *Coffea arabica* 128, 347-355;

Norgrove L. A. (1999), Crop, weed and soil responses to tree density and implications for nutrient cycling in a tropical agrisilvicultural system. Ph. D. thesis, University of London, UK. 287p, 449 refs;

Norgrove L., Hauser S. (2002a), Yield of plantain grown under different tree densities and 'slash and mulch' versus 'slash and burn' management in an agrisilvicultural system in southern Cameroon. Field Crops Research, 78, 185-195;

Norgrove L., Hauser S. (2002b), Measured growth and tree biomass estimates of *Terminalia ivorensis* in the three years after thinning to different densities in an agrisilvicultural system in southern Cameroon. Forest Ecology and Management, 166, 261-270;

Oduol P. A. (1986), The shamba system: an indigenous system of food production from forest areas in Kenya. Agroforestry Systems, 4, 365-373;

Ojeniyi S. O., Agbede O. O. (1980), Agri-silviculture in Nigeria: food crops and soil fertility. Journal of Agricultural Science, Cambridge 95, 725-727;

Palo M., Lehto E., Mery G. (1996a) Latin American deforestation and sustainability prospects. In: Palo M., Mery G. (eds) Sustainable forestry challenges for developing countries. pp 199-228. Kluwer Academic Publishers, Dordrecht, The Netherlands;

Palo M., Lehto E., Mery G. (1996b) Tropical Asian deforestation and sustainability prospects. In: Palo M, Mery G (eds) Sustainable forestry challenges for developing countries. pp 93-119 Kluwer Academic Publishers, Dordrecht, The Netherlands;

Peñafiel S. R. (1987), Taungya scheme increases growth of hanga. Canopy International, 13, 1-10;

Roder W., Keoboulapha B., Manivanh V., (1995), Teak (*Tectona grandis*), fruit trees and other perennials used by hill farmers of northern Laos. Agroforestry Systems, 29, 47-60;

Rowe E. C., Hairiah K., Giller K. E., van Noordwijk M., Cadisch G. (1999), Testing the safety-net role of hedgerow tree roots by 15 N placement at different soil depths. Agroforestry Systems, 43, 81-93;

Sanchez P. A., Palm C. A., Davey C. B., Szott L. T., Russell C. E. (1985), Tree crops as soil improvers in the humid tropics? In: Cannell M.G. R., Jackson J. E. (eds) Attributes of trees as crop plants. pp 327-358. Institute of Terrestrial Ecology, Huntingdon, UK;

Schaller N. (1993), Sustainable agriculture and environment: the concept of agricultural sustainability. Agriculture, Ecosystems and Environment, 46, 89-97;

Schultz B. B., Philips C., Rosset P., Vandermeer J. (1982), An experiment in intercropping tomatoes and cucumbers in southern Michigan, USA. Scientia Horticulturae, 18, 1-8;

Shankar U., Lama S. D., Bawa K. S. (1998), Ecosystem reconstruction through '*taungya*' plantations following commercial logging of a dry, mixed deciduous forest in Darjeeling Himalaya. Forest Ecology and Management, 102, 131-142;
Singh L., Singh J. S. (1993), Importance of short-lived components of a dry tropical forest for biomass production and nutrient cycling. Journal of Vegetation Science, 4, 681–686;
Stover R. H. (1987), The effect of temperature on ascospore germ tube growth of *Mycosphaerella musicola* and *Mycosphaerella fijiensis* var difformis. Fruits, 38, 625-628;
Thurston H. D. (1992), Sustainable practices for plant disease management in traditional farming systems. Westview Press, Boulder, USA;
Torquebiau E. (1984), Man-made dipterocarp forest in Sumatra. Agroforestry Systems, 2, 103-128;
Trenbath B. R. (1985), Weeds and Agriculture: A question of balance. Studies on Plant Demography. A festschrift for J L Harper. pp 171-183. Academic Press, London, UK;
Van der Hout P. (1984), Effects of wider initial spacing of teak (*Tectona grandis*) on income and distribution in the taungya system in Java. Netherlands Journal of Agricultural Science, 32, 139-142;
Vandermeer J. H. (1984), The interpretation and design of intercrop systems involving environmental modification by one of the components: a theoretical framework. Biological Agriculture and Horticulture, 2, 135-156;
Vernon A. J. (1967), New developments on cocoa shade studies in Ghana. Journal of Science of Food and Agriculture, 18, 44-48;
Visser T., Shanmuganathan N., Sabanayagum J. V. (1961), The influence of sunshine and rain in tea blister blight, *Exobasidium vaxans* Massee. Annals of Applied Biology, 49, 306-315;
Wade N L, Kavanagh E E, Tan S C 1993 Sunscald and ultraviolet light injury of banana fruits. Journal of Horticultural Science, 68, 409-419;
Watanabe H., Sahunalu P., Khemnark C. (1988), Combinations of trees and crops in the taungya method as applied in Thailand. Agroforestry Systems, 6, 169-177;
Willey R. W. (1975), The use of shade in coffee, cocoa and tea. Horticultural Abstracts, 45, 791-798;
Willey R. W. (1979a), Intercropping - its importance and its research needs. Part 1. Competition and crop yield advantages. Field Crop Abstracts, 32, 1-10;
Willey R. W. (1979b), Intercropping - its importance and its research needs. Part 2. Agronomic relationships. Field Crop Abstracts, 32, 73-85;
Willey R. W., Reddy M. S., Natarajan M. (1987), Conventional cropping systems for Alfisol and some implications for agroforestry systems. In: Proceedings of the consultants workshop on the state of the art and management alternatives for optimising the productivity of SAT Alfisols and Related Soils 1-3 December 1983, International Centre for Research in the Semi-Arid Tropics, India;
Xu Guangqi (1639), Nong Zheng Quan Shu (Complete book of agricultural administration) (in Mandarin);
Zinke P. J. (1962), The patterns of influence of individual forest trees on soil properties. Ecology, 43, 130–133.