3. Agroforestry

"If the indigo fields in the valleys of Aragua (Venezuela) were not abandoned and left fallow, and not planted with grain, but rather with other nutritious plants and fodder herbs - if in addition, farmers would choose plants from different families, ones that shade the ground with their broad leaves - then eventually the fields would improve and recover a part of their former fertility."

A. von Humboldt (1767-1831)[32]

3.1 Introduction

More than 180 years have passed since Alexander von Humboldt travelled through the tropics of South America. Nevertheless, until recently the kind of approach he suggests found no place in development strategies for tropical agriculture. Only in the past few years has a change in thinking taken place, in response to mounting evidence of environmental decline, ever scarcer non-renewable resources and the failure of the Green Revolution to improve the lot of smallholder farmers in tropical Africa. It is becoming increasingly clear that pure stands of single crops combined with intensive, mechanical tillage, mineral fertilizers and chemical plant protection may be "modern" but are incapable of conserving and improving the fertility and productivity of tropical cropland (JANZEN 1973; IGBOZURIKE 1977). "New" cropping and farming systems adapted to the special conditions of the tropics are being rediscovered and developed. The new development approach common to these is that agricultural activities must fit into the social and economic setting and take ecological requirements into account. The sustainability of production takes priority over short-term gains in yields and profits (IGBOZURIKE 1977; EGGER 1982; ALTIERI et al. 1983; KOTSCHI and ADELHELM 1984).

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[32] From: "Voyage aux régions équinoxiales du nouveau continent", translated from "Südamerikanische Reise" in: Alexander von Humboldt (1979).

Against this background, agroforestry methods are becoming increasingly important. The term "agroforestry" expresses the change in attitude that forestry experts and agronomists have been undergoing over the past decade. First gaining attention through the alarming shortage of firewood in the tropics, the vital role of trees and shrubs, with their manifold advantages for sustainable land use, is well recognized today - after generations of agricultural advisors have urged the removal of trees and shrubs from fields and boundary strips.

BUDOWSKI (cited in DSE 1983) defines agroforestry as follows: "By agroforestry we mean techniques of land use in which trees are combined with crops or pastures or with both. The combination can be simultaneous in terms of time and space or it can be phased. The objective is sustained optimization of total production per unit of area". Spatial gradation is also implied in the terms "multi-story vegetation" or "multi-story farming". The commonly used terms "agrosylvicultural", "sylvopastoral" or "agrosylvopastoral" (see e.g. NAIR 1985) are indicative of the various combinations of land use involved: that of field cropping with forest management, of forest with range management, or of field cropping, forest and range management.

The **aim** of agroforestry is to combine high, no-risk production with sustainable production (BUDOWSKI 1981). "Higher production" implies not only the higher productivity of land but also of human labor. At the same time the aim is also to maintain this productivity over a longer period of time. Agroforestry systems typically possess a high degree of diversity, on the assumption that greater diversity is associated with greater stability. The theory is that through co-evolution natural vegetation forms become so well adapted to the conditions of an environment that they arrive at optimal productivity and stability. A dynamic balance between harmful and beneficial organisms is reached and the ecosystem develops mechanisms for making optimal use of growth-limiting factors. For instance, higher nutrient turnover compensates for the lower amount of nutrients available in the rainforest. The dominant characteristics and patterns of natural ecosystems are consequently regarded as models in the development of new production systems. Agroforestry makes a decisive contribution here. An approximate simulation of natural ecosystems is the starting point for developing more appropriate approaches to land use in the tropics (UHL and MURPHY 1981; ALTIERI et al. 1983). If there is some question as to the productivity of these new systems, values from the natural, local plant associations serve as a point of reference.

Any type of land use - even an environmentally sensitive one - must lead away from a purely natural state because land use means altering the natural ecosystem with the aim of attaining outputs for use by people. Agroforestry generally seeks to keep such interference to a minimum. Hence it harnesses the regulatory mechanisms and productive powers that exist in natural ecosystems for the creation of agrarian - or better, human - ecosystems.

In the following section we present and discuss some of the relationships within agroforestry systems, with the help of applied systems theories and their hypotheses (e.g. the diversity-stability theory).

3.2 Establishing sustainable and stable agro-ecosystems

Determining the stability of an ecosystem is one of the most difficult tasks in ecology (ARNDT 1981). Nevertheless, the more knowledge is available concerning the organization and interrelationships of the components in an ecosystem, the easier the task becomes. Seen from the outside, an ecosystem functions as a single unit, albeit in reciprocal relationships with other units and with the external environment (HART 1979). Internally, ecosystems are regulated by complex subsystems, like a living organism. Many of these are feedback control systems, which are generally more numerous the more components are present in the system. Thus an ecosystem constitutes a systematic network of feedback circuits. An important mechanism in such feedback systems is the principle of negative feedback. However, this will not be discussed in detail here.

3.2.1 Ecosystem stability

The stability of ecosystems is based on their ability to oscillate around a state of equilibrium (dynamic equilibrium) or to return to a state of equilibrium after a perturbation (MARGALEFF 1969; ARNDT 1981). This is accomplished through structures which buffer disturbing influences from the outside (for example, ground cover that protects against the impact of rainfall and overheating of the soil), which reverse their effect (for example, nutrient reserves that help trees to recover rapidly from defoliation by insects), or which balance out disturbances within the system via negative feedback (for example, controlling a mass outbreak of pests through an increase in the parasites that feed on them or through a change in the composition of the stand (GIGON 1974).

There are two types of ecosystem, differing in their basic structure and their stage of stability: developing ecosystems and mature ecosystems.

* **Developing ecosystems** come into being as a result of changing environmental factors and are not yet fully mature. They contain a small to medium number of species, the relationships between which constitute an as yet relatively undeveloped network of internal dependencies, but a relatively large number of external ties. The species are mostly non-specialists having a wide range of tolerance, and their presence is strongly influenced by the physical environment. In such systems, the probability of a population explosion by a single species is comparatively high. That is, the fluctuations that occur as the system evolves towards a state of equilibrium can be quite large (relatively unstable equilibrium). Nevertheless, such systems are relatively "elastic", in the sense that less highly adapted species can and do take on a wider range of functions than those associated with species occupying a specialized niche.

* **Mature ecosystems** have developed under constant environmental conditions and possess a high diversity of species. Numerous interrelated networks within the system result in greater self-regulation and relative independence from outside influences. Exchange processes with the outside are limited to essentials. Internal biological factors dominate as regulators. Fluctuations either side of the equilibrium are small, and domination by a single population seldom occurs. Such an ecosystem is very stable, but also relatively "inelastic", because the specialists (i.e. highly adapted species) are seldom able to take over the disturbed functions of other components (ELLENBERG, ODUM, both cited in ARNDT 1981).

Table 3.1 presents a simplified and generalized view of the two types of ecosystem described above, with some of their most important characteristics[33].

Within the tropics, the first type of ecosystem is found primarily at subhumid non-equatorial latitudes and at high elevations subject to daily frost. The evergreen tropical rainforest is a typical example of the second type of ecosystem. Under the influence of the uniform inner-tropical climate, it has been able to develop into a fully mature or climax system.[34]

According to GIGON (1974) the following criteria are important for stability, regardless of an ecosystem's particular characteristics:

- **Circulation principle**: This permits operation with little imported material and avoids the accumulation of waste. For example, in a cropping system harvest residues may be left on the fields, and all processing residues and digestive wastes may be returned to the field as compost.

- **Nutrient capital:** This should be large in comparison with the nutrients in circulation. A system's imports and exports are often subject to fluctuations, but when the capital reserves are high, fluctuations have almost no impact. For instance, the nutrients contained in a harvest can be removed without seriously influencing the system if the reserves in the soil are relatively large.

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[33] Reality is usually more complicated. For example, the species diversity in disturbed or exploited grasslands can be higher than in undisturbed ones. This model is useful, however, as a working hypothesis.

[34] The term "climax" is not always applied in the same way. It is most often used to describe a community that has developed on a particular site under undisturbed, natural conditions, and which should then be described as "local climax formation" or "climax community".

- **The buffering capacity**: This is the ability to absorb imbalances, which should be well developed. For example, the humus economy of a soil offsets fluctuations in rainfall and chemical imbalances in the soil solution. A canopy of trees over coffee shields the coffee plants from frost or extreme heat.

- **Co-evolution:** This is the interrelated development of organisms within a common habitat. A plant (or plant community) which has evolved together with other plants or animals that are harmful to it will have developed a certain equilibrium with them. If a new antagonist is introduced or the plant is transplanted to a different environment, the danger is great that this equilibrium will collapse.

- **Negative feedback:** This principle of self-correction is vital and must not be disrupted or blocked.

- **Diversity:** This is the multiplicity of components and relationships within a system (MARGALEFF 1969). For example, roots permeating the soil at various depths and densities in a species-rich plant stand supply such a stand with considerable nutrient reserves and help it to withstand leaching.

Table 3.1. Some characteristics of two types of ecosystem

Characteristics	Developing ecosystem	Mature ecosystem
Food chain	Linear	Interlinked
Total organic matter	Low	High
Nutrients	Freely available	Incorporated
Species diversity	Low	High
Habitat range of organisms	Large, general	Small, specialized
Nutrient cycle	Open	Closed
Speed of exchange with the environment	Rapid	Slow
Symbiosis, parabiosis	Undeveloped	Developed
Nutrient storage	Low	High
Entropy (non-available energy)	High	Low
Elasticity (flexibility)	High	Low
Productivity	High	Low
Sustainability (stability)	Poor	Good

Source: Adapted from ARNDT (1981), and ODUM (cited in ARNDT 1981)

The fewer of these criteria that apply to an (agro)ecosystem, the more unstable it is - and the more caution, care and, often, work is necessary to keep it functioning.

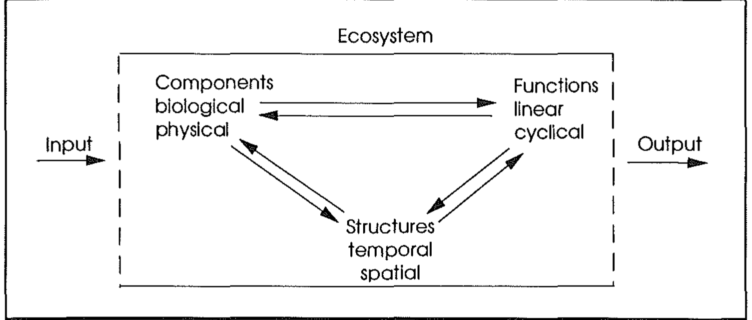
MARGALEFF (1969) and ARNDT (1981) point out that greater diversity is associated with greater stability. They add, however, that this is not a binding rule and that other factors, which they go on to list, also play a role. According to VARESCHI (1980) the degree of diversity depends primarily on site factors. That is, under constant "optimal" conditions, in which "many species can make the most of their reproductive potential", a system must by necessity develop a high level of diversity. If one of the site factors deviates from the optimum or dominates at the expense of the others, many species will be eliminated. In other words, a one-sided environment engenders a one-sided vegetation form.

Traditional rice ecosystems, reed ecosystems or mangrove forests appear to be exceptions to this rule. They are stable ecosystems or agro-ecosystems which, despite relatively constant environmental conditions, remain poor in species. However, on close scrutiny these frequently cited exceptions often prove to be only conditionally so. For one thing the presence of water works strongly against diversity in plant species. For another, the degree of diversity is not so low as might at first be thought. The genetic diversity (heterogeneity) *within* the species (land races, populations) contributes considerably to the stability of the system. This breaks down when the varieties that have evolved with the system are replaced by genetically uniform cultivars (for example, the rice variety IR 8). Finally, these systems appear monotonous when seen from the air, but a vastly greater variety of organisms exists beneath the surface of the water.

Year-round favorable conditions not only make greater variety possible but according to JANZEN (1973), they may even make it necessary. The diversity which at first appeared to VARESCHI as simply "given" turned out to be a consequence of functions in the ecosystem, such as the need to control pests (MARGALEFF 1969).

A third aspect of diversity arises out of how systems are structured. Many relationships in a system only occur if the components are ordered in a certain way. For example, half-shade occurs in an open, sparse arrangement of trees, whereas deep shade occurs only in a thicket-like arrangement. It is these three aspects and their interactions that together determine the nature of a system's diversity (Figure 3.1).

Figure 3.1. Composition of an ecosystem and the interrelationship of its basic elements



Source: Based on HART (1979)

Ecologically oriented agriculture is based on the hypotheses that diversity and stability are closely interlinked and that the local natural vegetation climax represents the optimum that can be achieved with regard to stability and productivity. In consequence, an effort is made to recognize the principles and structures of climax vegetations and to apply these in designing agricultural systems.[35] In the interests of sustainable production, the elements important to system stability should take first priority. As a second step, the system must then be modified with a view to achieving satisfactory productivity.

3.2.2 Ecosystem productivity

The argument against the idea of creating a farm vegetation like nature's own is that ecosystems with high diversity display very low productivity, whereas simple, "young" ecosystems are extremely productive (MARGALEFF 1969; in ARNDT 1981;

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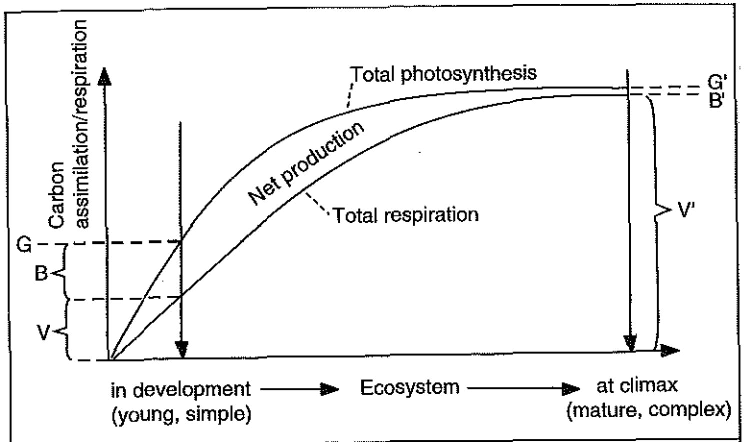
[35] These considerations do not rule out the possibility of altering the characteristics of a site, for example by draining, building terraces or irrigating. Such interventions are described by WISEMAN (in HARRISON and TURNER 1978) as "geo-intensive" measures, by analogy with "biologically" intensive measures. Geo-intensive measures have traditionally been used to alter the environmental characteristics of a site and so to change the type of plants that can be grown there.

see Table 3.1). Only in this context can the ecologist GIGON (1974) be understood when he writes: "The realization that climax ecosystems are not growth systems - although they do have a quite considerable net production - leads man to create simple ecosystems (e.g. wheat monocultures) since only simple systems are productive."

However, like beauty, productivity is in the eye of the beholder (see Figure 3.2). GIGON and others observe the ecosystem from the outside and find that the biomass growth in simple or young ecosystems is very high (called "net production" and marked "**B**" in Figure 3.2). This is the case because, of the total photosynthetic output (marked "**G**" in the figure) in a simple, developing stand (a half-grown maize field, for example), only a small portion (V) is exhaled again (old, dead leaves that are decomposed, i.e. exhaled, by micro-organisms). The net production (**B**) is then described as productivity.

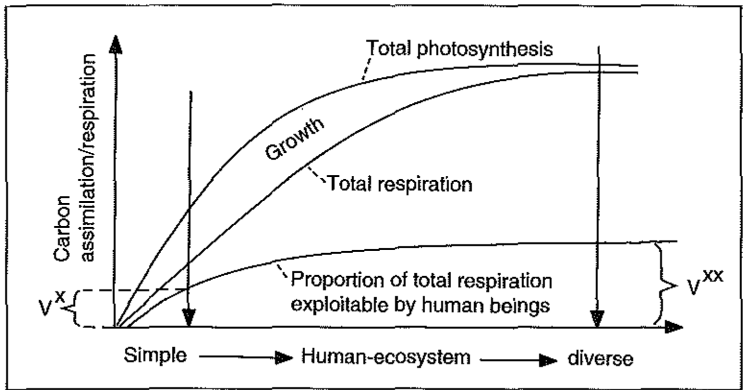
Figure 3.2. Production and exhalation in natural ecosystems of various types and ages



G, G': Total biomass production; B, B': Biomass increase; E, E': Exhalation

Source: Adapted from GIGON (1974)

Figure 3.3. Schematic diagram of ecosystem productivity showing the proportion (V) exploitable by human beings



V^x : Proportion in simple systems, V^{xx} Proportion in diverse systems

Source: MÜLLER-SÄMANN (1986)

The productivity of ecosystems looks completely different when we see ourselves not as an external observer but as part of the system, - the "human" ecosystem. From this standpoint man participates in exhaling the produced biomass, by consuming what he can in the form of food. The productivity of an ecosystem is no longer represented by the growth of biomass (net production) but rather by the proportion of total exhalation which people can directly or indirectly utilize.

If man can manage to achieve a vegetation which is like the natural climax but which is rich in plants that he can utilize, then it is wrong to contend that only simple systems are productive. On the contrary, it may be assumed that, because of their higher total photosynthetic performance, diversified systems are more productive than simple monocultures (providing the requirements for consistency, stability and sustainability can still be met)[36].

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[36] The influence of technology and labor on efficiency and productivity will not be considered at present.

The following sections will examine the contribution of agroforestry to sustainability and productivity in agro-ecosystems.

3.3 Examples of indigenous agroforestry systems

Research in the young field of agroforestry focused first on the study of existing production systems, many of which have been used for centuries. According to YOUNG (1989), there are probably more than a thousand different production systems with agroforestry components. A few examples are described below.

3.3.1 *Acacia albida* in semi-arid Africa

> "He who cripples an *Acacia albida* for no reason shall have an arm cut off, and whoever cuts down an *Acacia albida* without permission, he shall be beheaded".
>
> Decree of the Sultan of Zinder (Niger)[37]

Acacia albida is a relatively tall (15 - 20 meters) leguminous tree whose trunk can grow to more than a meter in diameter. It is found throughout Africa, from southern Algeria to the Transvaal and from Senegal to Somalia (MAYDELL 1981), mainly in semi-arid areas with annual rainfall between 400 and 900 mm and on deep, alluvial soils. It is a much valued tree in the fields and pastures of the Sahel, where the drastic punishments threatened by rulers such as the Sultan of Zinder may have helped to preserve it while other species succumbed to the charcoal burner's axe.

The tree is anti-cyclical, growing out of season. It drops its leaves at the beginning of the rains and first begins to bud when the growing period for crops is almost over. For this reason, it provides virtually no competition for water, light and nutrients, and crops can be planted right up to the base of its trunk.

POSCHEN (1986) reports a density of up to 10 trees per hectare on cropland (maize, millet) in the Hararghe highlands of Ethiopia. In Senegal, 50 to 60 trees per hectare is common (GIFFARD 1964). On their outlying fields, the Dagari of Burkina Faso cultivate a tree canopy consisting chiefly of *Parkia biglobosa* and *Butyrospermum parkii*, while on the land nearer home *Acacia albida*, pruned and tended to grow tall, forms dense stands.

The reason for the special regard shown for *Acacia albida* is its versatility. The tree's greatest virtue is its ability to improve the soil. Its leaves, falling at the beginning of the rainy season, supply the soil with nutrients and organic matter. As Table 3.2 shows, grain yields under the crown can be substantially higher than in the open field, with increases of between 36 and 178% noted in trials in Ethiopia and Senegal. Relative to the total area, a stand of 50-60 trees per hectare can increase yields by 50-100%.

Table 3.2. Grain yields inside and outside the crown overhang of *Acacia albida*

	Outside the crown overhang	Inside the crown overhang
Ethiopia*		
- Maize	1920 (100)	3390 (177)
- Sorghum	1570 (100)	2130 (136)
Senegal**		
- Millet	600 (100)	1669 (278)

* Hararghe Highland, Ethiopia, POSCHEN (1986)
** Sine Saloum, Senegal, CHARREAU and VIDAL (1965)

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[37] GIFFARD, P.L. (1964): Les possibilités de reboisement en *Acacia albida* au Sénégal.

Several factors explain these higher yields. The trials showed that soil organic matter, pH value, microbiological activity and cation exchange capacity, as well as the supply of macro-nutrients, were markedly higher under *Acacia albida* than on open land[38]. The deep taproot of *Acacia albida* means that nutrients from the deeper soil layers can be accessed. These are deposited on the soil surface when the leaves are shed. Thus the tree acts as a nutrient pump. Because the tree sends down such deep roots and grows anti-cyclically, competition with shallow-rooting agricultural crops is very slight. In addition, because the tree is a legume it fixes substantial amounts of atmospheric nitrogen. Finally, livestock provide future crops under the canopy with manure as, seeking shade, they graze beneath the trees during the dry season (MAYDELL 1981).

Acacia albida is known as an important fodder tree of the Sahel zone (MAYDELL 1981). Especially valuable are the fruits, which fall to the ground three months after flowering - that is, from about February to May, a critical feed supply period in the Sahel - and are eagerly eaten by livestock. In addition, the fruits store well and are often collected as a fodder reserve. Fully grown trees produce 120-140 kg of fruit per year, and very large trees considerably more[39]. A population of 10 trees per hectare produces an average of 1300 kg fruit, with a feed value of 1000 fodder units. This is the equivalent of about 1 tonne of barley. Thus the fruit alone substantially increases the carrying capacity of the land. Added to this are the leaves and young shoots, on which animals also enjoy feeding, either directly from the tree or from lopped off branches.

The wood of *Acacia albida* is normally used to make implements such as hoe handles, saddles and pestles. It is only occasionally used in construction. The bark is rich in tannin and rubber, like the resin, leaves and fruits, is used in a wide variety of ways to prepare traditional medicines. Soap is made from the wood ash and the flowers are good for honey.

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[38] See also Table 3.4.

[39] Measured in Bambey, Senegal; MAYDELL (1981).

In many parts of Africa, agroforestry with *Acacia albida* was and is an important "agrosylvopastoral" system, capable of increasing production on a sustainable basis. LEMAITRE (1954, cited in FELKER 1978) reports that the human population in villages with dense stands of *Acacia albida* is higher (25-40 inhabitants/km^2) than in villages with only a few trees (10-20 inhabitants/km^2).

3.3.2 The home gardens of Asia

Multi-story tree gardens or home gardens are widely found throughout the humid and subhumid parts of Asia, as for example in Sri Lanka, southern India, Vietnam, Indonesia and the Philippines (FERNANDEZ and NAIR 1986; NAIR and SREEDHAREN 1986; SOERMAWOTO et al. 1975; JACOB and ALLES 1987; etc). According to estimates by KARYONO (cited in CHRISTANTY 1981), home gardens comprise 17% of the land used for agriculture in Indonesia. In some villages in Java, their share is as high as 50% (MICHON 1983). Home gardens are less common, but still widespread in Africa and Latin America.

SOERMAWOTO et al. (1975), studying home gardens on the island of Java, see in them the result of a long evolutionary process which is still continuing: though having the same basic pattern, the gardens exhibit marked differences according to the socio-economic circumstances of a household and the physical environment, to both of which they continue to adapt. This man-made vegetation is similar to a forest in character and has only emerged in areas with a high population density, apparently in response to the need to use land more productively and with more regard for conserving resources than in traditional field-fallow farming (CHRISTANTY 1981).

As elsewhere in Asia, the home gardens of Java are part of a complex production system. They are often found in association with irrigated rice and rainfed agriculture. According to studies by TERRA (cited in CHRISTANTY 1981), the productivity of these gardens averages 3.5 million calories and 58 kg of protein per hectare. This is distinctly superior to dryland rice grown in rotation with a fallow[40]. Only wetland rice, with 5.2 million calories and 113 kg of protein per hectare, is more productive.

In home gardens, what appears at first glance to be wild disorder soon reveals itself as a cleverly conceived, highly productive cropping system, in which numerous different crop plants are grown close together. The diversity of the Javanese home garden is high and, according to studies by von KARYONO et al. (in CHRISTANTY 1981), the number of species is about the same as in the deciduous forests of central Florida or eastern Canada. Soil erosion in these gardens is very slight, despite the heavy rainfall characteristic of the island. SOERMAWOTO (1987) attributes this to the mulch layer made up of plant residues and leaf litter, which protects the underlying soils from the impact of large raindrops and encourages infiltration.

Perhaps the best example of a home garden is given by SIEBERT (1987), who investigated this system in the Philippines. The 828 m² garden represented in Figure 3.4 supplies a family of eight with vegetables, fruit and firewood. Some crops, such as tomato and chili, are also sold at market. The fruit and firewood trees (*Gliricidia sepium* and *Leucaena leucocephala*) serve as supports for climbing plants such as yams (*Dioscorea alata*), yam beans (*Pachyrrhizus erosus*), bitter melon (*Momordica charantia*) and various kinds of beans. All the space is used, resulting in an extremely productive, three-dimensional cropping structure.

SOMMERS (1978) also reports on the diversity of home gardens in the Philippines. In a study of 40 gardens in different provinces, the average cultivated area was 400-600 m². SOMMERS counted up to 40 different crop plants, and also observed the raising of smallstock. Composting was a further system component.

Similar cultivation systems in the tropical lowlands of East Nigeria were described by LAGEMANN (1981). Where high population densities had led to serious problems in maintaining the fertility of the predominant Ultisols, the local population had, as in Java, developed a complex multi-storied production system. Supplementary measures included applying animal manure (from goat keeping) and exporting as few nutrients as possible. Introducing the new farming system arrested and sometimes even reversed the decline in soil fertility. Yields on these sites were on average two to three times higher than on fields where cropping alternated with three-year periods of bush fallow (LAGEMANN 1981).

Figure 3.4. Home gardens in Buhi (Camarines Sur) in the Philippines

Useful plants:

Level 1 (0-0.6m):	Sweet potato, (*Ipomea batatas*); water spinach (*Ipomea aquatica*); Chinese cabbage (*Brassica chinensis*); paprika (*Capsicum frutescens*); squash (*Cucurbita maxima*); pineapple.
Level 2 (0.6-2m):	Black gram (*Phaseolus radiatus*); okra (*Hibiscus esculentus*; ginger (*Ziginber officinale*); aubergine (*Solanum melongena*); taro (*Colocasia esculentum*); tomato (*Lycopersicum esculentum*).
Level 3 (2-4m):	Cassava (*Manihot esculenta*); Sugar cane (*Saccharum officinale*); sweetsop (*Annona squamosa*); papaya (*Carica papaya*); abacá (*Musa textilis*).
Level 4 (4-8m):	Jackfruit (*Artocarpus heterophyllus*); soursop (*Annona muricata*); tamarind (*Tamarindus indica*); banana (*Musa* spp.); starfruit (*Averrhoa carambola*);
Level 5 (above 8m):	Star apple (*Chrysophyllum cainito*); pilo nut (*Canarium ovatum*); coconut palm *Cocos nucifera*);
Climbing plants:	Yam bean (*Pachyrrhizus erosus*); yams (*Dioscorea alata*); bitter melon (*Momorcardia charantia*); various beans.
Useful trees:	Quick stock (*Gliricidia sepium*); leucaena (*Leucaena leucocephala*.

Size of garden : 828 m²

Source: SIEBERT (1987)

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[40] The fuel and raw materials supplied are not taken into account.

3.3.3 Palm fallows in Benin

In Benin, on the Atlantic coast of West Africa, land use systems have changed drastically within just a few generations (FLOQUET 1990). Partly owing to population growth, but also to the establishment of large oil palm plantations by the state, smallholders have been confronted with an acute land shortage. Two generations ago, farmers left their fields fallow for seven- to eight-year periods following two to three years of cropping. As land became scarcer they conceded that "a three- to four-year fallow may be just sufficient, but it should be no shorter." Further pressure forced them to increase the ratio of the cropping period to the fallow period: they extended cropping from three to six years, while attempting to keep the three- to four-year fallow. But on many holdings the process of curtailing the fallow has continued, with some farms now practising permanent crop cultivation. This often leads to invasion by grasses such as *Imperata cylindrica* and andropogon, especially on soils with a poor nutrient supply. Cropping can still be carried out on the more fertile soils, but at very low yield levels.

Farmers were well aware of the need to maintain soil fertility and experimented with a whole range of approaches. One of these could be called the "palm fallow". In this approach the spontaneous spread of oil palm seedlings is developed into a systematic form of land use. For a period of three to four years, small palm plants are encouraged and sometimes transplanted to achieve an even stand. When the field is abandoned, a mixed vegetation of bush fallow and oil palms develops. The fields exhibit a wide range of intensity levels - one may be densely cultivated with palm, another only sparsely. The maximum density is about 600 saplings per hectare. The oil palms are grown for palm wine and for schnapps, the production of which starts when the trees reach six to seven years old (i.e. after three years of fallow). The "wine palm" is a medium-term capital investment for the farm. It is felled only when cash is required. Because the yield of palm juice increases with the age of the tree (up to about the fourteenth year), the system remains highly profitable. With this system, fallow periods that serve to regenerate the soil can be economically useful "on the side", with both benefits increasing over time.

3.4 Ecological effects of agroforestry systems

Competition, complementarity and synergism. Fearing competition between the plants for light, water and nutrients, many experts at first rejected the idea of combining different species of plants, whether in intercropping or agroforestry systems, promoting monocropping instead.

Competition still exists between plants[41] of the same species if they are planted too closely together, as is the case with many cultivated crops grown in monoculture. It is important to recognize that, besides the inhibitory effects of competition, there are also complementary and even synergistic effects, which may improve the use of growth factors and can thus increase the productivity of a field. For a long time such effects were ignored or not taken adequately into account. It is now known that the inhibiting effects are smaller and the positive effects greater than was previously assumed. Research during the 1980s has shown that mixed cropping systems often produce higher yields than monocultures. The key to developing productive agroforestry systems is to arrange all of the vegetation elements in such a way as to minimize competition and encourage synergism. For this reason we speak of "vegetation design".

These effects together form a complex feedback control system in which individual effects are difficult to isolate and measure through empirical research. Hence our discussion of these effects must be mainly theoretical. The most important areas in which competition, complementarity and synergism occur in agroforestry systems concern plant responses to light and temperature conditions - the essential factors in the climate of a stand - as well as water and nutrients in the soil.

Besides the immediate effects of a cropping system on stand climate, nutrient status and water relations, the long-term influence on soil fertility, structure and stability must be considered.

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[41] A distinction is made between intraspecific competition, which is between plants of the same species, and interspecific competition, between plants of different species.

3.4.1 Stand climate

The climate of agroforestry stands differs, sometimes considerably, from that of pure stands. Differences in insolation, temperature and relative humidity can lead to favorable or unfavorable growing conditions. In contrast, changes in the CO_2 economy can be largely ignored (SUKACHEV and DYLIS 1964).

Insolation. Multi-story stands of plants with varying crown structures make better use of available sunlight. This is especially true of home gardens (OKIGBO and GREENLAND 1976; OKIGBO 1980; MICHON 1983). At the same time, however, lack of sunlight can constitute a limiting factor for plant growth at the lower levels. Photosynthetic efficiency declines, causing among other disadvantages, poor root growth. This in turn means that plants cannot make effective use of nutrients and water in the soil (DONALD 1958). Moreover, in legumes the formation of bacteria on the nodules, and hence nitrogen assimilation, is reduced. Excessive growth of stem tissue (etiolation) and the consequent weakening of these tissues increases the plant's susceptibility to fungal infections.

Lack of light has a different effect on different plant species. According to MONTEITH (1972), C4 plants such as maize, bulrush millet, and grasses respond mainly in a linear manner to the supply of light. The more light they receive, the better their performance. They are classed as "light-demanding", and in an agroforestry crop require the positions with the most sunlight. Other plants, on the other hand, are satisfied with less than full radiation intensity and are classed as "shade-tolerant". Numerous tubers, including cassava, *Dioscorea spp.* and *Colocasia spp.*, and several tropical legumes fall into this category (MOTT and POPENOE 1977). A third important group embraces plants that actually profit from shade. Coffee plants, for example, develop better in half-shade (HUXLEY 1967), and cardamon, vanilla and pepper are known as shade-loving plants. These different responses can be accommodated by assigning plants to "their places" in the cropping system. Declines in yield due to light blockage can be kept to a minimum in this way.

To increase the availability of light in an agroforestry stand, it is crucial to choose suitable trees and arrange them effectively. Trees with open crowns that allow light through are particularly suitable. This characteristic is essentially determined by the nature of the leaves. Broad, horizontal leaves produce deep shade, while small, narrow, slanting, pinnate leaves produce more light areas, with some dense shade and a high proportion of penumbra shade. Legumes such as *Sesbania grandiflora*, *Prosopis* spp., *Cassia* spp. and *Leucaena* ssp. are therefore especially appropriate. Less dense crowns, dappled shade and a high proportion of light areas provide the lower stories with more light.

Another important factor is the distance of the crown from the ground. The higher the crown, the stronger is the lateral incoming light, as NAIR (1979) noted in his study of coconut palms. As trees increase in age the height and size of the crowns change. Lateral insolation increases, but so also does the shadow density of the crown.

Several authors (DHILLON et al. 1979; SCHWANK 1982; HADFIELD 1984) advise orienting rows of trees along an east-west axis so as to supply the lower stories with as much even sunlight as possible for the entire day. As regards the selection and arrangement of crops in the lower stories, these authors also recommend that plants that demand more light (see above) be planted in the spaces where the most sunlight comes through, whereas shade-tolerant species can grow closer to the tall trees.

It is also important to determine what density of trees is optimal for a stand. This depends on the species and age composition of the trees. For example, in the Nyabisindu region of Rwanda, NEUMANN and PIETROWICZ (1986) recommend 250-350 *Grevillea robusta* trees per hectare, with a rotation period of 9-10 years; the result is a 20-30% crown coverage. This value can of course serve only as a rough estimate. When advising farmers, local variations in site factors must be taken into account. The water supply, elevation, temperature, type of undergrowth etc can all contribute substantially to different recommendations.

Careful tending of the trees is indispensable. The branches must be thinned out to produce good stem timber. Thinning the crown and the surface roots reduces the competition between an individual tree and the undergrowth. Regular tending makes it possible to grow twice as many *Grevillea robusta* trees in a stand while still maintaining the level of yields from the understory. At the same time, tending operations usually provide the first production a farmer receives from his tree crop (NEUMANN and PIETROWICZ 1986).

Temperature and relative humidity. The shade cast from trees and shrubs alters the temperature both at the soil surface and in the undergrowth. Excessive heat during the noon hours and too great a heat loss during the night are both avoided. In other words, maximum and minimum temperatures are less extreme. This benefits the status of humus by reducing its decomposition through mineralization. In addition, lower temperatures induce higher relative humidity. The trees create a climate in which the transpiration pressure on crops falls, permitting more productive use of scarce water.[42] NEUMANN and PIETROWICZ observed in Rwanda that in open fields on clear, sunny, hot days crops already showed signs of wilting by late morning. In contrast, this phenomenon was not observed in plants shaded by trees. In open fields, photosynthesis is often suspended around noon due to heat and lack of water.

Thus two opposing forces are at work: reduced sunlight under the trees may limit photosynthesis, but lower temperatures and higher relative humidity occasionally bring about the opposite effect. The object is to achieve a positive balance.

The **protection from the wind** that trees provide can markedly improve the climate of a stand and ease soil water conditions. Studies on the effects of windbreaks in semi-arid climates confirm this. While temperature extremes on the sheltered side of a windbreak are more pronounced, relative humidity is also usually higher, because of the decreased air movement (ROSENBERG et al. 1983; GUYOT 1986). Higher relative humidity reduces evaporation from the soil and transpiration from the plants (NÄGELI 1943). This is especially true for places with strong winds. ROSENBERG et al. (1983) estimate the reduction in evapotranspiration through wind protection in semi-arid locations as 20%. This does not necessarily mean that soil moisture

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[42] If potential evapotranspiration exceeds the supply of water, plants close their stomata, cutting off the exchange of gases. The longer this interruption lasts, the more severely photosynthesis is hindered. C4 plants are less affected than are C3 plants.

increases or that plants transpire less, but it does allow plants to utilize water more economically, increasing their photosynthetic performance per unit of water. GUYOT (1986) holds that reducing evaporation through wind protection has a yield-increasing effect in subhumid and semi-arid locations, but not in humid locations.

3.4.2 Effects on soils

Mobilization of nutrients from the soil substrata. Trees and shrubs are mostly deep-rooting plants. A part of their root system extends down into the B/C or even into the C horizon - depths that few annual crop plants are able to reach. Organic root acid excreted in the deeper soil layers promotes the disintegration of parent rock and assimilates liberated nutrients, especially potassium, phosphorus, calcium and magnesium, as well as trace elements. Deep roots are also capable of reabsorbing nutrients that have been washed down to the lower strata from the upper soil layers. For example, for a 40-year-old secondary forest in Kade, Ghana[43], NYE and GREENLAND (1960) calculated that 20% of the assimilated nutrients were "pumped up" from soil horizons below 30 cm. This constituted 40 kg N, 6.4 kg P_2O_5, 58 kg K, 62 kg Ca, and 12 kg Mg per hectare per year. The authors assumed a similar level for young fallows, providing root systems and tree crowns were properly developed. Considerable amounts of nutrients can thus be mobilized from otherwise untapped soil horizons. However, smaller proportions must be expected in agroforestry systems, because tree/shrub stands are less dense.

This nutrient "gain", at first fixed in the tree biomass, eventually enriches the upper soil, where annual crops grow. Here the leaf litter plays a significant role, especially during the establishment phase of agroforestry systems. Dying organic matter is mineralized; the nutrients thus released pass into the humic matter, where they may or may not become fixed, and are thus directly or indirectly available to annual crop plants. This nutrient enrichment in the upper soil has been studied by a number of authors. A favorite method is to analyze the soil at various distances from a particular tree. Two examples will be discussed here.

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[43] Approximately 1700 mm annual rainfall.

On a cocoa plantation ("low-humic gley") in a humid location in Bahia, Brazil, CADIMA and ALVIM (1967) analyzed the soil chemistry within an area influenced by a shade tree, *Erythrina fusca*. As Table 3.3 shows, they found higher levels of cations and organic matter. This has a positive influence on base saturation and cation exchange capacity (CEC), meaning that more nutrients are available and the capacity of the upper soil to absorb nutrients is improved.

Table 3.3. Soil chemistry of topsoil (0-20 cm) at various distances from *Erythrina fusca*, a shade tree, on a cocoa plantation in Brazil

Distance from trunk	pH	C (%)	N (%)	Ca (mg/ 100g)	Mg (mg/ 100g)	K (mg/ 100g)	CEC (meq/ 100g)	Base saturation (%)
2.5 meters	4.8	1.25	0.147	4.03	2.17	0.28	11.86	58.0
8.4 meters	4.7	0.91	0.115	2.57	1.47	0.11	9.48	46.8

* The age of the trees was not given.

Source: CADIMA and ALVIM (1967), p. 367

At a semi-arid site in Senegal, CHARREAU and VIDAL (1965) investigated the effect of *Acacia albida* on the soil and arrived at similar results (Table 3.4). These relationships were confirmed in numerous further studies[44].

Nitrogen assimilation. The assimilation of atmospheric nitrogen can be substantially increased through agroforestry, especially when the system includes leguminous trees or shrubs. The findings of CHARREAU and VIDAL (Table 3.4) demonstrate this particularly well. The quantity of nitrogen gained through the presence of an upper tree story or hedges depends on many factors, including the site, the species used, management practices, etc). YOUNG (1989) reckons that a productive agroforestry system should gain in the order of 50-100 kg N per hectare per year.

Table 3.4. Soil chemistry of topsoil (0-20cm) at various distances from 30-year-old *Acacia albida* trees on a millet field in Senegal

Distance from trunk	pH	C (%)	N (%)	P_2O_5 total (ppm)	CEC (meq/100g)	Base saturation (%)
0-5 meters	6.50	5.32	0.60	190	4.13	100
5 meters to edge of crown	6.34	4.80	0.52	147	3.69	96
Outside tree crown	6.14	3.29	0.31	148	2.81	80

Site: Weakly lessivated sand

Source: CHARREAU and VIDAL (1965)

Effect on soil acidity (pH). In principle, trees and shrubs can reduce the acidifying effects of leaching, as is apparent in the trial results given in Tables 3.3 and 3.4, although usually their influence is not significant. YOUNG (1989) writes: "...Whether tree litter can be a significant means of raising pH on acid soils is doubtful, owing to the orders of magnitude involved, except through the release of bases that have been accumulated during many years of tree growth, as in forest clearance or the *chitemene* system of shifting cultivation. (...) The situation is different with respect to checking acidification. In the first place, if the tree component is employed as the means for fertility maintenance, then no tendency towards acidification should arise. Secondly, where fertilizers lead to a trend towards acidification, this is of the order of 0.1 pH points per year. The recycling of bases in tree litter could quite probably be sufficient to counteract an effect of this magnitude."

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[44] See especially the work of AGGARWAL (1980) with *Prosopis spp.* in northern India, and of RADWANSKI and WICKENS (1981) with *Azadirachta indica* in the dry savanna of northern Nigeria, as well as studies by RACHIE and ROBERTS (1974), GERAKIS & TSANGARAKIS (1970), COMBE (1979) and HESMER (1970).

Trees can also succeed in **reducing salinity and sodicity** and can contribute towards making saline and alkaline soils arable. GILL and ABROL (1986) and GREWAL and ABROL (1986), for example, report the results of trials in Karnal, India, with the tree species *Acacia nilotica* and *Eucalyptus tereticornis,* in which the pH was reduced from 10.5 to 9.5 and electrical conductivity from 4 to 2.[45]

Effect on humus status. At least as important as renewing the nutrients in the upper soil is the regeneration of the humus content through the addition of organic matter. A decisive question here is whether or not enough biomass is produced to maintain the soil humus content of a site at a productive level. To answer this question, YOUNG (1989) suggests the use of a relatively simple formula based on the following assumptions:

- **Reference quantity** is the surface soil (0-15 cm);
- **Desired content of organic matter** is assumed to be 4 percent, 2 percent and 1 percent for humid, subhumid and semi-arid sites respectively. This represents a carbon content of about 2%, 1% and 0.5%, or calculated at absolute values: 30,000, 15,000 and 7,500 kg C/ha.
- The loss through oxidation is based on an average **humus decomposition rate** of 4% per year, although it must be taken into account that the decomposition rate on new cropland is considerably higher and can lie far below this level on severely degraded soils.
- For the **loss of C through erosion**, a yearly soil removal of 10 t/ha is assumed - an order of magnitude still within tolerable limits and very widespread. As this loss of soil only affects the top layer, the affected C-content is assumed to be twice as high as in the entire 0-15 cm horizon.
- The **total amount of C lost** through oxidation and erosion is reckoned as the amount of soil humus that must be rebuilt by the addition of organic matter.
- To calculate the required **amount of biomass**, it is assumed that roots may be estimated at 40% of the net above-ground biomass production. The losses incurred in converting the organic matter into humus are estimated at 85% for the above-ground plant parts and at 67% for the roots.

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[45] Gypsum and manure were applied when the trees were planted.

- The dry weight is estimated at a fixed 50% and the result rounded upward or downward to the nearest 100 kg/ha.

The results are set out in Table 3.5. These calculations produce the following orders of magnitude for the dry weight per hectare per year that must be produced and added to the soil to maintain the humus content at a constant level: in the humid tropics, 8,400 kg; under subhumid conditions, 4,200; and at semi-arid locations, 2,100 kg. These figures are of course only rough estimates, but provide useful guidance when the data base is small. In addition, YOUNG and MURAYA (1990) offer the computer program SCUAF (Soil Changes Under Agroforestry), with which the contents of organic matter can be determined more precisely.

Table 3.5. Indicative plant biomass requirements for maintenance of soil organic matter

	Humid zone	Subhumid zone	Semi-arid zone
Initial topsoil carbon (kg C/ha)	30,000	15,000	7,500
Initial topsoil carbon (%)	2.0	1.0	0.5
Oxidation loss (kg C/ha/yr)	1,200	600	300
Erosion loss (kg C/ha/yr)	400	200	100
Required addition to soil humus (kg C/ha/yr)	1,600	800	400
Required plant residues added to soil (kg DM/ha/yr)			
* above ground	8,400	4,200	2,100
* roots	5,800	2,900	1,400

Source: YOUNG (1989)

There have been few studies, using either models or field data to estimate or measure the net primary biomass production of whole agroforestry systems. Consequently, the question posed above - "Is the biomass production sufficient?" - can only be answered for a few cases.

The best studied production systems in humid locations have been permanent crops of coffee and cocoa combined with shade trees. Of special interest here are those trees that produce a lot of leaf litter. Inga species, for example, produce from 5 to 8 t dry matter (DM) per hectare per year of nitrogen-rich leaf litter (JIMENEZ and MARTINEZ 1979, see Table 3.6)[46]. This is sufficient to meet YOUNG's estimated requirement of 8,400 kg DM per hectare per year for the regeneration of humus. Further studies by GLOVER and BEER (1986), RUSSO and BUDOWSKI (1986), ALPIZAR et al. (1986 and 1988) confirm these findings or arrive at even more favorable results.

Table 3.6. Annual production of litter in different agroforestry production systems in Coatepec, Mexico (kg DM/ha/year)

	System			
	Coffee, Inga, Musa	Soil flora, Coffee, Inga	Soil flora, Coffee, Inga	Soil flora, Coffee
Soil flora	-	143	2600	3963
Coffea arabica	1104	1380	1527	2079
Inga sp.	4918			
Inga inicuil		6857		
Inga leptoloba			8348	
Musa sp.	4227			
Total	10249	8380	9475	6042

Source: JIMENEZ and MARTINEZ (1979)

At subhumid sites alley cropping[47] systems were studied, especially at IITA in Nigeria (WEERAKON 1983; KANG et al. 1985; YAMOAH et al. 1986; BAHIRU DUGUMA et al. 1988). The above-ground biomass produced by the shrubs used, *Leucaena leucocephala, Gliricidia sepium, Sesbania grandiflora* and *Cassia siamea*, is considerable: 3,000 to 8,000 kg DM/ha/year. However it must be borne in mind that the trial conditions differ widely from the real-life situation of the smallholder in several ways:

* In most of the trials, substantial amounts of P and K fertilizers were applied.

* In field trials, the hedges supplying the biomass took up 15-25% of the area. The amount of labor required to prune them regularly is high, and the work must be carried out during peak periods (when the fields are being prepared for sowing). For these reasons this model of alley cropping, with the large area it requires for the shrubs, has not been widely adapted by smallholders (see also Section 3.6).

A further issue is important in assessing the effects of agroforestry systems on humus: trees and bushes are not planted solely to enhance but must also meet other needs, such as the supply of livestock fodder or firewood. These and other possible uses subtract from the amount of biomass available for humus regeneration. In many situations demand of this kind probably exceeds supply.

The effects of trees and bushes on soil physical properties are obvious, yet studies to quantify these effects in agroforestry systems are entirely lacking. It is assumed that the breakdown of organic matter strengthens soil structure[48] and that the pore volume increases, with the result that the infiltration rate, field capacity and amount of water available to plants are probably much higher than in production systems without an agroforestry component. As well as improving water conditions, better soil structure helps prevent erosion.

Also still unexplored are the effects on soil biological properties. Shade and mulch improve moisture and temperature conditions at the soil surface, while mulch and leaf

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[46] On coffee plantations in India, the litter from these trees provides 134 kg N, 78 kg P_2O_5 and 22 kg K_2O per hectare per year (NWOBOSHI 1981).

[47] Also known as "hedge-row intercropping". See also Chapter 3.5.3.

[48] Products of metabolism (mucin) from micro-organisms bind inorganic particles together; fungal mycelia result in living structures.

litter offer the necessary nutritional basis for active soil flora and fauna. This in turn influences the humification process, nitrogen assimilation and the availability of nutrients. There is no doubt that all of these effects are positive, but empirical values are not known.

3.5 Technology development: Three examples

3.5.1 Niger: Windbreaks in semi-arid areas

The site. The Majjia Valley is about 4 km wide and lies at an elevation of 300 to 400 m. Annual rainfall is 400-600 mm, compared with potential evaporation of about 2,200 mm. With donor support, the Niger forestry service planted 500 ha of windbreaks consisting of neem trees (*Azadirachta indica*) in the valley between 1975 and 1988.

The technology. The neem trees were planted in double rows at a distance of 4 m apart. The windbreaks are 120 m apart and reach a height of 7-10 m and a width of 8 m. During the first three years the trees must be protected from browsing livestock browsing.[49] The first harvest (lopping of the crown) is possible after 8 to 10 years. Thereafter the trees can be harvested at 4-year intervals. It is recommended that every year one tree out of four be used. The trees are cut above the reach of goats and cattle, so as to protect new shoots.

Effects on crop growing. The first measurements of crop yields between windbreaks were carried out by BOGNETTEAU-VERLINDEN (1980). Selected results are shown in Table 3.7. Millet yields with wind protection are definitely higher than in open fields without windbreaks. The yield starts to increase some 35 m behind the windbreak, rising to 156% and then falling to 122-129% towards the next windbreak. Similar yield patterns are reported elsewhere, for example by SHEIKH 1983. Taking into account the loss of land, BOGNETTEAU-VERLINDEN calculated an average yield increase of 23%.[50] Smaller increases were calculated in studies conducted in subsequent years, however (RORISON and DENNISON 1986).

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[49] During the first 2-3 years, the newly established windbreaks were guarded by the Nigerian forestry service. Stray animals were caught and only returned to their owners on payment of a fine.

BOGNETTEAU-VERLINDEN reported that wind speed was lowest where millet yields were highest. The hypothesis is that reduced wind movement lowers the saturation deficit of the air. The pressure on the plants to transpire and the evaporation from the soil are thus decreased, and more productive use is made of scarce water.

While there are gains to be had from an improved microclimate, these may be offset by losses due to lost cropland and shade cast on the edges of fields. Root competition appeared to be of little significance, although neem roots could still be found at a distance of 5 m from the trees.

Table 3.7. The influence of windbreaks on microclimate and millet yields (kg/ha) in Majjia Valley, Niger 1979

	Without windbreak	Distance behind windbreak (m)				
		7	35	60	84	112
Relative wind velocity (%)	100	78	47	60	72	63
Millet yield (kg/ha)	854	1106	1332	1043	1070	944
(%)	100	130	156	122	125	129

Windbreaks: 120 m apart, 8 m wide, planted with neem 4 x 4 m, 7 m high.
Location: Garadome, 450 mm mean annual rainfall

Source: BOGNETTEAU-VERLINDEN (1980)

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[50] At a planting distance of 120 m between windbreaks, trees that are not cut occupy 17.4% of the total area; lopped trees take up 6%.

Wood production. The wood harvest proved to be the main benefit from the windbreaks. According to KERKHOF (1990), nearly 450 poles and 13m^3 of firewood can be obtained from one km of the windbreaks in a 4-year utilization cycle.

Evaluation of the project. As the results given above indicate, the project was successful from both an agronomic and an economic point of view. However, dependence on a single species of tree is ecologically risky. Many species of acacia would have been equally suitable. And experience elsewhere shows that effective protection from the wind can be achieved from individual trees scattered over the field.

According to the results of a survey conducted by DELAHANTY et al. (1985), the local population felt that the windbreaks were useful, but thought of them as the property of the Niger forestry service and did not identify with the project.[51] It was therefore unclear how and by whom the trees were to be utilized. The local people complained that the windbreaks did not conform to traditional field borders and that they had had no opportunity to participate in planning and establishing the windbreaks. They also said that excluding livestock from the fields had had a negative impact, especially on Hausa women. On the other hand, the additional supplies of fodder (increased millet straw and neem leaves) were appreciated.

The Niger forestry service is now offering only planting materials and advisory services. Based on a contract between the forestry service and each village involved, which clearly states the inputs and the tasks of both parties, it is hoped that the windbreak technology will spread spontaneously from now on.

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[51] Only 2% regarded the windbreaks as their own property.

3.5.2 Rwanda: Contour planting in tropical mountain areas

The site. For many years now, a Rwandan-German project has been developing agroforestry technologies in Nyabisindu, Rwanda.[52] The project area lies in the southern part of Central Rwanda.[53] The altitude ranges from ca 1400 m in the east to 1900 m in the west, and the annual mean temperature from 16° to 20° C. The average rainfall (divided over two rainy seasons) increases with elevation from 1050 to 1400 mm/year.

The technology. In many mountainous areas of the tropics, trees and shrubs are planted along the contour line, often in combination with grasses and other cover plants, which may include crops. This principle is illustrated in Figure 3.5. The strips confine the area over which soil moves to the areas between them, leading eventually to the formation of terraces. Contour strips help protect the soil from erosion, improve soil fertility and generate extra income. They are generally 1-2 m wide. The distance between them depends on the slope: the steeper the slope, the closer together they must be if they are to ensure efficient protection against erosion. The width of the strips should also increase with the steepness of the slope.

In Nyabisindu, *Grevillea robusta* proved particularly suitable for use in such contour strips. This tree grows quickly, developing a straight trunk with few branches. For the favorable conditions of trial fields, NEUMANN and PIETROWICZ (1986) recommend a planting density of 400-600 trees/ha with a rotation period of 9-10 years and a stand density of 250-350 trees/ha.[54] They calculate that this will produce a crown cover of about 20-30%.

Wood production. What contribution does the wood crop make to the self-sufficiency or income of a farm? NEUMANN and PIETROWICZ (1986) carried out extensive measurements on two trial fields laid out in 1976 in Gasoro and Gihisi. (Only here did

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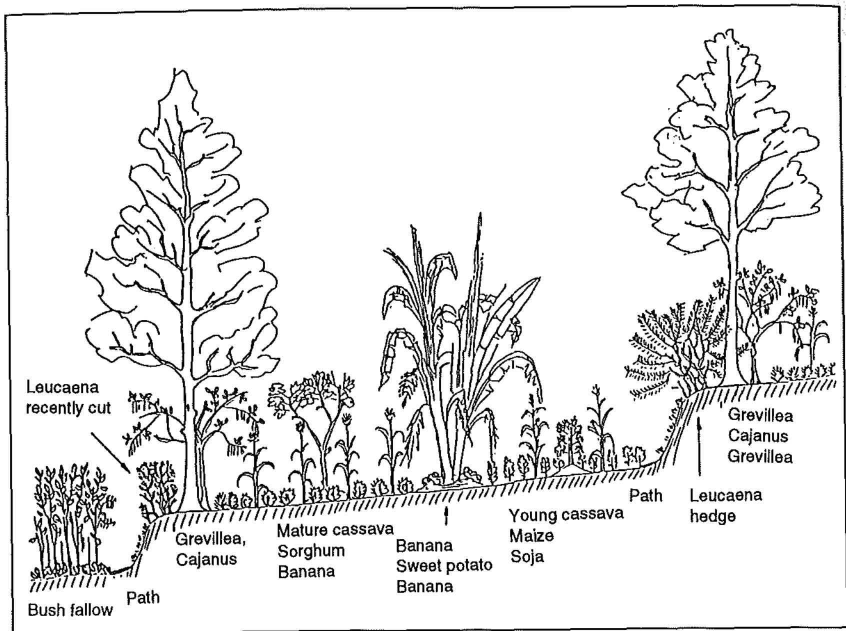
[52] The Project Agropastoral de Nyabisindu (PAP).

[53] Agrar-ecological zone "Dorsale Granitique", as well as parts of the "Mayaga" and the southern "Plateau Central".

[54] The distance between strips is 10 m. Strips 1m in width take up 10% of the trial area.

trees exist of sufficient age in 1980-85.) They examined many individual trees, recording height, diameter at breast height and productive growth based on leaf, branch and wood yield from the trunk.

Figure 3.5. Terrace formation and anchoring the edges of terraces with trees



Source: KLAER and EGGER (1984)

As might be expected, local site factors, especially soil quality, had a decided influence on tree growth. Surprisingly, however, crop cultivation almost always had a positive effect, especially on marginal soils. Up to 400% higher growth was recorded when *Grevillea* was planted with cassava than when it was planted in pasture, and the survival rate of the young trees was twice as high. Regular cultivation of the soils, weed control and better aeration were the factors responsible.

Table 3.8 indicates the development and production of five- to six-year old *Grevillea robusta* on the two trial fields. In Gasoro, tree density was 280 trees per hectare, about one third of these being *Leucaena leucocephala* and *Cedrela odorata*. The lower story consisted of food crops rotated with green manure. In Gihisi, tree density was 500 *Grevillea* per hectare. The trees had been planted in mulched coffee fields. Almost the same yield was obtained at the two locations, suggesting that density does not greatly influence yields while the trees are young. The differences in yields of branch wood can be explained by the fact that in Gasoro branches had been trimmed back just before the measurements were made. Yields at both locations were extremely high. The annual yield per hectare for Gihisi came to about 9 m^3 of timber, 8.7 t of fresh branch wood and 2.6 t of fresh leaves. Given the degraded state of the trial sites at the time of planting, similar yields may be expected from smallholdings.

Table 3.8. Development and production of five to six-year-old *Grevillea robusta*

Tree density	280 trees/ha	500 trees/ha
Site	Gasoro	Gihisi
Average height (m)	11.5	11.5
Leaves (kg DM/tree)	33.0	32.0
Branches (kg DM/tree)	45.0	105.0
Trunk wood (m^3/tree)	0.12	0.11

Source: NEUMANN and PIETROWICZ (1986)

PREISSLER and BENNET (1987) also estimated the yields of natural products from a six-year and a nine-year harvesting cycle (Table 3.9)[55]. Lengthening the cycle from six to nine years more than doubles the biomass. Based on these findings, a rotation

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[55] The tree densities are consistent with advisory service recommendations and are calculated so that shade from the trees does not hinder the growth of the understory crops. However this is only possible if rigorous pruning of the crown and regular cutting of the roots is carried out.

cycle of nine years is recommended as optimal for *Grevillea robusta*. At a density of 360 trees per hectare, 39 trees are thus felled annually and replaced by new plants. Wood yields can be increased considerably, however, if a number of especially well developed trees are left standing beyond the nine-year cycle as "survivors" and then sold at the age of 20-25 years as wood for furniture. At this age each tree produces approximately 0.8 m^3 of trunk wood. In order not to obstruct the undercrop, no more than five "survivors" per hectare should be left standing (NEUMANN and PIETROWICZ 1986).

Table 3.9. Yield from strips planted with *Grevillea robusta* in six- and nine-year rotation cycles

Harvesting cycle	6-year cycle 420 trees/ha	9-year cycle 360 trees/ha
Leaves (kg DM/ha)	2380	4400
Branch wood (kg DM/ha)	4760	8800
Trunk wood (m^3/ha)	ca. 4.2	ca. 9.0

Source: PREISSLER and BENNET (1987), extrapolated from NEUMANN and PIETROWICZ (1986).

Effects on undercrops. In a field trial lasting two-and-a-half years (1981-83), the effects of trees on the crops growing beneath them was investigated. Following this study, the performance of the new production system as a whole was assessed. The "control" (Variant A) was an open field, representing the "traditional" production system. Variant B was a field with *Grevillea robusta* trees planted 10 meters apart in rows along the contour lines. The density was 550 trees/ha, but only 250 trees were over 4 years old and could be considered to have an influence on the undercrops. Table 3.10 summarizes the treatments.

Table 3.10. Outline of the Agroforestry Nyabisindu field trial

Treatment	A:	Without trees
	B:	With 250 trees/ha (*Grevillea robusta*)
Repetition	Three (planting years)	
Sequence	Year 1:	Green manuring (*Tephrosia, Crotalaria*, pigeonpea)
	Year 2:	Long season: maize/soybean/sweet potato short season: maize/beans
	Year 3:	As Year 2, with the addition of 20 t/ha of manure

Source: NEUMANN and PIETROWICZ (1986)

Although the field crops in Variant B were planted right up to the trunks of the trees, a survey determined that 10% of the cropland was lost to the rows of trees. The yield values were therefore multiplied by 0.9 to avoid misleading results.

The results are shown in Table 3.11. Despite the loss of area taken up by the rows of trees, almost all the crops in the agroforestry system produced higher yields - as much as 25% higher in the case of sweet potato. Soybean suffered a considerable drop in yield, probably owing to its sensitivity to shade. Differences in straw and leaf yields were less pronounced, but followed the same trend. The trees appeared to make little difference to the yields of green manure, but weed development without the trees was definitely less.

The yield from the trees added considerably to the production performance of Variant B. From a stand of 250 trees per hectare, an annual yield per hectare of 5.9 m^3 of trunk wood 3.8 t of branches and 2.1 t of leaves can be obtained over a nine-year rotation period. If firewood consumption is 1 m^3 per person per year, this would be enough firewood for 10 people.[56] No significant differences between the two variants could be found for soil moisture.

Table 3.11. The effect of trees on crop and green manure yields and on weed development in the field (Nyabisindu,Rwanda)

Treatment	A Without trees	B 250 trees/ha		Significance
Maize (kg/ha)	1,204	1,328	(+10%)	0.01
Beans (kg/ha)	798	797		----
Soybean (kg/ha)	312	220	(-30%)	0.05
Sweet potato (kg/ha)	2,439	3,038	(+29%)	0.05
Green manure (kg DM/ha)	14,560	13,742	(-6%)	0.05
Weeds (kg DM/ha)	1,679	1,985	(+18%)	0.05
Trunk wood (m^3/ha)	-----	5.9		----
Branch wood (kg/ha)	-----	4,800		----
Leaves (kg/ha)	-----	2,100		----

* A loss of 10% of crop area was assumed for the strip of trees; yields from the field crops were therefore multiplied by a factor of 0.9.

Source: KOTSCHI (1987), adapted from NEUMANN and PIETROWICZ (1986)

Protection against erosion. Recent studies (KÖNIG 1990 and ISAR 1989) provide information on the erosion-reducing effects of contour strips. In traditional farming, soil losses are in the order of 100 to 300 kg/ha/year. Establishing contour strips in the project area reduced these levels to 10-15 t/ha per year in just three years (Table 3.12).

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[56] According to data from PREISSLER (1985); NEUMANN and PIETROWICZ (1986) determined that 1050 kg of fresh branches represents 1m^3 of solid wood. The values given here are for fresh weight. To calculate the dry weight of leaves and branches, multiply by 0.50 and 0.65 respectively.

Table 3.12. Soil removal (t/ha per year) in the project area with and without contour strips

	No erosion protection (%)	Contour strips with *Grevillea* and *Calliandra* (%)
Butare 87/88-89/90* (Slope gradient 28%)	290 (100)	12 (4.2)
		Contour strips with *Setaria* and *Sesbania*
Rubona 1988/89**	(100)	(68)
		Contour strips *Calliandra* and *Setaria*
Nyarutovu 1988/89**	119 (100)	12 (10)

Sources: * KÖNIG (1990), ** ISAR (1989)

Adoption. The number of trees in the Nyabisindu Region of Rwanda has increased considerably in the past 15 years. Planting *Grevillea* trees in erosion protection strips has become common, as has their distribution as single trees in fields.

3.5.3 Sri Lanka: Alley cropping in humid locations

The site. Alley cropping[57] was investigated in the Anurhadapura and Kurunegala Districts of Sri Lanka's hilly central region. Here 1200 to 2000 mm of annual rainfall is distributed over two rainy seasons.[58] The non-irrigable areas have been farmed for

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[57] Also known as "hedgerow intercropping".

[58] The long rainy season, *Maha*, begins in October and lasts to the end of January; the short rainy season, *Yala*, extends from the end of March to the end of May.

many generations under a slash-and-burn shifting cultivation system. Because of increasing population pressure, fallow periods, once lasting 10-20 years, have shrunk to 0-6 years. Alley cropping constitutes an effective alternative for maintaining soil fertility, even under continuous cropping.

The technology. Developed for use in Africa by IITA in Nigeria, alley cropping is proposed as an alternative to the field-fallow method of farming in the humid and subhumid zones. Field crops and perennial fast-growing shrubs - preferably legumes such as *Leucaena leucocephala* and *Gliricidia sepium* - are planted in parallel rows (see Figure 3.6). The hedgerows are 4-5 m apart. At the beginning of the rainy season, usually after the field crop has been planted, the hedges are cut back. The green parts, which can easily be separated from the lopped branches, serve as a mulch for the food crops, protecting the soil from evaporation and erosion and enriching it with organic matter and nutrients. The woody parts are usually removed from the system and used for firewood. The shrubs often sprout vigorously, requiring that the hedges be cut back regularly during the growing season so as not to interfere with the growth of the field crops. After the harvest the hedges continue to grow undisturbed, shading the soil and suppressing weeds. Then, at the beginning of the next growing season, the next radical pruning is carried out and the cycle is repeated.

Effect on yields.[59] The hedges have a twofold effect on yields. On the one hand they compete with the field crops for space, light, water and nutrients, while on the other they encourage their growth by supplying nutrients, suppressing weeds, improving soil structure and reducing surface runoff and evaporation. The overall impact may be positive or negative, depending on the management of the hedges and the species of field crop grown.

Results across different locations in the developing world show that tall crops with a high demand for nitrogen, such as maize, respond with increased yields, while short and/or nitrogen-fixing crops such as cowpea tend to respond with decreased yields.

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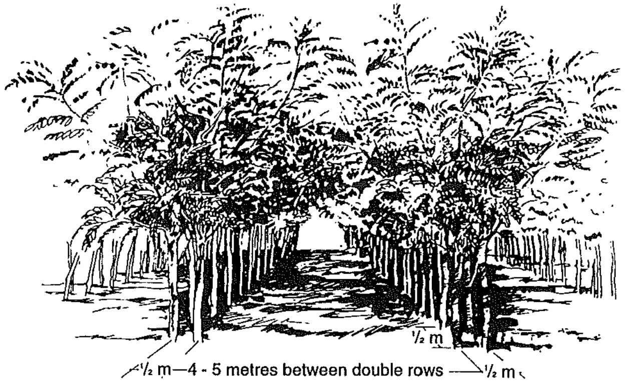
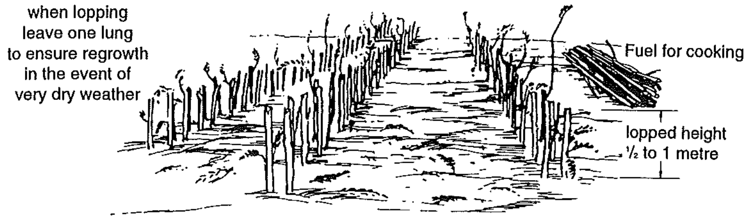
[59] The following discussion refers to the total area of a field, i.e. including the area taken up by the hedges.

Figure 3.6. Diagram of an alley cropping system during the growing season.



a) Double-hedge rows planted in Gliricidia or Leucaena forming dense shade over the avenues during dry (non-farming) season.



b) Hedgerows lopped, and mulch laid on avenues

c) Crops growing in the avenues in light shade from the hedgerows which are then lopped perodically during the growing season for "top dressing" mulch and providing optimum light for the maturing crop

Source: WIJEWARDENE and WAIDYANATHA (1984)

In the case of cowpea, LAL (1989) also observed indications of allelopathic effects from the incorporated *Leucaena* and *Gliricidia* leaves. For maize the rule is: the more a yield in an existing farming system has already been increased through mineral fertilizers, the smaller the increase that can be expected through alley cropping (see also TORRES 1983). The relative increase in yield is likely to be especially high on degraded soils (KANG and REYNOLDS 1986; see also GAISER 1988).

At the site in Sri Lanka, WIJEWARDENE and WEERAKON (1982) found that the maize yield was increased through alley cropping with *Leucaena* by 47% (795 kg/ha), whereas the cowpea yield fell by 26% (151 kg/ha). Even more interesting are the results of HANDAWELA (1986), obtained with widely spaced *Gliricidia maculata* (Table 3.13). This trial was carried out on degraded land near the experimental station of Maha Illuppallama. The trial areas had been cleared of forest for over 50 years and had been permanently in use since then. In 1977 the first *Gliricidia* trees, propagated from cuttings, were planted at a spacing of 5 m by 5 m. In 1980 the distances within the rows were reduced by planting new trees at 5 m by 1 m. By 1981 yields had begun to improve substantially. This experiment shows the following:

* The yields of *Gliricidia* mulch do not appear to depend on the amount of fertilizer applied. This contradicts CHADHOKAR's (1982) statement that the growth of *Gliricidia maculata* is markedly better on well fertilized and/or fertile soils.

* About 3 tonnes dry weight of *Gliricidia* mulch (containing approximately 108 kg N, only one third to half of which is available in the same season) has a far greater impact on yield than does 60 kg of mineral N (with or without P and K) applied to fields without alley cropping. This demonstrates that the yield-increasing effect of alley cropping extends beyond the pure nitrogen contribution of the mulch.

* The yield under alley cropping can be increased to only a limited extent using N fertilizer alone, but substantially using NPK. This shows that the supply of N is of secondary importance as a yield-limiting factor. It can also be concluded that alley cropping still increases yields at relatively high fertilization levels.

Table 3.13. Effect on maize yields of alley cropping with widely spaced *Gliricidia*

Treatment	No alley cropping	With alley cropping			
	Yield (kg/ha)	Mulch (kg/ha)	Yield (kg/ha) (%)	Increased yield (kg/ha)	(%)
1980 *Gliricidia* planted at 5 m x 5 m					
Without mineral fertilizers	1163	561	1373	210	18
+ PK	--	663	1841	---	--
+ N	--	579	3002	---	--
1981 *Gliricidia* planted at 5 m x 1 m					
Without mineral fertilizers	680	2811	1561	881	130
+ N	1385	3129	1921	536	39
+ NP	1251	2986	2476	1225	98
+ NPK	1354	2963	2728	1374	101

Fertilizer levels: 60 kg N/ha, 60 kg P_2O_5/ha, 60 kg K_2O/ha

Source: HANDAWELA (1986)

Little is known about the sustainability of yields under alley cropping. Two trials carried out by IITA in Nigeria over a period of six years produced conflicting results. Both suffered from faulty methodology. In the first trial, instead of taking a field without *Leucaena* as the control, the material lopped from the hedgerows was removed from the alleys (KANG et al. 1981; KANG et al. 1985; KANG and DUGUMA 1985; WILSON et al. 1986). This meant that the control contained the negative effect from competition but not the offsetting positive effect from the mulch. Here maize yields fell steadily (to less than 0.5 t/ha), while on the mulched plots they remained stable at a relatively high level (about 2 t/ha).

In the second trial (LAL 1989), maize yields fell markedly both with and without alley cropping. In the last two years of the trial the crop suffered extensively from drought during the first months. Also the fall under alley cropping was relatively small, and means little as overall yield levels were quite high (about 3.5 t/ha) due to generous applications of mineral fertilizer (120 kg N, 25 kg P, 30 kg K). For this reason the additional nitrogen received from the mulch had little further impact.

The only other possible reason for a decline in yields over time would be the removal of nutrients from the system, especially P, K, and Ca. YOUNG (1989) quotes a verbal communication from WEERAKON, that the soil nitrogen content remained constant after several years of alley cropping in Sri Lanka but that a deficit of phosphorus became noticeable. Such deficits can be made up by mineral fertilizers where necessary.

Soil erosion can be significantly reduced through alley cropping. LAL (1989) reported a decrease in the amount of soil lost from trial areas in Nigeria. By incorporating material lopped from *Leucaena* or *Gliricidia*, he reduced erosion by 92 to 86% compared with conventionally cultivated (plowed) control plots. Using the cuttings as mulch would probably reduce erosion still further, as has occurred in field trials conducted by other authors (DHARMASENA 1989; ROOSE 1981).

Few measurements are available for the study area. According to DHARMASENA (1989) the values are about 3 to 7 t/ha during the *maha* season and 1.5 to 4.2 t/ha in the *yala* season[60], totalling 4.5 to 11.2 t/ha over the year. If these values were to be reduced through alley cropping, they would certainly fall within any conceivable tolerance limit.

Various soil properties, including the contents of humus, nitrogen and available phosphorus, as well as the cation exchange capacity, are improved through alley cropping (see AGBOOLA et al. 1984, cited in ATTA-KRAH and SUMBERG 1988). YAMOAH et al. (1986) showed an improvement in soil physical and biological properties such as pore volume, water-holding capacity and soil biomass. In Sri Lanka, they reported the maintenance or improvement of nitrogen content, organic matter content and soil structure (see also HANDAWELA 1986 and WEERAKON, personal communication in YOUNG 1989, p. 187).

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[60] All measured on areas of 20 m^2 with a slope gradient of 2% to 5%.

The economic aspects of alley cropping will be discussed in Section 3.6.

3.6 Micro-economic evaluation

No matter how ideal agroforestry practices and technologies appear for the purposes of maintaining soil fertility and preventing erosion, they stand little chance of being more widely adopted unless they are both economically viable and socially acceptable. Productivity gains are not the sole criterion affecting adoption. Returns to labor, the distribution of labor over the cropping calendar, and effects on the division of labor within the household are also important.

KOTSCHI et al. (1991) address some of these issues, applying a modelling approach to the analysis of specific cases. Two of the three examples described in Section 3.5, contour strips in Nyabisindu, Rwanda and alley cropping in Sri Lanka, were submitted to comprehensive evaluation.

Evaluation method. The authors chose for comparison two production systems that differ from each other only with respect to agroforestry components. Because of the long time-lag between the introduction of an agroforestry technology and the full expression of its effects, they suggested that the comparison be made over 40 years. The evaluation criteria are given in Table 3.14.

Table 3.14. Criteria for evaluating agroforestry technologies in smallholder farming systems

Ecological performance	**Measurement unit**
* Maintenance of soil productivity[1]	Biomass production (t/ha) over time
* Reduction of soil erosion	Topsoil lost (t/ha) over time
Economic performance	
* Net return to cultivated land	US $/ha
* Net return to labor	US $/person-hour
* Average labor intensity	Person-hours/ha/year
* Labor intensity at peak work times	Person-hours/ha/month
Indicators of carrying capacity[2]	
* Supply of nutritional energy	Megajoule/ha
* Supply of protein	kg protein/ha
* Supply of fuel energy	kg firewood/ha

[1] without mineral fertilizers
[2] related to whole production system (fallow land included)

Source: KOTSCHI et al. (1991)

Results. The introduction of contour strips in Rwanda on the sloping fields of a typical smallholding[61] had a positive effect in terms of both the individual farm and the overall economy. Both net returns to land and to labor were increased and no extra demand for labor occurred during peak periods (see Table 3.15). According to this analysis, contour strips should be fairly widely adopted. One disadvantage, however, is the investment necessary over the first three years. The temporary sacrifice of land results in lower profit margins in the short term. Similarly, the greater labor intensity during this period reduces net returns to labor.

Table 3.15. Changes in net returns to land and to labor (%) through the introduction of contour strips with trees in Nyabisindu, Rwanda

	Net return to land		Net return to labor	
	Without	With	Without	With
Year	Contour strips		Contour strips	
0	100	100	100	100
1	97	88	97	88
3	91	104	92	111
5	84	114	86	120
10	69	241	73	243
40	0	241	0	243

Source: KOTSCHI et al. (1991)

With the contour strips, the food energy produced by the household rose from 116% of total requirements to 120%. Without them, it fell to 105% (Table 3.16). All the wood produced by the farm was counted in determining the fuel energy provided, regardless of how it might eventually be used (building or fencing are alternate uses). The contour strips start producing significant wood yields in the third year. Yields continue to increase until the tenth year, when 89% of firewood needs are covered. In contrast, no wood at all is produced on traditionally managed farms. The increased supplies of food and fuel contribute to the rise in carrying capacity. Such a rise will be necessary if poverty is to be reduced (Table 3.16).

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[61] Field area of 0.4 ha, of which 0.15 ha is located on slopes to be planted with contour strips. The smallholding supports 1 farmer, his wife, 2 children under 10, and 1 youth.

Tab.3.16. Self-suffiency (% of total requirement) in food** and firewood for a medium-sized farm* in Nyabisindu, Rwanda

	Food		Firewood	
	Without	With	Without	With
Year	Contour strips		Contour strips	
0	116	116	---	---
1	115	113	---	---
3	114	114	---	4
5	113	116	---	12
10	110	120	---	89
20	105	120	---	89

* Calculated for a total farm area of 0.4 ha, of which 0.15 ha suitable for contour strips; Household size: six persons.
** Food self-sufficiency calculated in Megajoule/ha.

Source: KOTSCHI et al. (1991)

The outcome for the Sri Lanka analysis was totally different. Here the introduction of alley cropping[62] resulted in a slight decrease in net return per unit area and a marked decrease in net return to labor. The additional labor required, especially for lopping the hedgerows, reduced the latter by 60 to 65%. After 3 years labor productivity improved, but not sufficiently to make the technology competitive. The distribution of labor over the season was also problematic. The hedges needed to be cut back at the same time as the fields were being prepared for planting[63], adding considerably to peak labor requirements. Despite its positive ecological effects in the form of erosion control and soil fertility maintenance, the contribution of alley cropping to increasing carrying capacity appeared small. Adoption is likely to be poor, not least because the rainfed crop is less important to the farmer and his family than the wetland rice and the home garden (KOTSCHI et al. 1991).

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[62] On a farm totalling 0.8 ha in size, of which 0.3 ha was cultivated to rainfed crops and was suitable for alley cropping, wetland rice was grown on 0.4 ha, and the home garden occupied 0.1 ha.

[63] Alley cropping is only efficient if tending and pruning are carried out exactly on time.

3.7 Zonal considerations

The humid lowland tropics possess the broadest range of agroforestry systems, and agroforestry plays the most important role in this zone. Numerous forms of home gardens and multi-story cropping systems are found here.

The semi-arid and subhumid zones are dominated by (agro)sylvopastoral systems. Firewood is a central problem. The optimal tree density is considerably lower than in the humid zone. Windbreaks are the most common form of technology used.

In tropical highlands, erosion is the greatest risk and determines the form of agroforestry system used. Erosion control strips are quite common, but there is still considerable scope for more widespread adoption.

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