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Science and Practice of Agroforestry 1

Soil productivity aspects of agroforestry

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ICRAF
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Science and Practice of Agroforestry

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This is an on-going series of small booklets covering a range of scientific and practical topics in agroforestry. It is aimed at a wide audience: high school, college and university students, resource planners, administrators and scientists and development personnel in agroforestry and related disciplines.

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Agroforestry in Kenya: an outline *P O'Keefe (ed)*

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P.K.R. Nair

Foreword

This is the first in what is intended to be a continuing series of booklets under the name "Science and Practice of Agroforestry". The range of topics that will be covered in these booklets is very wide. Practical handbooks and manuals, descriptions of research methods, species/genus monographs, analyses of specific agroforestry technologies (e.g. alley cropping, shelterbelts, etc.), geographical accounts of agroforestry practices and systems, reviews on special aspects of agroforestry (e.g. this volume), etc. are some of the types of topics covered by booklets which are already at different stages of preparation.

There will be three loosely unifying features of the series:

- the format, 80-120 pages each, will be the same,
- each booklet will stand by itself as a "complete" treatment of its subject,
- each booklet will be directly related to agroforestry and will be directed to practitioners, scientists and /or students of agroforestry.

Given the definition of agroforestry used at ICRAF - "all land use practices and systems where woody perennials are deliberately grown on the same land management unit as annual crops and/or animals" - the last feature will not be too much of a restriction.

Authors and editors of booklets will be drawn from ICRAF's scientific staff but may also be invited from outside ICRAF to write on topics of their speciality. In due course, as the series picks up momentum and becomes more well known, voluntary contributions from scientists and practitioners of agroforestry will also be welcome.

It is very appropriate that the first title in the series, by Dr. P.K.R. Nair of ICRAF, deals with soil productivity aspects of agroforestry. Among all the things that have been said about potentially positive effects of agroforestry, few have been repeated so often and so emphatically as the alleged soil fertility restoring and improving features of trees. Much of what has been written or said on this topic is myth or intelligent speculation. Over-simplifications and scientifically unacceptable generalizations are very common.

In this booklet, Dr. Nair has analysed and compiled what is *actually* known on the subject, drawing on relevant information and research from across disciplinary and geographic boundaries. Equally, or even more importantly, he has pointed at what is *not* sufficiently known and outlined priority research fields which scientists can pursue in order to make valuable contributions, eventually leading to better use of soil resources in agroforestry and other forms of land use in the tropical and sub-tropical developing world.

B. Lundgren
Director, ICRAF

1

Introduction

Agroforestry has generated rather high levels of enthusiasm in recent years among researchers, developmental experts, and policy planners concerned with tropical land-use systems. This euphoria about the agroforestry concept has led to a false belief in some quarters that agroforestry is a completely new practice, and even a panacea for all the defects and shortcomings of land management in the tropics. Although it is true that the scientific principles of agroforestry are only now being examined - and hence understood - the practice, in some form or other, has been in existence since very early times, especially among farmers in the warmer parts of the world. But these practices have hitherto been by-passed, if not neglected, by researchers and other experts and consequently have not been a major part of resource-rich farming. However, agroforestry and other integrated approaches to land use have now come in the limelight in the wake of mounting population pressure, the consequent destruction and mismanagement of forests by man in his quest for food and wood products and the environmental problems that have ensued. The increasing dependence of modern agricultural technology on high-value inputs, on the one hand, and the deteriorating economic situation of most of the developing countries, on the other, have led to a renewed awareness of the productive and protective value of trees, and a realization of the potentials of age-old conservation farming techniques. Consequently, efforts are now being made to devise the most appropriate ways to integrate the production of trees and other woody species with the production of agricultural crops and/or livestock simultaneously from the same piece of land in a sustainable manner.

Agroforestry has the most apparent potential in "marginal" areas and in resource-limiting smallholder systems where monocultural agriculture or forestry may not be most feasible or desirable. This implies that the agroforestry approach is based on the principle of "self-maintenance". Thus the systems and the management practices associated with them should strive to attain maximum efficiency of inputs, whilst maintaining the productivity of the soil in a sustainable manner; they should also show a strong bias towards resource conservation. The productivity of the soil that supports such a system is a matter of utmost concern in this context. Therefore it is prudent to examine the likely effect of agroforestry practices on the long-term productivity of soil, and to suggest appropriate soil management practices.

Agroforestry is, by its very nature, both an integrative and an interactive discipline. It covers the domains of traditional production-oriented disciplines, like agronomy and forestry, and its scientific premises and principles are based on disciplines - such as soil science, plant physiology and others - that are basic to all land-use systems. Moreover, since the *science* of agroforestry is still in its infancy, there is no substantial body of primary knowledge on any of its

operational aspects, including soil management. The time needed to generate such research data from well conducted experiments will be long. At the same time such data is urgently needed to promote and put into practice sound agroforestry systems. In this situation the best alternative seems to be to develop the concepts by a scientific synthesis of the existing knowledge that is derived from situations similar and relevant to agroforestry, and arrive at meaningful predictions. The approach was much the same when multiple cropping emerged as an area of scientific inquiry in the late sixties and early seventies.

An overview of such information indicates that it emanates from two sets of situations: first, from the widely practised land-use systems that have relevance to agroforestry, and secondly, from an understanding of the role of trees in enriching and/or conserving the ecosystem. Therefore, these situations can usefully be considered in some detail.

2

Land-use systems related to agroforestry

In spite of the considerable interest currently being shown in agroforestry, confusion and ambiguity regarding its nature prevail. Various definitions have been suggested for the term 'agroforestry' (see *Agroforestry Systems*, Vol. 1, No. 1 (1982), pp. 7-12). However, it seems to be generally agreed (Nair, 1983a) that agroforestry represents an approach to integrated land use involving the deliberate mixture or retention of trees or other woody perennials as part of the crop/animal production enterprises. Thus, it combines elements of agriculture, whether crop- or animal-based, with elements of forestry in sustainable production patterns on the same piece of land, either simultaneously or sequentially. The objective of most agroforestry systems is to optimize any beneficial effects of the interactions of the woody components with the crop and/or animal components to obtain a production pattern that, in terms of total quantity, diversity of end-products, or sustainability, is preferable to what is usually obtained from the same resources under prevailing social, ecological and economic conditions.

If we look at existing land-use systems with this broad concept of agroforestry in mind, we find that various types of agroforestry systems abound around the world (Nair, 1980, 1983b). The International Council for Research in Agroforestry (ICRAF) is currently undertaking a global inventory of existing agroforestry systems and practices. Table 1, which was prepared as a basic document for this project, shows a preliminary overview of the situation in the developing countries, indicating the most prominent examples to be found in the different regions. Though based on the existing knowledge prior to the commencement of the formal survey phase of the project, the Table clearly reveals a great diversity of agroforestry systems and practices. However, from the point of view of the need to understand the principles of soil productivity and soil management in agroforestry, the relevant land-use systems on which soil-related research results are available are few. Shifting cultivation, the taungya system, agricultural plantation crops, plantation forestry and multiple cropping are the dominant systems that are of significant relevance in this context. We need, therefore, to examine the more important soil management and productivity considerations of these systems.

Table 1 Some examples of prominent agroforestry systems and practices in the developing countries

Prominent Systems	SYSTEMS AND PRACTICES IN DIFFERENT GEOGRAPHIC REGIONS					
	S E Asia	S Asia	Mediterranean & Middle East	Eastern, Central & Humid West Africa	Arid and Semi-Arid West Africa	American Tropics
Agro-silviculture	1 Commercial trees among crops 2 Fruit/shade trees among crops 3 Live fences 4 Shelterbelts 5 Taungya 6 Shifting cultivation systems 7 Intercropping in plantation crops (rubber, oil palm, coconut)	1 Taungya 2 Plantation crops + arable crops 3 Commercial trees and fruit trees with crops 4 Live fences + shelterbelts 5 Various trees on farmlands for productive functions 6 Various forms of shifting cultivation 7 Medicinal plants + agri species	1 Olive + cereals (on terraces, "banquettes", "cuvettes", etc 2 Poplars along irrigation canals 3 Trees for sand dune reclamation 4 "Huertas" - small plots irrigated crops + fruit trees 5 Aromatic, medicinal and fruit trees with crops	1 Taungya 2 Cacao/food crops/forest complex 3 Plantation crops (oil palm/rubber) and root crops complex 4 Coffee + banana 5 Mixed perennial crops 6 Gum arabic + millet 7 Shifting cultivation/bush fallow systems	1 Use of trees on farmlands for protective role (windbreaks, dune fixation) 2 Productive + protective role of trees on farms (*A albida* Leucaena + agric crop systems	1 Trees in perennial cash crops (coffee, cacao, tea) 2 Trees for organic matter and mulch with annual crops 3 Tree live fences 4 Windbreaks and shelterbelts 5 Trees as support for climbing commercial crops 6 Taungya 7 Shifting cultivation systems
Silvo-pastoral	1 Pasture in forest plantation 2 Pasture in secondary forests 3 Commercial trees in pastures 4 Fruit shade trees in pasture 5 Fodder trees 6 Coconut + pasture	1 Pasture under trees 2 Plantation crops + cattle grazing 3 Fodder trees and shrubs 4 Fruit trees and commercial trees in pastures	1 Oak forest + grazing 2 Pig breeding and forestry 3 Rangeland improvement	1 Gum arabic + livestock 2 Plantation crops (coconut/cashew) + pasture	1 Nomadic/semi-nomadic/transhuman 2 Sedentary livestock grazing systems browsing systems 3 Fodder tree shrub systems	1 Trees in pasture 2 Pasture in natural regeneration forest 3 Trees lopped for fodder 4 Trees used for browsing
Agro-silvo-pastoral	1 Crops and grazing in plantations 2 Agri tree crops + grazing in forest plantation 3 Multipurpose trees with crops/animals 4 Integrated farming systems with agric plantation crops (rubber, coconut, oilpalm)	1 Plantation crops + arable crops + livestock 2 Agric tree crops + grazing in forest	Rangeland management	1 Coconuts other plantation crops + food crops + grazing 2 Coffee + banana + dairying 3 Horticultural complex systems 4 Plough culture complex systems	1 Forestry dominating (forest lands) 2 Agriculture dominating (crop lands) 3 Livestock dominating (rangelands)	1 Agric plantation crops (coconut, rubber, fruit trees) with crops and pastures
Home gardens	Various forms of multispecies combination	1 Multistorey plant canopies in humid regions 2 Arid/semi-arid systems	Mainly in large cities	Various forms	Various forms	Various forms
Others	1 Silviculture in mangrove forests 2 Agri-silvi-fishery 3 Trees on bunds in fish breeding ponds 4 Swidden farming 5 Fuelwood agroforestry	1 Mixed perennial cropping 2 Irrigation systems 3 Various site-specific systems 4 Fuelwood systems	1 New system in Morocco (spice plantation for erosion control) 2 Apiculture + forestry 3 Fruit trees in deserts 4 Mushroom cultivation in forest	1 Pastoral systems with central farming (highland lowland interactive systems) 2 Mixed perennial cropping	1 Oasis 2 Irrigation systems 3 Various site-specific systems	Mixed perennial cropping

Source: ICRAF (1983)

2.1 Shifting cultivation

2.1.1 System overview

Shifting cultivation - also known as the bush fallow system, slash and burn agriculture, swidden farming, and by a large number of local terms - is still the dominant crop production system practised in the tropics. It is estimated to extend over approximately 30 percent of the exploitable soils of the world, 360 million hectares, and provides 250 million people (or about 8 percent of the world's population) with a means of subsistence (FAO/SIDA, 1974). The practice can be described, in simple terms, as a land-use system in which forested land is cleared and cropped for a few years, and then left for the regeneration of the bush (fallow period), the duration of the fallow period being much longer than that of the cropping period. Although the system is dominant mainly in the sparsely populated and least developed areas where technological inputs for advanced agriculture, such as fertilizers and farm machinery, are not available and/or are not usually used, it is found all over the tropics in Asia, Africa, and Central and South America; even in densely populated Southeast Asia, it is a major agricultural system (Spencer, 1966; Grandstaff, 1980; Ruthenberg, 1980; Kyuma and Pairinta, 1983).

Despite the remarkable similarity in shifting cultivation practices in different parts of the world, two main forms can be distinguished: shifting cultivation in forests and shifting cultivation in savannas. The former, which is the commonest, and an example of which is given in Fig. 1A, consists of clearing a patch of forested land during the dry (or lowest rainfall) period, burning the debris *in situ* shortly before the first heavy rains, and planting crops, such as maize, rice, beans, cassava, yams and plantain, in the holes dug amidst the burnt and decaying debris. Irregular patterns of intercropping and other systems of convenience are the usual practices. The crops are occasionally weeded manually. After 2 or 3 years of cropping, the field is 'abandoned' to allow rapid regrowth of the forest; the farmer returns to the same plot after 5 to 20 years, clears the land once again, and the cycle is repeated.

In the major form of shifting cultivation that is practised in savannas, especially in West Africa, the vegetation, consisting primarily of grasses and some scattered trees and bushes, is cleared and burned in the dry season. Then mounds, about 50 cm high, are formed, on which root crops, usually yams, are planted. Maize, beans and other crops are planted between the rows. The mounds are levelled after the first year of yams; maize, millets, peanuts, and others are planted for the next 2 to 3 years (Fig. 1B). Thereafter the land is kept fallow and regrowth of coarse grasses and bushes occurs. The fallow period lasts for about ten years. Thus, compared with the shifting cultivation in forests, this form of shifting cultivation causes a more thorough working of the soil for cropping, longer cropping periods and, ultimately, a more severe weed infestation. Moreover, soil erosion hazards are also higher when the soil is bare after the clearing and burning in the dry season.

The literature on the various aspects of shifting cultivation is voluminous and fairly well documented. Grigg (1974) has examined the evolution of shifting cultivation as an agricultural system, while the anthropological and geographical information on the practice have been compiled by Conklin

Fig. 1A Shifting cultivation in forests. The forested area is cleared (foreground) and planted with crops, such as maize, rice, beans, cassava, yams, plantain, and so on, for 2 to 3 years (background). Note that the soil of the freshly cleared site on the foreground is practically bare and, hence, subject to erosion. Moreover, from the colour of it, the bare soil appears rather infertile. Contrary to popular belief, most of the soils that support lush green forest vegetation are of relatively low fertility status and cannot sustain permanent agriculture. (See sections 2.4.2 and 3.2.3 of the text for a discussion on this aspect.)
Photo credit: ICRAF

Fig. 1B Shifting cultivation in savannas. The vegetation, consisting primarily of grasses and some scattered trees and bushes, is cleared and burned in the dry season, and crops are grown in the following rainy season(s).
Photo credit: Neill McKee, IDRC

(1963). Sanchez (1973), Greenland (1974) and Ruthenberg (1980) have described the various forms of shifting cultivation and the studies on soils under shifting cultivation have been evaluated in excellent publications on the subject by Nye and Greenland (1960), Newton (1960), FAO/SIDA (1974), and Sanchez (1976). Research results and other information concerning shifting cultivation are directly relevant to agroforestry practices because the agroforestry approach *per se* encompasses the basic elements of shifting cultivation, on the one hand, and yet attempts to alleviate some of its drawbacks, on the other.

2.1.2 Soil management

It is generally accepted that traditional shifting cultivation with adequately long fallow periods is a sound method of soil management, well adapted to the local ecological and social environment. Before clearing the forest a closed nutrient cycle exists in the soil-forest system. Within this system, most nutrients are stored in the biomass and topsoil and a constant cycle of transfer of nutrients from one compartment of the system to another operates through the physical and biological processes of rainwash, litterfall, root decomposition and plant uptake. The amounts of nutrient lost from such a system are negligible. Part of this process is evident from Table 2, which gives some data on the amounts of nutrients that are added to the soil from tropical rainforest through litter.

Clearing and burning the vegetation leads to a disruption of this closed nutrient cycle. During the burning operation the soil temperature increases, and afterwards more solar radiation is received on the bare soil surface resulting in higher soil and air temperatures (Ahn, 1974; Lal *et al.*, 1975). This change in the temperature regime causes changes in the biological activity in the soil. The addition of ash to the soil through burning causes important changes in soil chemical properties and organic matter content (Jha *et al.*, 1979). Some data on the soil properties before and after burning are given in Table 3. In general, exchangeable bases and available phosphorus increase slightly after burning; pH values also increase, but usually only temporarily. Although no data on organic matter content are given in the Table, organic matter content is also expected to increase by burning, mainly because of the unburnt vegetation left behind. (For a detailed discussion on soil dynamics after clearing tropical forests, see Sanchez and Salinas, 1981.)

These changes in the soil after clearing and burning result in a sharp increase of available nutrients, so that the first crop that is planted benefits considerably. Afterwards, the soil becomes less and less productive and crop yields decline. Some examples of yield decline under continuous cropping without fertilization in different shifting cultivation areas relating to soil, climate and vegetation are given in Fig. 2. The main reasons for the decline in yield are soil fertility depletion, increased weed infestation, deterioration of soil physical properties, and increased insect and disease attacks (Sanchez, 1976). Finally, the farmers feel that further cultivation of the fields will be difficult and non-remunerative, they abandon the site and move on to others, knowing fully well that the abandoned site will be reinhabited by natural vegetation (forest fallow) and that during the fallow period, the soil will regain its fertility and productivity, so that they can return to the site after a lapse of a few years.

This cycle has been repeated in many regions where shifting cultivation has continued for centuries, though at low productivity levels. However, over a long

Table 2 Addition of nutrients from some tropical forests to the soil via litter

Location	Vegetation type	Litter dry matter t ha^{-1} yr^{-1}	Nutrient additions (kg ha^{-1} yr^{-1})					Reference
			N	P	K	Ca	Mg	
Manaus, Brazil	Virgin forest	7.3	106	2	13	18	13	Fittkau and Klinge (1973)
Merida, Venezuela	Virgin forest	4.6	57	3	20	31	12	Fassbander (1977)
Carare, Colombia	10-yr-old forest plantation	9.5	108	2	29	58	18	De las Salas (1978)
Kade, Ghana	Virgin forest	12.5	199	7	68	206	45	Greenland and Kowal (1960)
Dehra Dun, India	*Eucalyptus globulus* plantation		25.4	1.3	11	15.5	1.5	Tejwani (1979)
	Shorea robusta plantation			9	19	77	10	Seth *et al.* (1963)
Melayo, N. Trinidad	Natural vegetation	7.45	98	3	5	68	14	Cornforth (1970)
Usambara Mts., Tanzania	Natural forest	8.80	142	8	35	104	23	Lundgren (1978)
Ghana	Semi-deciduous forest	10.50	199	7.3	68	206	45	Nye (1961)
Congo	Mixed forest	12.50	228	4.6	103	127	38	Laudelout (1954)
Different closed natural forest types from 18 locations around the tropics		8.9	134	7	53	111	32	Lundgren (1978)
Standard deviation of these 18 values		(2.0)	(44)	(4)	(41)	(65)	(16)	

Table 3 Summary of changes in topsoil chemical properties before and shortly after burning tropical forests in Ultisols and Oxisols of the Amazon

		Yurimaguas		Manaus (mean of 7 sites)	Belem (mean of 60 sites)	Belmonte Bahia (1 site)
		Site I	Site II			
Months after burning		1	3	0.5	12	1
pH (in H_2O)	Before:	4.0	4.0	3.8	4.8	4.6
	After:	4.5	4.8	4.5	4.9	5.2
Exch. Ca+Mg	Before:	0.41	1.46	0.35	1.03	1.40
(meq 100 g^{-1})	After:	0.88	4.08	1.25	1.97	4.40
		(0.47)	(2.62)	(0.90)	(0.94)	(3.00)
Exch. K	Before:	0.10	0.33	0.07	0.12	0.07
(meq 100 g^{-1})	After:	0.32	0.24	0.22	0.12	0.16
		(0.22)	(0.09)	(0.15)	(0.00)	(0.09)
Exch. Al	Before:	2.27	2.15	1.73	1.62	0.75
(meq 100 g^{-1})	After:	1.70	0.65	0.70	0.90	0.28
		(0.57)	(1.50)	(1.03)	(0.72)	(0.47)
Al satn.	Before:	81	52	80	58	34
(%)	After:	59	12	32	30	5
Avail. P(ppm)	Before:	5	15	—	6.3	1.5
	After:	16	23	—	7.5	8.5
		(11)	(8)	(—)	(1.2)	(7.0)

Source: Sanchez (1979)

period of time, during which population pressure has steadily increased, the fallow periods have become shorter and shorter and farmers have returned to the fallow sites before these have had enough time for fertility to be sufficiently restored. The introduction of industrial crops and modern methods of crop production have also caused a shift in emphasis on the importance of the fallow period in traditional shifting cultivation.

Shifting cultivation has tended to be denigrated as being wasteful and inefficient because of the relatively low crop yields and the potential decline of soil productivity in some areas occasioned by the shortening of the fallow period (FAO/SIDA, 1974). However, the fact remains that shifting cultivation continues to be the mainstay of traditional land-use systems over very large areas in many parts of the tropics Moreover. the practice is likely to continue until viable and acceptable alternatives are evolved and adopted.

The important phenomenon in shifting cultivation that is of considerable relevance to the agroforestry approach is the restoration of soil fertility during the fallow period through the biological processes associated with revegetating the area. This has been demonstrated by numerous studies (see, for example, Nye and Greenland, 1960; Sanchez, 1976; Aweto, 1981; Koopmans and Andriesse, 1982; Mishra and Ramakrishnan, 1983). Based on this principle,

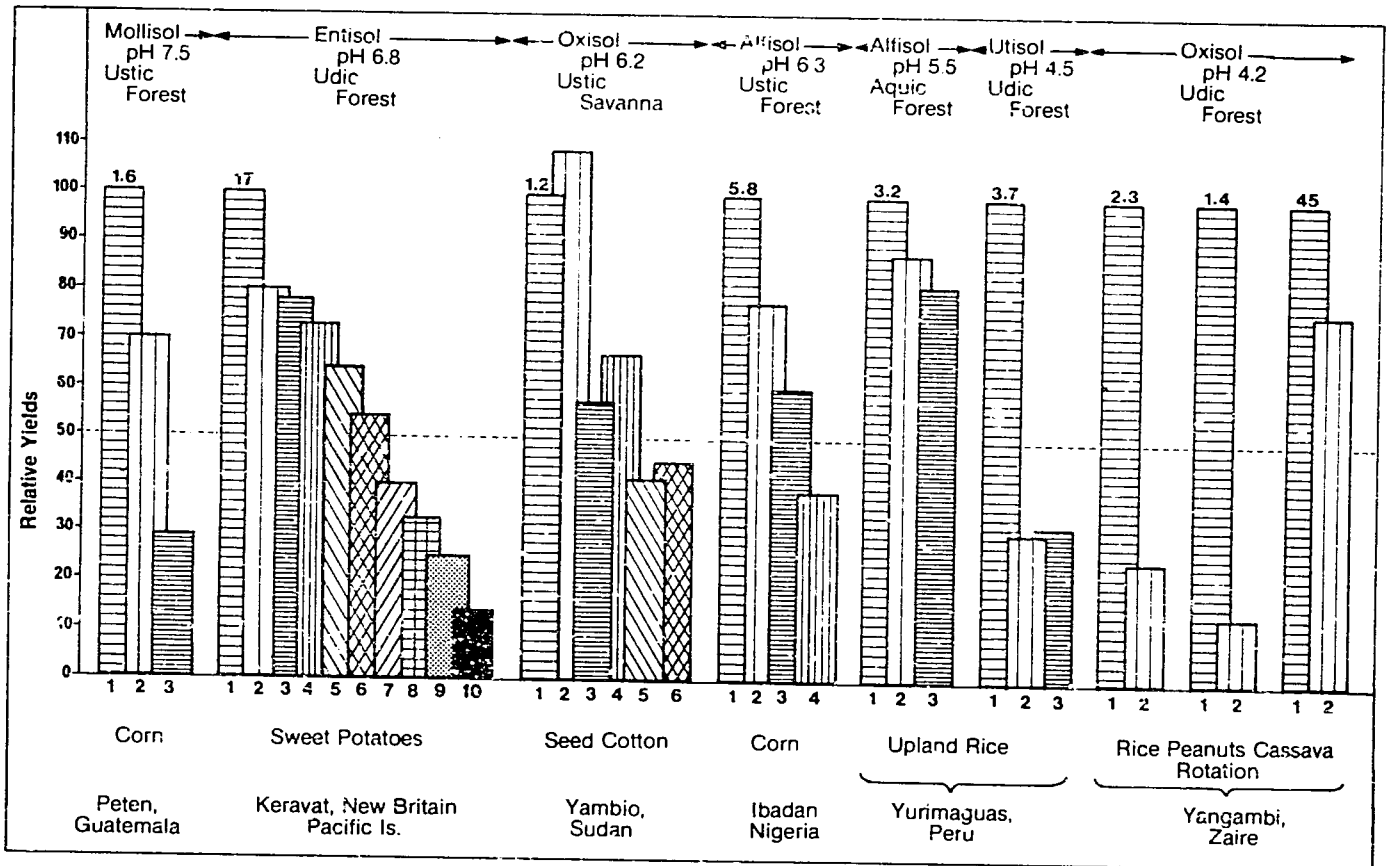

Fig. 2 Examples of yield declines under continuous cropping without fertilization in shifting cultivation areas as a function of soil, climate, and vegetation. Numbers on top of histograms refer to economic crop yields (tons/ha). Numbers on x-axis refer to consecutive crops.
Source: Sanchez (1976)

several alternatives to or improvements on shifting cultivation have been proposed. Such alternatives include the corridor system in Zaire (Jurion and Henry, 1969), improved cropping systems in India (Bonthakur *et al.*, 1981), and the use of fertilizers and other modern methods of farming for increasing crop yields within the cropping period in Peru (Nicholaides *et al.*, 1983).

An improvement in the effectiveness of the fallow period has also been attempted by planting appropriate species. Fast-growing tree species, such as *Acioa barteri*, or legume cover crops have been tried as artificial fallows; in general, however, they have been found to be no better than the natural forest or bush fallow as far as nutrient immobilization or subsequent crop yields are concerned. For example, the results of Jaiyebo and Moore (1964), summarized in Table 4, illustrate this point. They cleared an Alfisol forest in Ibadan, Nigeria and planted several artificial "fallow" species. The fallow species were cleared and burnt after seven years and the area pla ed with maize without applying additional fertilizer. The results indicate that maize yield and nutrient uptake were essentially the same when preceded by the natural fallow or by kudzu (*Peuraria phaseoloides*). Thus, in those circumstances, a mere change of the fallow species did not result in any additional benefit.

Table 4 Effects of 7-year fallows on soil and biomass storage of an Alfisol in Ibadan, Nigeria

Type of fallow	Biomass before clearing						Soil properties (0-10 cm)			
	Dry Matter (t ha^{-1})	N	P	K	Ca	Mg	pH	O.M. (%)	Bray P (ppm)	Exch. K (meq 100 g^{-1})
		(kg ha^{-1})								
Forest	39.6	433	27	304	407	52	6.6	4.4	5	0.4
Kudzu	8.7	187	11	103	113	38	6.4	3.4	4	0.3
Stargrass	16.9	120	10	146	64	23	7.1	2.8	4	0.3
Grass mulch	47.7*	—	—	—	—	—	6.5	2.3	8	0.4
Bare soil	—	—	—	—	—	—	6.8	1.4	4	0.1

Source: Adapted from Jaiyebo and Moore (1964) and Sanchez (1976)

* Total added in 7 years as *Imperata cylindrica*.

In many shifting cultivation areas, another potential improvement is the conversion of land to tree growing so as to produce an improved economic output. The large-scale establishment of permanent tree crops, such as rubber and oil palm, and commercial timber species, such as teak, are examples of this kind. The soil productivity aspects of these practices will be considered in more detail in sections 2.3 and 2.4.

In recent years, the soil-enriching attributes of the fast-growing woody perennials have been exploited by planting such species in crop production fields. The practice, known as hedgerow intercropping, or "alley cropping", aims at eliminating the fallow period altogether by combining such tree species with crops. The merits of the practice will be considered in detail in section 4.1.

In summary, the soil improvement that takes place during the fallow period of shifting cultivation as well as the possibility for replacing the "traditional" fallow species with other useful plants provide sound guidelines for agroforestry as an approach to improved land management in such areas (Nair and Fernandes, 1983).

2.2 The taungya system

2.2.1 System overview

Like shifting cultivation, the taungya system in the tropics is also a forerunner to agroforestry. It is reported to have originated in Burma (Blanford, 1958) and the word in Burmese language means hill (*taung*) cultivation (*ya*). Originally it was the local term for shifting cultivation, which was subsequently used to describe the afforestation method. In 1856, when Dietrich Brandis was in Burma, then part of British India, shifting cultivation was widespread and there were several court cases against the villagers for encroaching on the forest reserves. Brandis realized the detrimental effect of shifting cultivation on the management of timber resources and encouraged the practice of "regeneration of teak (*Tectona grandis*) with the assistance of taungya", based on the well known German system of *Waldfeldbau*, which involved the cultivation of agricultural crops in forests. Two decades later the system proved so efficient that teak plantations could be established at a very low cost in the taungya way. The villagers, who were given the right to cultivate food crops in the early stages of plantation establishment, no longer had to defend themselves in court cases on charges of forest destruction; they promoted afforestation on the cleared land by sowing teak seeds. The taungya system was soon introduced into other parts of British India, and later it spread throughout Asia, Africa and Latin America.

Figures 3A and 3B show the establishment of a forest plantation in the taungya way. Today the taungya system is known by different names, some of which are also used to denote shifting cultivation: *Tumpangsari* in Indonesia; *Kaingining* in the Philippines; *Ladang* in Malaysia; *Chena* in Sri Lanka; *Kumri, Jhooming, Ponam, Taila,* and *Tuckle* in different parts of India; *Shamba* in East Africa; *Parcelero* in Puerto Rico; *Consorciarcao* in Brazil, etc. (for details see King, 1968). Most of the forest plantations that have been established in the tropical world, particularly in Asia and Africa, owe their origin to the taungya system (von Hesmer, 1966, 1970; King, 1979).

The taungya system can be considered as a step further in the process of transformation from shifting cultivation to agroforestry. Shifting cultivation is a sequential system of growing woody species and agricultural crops, whereas taungya consists of simultaneous combinations of the two components during the early stages of forest plantation establishment. Although wood production is the ultimate objective in the taungya system, the immediate motivation for practising it, as in shifting cultivation and other smallholder systems, is food production. From the point of view of soil management, both taungya and shifting cultivation systems have a similarity: agricultural crops are planted to make the best use of the improved soil fertility built up by the woody plant components. In shifting cultivation the length of the agricultural cycle can last

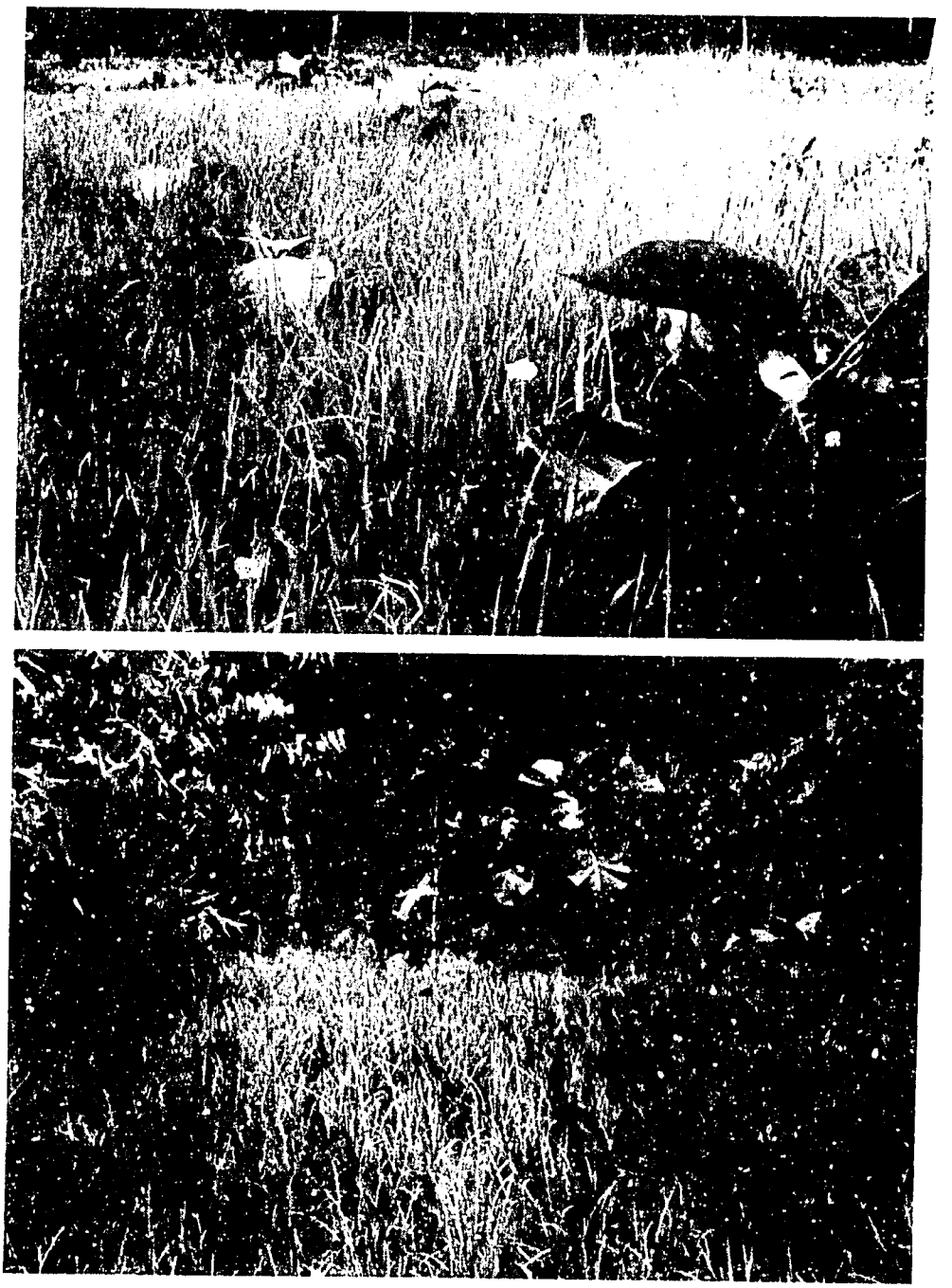

Fig. 3 The taungya system. Establishment of teak (above) and teak + Eucalyptus (below) in the taungya way in Thailand, the former in the first year and the latter in the second year of establishment. The decline in the productivity of soil is already evident from the stand of the rice crop in the second year.
Photo credit: P.K.R. Nair

only as long as the soil sustains reasonable crop yields; in taungya it is primarily dependent on the physical availability of space based on the planting patterns of trees. Taungya has been criticised, however, as a labour-exploitive system. It capitalizes on the poor forest farmer's demand for food and his willingness to offer labour for plantation establishment free of charge in return for the right to raise the much-needed food crops during only a short span of time.

2.2.2 Soil management

There are numerous reports describing different taungya practices and the growth of different plant species in the system (Aguirre, 1963; Anonymous, 1979; Cheah, 1971; George, 1961; Manning, 1941; Mansor and Bor, 1972; Onweluzo, 1979; unpublished reports on the 'shamba' system from the Kenya Agricultural Research Institute, Nairobi). But research data on changes in soil fertility and on other soil management aspects seem to be scarce. Alexander *et al.* (1980) reported from a two-year study in the Oxisols of Kerala, India (about 10°N latitude, 2500-3000 mm rain per annum) that the greatest disadvantage of taungya was the erosion hazards caused by soil preparation for planting crops: the surface horizons became partly eroded and sub-surface horizons were gradually exposed. The addition of crop residues to the soil surface was found to be a very effective way of minimizing such hazards. From an agrisilviculture study in southern Nigeria consisting of interplanting of young *Gmelina arborea* with maize, yam or cassava, Ojeniyi and Agbede (1980) found that the practice usually resulted in a slight but insignificant increase in soil N and P, a decrease in organic C, and no change in exchangeable bases and pH compared with sole stands of *Gmelina*. Ojeniyi *et al.* (1980) reported similar results from investigations in three ecological zones of southern Nigeria and concluded that the practice of interplanting young forest plantations with food crops would not have any adverse effect on soil fertility. However, Nwoboshi (1981) reported from studies at Sapoba, Nigeria that intensive cultivation and cropping practised in forest nurseries depleted the fertility of the soil within one year to two (Table 5). He argued that although trees are usually planted at 6 to 12 times wider spacings than in nurseries, the inclusion of arable crops in the plantation would have effects similar to those of frequent cultivation in nurseries as far as depletion of soil fertility was concerned.

It can be surmised from these reports that in most taungya systems erosion hazards, rather than soil fertility, are likely to pose greater problems of soil management. The long-term effect of the practice on soil fertility will, however, largely depend on the management practices adopted when clearing the area and re-establishing the second and subsequent rotations. In any case, soil fertility and the related soil management practices are only of secondary importance as far as the continuation of the traditional type of taungya system is concerned. Socio-political factors and/or the biological difficulties of continuing cropping under an increasing volume of the overstorey tree canopy would make it impossible to continue cropping after the initial two to three years in most cases.

Table 5 Soil properties of teak and mahogany nurseries compared with those of freshly cleared and burnt sites at Sapoba, Nigeria.

Soil depth	0 - 5 cm			5 - 15 cm			15 - 30 cm		
Soil properties	1	2	3	1	2	3	1	2	3
pH (H_2O)	8.65	7.45	6.58	7.73	7.51	6.57	7.11	7.12	6.32
Loss on ignition (%)	6.16	4.14	4.32	4.06	3.06	3.52	3.23	2.66	3.28
Total nitrogen (%)	0.014	0.003	0.005	0.016	0.002	0.004	0.016	0.004	0.005
Available P (ppm)	52.10	34.80	28.40	49.30	18.80	18.00	40.10	12.20	14.90
Total exch. bases (meq 100 g^{-1})	14.23	6.65	6.01	10.00	6.11	4.01	4.28	3.81	3.18

Source: Nwoboshi (1970)

1 Freshly cleared and burnt sites
2 Teak (*Tectona grandis*) nursery
3 Mahogany (*Lovoa trichilioides*) nursery

2.3 Woody perennial plantation agriculture

2.3.1 System overview

The term 'plantation crops' usually refers to a group of plants. that include woody perennials, such as oil palm, rubber, coconut, cacao, coffee, tea, cashew and others. They are usually cultivated with high inputs, on large areas and on a monocultural basis, and their multiple harvests form, after processing, high-value commodities of international trade.

According to FAO statistics, these permanent crops (including the perennial field crops, such as sisal, pineapple, and sugarcane) occupy about eight percent of the total arable area in developing countries (FAO, 1978). Modern commercial plantations of these high-value crops represent a well managed, profitable, usually environmentally stable, input-intensive land-use activity (see Fig. 4A) that is ably supported by well organized research efforts, although these are usually oriented towards single commodities. The production strategy with respect to land-use patterns in such plantations continues to be monocultural production of a crop grown primarily for export with, usually, a high manual labour input. But the plantation crops are rather unique among agronomic systems in that a large proportion of the land area occupied by them remains uncovered by the canopy of the main crops during their early growth phase (Nair, 1983c), or after pruning in the case of those species that are regularly pruned.

Fig. 4A Establishment of a commercial plantation of oil palm in Para State of Brazil. Growing fast-growing leguminous cover crops, such as kudzu (*Pueraria phaseoloides*), as seen in the photograph, is a common soil management practice in such enterprises. *Photo credit: P.K.R. Nair*

Contrary to popular belief, however, a sizeable percentage of the total production of most of the plantation crops is produced in smallholdings. These form a significant proportion in terms of both the population they support and the area they cover. In these smallholdings the farmers usually integrate crops and animal production with perennial crops, primarily to meet their food requirements. Examples of some such profitable production systems from different parts of the world have been described by Ruthenberg (1980). These include smallholder integrated production systems with cacao, rubber, coffee, coconut, and cashew, and the indigenous groves of oil palm (in West Africa). Integrated land-use systems are a logical consequence in these smallholder areas (Fig. 4B) because of the demographic and socio-economic characteristics of such areas. Moreover, planting patterns and other management aspects of the smallholdings are not as systematic as in the commercial plantations.

Fig. 4B Integrated land-use systems involving plantation crops in smallholdings. Contrary to popular belief, a sizeable percentage of the total production of most of the woody plantation crops, such as coconut, cacao, coffee, rubber, black pepper and other spices, are produced in smallholdings; in most of these smallholdings these perennial crops are grown in intimate association with arable crops and/or animals. Picture shows a multispecies combination of coconut, banana, cacao, mango and others - a typical scene in southeast Asia.
Photo credit: A. Manap Ahmed, Malaysia

2.3.2 Soil management

The commercial plantation crop production systems are economically viable enterprises and the soil management in such systems consists of practices that are fairly well established for individual crops based on extensive research (for example, see Pushparajah and Amin, 1977). It is an established practice in

many of the commercial plantation crop systems, particularly rubber and oil palm, to cultivate fast-growing leguminous cover crops (Fig. 4A). A recognised advantage of the practice is the di-nitrogen fixation that usually occurs; some examples are given in Table 6. Broughton (1977) computed the total potential benefit to Malaysia accrued from the presence of leguminous cover crops in rubber plantations in the country in 1975 at about US $175 million. Approximately 96 percent of this total monetary benefit was due to the increased rooting capability of the *Hevea* (rubber) trees, supposed to have been facilitated by the presence of such legume covers. In addition to the legume covers, the commercial plantation farmers, who are prompted by the profit motive, also adopt other appropriate soil management practices in the plantations to maintain their productivity at optimum levels.

Table 6 Observed rates of Nitrogen fixation in tropical creeping legumes

Legume	Habitat (and locality)	Nitrogen excess in soil (kg ha^{-1})	Reference
Glycine javanica	Cover crop (Kenya)	200	Jones (1942); see also Henzell and Norris (1962)
Centrosema pubescens	Pot (Malaysia)	235	Watson (1957)
C. pubescens intermixed with *Cyndon plectostachyus*	Pasture (Nigeria)	280	Moore (1962)
Pueraria phaseoloides	Cover crop (Nigeria)	650	Jaiyebo and Moore (1963)
Calopognium muconoides plus *C. pubescens* plus *P. phaseoloides*	Cover crop (Malaysia)	170 (maximum)	Watson *et al.* (1963)
C. pubescens with *Panicum maximum*	Pasture (Australia)	100	Bruce (1965)
Desmodium uncinatum	Pasture (Australia)	125	Henzell *et al.* (1966)
Phaseolus atropurpureus or *Stylosanthes humilis*	Pasture (Australia)	20-290	Henzell (1968)
P. atropurpureus	Pasture (Australia)	44-81	Vallis (1972)
C. muconoides *C. pubescens* *P. phaseloides*	Cover crop (Malaysia)	151 (average) 200 (maximum)	Broughton (1977)

Source: Adapted from Broughton (1977)

In smallholder plantation crop systems, such conventional soil management practices like cover crops, soil conservation measures, etc. are not practised so systematically, nor do they appear to be as necessary as in commercial plantations. The intimate association of plants in the smallholder integrated systems minimizes erosion hazards and precludes the possibility, and even the necessity, of cover crops. However, application of manures and fertilizers and other soil management considerations are important if reasonable yields of interplanted crops and the main (plantation) crop are to be ensured (Nair, 1979). Kowal and Tinker (1959) found that certain nutrients were depleted when the oil palm was intercropped for 12 years with food crops (yams, cassava, and maize), while oil palm production was not affected. However, reports about other plantation crop systems indicate that if the interplanted crop and the main crop are not adequately fertilized, the yields of both will be adversely affected (Nair and Varghese, 1980).

It is also customary to grow perennial plantation crops, such as coffee and cacao, under tall-growing shade trees (Fig. 4C). The soil management aspects, especially nitrogen cycling, in such systems have been studied by various workers (Bornemisza, 1982; Aranguren *et al.*, 1982). Those studies have indicated that the net nitrogen harvest output from those systems could be amply compensated for by inputs of N in the shade-tree leaf litter alone (for details see section 3.2.3 on nutrient cycling).

A special aspect of woody plantation crop systems is the relatively low amounts of biomass (and, therefore, nutrients) that are "exported" from the soil-plant system, on the one hand, and the considerable amounts of biomass that are continuously being added to the soil from the plants themselves, on the other. Moreover, as Alvim (1981) points out, the products harvested from the plantation crops (rubber, vegetable oils, fibres and starch foods) are basically composed of carbon, hydrogen and oxygen with only a small fraction of mineral elements extracted from the soil. In other words, the plantation crops "export" from the field mainly elements extracted from the air (carbon and oxygen) and water (hydrogen), so that the stress on mineral nutrients of the soil will be relatively low. Furthermore, in the well managed integrated systems, a closed nutrient cycle is likely to remain in constant operation, as in the forests (sections 2.4.1 and 3.2.3). The presence of more plant cover on the soil surface will also reduce erosion hazards and ensure better efficiency in the utilization of the "native" and applied nutrients (Nair and Khanna, 1978). These aspects will be considered in some detail in section 4.3. As a result of all these factors, the plantation crop systems - whether commercial or smallholder - represent reasonably stable and sustainable land-use systems.

In summary, the principles of soil management from these systems that are of relevance to agroforestry are the nitrogen contribution and other benefits of the legume covers, efficient nutrient recycling, and sustainable productivity in intimate plant associations that involve woody perennials.

Fig. 4C Coffee in smallholder production systems. The picture above shows coffee in secondary forest in northern Brazil. The one below is of the traditional *Chagga* system in the region of Mt. Kilimanjaro in Tanzania, showing coffee, banana and low-growing vegetables under an over-storey of *Cordia africana* and *Albizzia* sp.
Photo credit: P.K.R. Nair (picture above); E. Fernandes (picture below)

2.4 Plantation forestry

2.4.1 System overview

Man-made forests for wood production have existed on a small scale in the tropics for well over a century (see Fig. 5 for an example); some plantations in India are more than 120 years old. But it is only during the past two to three decades that plantation forestry has become an economic land-use activity in many tropical countries. The area under such man-made forests in the tropics as a whole in the early 1970's was estimated to be a meagre 6 to 8 million hectares (Persson, 1974). But the techniques developed recently to use mixed tropical hardwoods for the pulp and paper industry have led to large projects based on plantations for pulp mills, and a rapid shift from natural forests to man-made softwood forest seems to be the trend in many tropical countries.

Many species of different origin have been tried in tropical plantations - in East Africa alone, more than 100 species of eucalyptus and 50 species of pines have been tried (Lundgren, 1978). Basically, the various species that are tried fall under three major groups: one or the other species of the genus *Eucalyptus*, tropical hardwoods, such as teak and mahoganies, and tropical and sub-tropical conifers, mainly belonging to the genera *Pinus*, *Cupressus* and *Araucaria*. Several reports are available describing and discussing the merits and limitations of such tropical plantations (for example: Wood, 1974, 1976; Johnson, 1976; Evans, 1982; various technical reports from the Forestry Department of FAO). The relevance of plantation forestry to agroforestry stems from two main issues. First, in many places agroforestry development is an

Fig. 5 An 80-year-old teak (*Tectona grandis*) plantation in East Java, Indonesia, underplanted with tumeric (*Curcuma longa*)
Photo credit: P.K.R. Nair

activity of foresters who, naturally, have a tendency to relate agroforestry to the professional activity with which they are more familiar, that is, plantation forestry, and, secondly, most of the tropical plantations are established according to taungya, an agri-silviculture practice (section 2.2).

2.4.2 Soil management

The structure and function of tropical forests with respect to nutrient cycling and other soil management characteristics have been investigated by several agencies in different parts of the world, for example, the International Biological Programme (IBP), and the Man and Biosphere Programme (MAB) of UNESCO (Brunig, 1977; Clark *et al.*, 1980). It is generally understood that the production of high amounts of biomass and organic matter in the tropical forests does not always mean that the inherent fertility of the soils under these forests is high; on the contrary, the closed nutrient cycle between soil and vegetation and the various nutrient-conserving mechanisms that are operative in the forest ecosystem (surface accumulation of feeder roots, abundant litter and organic matter, mycorrhizae association, nitrogen fixation and minimum leaching and erosion) enable even inherently poor soils to support luxuriant rain forests.

This situation of effective nutrient conservation and sustainable soil productivity in a tropical forest does not exist in man-made commercial timber plantations. There have been several reports on site quality changes - mostly deterioration - in planted forests. But there are very few explanations for this behaviour or the machanisms involved. After a comprehensive review of the subject, Lundgren (1978) concluded that the establishment of the most commonly used fast-growing plantation species after forest clearing (conifers, eucalyptus, and teak) is associated with pronounced deterioration of soil physical, biological and/or chemical conditions. Indeed, from a study of the effect of monocultural plantations of fast-growing species (*Gmelina arborea* and *Pinus caribaea*) on soil properties in the lowland humid tropics of Brazil and West Africa, Chijioke (1980) found that a short-rotation *Gmelina* stand was at least twice as demanding as older stands as far as nutrient requirements were concerned. However, he also reported that there was no evidence that monocultures of fast-growing species *per se* did not lead to a more rapid depletion of soil nutrient reserves than would mixtures of species with the same biomass production rate, rotation length, and proportion of crop removed in harvesting. The beneficial effects of plantations in restoring the fertility and physical conditions of soils have been reported only where degraded soils have been reforested or brought under some evergreen hardwoods.

The most commonly reported observation concerning soils under plantation forests is the increased erosion hazards. A rapid decline in fertility and changes in the bulk density of the soil have also been reported (Florence, 1967; Cornforth, 1970; Reynolds and Wood, 1977). However, it should not be forgotten that the magnitude of the deterioration in soil quality under planted forests depends upon a large number of factors, including the species, soil types, climatic factors, management techniques (including establishment), and so on. Figure 6 gives a generalized picture as proposed by Lundgren (1978) of the different ecological and management phases in the conversion of natural forests to short-rotation plantation and the likely changes in the mineral and organic matter content of the topsoil during these phases.

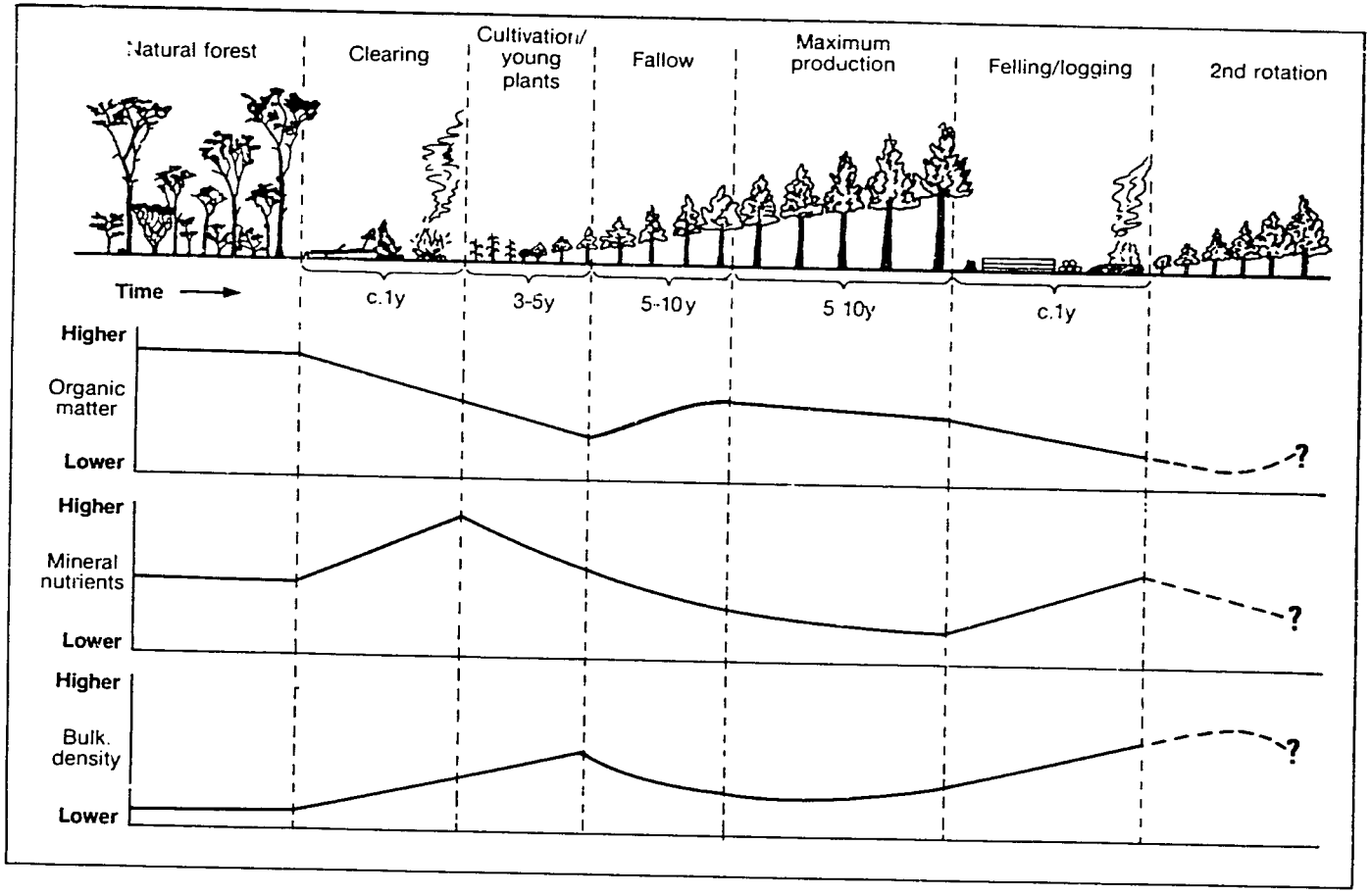

Fig. 6 A generalized picture of the likely changes in organic matter status, nutrient content and bulk density of topsoil during different management phases in the conversion of natural forest to short-rotation plantations (*Lundgren, 1978*)

2.5 Multiple cropping

2.5.1 System overview

Multiple cropping is the term that is used broadly to denote the practices aimed at increasing crop production by multiple use of the same resources within a year, or other relevant time span, through repeated and/or intensified cropping. Because of the variations in the practices in different parts of the world, and the range of crops and other factors that are involved, a universally acceptable definition of multiple cropping has not been evolved. Essentially, multiple cropping is a generic term. There are various manifestations of the practice and several terms have been coined to denote them: for example, intercropping (mixed-, row-, strip-), relay cropping, sequential cropping (double cropping, triple cropping, ratoon cropping), parallel cropping, multistorey cropping, and others (Andrews and Kassam, 1976; Nair, 1979; Beets, 1982).

The history of the scientific development of multiple cropping is very recent and quite similar to that of agroforestry. Even in early reviews of cropping systems in the tropics (for example, Wood, 1934), it was pointed out that crop mixtures rather than single stands are predominant in small farming systems. These smallholder farmers depend on their farms for most of the food needs of the family, and the farm operations are based on the family's manual labour. Therefore it is only natural that farmers should adopt farming systems that take advantage of the year-round availability of adequate temperature and solar radiation. Often, under the conditions prevailing on small farms in the tropics, such crop mixtures have proved to be relatively more productive and the total output more stable. They have been and still are, therefore, more attractive to tropical farmers in many cases as compared to sole crop stands.

But scientific innovations in agriculture, which were based mostly on the needs of farmers growing evenly spaced rows of single-crop stands in the temperate zones, did not permeate to these traditional tropical land-use practices until the late 1960's. Consequent upon the pioneering work of Bradfield (1969, 1970, 1972) in the Philippines that attracted international attention, systematic research on multiple cropping was initiated in other parts of the tropics (for example, Nair and Singh, 1971; Nair *et al.*, 1973a, 1973b, 1973c; Monyo *et al.*, 1976; Weber *et al.*, 1979). Since then, a veritable explosion of research on various aspects of multiple cropping has taken place throughout the tropics, so that scientific journals dealing with tropical agriculture are replete with research results on multiple cropping, and very profitable multiple cropping systems have been evolved and adopted (see Fig. 7 for an example).

The relevance of research data on multiple cropping to agroforestry is that both systems encompass intimate plant associations. Although multiple cropping usually refers to annual crops and intensive management conditions, the principles have been applied to tree crop systems too. Moreover, the research information on plant behaviour under intensive management and intimate associations, as in multiple cropping with several plants, indicates the type of plant interactions that could be expected when plants are grown in close proximity situations in agroforestry systems.

Fig. 7 Multiple cropping: a very promising plant association of maize and beans in an intensively managed multiple cropping system in northeast Brazil.
Photo credit: P.K.R. Nair

2.5.2 Soil management

Out of the several state-of-the-art descriptions and various other reports that are available on different aspects of multiple cropping systems, only a few deal with soil-plant relationships. Most of the soil management considerations in multiple cropping have been based on the expected requirements of each crop in sequential cropping systems, and on the expected interactions between neighbouring plants in intercropping systems. For example, when multiple cropping research was emerging as a scientific pursuit in the early 1970's, there was very little direct information on fertilizer practices and soil management for multicropped soils with concentrated inorganic chemicals. Therefore, the early researchers on this aspect (Bradfield, 1970; IRRI, 1973; Nair and Singh, 1971; Nair *et al.*, 1973a, 1973b) adopted the procedure of applying the sum of the optimum fertilizer requirements of the individual crops based on data on single-crop responses. The practice looked adequate from the point of view of soil fertility under conditions of intensive sequential multiple cropping. The example given in Table 7 is based on the work of Nair and his colleagues in the fertile alluvial Mollisols of northern India. They attained fairly high levels of production with three crops a year with very little time between crops. In spite of the high amounts of nutrient removal, there were no appreciable changes in soil organic carbon, total nitrogen, and available phosphorus and potassium (Nair *et al.*, 1973b).

Table 7 Annual production and nutrient budgets in heavily fertilized triple-cropping systems in a Mollisol of Pantnagar, U.P., India: average figures of 2 years. (Nutrient data are the average of puddled and upland rice systems.)

Cropping sequence	Grain or tuber yield ($t\ ha^{-1}$)			Total cropping duration (days)	N ($kg\ ha^{-1}$)		P ($kg\ ha^{-1}$)		K ($kg\ ha^{-1}$)	
	Crop 1	Crop 2	Crop 3		Fertilizer added	Crop removal	Fertilizer added	Crop removal	Fertilizer added	Crop removal
Upland rice-wheat-millet	5.1	6.4	1.3	339	310	323	74	84	98	296
Puddled rice-wheat-millet	4.8	6.2	1.5	343						
Upland rice-wheat-mung bean	5.2	5.7	1.3	342	337	401	94	89	83	290
Puddled rice-wheat-mung bean	5.2	5.6	1.4	345						
Upland rice-potato-wheat	5.4	11.7	4.5	311	360	383	96	98	150	342
Puddled rice-potato-wheat	4.9	18.5	4.4	315						

Source: Adapted from Nair et al. *(1973b, 1973c)*

This is but one example to illustrate the feasibility of maintaining high yields with no adverse effect on soil under conditions of intensive management and good soils. The authors attributed the stable levels of organic matter to the annual addition of 4 to 6 t ha^{-1} of roots and stubbles from the crops. Those sorts of residual and interactive effects, especially under tree cultures, are often not properly understood and are hence ignored. Interactions between neighbouring plants with respect to growth factors are commonly described as forms of "competition" because normally in a plant community, interference between plants lowers absorption/interception rates of growth factors relative to those in isolated plants, and competition for these factors will set in. However, there is evidence to suggest that it is also possible that plants may complement each other by sharing growth factors, thus resulting in better overall utilization of these factors. For example, such a phenomenon has been noticed in a crop combination of coconut and cacao (Nair *et al.*, 1975; Nair, 1979), which will be described in detail in section 4.3. Therefore, the approach of applying fertilizers according to the estimated requirements for each individual crop may not be the most efficient and economical way of utilizing the nutrients that are either externally applied or inherently present in the soil. Data on the total nutrient demand of each species, nutrient removal in harvested and non-harvested products, rate of nutrient accumulation during ontogeny, addition of nutrients through litter fall and other plant residues, interactive effects of plant associations on nutrient relations, and so on, are needed for each component of a multi-cropped system to enable one to arrive at answers on the rate, time, source, and placement of various nutrients.

One of the advantages of having a number of crops per year is the beneficial effect of the practice on soil structure. Obviously the effect will depend on soil properties and management. Table 8 shows an example of the effect of increasing the number of crops per year on the infiltration rates of a poorly aggregated, slowly permeable alluvial soil near New Delhi, India. The authors considered this increase in infiltration rate as a direct consequence of the improvement in physical conditions because of a reduction in the number of tillage operations. But in strongly aggregated soils, such as Oxisols, effects of this kind may be of less importance.

Table 8 Effects of increasing the number of crops per year on the infiltration rates of an alluvial soil near New Delhi, India

Cropping sequence*	Infiltration rate (cm hr^{-1})
Maize-wheat (cultivated)	0.6
Mung bean-maize-wheat (cultivated)	1.2
Mung bean-maize-wheat (no additional cultivation)	1.7
Mung bean-maize-mustard**- wheat (relay intercropped; no additional cultivation)	2.7

Source: IRRI (1972)

*Tillage after land preparation as indicated
***Brassica campestris*

The decreased tillage operations will also benefit the second crops in areas where such second crops depend almost entirely on residual soil moisture. Other advantages attributed to a reduced number of tillage operations are so well known that a discussion on them is not warranted here in this context.

Yet another principle of soil management in multiple cropping that is relevant to the understanding of agroforestry is the sustainability of production under continuous cropping. However, this aspect will be discussed more thoroughly after examining the role of trees in imparting sustainability to farm production systems, especially with evidence from intercropping systems involving trees.

3

The role of trees in soil productivity and conservation

An appraisal of the role of trees in augmenting sustainable productivity on farmlands, and in conserving other ecosystems, is central to soil productivity and management considerations in agroforestry. Many literature references underline the general role of trees in improving the productivity of the soil and imparting stability to the ecosystem. For example, the topic was highlighted at ICRAF's expert consultation on soil research in agroforestry (Mongi and Huxley, 1979).

Micro-site enrichment by trees is a net effect of several factors and the most important among them can be grouped into two broad categories: soil fertility and soil physical conditions. Before considering these aspects in some detail, it is worthwhile examining the general characteristics of tree root systems because they are important not only in the usually understood function of absorption of nutrients and water, in providing anchorage, and so on, but also in organic matter relations and complementary and competitive interactions with co-habiting species.

3.1 Rooting patterns

There is a general belief that trees have deep and spreading roots and are, therefore, capable of exploiting more soil volume and taking up nutrients and water from layers that are usually not contacted by herbaceous crops. This process of taking up nutrients from deeper profiles of the soil and eventually depositing at least a part of them on the surface layers through litter fall and other mechanisms is referred to, albeit erroneously, as "nutrient pumping" by trees. However, there is a considerable difference between the situations found in a forest, or a plantation, and that of an individual tree (as, sometimes, in agroforestry) with regard to both rooting patterns and root system functions, including the so-called nutrient pumping effect. It is well known that, within the limits of genetic restrictions, the root development of plants will depend on a number of site characters and environmental conditions. In agroforestry systems the woody species often do not exist in such close proximity as in monospecific forest plantations. Therefore it is to be expected that the root development pattern of woody species, and consequently the extent of their root interaction with other species, will be of a different order of magnitude compared to the situation in forests or plantations.

The difficulty in predicting the rooting pattern and root interaction of woody species in agroforestry is further compounded by the fact that the root systems of most tropical trees have been only scantily investigated (Halle *et al.*, 1978). Some of the reviews that are available on the work (e.g. Kerfoot, 1963; Jenik, 1977) indicate that for many woody species the largest number of roots, and the majority of fine roots, are located in the uppermost fertile portion of the soil profile. Some species of trees are consistently shallow-rooted, while others exploit the soil to a considerable depth. For example, *Prosopis chilensis*, a woody species native to the Pacific coast of Latin America, has a shallow and spreading root system. On the contrary, another species of *Prosopis*, *P. juliflora*, also native to the American tropics, is known to have a very deep root system. An example of the depth to which roots of *P. juliflora* can grow is the report of Phillips (1963) that *P. juliflora* roots were found at 53 m depth in a mining excavation in southern Arizona. Such variations in rooting patterns are also found among different species of *Acacia* trees. Apart from these genetically induced variations, environmental conditions, including soil type, can also influence the rooting pattern, which, in turn, can affect the physical form of the plant. A typical example is *Acacia tortilis*, an African native found throughout the arid and semi-arid regions. Usually it is a medium-sized (4 to 15 m tall) tree, but under conditions of extreme aridity and shallowness of soil, it becomes a shrub.

The extent of root proliferation of a plant is usually expressed as the depth of rooting or the depth of solum. But more useful approximations of rooting space are root system sorption zone and root surface sorption zone (Armson, 1977). The former refers to the volume of soil occupied by roots, as determined by using a segment of a sphere with a mean radius of rootspread and depth of rooting, and thus gives a quantitative approximation of the total soil volume of root exploitation, but not necessarily of root intensity. Root surface sorption zone, on the other hand, refers to the volume of soil within one centimetre of any root surface determined by calculating the volume of soil associated with root lengths by diameter classes. It is thus an indirect measure of rooting intensity. However, the use of a 1-cm distance to define the root surface sorption zone is arbitrary. In terms of water supply, this distance will vary in effectiveness with both soil moisture level and the pore system as reflected by texture and structure. For nutrients, the distance will be significantly less for relatively immobile nutrients like phosphorous, compared to mobile ones like potassium. (For a detailed treatment on solute movement to roots, see Nye and Tinker, 1978). The root system sorption zones of individual trees may be much larger than those of herbaceous crops. However, the picture would be quite different when a community of trees or the sorption zone per unit amount of above-ground biomass, is considered. It may, however, be pointed out that occupation of soil by roots is neither uniform nor static, and this applies to individual trees as well as plant communities. Similarly, the amount of roots within a soil is very much a function of the stage of development of the vegetation and the choice of parameter - length, surface area, volume, weight, and so on - of roots.

Obviously there is a great deal more that can be said about the rooting characteristics of woody perennials in relation to agroforestry. In fact that, by itself, could be the topic for a separate review. The organic matter relations and nutrient cycling aspects of roots will, however, be considered in subsequent sections dealing with those aspects.

3.2 Soil fertility

3.2.1 Organic matter and nutrient addition to the soil

Forests characteristically contain large quantities of "living" biomass (including wood) and, therefore, a large inventory of chemical elements. Some estimates of biomass are given in Table 9. About 20 to 25 percent of the total living biomass of the trees is in roots (Armson, 1977), and there is a constant addition of organic matter to the soil through dead and decaying roots. Nye (1961) estimated that under a moist tropical forest the net annual contribution of dead roots was around 2,600 kg ha^{-1}. In addition to this, there could be a significant formation of soil organic matter during active root growth, much of it directly from the root tissue without the intervention of soil microfauna (Martin, 1977). In tracer experiments with annual plants (wheat and mustard) Sauerbeck and Johnen (1977) found that the total production of microbially decomposable organic matter by the plants can be 3 to 4 times greater than the amounts of root residues at harvest. They found that although "rhizodeposition", that is, the amount of organically bound root carbon in the soil at harvest (Shamoot *et al.*, 1968), exceeded conventionally recovered root matter by about 23 percent, the overall organic matter deposition during the growth period was still 2 to 3 times greater. Martin (1977) suggested that this steady release of carbohydrate-rich organic material from actively growing roots would represent an energy input into the soil ecosystem capable of supporting a substantial microbial population. This phenomenon would be very important in the organic matter and nutrient relations of soils under trees.

The major recognized avenue for addition of organic matter (and, hence, of nutrients) to the soil from the trees standing on it is through litter fall, that is, through dead and falling leaves, twigs, branches, fruits, and so on (Brinson *et al.*, 1980). There are several studies on this aspect from tropical forests, which include Malaisse *et al.* (1975) in Africa; Koriba (1958), Kira and Shidei (1967) and Kira (1969) in Asia; Edwards (1977) in New Guinea; Klinge and Rodrigues (1968), Medina (1968), Cornforth (1970), Klinge (1977) and Kunkel-Westphal and Kunkel (1979) in South America; and others. Some data on nutrient addition to the soil from some tropical rainforests via litter were given in Table 2. The bulk of the organic matter and nutrients that are so added to the soil are located in the topsoil. Potassium, calcium and magnesium, on the other hand, are concentrated in the biomass, except in high base status soils (Foelster *et al.*, 1976; Chijioke, 1980). That is why forest clearing leads to a considerable loss of the nutrients - those in the biomass being "exported" from the system, and those in the soil being lost by leaching and runoff. Some data on the concentrations of nutrient elements in the surface soil of tropical forest in different parts of the world are given in Table 10. Table 11 shows the proportion of total nutrients stored in some tropical forest ecosystems. Obviously there is a great deal of difference between a sample drawn to 5 cm and one drawn to 15 cm depth. But the depth of sampling has not been mentioned in many of these reports. However, the purpose here is not to make a comparison between sites, but rather to use the data as indicators of both the quantities and the pattern of elemental concentrations in tropical forests soils.

There is also some evidence to indicate higher nutrient content in soils under

Table 9 Biomass (dry weight, t ha^{-1}) of forest communities

Forest type	Canopy leaves	Canopy stems	Understorey	Roots	Litter	Reference
Thailand, rainforest	8.2	360	2.4	33	3.5	Ogawa *et al* 1965
Thailand, monsoon forest	3.8	261	2.0	25	—	Ogawa *et al.*, 1965
Thailand, dry evergreen forest	5.6	229	2.9	—	—	Sabhasri *et al.*, 1968
Ghana, moist tropical forest	—	187	—	25	2.3	Greenland and Kowal, 1960
Congo, secondary forest	6.5	116	—	31	5.6	Greenland and Kowal, 1960
Puerto Rico, lower montane forest	8.1	269	—	71	19.3	Odum *et al.*, 1970
Brazil, mountain evergreen forest	9.1	131	—	33	—	Rodin and Bazilevich, 1967
Panama						
tropical moist dry	7.3	252	3.9	13	6.2	Golley *et al.*, 1975
tropical moist wet	11.3	355	1.7	10	2.9	Golley *et al.*, 1975
premontane wet	10.5	258	0.8	13	4.8	Golley, *et al.*, 1975
Riverine	11.3	1163	1.1	12	14.1	Golley *et al.*, 1975
mangrove	3.5	159	0.1	190	102.1	Golley *et al.*, 1975
Temperate forests						
Pine forest	6.4	122	4.0	29	37.5	Ovington, 1965
coniferous forest	10.4	114	2.0	38	36.6	Ovington, 1965
deciduous forest	2.6	142	3.0	37	10.5	Ovington, 1965

Table 10 Elemental concentrations (ppm) in surface soil of tropical forests

Forest	Location	P	K	Ca	Mg	Exchangeable or total concentration	Reference
Tropical moist	Panama	7.6	117	4232	645	Total	Golley *et al.* (1975)
Tropical moist	Panama	9.1	650	2420	700	Exchangeable	Gamble *et al.* (1969)
Tropical moist	Costa Rica	1.1	82	1534	600	Exchangeable	Holdridge (1971)
Premontane wet	Panama	0.2	69	466	302	Total	Golley *et al.* (1975)
Premontane wet	Costa Rica	0.9	27	246	71	Exchangeable	Holdridge (1971)
Rain forest	Surinam	113	500	900	1400	Total	Stark (1970)
Deciduous diptocarp	Thailand	—	140	576	383	Exchangeable	Tsutumi *et al.* (1967)
Dry evergreen	Thailand	—	86	120	22	Exchangeable	Tsutumi *et al.* (1967)
Moist tropical	Ghana	—	109	360	133	Exchangeable	Nye and Greenland (1964)
Most deciduous	India	—	328	2940	672	Exchangeable	Singh (1968)
Wet evergreen	India	—	1271	2340	780	Exchangeable	Singh (1968)
Semi-evergreen	India	—	702	2620	492	Exchangeable	Singh (1968)
Soils	World-wide	650	400 to 30000	7000 to 500000	600 to 6000	Not indicated	Bowen (1966)

Table 11 Proportion of total nutrients stored in the soil in some tropical forest ecosystems

Location	Forest type	Percentage of total nutrients found in the topsoil					Reference
		N	P	K	Ca	Mg	
Manaus, Brazil	Virgin	73	69	11	0	8	Fittaku and Klinge (1973)
Merida, Venezuela	Virgin montate	81	91	14	31	31	Fassbander (1977)
Carare, Colombia	Virgin	71	85	28	5	21	De las Salas (1978)
Magdalena Valley, Colombia	Secondary forest:						Foelster *et al.*, (1976)
	16 yrs old	87	77	16	11	26	
	5 yrs old	97	92	29	52	68	
Kade, Ghana	Virgin	81	—	56	61	61	Greenland and Kowal (1960)

scattered trees or bushes. From a detailed study on the extent and mechanism of soil nutrient enrichment by some of the common savanna tree and shrub species growing in highly weathered and infertile Ultisols of the Mountain Pine Ridge savanna of Belize (17°N latitude, 89°W longitude), Kellman (1979) reported that trees showed preferential enrichment of the soil below them in terms of Ca, Mg, K, Na, P and N. In some cases the levels of these nutrients approached or exceeded those found in the nearby rainforest. Some of his results are given in Table 12. The savanna trees were not deep-rooted, which, he suggested, was an indication that the capture of precipitation was the major source of mineral nutrient input. The author concluded that the gradual accumulation of mineral nutrients by perennial, slow-growing trees, and the incorporation of these into an enlarged plant-litter-soil nutrient cycle was the mechanism responsible for this soil enrichment. Similar results of an increase in nutrient content of soils under species of *Prosopis* growing in an arid environment in India are presented in Table 13. Felker (1978) has also reported such results under scattered *Acacia albida* trees in West Africa.

Table 12 Mean values (± S.E.) of properties of surface soils beneath savanna, *Byrsonima* and *Pinus caribaea* covers in Belize

	Savanna (n = 13)	*Byrsonima* (n = 6)	*Pinus* (n = 9)
Exchangeable cations (meq 100 g^{-1})			
Ca	0.21 ± 0.03	0.74 ± 0.16**	0.19 ± 0.02NS
Mg	0.20 ± 0.02	0.35 ± 0.03**	0.20 ±0.02NS
K	0.08 ± 0.01	1.10 ± 0.004**	0.08 ± 0.01NS
Na	0.035 ± 0.003	0.033 ± 0.01NS	0.037 ±0.005NS
Available PO_4 (ug^{-1})	2.40 ± 0.03	2.58 ± 0.17NS	2.64 ± 0.28NS
Cation exchange capacity (meq 100 g^{-1})	21.1 ± 0.81	22.6 ± 0.73NS	19.9 ± 0.79NS
Base-saturation (%)	2.5 ± 9.22	5.3 ± 0.69**	2.6 ± 0.22NS
Organic carbon (%)	2.76 ± 0.10	3.24 ± 0.22NS	2.66 ± 0.19NS
Moisture content at 1/3 bar (%)	23.3 ± 0.89	23.5 ± 0.72NS	20.5 ± 1.78NS

Source: Kellman (1979)

Significance of differences between savanna and *Byrsonima* and savanna and Pinus, using a t-test, are given (* P = 0.05, ** P = 0.01, NS = not significant)

This phenomenon of micro-site enrichment by some species of woody perennials is extremely important in agroforestry. It could well be that there are several such species that already play a significant role in many traditional farming systems, but whose potentials have scarcely, if at all, been scientifically studied and quantified. As pointed out by Nair (1983b), one of the most significant opportunities offered by agroforestry lies in exploiting the potential of those species that have hitherto not attracted scientific attention.

Table 13 Nutrient content of soils under two *Prosopis* species in arid regions of India

Trees	Site	Org. C (%)	Total N (%)	Total P (mg 100 g^{-1})	Total K (mg 100 g^{-1})
Prosopis juliflora	under tree	0.73	0.075	37	296
	open area	0.25	0.027	31	294
Prosopis cineraria	0-30 cm				
	under tree	0.37	0.045	3.82	12.20
	open area	0.25	0.038	1.52	7.52
Prosopis cineraria	31-60 cm				
	under tree	0.11	0.020	1.95	9.31
	open area	0.04	0.010	1.23	6.36

Source: Singh and Lal (1969)

3.2.2 Di-nitrogen fixation by trees

One of the advantages that is most commonly attributed to agroforestry is the possibility for improvement of fertility status of agricultural lands through additional amounts of nitrogen that could be added to the system by the tree legume component. Although legumes are not the only group of woody species that have a potential role in agroforestry, the family Leguminosae offers by far the greatest choice of woody species for agroforestry in terms of economic uses as well as ecological adaptability.

The role of woody perennial legumes in agroforestry and the range of opportunities offered by legumes have been described by various authors (Brewbaker and Hu, 1981; Vergara, 1982; Nair *et al.*, 1984). However, di-nitrogen fixation is not a natural phenomenon that is universally present in *all* members of the Leguminosae family. Out of the three sub-families of Leguminosae, the majority of both Mimosoideae and Papilionoideae are known to fix nitrogen, as contrasted to only a smaller percentage of the members of Caesalpinioideae (Brewbaker and Hu, 1981; Duke, 1982). According to the estimates of Allen and Allen (1961), there are about a thousand species of tropical woody legumes forming di-nitrogen-fixing root nodules. A few significant non-leguminous tree genera can also fix nitrogen, notably the tropical genus Casuarina.

Various estimates are available of the amounts of nitrogen fixed under natural conditions of tropical forests and grasslands. Greenland (1975) estimated that a young redeveloping tropical forest vegetation accumulated nitrogen at the rate of approximately 100 kg ha^{-1} yr^{-1}. Greenland and Nye (1959) estimated that the soil increment is probably between 20 and 50 kg ha^{-1} yr^{-1}, in which case the minimum fixation rate is in the order of 120 kg ha^{-1} yr^{-1}, less smaller quantities added through rainfall and dust. Some grasslands are also reported to accumulate nitrogen at a rate equivalent to that in forest vegetation (Dobereiner *et al.*, 1972; Misra, 1979). Various such estimates of the di-nitrogen fixation rate are available under different ecosystems (see, for example, Keya, 1979; Dommergues *et al.*, 1979). However, the significant point here is the additional benefit that is likely to accrue from a woody legume component to an agroforestry system as compared to, say, an agricultural system that does not

have such a legume component. Therefore, among the various avenues of addition of nitrogen to a soil through natural and biological means, the most significant one that is brought about by the presence of trees on agricultural lands could be nitrogen fixation by leguminous trees.

Estimates of such amounts of nitrogen fixed by tree legumes are derived either from the N content of sustained yield harvests or from differences in the N content of soils that are adjacent to areas under such tree legumes. The largest values for nitrogen fixed by tree legumes are from an analysis of sustained yield forage productivity of *Leucaena leucocephala* grown in Australia. When grown for forage leucaena dry matter yields of forage, protein, and nitrogen were found to be 12,600, 3,600 and 575 kg ha^{-1} for a 9-month growing season in Australia receiving 1,000 mm annual rainfall (Hutton and Bonner, 1960). The trial had previously been grazed for three years, and given phosphate and potassium fertilizers but no supplemental nitrogen or irrigation; therefore the 575 kg of nitrogen represented the minimum value for di-nitrogen fixation by leucaena. From a study of soil nitrogen changes in a 30-year-old *Acacia mearnsii* tannin plantation and an adjacent grassland field in South Africa, Orchard and Drab (1956) estimated a di-nitrogen fixation rate of 200 kg ha^{-1}. *Prosopis tamarugo*, which grows in the Chilean salt flats of "Pampa del tamarugal", an area that is "rainless" (0.7 mm yr^{-1}) but has a 3 to 6 m deep groundwater aquifer, is estimated to fix 198 kg N ha^{-1} yr^{-1} (Salinas and Sanchez, 1971; Pak, *et al.*, 1977). Felker (1978) has given an estimate of di-nitrogen fixation by *Acacia albida* growing in association with millets and peanut in West Africa. Since soil nitrogen was found to increase under *A. albida* but not under the non-leguminous trees *Balanites aegyptiaca* and *Guiera senegalensis* (Radwanski and Wickens, 1969), he concluded that *A. albida* was a source of additional nitrogen input to the soil. Assuming an 800 kg ha^{-1} yield and 3 percent nitrogen (18.75 percent protein) content of peanuts, the nitrogen removed by a peanut crop growing under *A. albida* was calculated as 24 kg ha^{-1} yr^{-1}. Of this, 2 kg was assumed to be fixed through electrical storms and 1 kg by free living nitrogen fixers as reported by Paul *et al.* (1971). The remainder of 21 kg ha^{-1} yr^{-1} of nitrogen was assumed to be fixed by *A. albida*. In this calculation he assumed no nitrogen input through fixation by peanut (although peanuts can fix nitrogen), the argument being that peanuts cannot sustain a high soil nitrogen and organic matter content or a high yield without *A. albida*. Moreover, the peanut roots and stubble were assumed to be returned to the soil. Cattle and other animals were expected only to redistribute and transform fixed nitrogen from one form to another, rather than act as a source of nitrogen *per se*.

Like other biological processes, the quantities of nitrogen fixed by a tree legume species will depend upon various environmental factors as well as plant characters. Therefore it is difficult to extrapolate the nitrogen fixation data from one set of conditions to another. However, Felker *et al.* (1980) proposed an upper estimate of nitrogen fixation using empirically derived coefficients. If the annual rainfall was 500 mm, the soil water recharge 75 percent of the rainfall, the water use efficiency 1,000 kg of water per kg of dry matter, the dry matter required per gram of nitrogen 7 g (Herridge and Pate, 1977), and if 50 percent of the dry matter were used for nitrogen fixation, then 267 kg of nitrogen and 1,875 kg of dry matter could, potentially, be produced annually per hectare. Most plant dry matter has a nitrogen content of about 1.5 percent; therefore only 28 kg of N would actually be required for the 1875 kg of dry matter. Based

on these calculations, and on the observed values of di-nitrogen fixation in some situations, the authors predicted that di-nitrogen fixation rates of the order of 100 kg N ha^{-1} yr^{-1} were possible in areas receiving 500 mm annual rainfall.

Until recently field evidence has, however, not been quite so convincing about di-nitrogen fixation by trees. For many leguminous trees di-nitrogen fixation has so far not been demonstrated in the field. Nodulation, which is considered to be an indication of di-nitrogen fixation, is absent in mature *A. albida* trees, and until 1972 *Prosopis* spp. were reported to be non-nodulating (Gupta and Balera, 1972). However, the situation is now changing with the accumulation of more and more research reports. Acetylene reduction by detached nodules of *Prosopis* has been reported (Eskew and Ting, 1978) and 12 Prosopis species representing African and North and South American germplasm were nodulated in the greenhouse when inoculated with a strain of *Rhizobium* isolated from a North American *Prosopis* sp. (Felker and Clark, 1980). Hoegberg and Kvarnstroem (1982), who studied the di-nitrogen fixation rate in a 4-year-old stand of *Leucaena leucocephala* in the field at a semi-arid site in Tanzania by the acetylene reduction technique, calculated the amount of nitrogen fixed annually to be 110 ± 30 kg ha^{-1}. Other reports show that di-nitrogen fixation by *L. leucocephala* can range from 70 to 500 kg ha^{-1} under different conditions (Vergara, 1982).

The lack of nodulation on mature *A. albida* trees is explained as a consequence of adverse soil moisture stress and decreasing nodule abundance with increasing soil fertility (Felker, 1978). In actual field situations, farmers in West Africa are quite appreciative of the value of retaining *A. albida* trees on the farmland (Pageard, 1971; Pelissier, 1967; Seif-el-Din, 1981). The practice is reported to cause yield increases of the order of 300 to 400 kg ha^{-1} of millet and peanut crops growing under such trees, and the main reason for these increases is supposed to be di-nitrogen fixation by the trees (Felker, 1978).

In the light of this evidence, the capability of leguminous tree species, or at least some of them, to fix atmospheric nitrogen can be considered firmly established. Therefore, from the point of view of soil productivity and management, nitrogen-fixing woody perennials will clearly have a very important role to play in agroforestry systems.

3.2.3 Nutrient cycling

One of the main principles of soil management in agroforestry is to make the best use of its resource-conserving and resource-sharing potentials. Therefore, it is extremely useful to have a proper nutrient budget for the whole system based on nutrient requirements of individual components and the nutrient dynamics within the system. Nutrient cycling processes that take place to varying degrees in all land-use systems (for a good example, see Rosewell, 1980) become particularly relevant in the agroforestry context because of the likely effects of trees on such processes. "Closed" nutrient cycles are known to operate in mixed evergreen natural forests. A simplified model of the nutrient cycle in a forest ecosystem is presented in Fig. 8.

The model consists of the soil-plant system that is partitioned into several compartments. The crown surface forms the boundary of the system where input of bioelements occurs through precipitation. The soil surface is the entry point for inputs into the soil compartment, occurring through fertilizers, rainfall

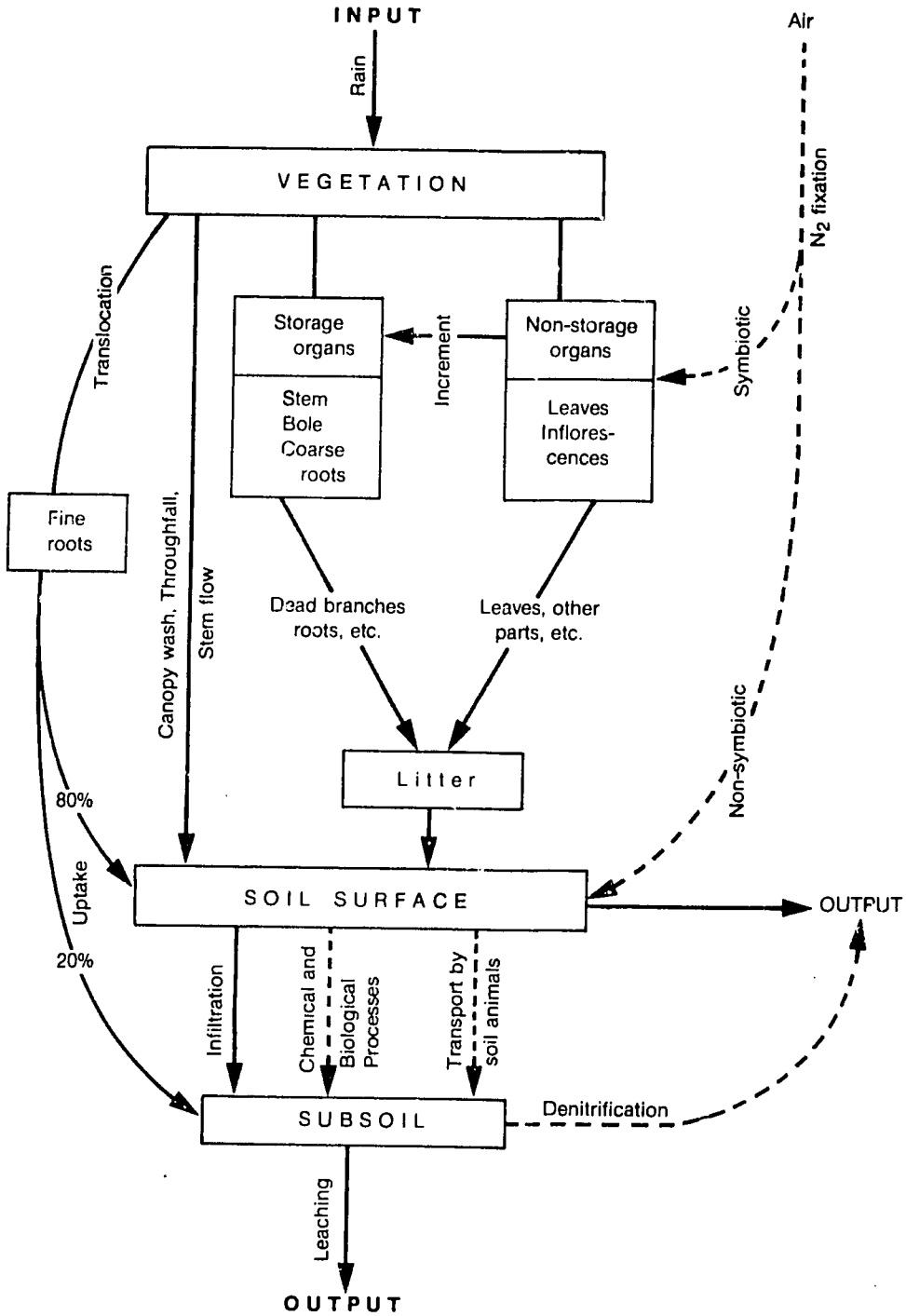

Fig. 8 A simplified model of nutrient cycling in a forest ecosystem. Dotted lines indicate the biological processes taking place with the involvement of other organisms.

and stem flow. The surface soil layer could be considered as the zone of intensive root activity, with the subsoil constituting the extensive root activity zone. The lower end of the extensive root layer is the boundary of the ecosystem to the hydrosphere and lithosphere. Bioelements transported beyond this layer are lost from the ecosystem and appear as output from the system.

Nutrients taken up by the plant are either stored in an increment (storage) compartment or are used for the production of non-storage organs. It is well known that fertilizer application results in an input of nutrients and the accompanying ions into the solid phase of the uppermost layer of the soil. Depending on the water content of the soil and the solubility of the fertilizers, they pass on to the solution phase of the same soil layer, and then spread simultaneously - depending on the mobility of the ions - in different layers of the soil, and into the plant stand *via* uptake. Based on the flow rate of percolating water and the soil properties, part of the nutrients that are in the soil solution is washed out of the nutrient-absorbing zone, and it represents a loss (output) from the system. Dissolved nutrients, especially ions like nitrate, which show no significant interaction with the soil matrix, will be washed out in the unsaturated flow of water. Phosphates which possess low solubilities or are transformed into compounds of low solubility are least affected by this leaching or percolation loss, whereas the magnitude of loss of cations like potassium depends on the exchange capacity of soils (for a description of this, see Ulrich, 1976).

Part of the nutrients that are taken up by the plants are also returned to the soil through two avenues. First, litter fall (Table 2) and, secondly, through the processes of plant cycling. The latter represents that part of the total uptake of nutrients which is again leached out from the vegetative parts through crown washout, occurring as canopy drip and stem flow. Although this phenomenon is usually not recognized in nutrient cycling studies, its magnitude is of importance, especially in deciduous trees. The presence of this fraction, which is circulated within the ecosystem, is a sort of "necessary waste" (Nair, 1979), and it indicates the amount of "losses" of nutrients that must be accounted for while calculating nutrient budgets of plant communities. The total amount involved in this cycling depends on the nutrient content of leaves, the intensity and frequency of rain, the age and arrangement of leaves, and so on (Ulrich *et al.*, 1977).

The major avenue of output from the total system is "export" through harvested produce. Such exports are generally more for annual agricultural crops in terms of the total quantity removed per unit area and unit time. In the case of woody perennials, it depends on the frequency and intensity of harvesting. But because even repeated harvests do not amount to destructive harvesting in woody perennials, the rates of their "export" out of the soil-plant system are relatively low compared to annual agricultural crops (see also section 2.3.2). For example, Araunguren *et al.* (1982) studied the distribution of fluxes of nitrogen in some parts of coffee and cacao plantations under shade at a typical highland location in Venezuela (1380 m above sea level). The N-flow associated with litter fall in the coffee system was dominated by the shade tree (*Erythrina* sp. and *Inga* sp.) fraction amounting to a transfer of 86 kg ha^{-1} yr^{-1} of the total 189 kg ha^{-1} yr^{-1}. The N output (export) from the system by harvest (17 kg ha^{-1} yr^{-1}) was thus much less than the contribution (input) by the shade trees. The average litter decomposition constant (k) of the shade tree leaves,

expressed in terms of N, was estimated to be 4.5, equivalent to a half-life of approximately 2 months. The cacao system consisted of 302 kg N ha^{-1} in the plants, of which woody above-ground parts made up 50 percent; fine roots and leaves contained about 60 kg N ha^{-1}. Litter on the soil surface, sampled quarterly, was found to contain an annual average of 37 kg N ha^{-1}, with shade tree leaves making up 61 percent of the total. Out of a litterfall rate of 2.9×10^3 kg dry matter ha yr^{-1}, the shade tree leaves accounted for 50 percent. The rate of N transfer by litter fall was 321 kg N ha^{-1} yr^{-1}, decomposition constants (k) for shade tree leaves and cacao leaves being 7.7 and 9.5 respectively. N output by harvest was about 45 kg ha^{-1} yr^{-1}, with about 20 kg N being returned annually to the field with cacao pod shells after processing. Thus, in both these systems (coffee and cacao), the net harvest output could be amply compensated for by N input by shade tree leaf litter alone, and, of equal importance, much of this shade tree N could be from soil horizons deeper than those exploited by coffee or cacao and possibly from biological di-nitrogen fixation by the shade trees.

Plant nutrients are, therefore, involved in a constant and somewhat closed cycling within the soil and plant compartments of tree-based ecosystems, with minimal output (loss) from the system. The extent to which the system is "closed" or "open" will depend upon various factors, the decisive one being the tree/crop proportion. Even in agroforestry systems with a high proportion of woody perennials, the frequency and method of harvesting their produce, the structure and density of the root system, the type of magnitude of disturbance (including management) to the system, and the spatial and temporal arrangement of species are among the important factors that contribute to the effectiveness of the nutrient cycling processes in soil productivity.

3.3 Soil physical conditions

3.3.1 Soil conservation

The establishment of a vegetative cover is one of the most effective ways of soil and water conservation. There are several reports to illustrate this (see, for example, Wenner, 1980). When the protective cover of vegetation on the soil is removed, the structurally unstable tropical soils are exposed to the beating action of rains. Losses due to erosion immediately after land clearing are normally alarmingly large. Experiements at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria indicate a soil loss of up to 120 t ha^{-1} in the first year after land clearing (Lal, 1974). Fournier (1967) reported significant erosion losses even from soils with a 1.5 percent slope. As is well known, the magnitude of loss depends upon several factors, such as erodibility of the soil, erosivity of rain, slope, vegetation types, management practices, and so on. To cite two examples, the range of magnitude of erosion under various vegetation covers is shown in Tables 14A (West Africa) and 14B (The Philippines).

The potential role of trees in reducing runoff and erosion losses is well appreciated and understood, but not well documented. The physiognomy of natural forest communities is such that it provides a multi-layer defence against the impact of raindrops. The different strata of the canopy progressively reduce the force of rain, thereby reducing the adverse effect of the impact on the soil

Table 14A Runoff and erosion under various covers of vegetation in parts of West Africa

Locality	Study period	% slope	Average annual rainfall (mm)	Annual runoff, %			Erosion (t ha⁻¹)		
				Forest	Crop	Barren soil	Forest	Crop	Barren soil
Ouagadougou (Upper Volta)	1967-70	0.5	850	2.5	2-32	40-60	0.1	0.6-0.8	10-20
Sefa (Senegal)	1954-68	1.2	1300	1.0	21.2	39.5	0.2	7.3	21.3
Bouake (Ivory Coast)	1960-70	4.0	1200	0.3	0.1-26	15-30	0.1	1-26	18-30
Abidjan (Ivory Coast)	1965-70	7.0	2100	0.1	0.5-20	38	0.03	0.1-90	108-170

Source: Charreau (1972)

Table 14B Effect of vegetation cover on runoff and soil loss under shifting cultivation in Mindanao Region in the Philippines

Vegetation cover/ land use	Percentage runoff during			Soil loss during	
	Cropping period	uncropped period		Cropping period (g day⁻¹)	Plant-harvesting period (g day⁻¹)
		Pre-cropping	Post-cropping		
Primary forest	0.26	—	—	0.20	—
Softwood tree fallow	0.26	—	—	0.29	—
Imperata grassland	3.0	—	—	0.40	—
New abaca plantation	0.35	—	—	0.47	—
10-yr-old abaca plantation	0.64	—	—	0.59	—
New maize swidden	1.52	—	0.86	3.03	0.65
New rice swidden	1.08	0.69	0.42	1.45	0.37
Two-yr-old maize swidden	1.78	—	4.08	12.05	9.81
12-yr-old rice swidden	11.64	6.73	14.15	119.31	6.32

Source: Kellman (1969)

below. Moreover, the litter and the humic layers on the soil surface act as a cushion against erosion. A report from China (Xiaoliang, 1977) indicates that under a tropical monsoon climate, the establishment of forest on eroded slopes reduced annual soil erosion from about 15,000 to 3,000 $m^3 km^{-2}$ over a period of 10 years. Similarly several reports from India indicate that improvements in soil physical properties by afforestation reduce water runoff and erosion (Tejwani, 1979).

The soil conservation benefit of woody perennials can conveniently be made use of in agroforestry in various situations if the species chosen can provide additional benefits and outputs, such as fodder, fuel, wood, food, and so on. This is particularly important in highlands with rolling topography and steep slopes, which are increasingly being brought under cultivation. For example, in Southeast Asia, especially Indonesia, there is a long tradition of planting *Leucaena leucocephala* in contour hedgerows for erosion control and soil improvement. Indirect terraces are also formed when the washed-off soil is collected behind the hedges as can be seen from Fig. 9. These contour rows of leucaena survive through the long dry season because of their long taproots, which can reach water deep in the ground. Loppings and prunings from the hedgerow species could also provide mulch to aid in preventing sheet erosion between trees. A schematic representation of a typical planting pattern of hedgerow for soil conservation is given in Fig. 10.

Fig. 9 Agroforestry for soil conservation: *Leucaena leucocephala* in contour hedgerows (in Indonesia) facilitates the formation of terraces when the washed-off soil is collected behind the hedges.
Photo credit: World Neighbors, Oklahoma, USA

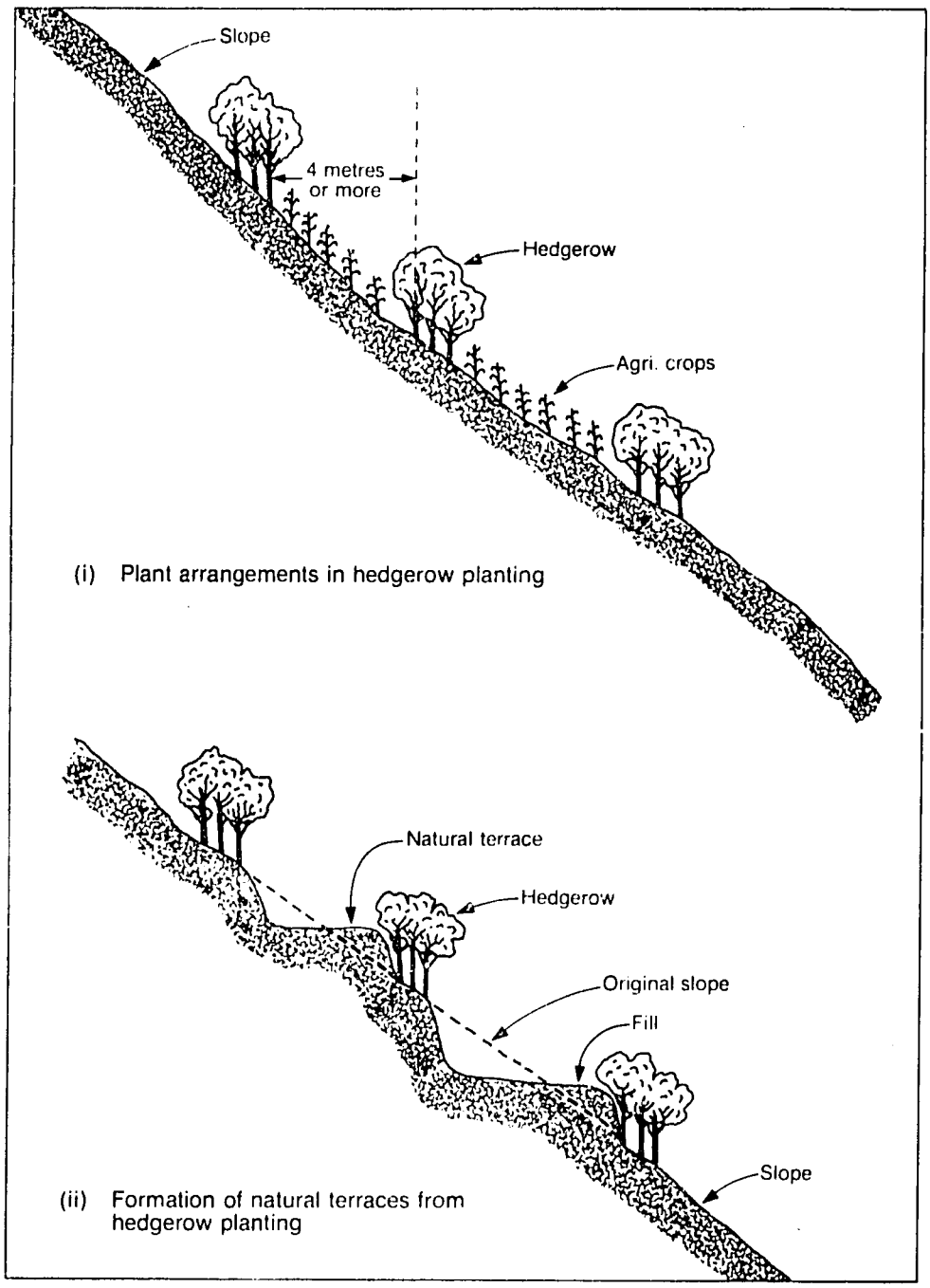

Fig. 10 Hedgerow planting for soil conservation (*adapted from Vergara. 1982*)

A combined stand of plants of different growth habits and forms can be of considerable advantage in soil protection. The presence of more plant cover on the soil, either alive or as mulch, reduces the impact of raindrops on the soil and thus minimizes splash and sheet erosion. Similarly, conventional land preparation methods for agricultural species can aggravate soil erosion and impair soil physical conditions. Incorporation of woody perennials on such fields can provide a regulatory effect to modify the method and intensity of such tillage operations. Several other possibilities for exploiting the soil conservation and protection benefits of agroforestry have been discussed by Lundgren and Nair (1983).

3.3.2 Soil physical properties

In undisturbed forest ecosystems, water movement under saturated conditions takes place in soils through macro-pores that dominate the pore space (Humbel, 1975) and, therefore, surface runoff is generally low, even in regions of intense rains with a high drop-size distribution. The honeycomb-like structure of the surface horizons also favours high infiltration rates in such soils (Lal, 1975; Wolf and Drosdoff, 1976). The removal of the vegetative cover from the soil generally results in an increase in bulk density, a decrease in porosity, and a reduction in infiltration rate (Weert and Lenselink, 1972; Wood, 1977).

The data of Wilkinson and Ania (1976) from Ife, Nigeria on the high rates of infiltration and water entry into the soil (sandy soil, 10 percent clay) under tropical forest fallow, and the reduction of the rates after two subsequent years of maize cropping (Table 15) are quite illustrative. "Infiltration capacity" here refers to water entry into saturated soil when lateral flow is not restricted, and "infiltration rate" to the rate of entry when horizontal movement is prevented. In other words, subsoil permeability determines infiltration *rate*, which is barely influenced by clearing and cultivating, but the infiltration *capacity* is reduced considerably by compaction of the well structured topsoil by cultivation. Similar results on infiltration rates under various ecological and vegetation conditions

Table 15 Equilibrium infiltration capacities and rates of water entry into crust-free Iwo and Oba (Ife, Nigeria) soils in bush fallow and after two sebsequent years of annual crops (maize)

Soil condition	Iwo		Oba	
Soil condition	Infiltration capacity (cm hr^{-1})	Infiltration rate (cm hr^{-1})	Infiltration capacity (cm hr^{-1})	Infiltration rate (cm hr^{-1})
Bush fallow	118.9	21.1	107.7	25.4
After first cropping year	44.7	20.5	48.8	25.1
After second cropping year	49.5	22.4	21.6	9.1

Source: Wilkinson and Ania (1976)

in India are given in Table 16. A large volume of related data on the effect of clearing and cultivation of forested land on soil physical characters is available from the results of IITA experiments (Lal, 1976; Lal and Greenland, 1979; Lal *et al.*, 1979; Lal and Russel, 1981).

Table 16 Infiltration rates under different vegetative covers in India

Location and vegetation cover/land use	Infiltration rate (cm hr^{-1})	Remarks
Bellary		
Woodland	17.00	For one hour run
Grassland	2.60	"
Agricultural land	1.00	"
Ootacamund Study No. 1		
Shola forest	16.84	For three hours run
Blue gum plantation	20.69	"
Grazed grassland	5.13	"
Ootacamund Study No. 2		
Shola forest	12.50	"
Broom (*Cytisus scoparius*)	11.25	"
Grazed grassland	6.25	"
Ranchi		
Forest	20.00	"
Permanent natural grass	8.00	"
Cultivated farmland	2.00	"

Source: Tejwani (1979)

The presence of trees in a landscape affects its hydrological characteristics. Studies on the taungya or *shamba* systems in Kenya (Pereira, 1973; Pereira, 1979) have demonstrated the favourable influence of trees on the hydrological characteristics and water balance of the area. Research workers at the then East African Agriculture and Forestry Research Organization (EAAFRO) examined the hydrological effects of changes in land use in some East African catchment areas. The development of tea estates in a tall rain forest caused a considerable increase in storm runoff during the initial clearing and terracing operations, though the tea canopy, once established, gave good protection (Pereira *et al.*, 1962). The special issue of the *East African Agricultural and Forestry Journal* (Vol. 27, March 1962) summarizes the results of various investigations that have been conducted on these aspects. Studies conducted by the Kenya Soil Survey (Muchena, 1979) indicated that infiltration rates were high on forest topsoils if not eroded and that infiltration was often greatly reduced by compaction caused by grazing animals. A record of the ravine reclamation by reforestation in the borders of Rajasthan and U.P. States of India (Patnaik, 1978) also revealed the important role of trees in influencing hydrological characteristics in addition to stopping gully erosion, stabilizing the soil and preventing sedimentation, which were the expected role of trees in the programme.

In addition to these direct effects of trees on the physical properties of soils,

there are also indirect advantages that could profitably be made use of in soil management for agroforestry. For example, one of the well accepted effects of mulching (which is one of the most feasible soil management practices in agroforestry) is the improvement of soil physical properties. Then there are several reports on soil physical conditions via-a-vis soil management and crop growth, but mostly in relation to agricultural crops (see, for example, Lal and Greenland, 1979). All these suggest the possibility of combining the various principles to evolve sound soil management practices for specific agroforestry systems.

3.3.3 Shelterbelts and windbreaks

Moderate to strong winds that blow continuously, as in coastal areas, high plateaus and mountain tops, can have direct and indirect harmful effects on plants. Direct effects are often obvious from the physical deformation of plant parts and their growth forms. Indirect effects concern mainly the water balance of plants and the moisture content, erodibility and other properties of the soil. The use of trees and other woody perennials to protect agricultural fields from these adverse effects of wind is a wide-spread practice in many agricultural systems. The principle can be of considerable value in developing sound agroforestry technologies for areas that are prone to wind damage. Here, again, it is important to select appropriate species of woody perennials and manage them accordingly with a view to obtaining multiple outputs from them, in addition to realising the expected windbreak/shelterbelt effects.

In this regard, very encouraging results have, for example, been reported from the studies conducted at the Pakistan Forestry Research Institute, Peshawar (Sheikh and Chima, 1976; Sheikh and Khalique, 1982). Darnhofer (1982) examined the physical, ecological and biological considerations involved in the design of agroforestry shelterbelts and concluded that the design has to be site-specific depending on a large number of factors, such as major components of farming systems (crops/livestock), the desired pattern of windbreak (simple, multiple, successive) or network systems (with or without secondary hedgerows), and so on. The choice of the woody perennial species to be used as a windbreak is also very important and, as in other agroforestry systems, it will depend upon their phenology, growth habit, multipurpose nature, and complementarity and compatibility with agricultural species.

The increased aerodynamic roughness offered by trees acting as windbreaks and shelterbelts also assists in regulating the ecoclimate within the tree stands. On the west coast of India, for example, Nair and Balakrishnan (1977) observed markedly reduced rates of evaporation and lower temperature regimes even within a plantation of coconut palms (which have long unbranched stems) compared to the bare soil (Table 17).

3.3.4 Ecosystem stability

The role of the protective action of trees in imparting stability to the whole ecosystem is also very well known. The clearing of vegetation affects not only the farmlands in the immediate vicinity, but also destroys the water catchment

Table 17 Evaporation from different ecoclimates of coconut-based systems expressed as percentages of evaporation from the open area on the west coast of India

Months	Ecoclimates of			
	1	2	3	4
			1974-1975	
November	100 (7.4)	75.7	66.2	36.5
December	100 (6.2)	75.8	69.4	30.6
January	100 (5.8)	79.3	62.1	27.6
February	100 (5.3)	83.0	56.6	24.5
March	100 (5.0)	102.0	76.0	32.0
April	100 (6.1)	86.9	68.8	30.6
May	100 (5.8)	84.5	58.6	29.3
Mean	100	80.9	65.4	30.1
			1975-1976	
November	100 (5.7)	68.4	52.6	29.8
December	100 (5.9)	71.2	61.0	30.5
January	100 (6.2)	64.5	51.6	27.4
February	100 (6.3)	68.3	47.6	25.4
March	100 (6.3)	69.8	44.4	22.2
April	100 (6.3)	82.4	52.7	25.7
May	100 (7.4)	91.9	68.9	28.4
Mean	100	73.8	54.1	27.0

Source: Nair and Balakrishnan (1977)

Figures in parentheses are the mean monthly values of evaporation (mm day^{-1}) from the open area

1 Open area
2 Unirrigated coconut
3 Irrigated coconut
4 Coconut + cacao combination

areas, causing flooding of rivers and rapid silting of dams. A study conducted at 17 reservoirs in India has shown that when trees were destroyed in the catchment areas, the annual inflow rate of silt was 917 m^3 km^{-2}, resulting in the shortening of the expected life of the dams by two-thirds (Tejwani, 1977).

Similarly, the incidence of flooding in the Indus river system of Pakistan and the Indo-Gangetic plains of India has been far higher in the past 25 years than during the previous 60. The increased flooding is partly attributable to the denudation of catchment areas. Flood damage below the deforested Himalayan catchment areas of northern India has affected an area averaging 6 million hectares a year over the period 1971 to 1980 and the cost of crop losses and repairs to flood damage has averaged about US$ 250 million annually (World Bank/FAO, 1981).

Forests and other tree communities also influence the ecoclimate of a region. The effect of forest on the rainfall pattern in the tropical belt is a controversial subject. It is argued by some researchers that because the albedo in forests is low and an increase in albedo can cause a decrease in rainfall, any tendency for plant cover to diminish would result in a decrease in rainfall and initiate or aggravate drought (Charney *et al.*, 1975). Because of their thick and complex

structure, forests have a low heat conductivity and large amounts of latent heat are involved in the evapotranspiration process. This enables forests to exercise a buffering effect against rapid cooling or heating and thus regulate the heat released to the ground (FAO, 1972). In bare, exposed, cultivated lands, supra-optimal temperature has been observed in West Africa (Lal, 1975, 1976) and in the upper Amazon regions in South America (Fougerouze, 1966; Decico and Santos, 1976). On the other hand there are also reports that in the highlands of Kenya, exposed bare soil had lower temperature regimes compared to those in adjacent tree stands resulting in low maize yields (Cooper, 1974; Law and Cooper, 1976).

These attributes of trees and their influence on the favourable effects on soil conservation, physical properties, the hydrological balance, microclimate and shelterbelt effect are sufficiently large to indicate the beneficial role of trees in conserving and stabilizing the ecosystem. But most of the examples mentioned here are from forests and other reasonably large tree communities. Moreover, the adverse influence of trees on understorey species, mainly by competition for moisture and nutrients and through shading effects, has not been touched upon. However, in the light of the available evidence of micro-site enrichment qualities of individual trees and tree communities that are much less dense than forests, a generalized scheme can be conceptualized to project the advantages of agroforestry, as shown in Fig. 11.

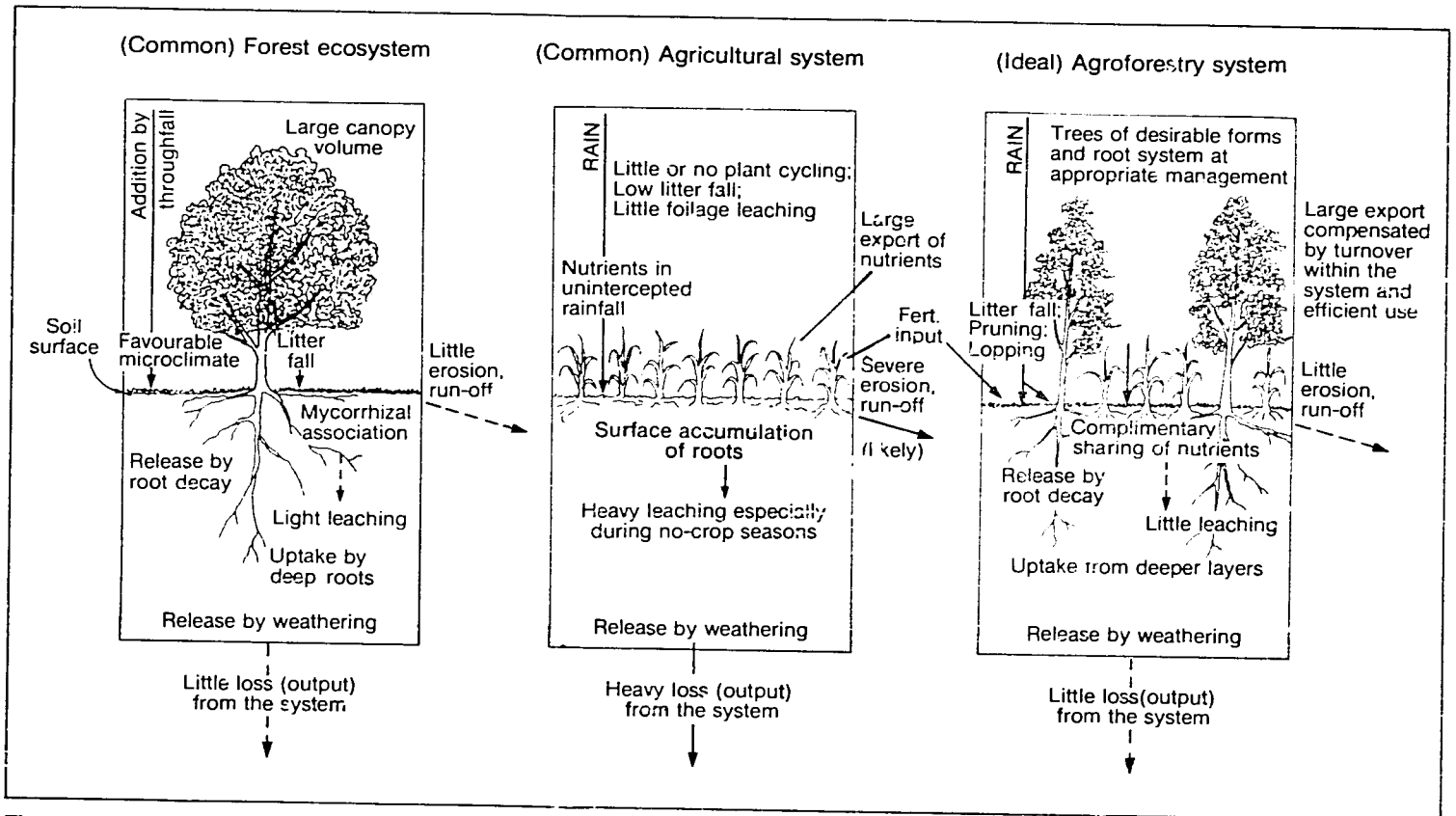

Fig. 11 Schematic representation of nutrient relations and advantages of ideal agroforestry systems in comparison with common agricultural and forestry systems.

4

Research results from some field examples of agroforestry

The foregoing considerations of some land-use systems, together with the assessment of the beneficial effects of trees from the point of view of soil productivity and protection, are strong arguments in favour of incorporating trees on farmlands where this is socially and economically desirable. However, it is important to stress, again, that several of these desirable qualities of trees are often manifested to any discernible extent only in a *community* of trees. In many agroforestry situations, the farmer's primary objective of, say, food production sets limits to the number of trees that can be included per unit of farmland. The question then arises as to the extent to which the desirable attributes can be exploited from such low-density stands of trees. This fact seems to be often overlooked, and the likely benefit from trees exaggerated, when general statements are made on soil fertility restoration and the other potential qualities of trees. Therefore the crucial point is to have a realistic assessment of the likely advantages that can be realized from trees, keeping in view the limits within which trees can become useful components of desirable farming systems in practice. With this in mind, it is appropriate to examine some case studies from different parts of the tropics.

4.1 Hedgerow intercropping (alley cropping)

One of the agroforestry technologies that is becoming the subject of research under a wide range of situations is hedgerow intercropping. It refers to a cropping system where arable crops are grown in the interspaces (or alleys) between rows of planted trees or woody shrubs, which are pruned periodically during the cropping season to prevent shading and to provide green manure and/or mulch to the arable crop (Figure 12A). Promising results have been obtained from this type of study conducted at IITA, Ibadan, Nigeria (Wilson and Kang, 1981; Hartmans, 1981), where the practice is called "alley cropping". IITA's work that led to the alley cropping concept started in early 1972 with the evaluation of legumes as soil conserving/improving crops; the legumes include woody perennials, such as *Leucaena leucocephala* and *Cajanus cajan*.

Preliminary results under upland conditions at the IITA research farm at Ibadan showed that the alley cropping system based on leucaena/maize was particularly promising, and much effort has since been put into developing this system. With the immediate applicability of the system under farmers'

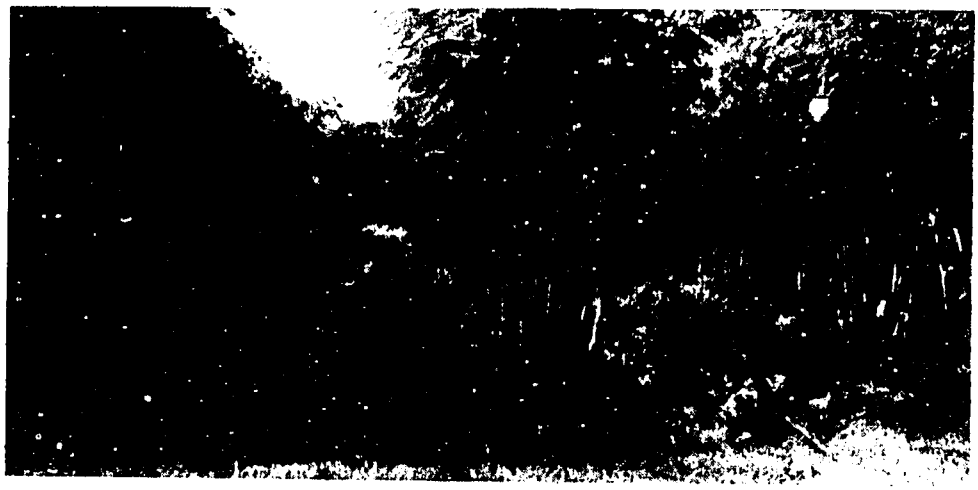

Fig. 12A Hedgerow intercropping or "alley cropping": growing arable crops in the interspaces (or alleys) between rows of planted rows of woody shrubs. The woody species are kept pruned periodically during the cropping season to prevent shading and to provide green manure and/or mulch to the arable crop. The pictures from IITA, Ibadan, Nigeria show the establishment of *Leucaena leucocephala* hedgerows in a standing crop of maize.
Photo credit: B.T. Kang, IITA

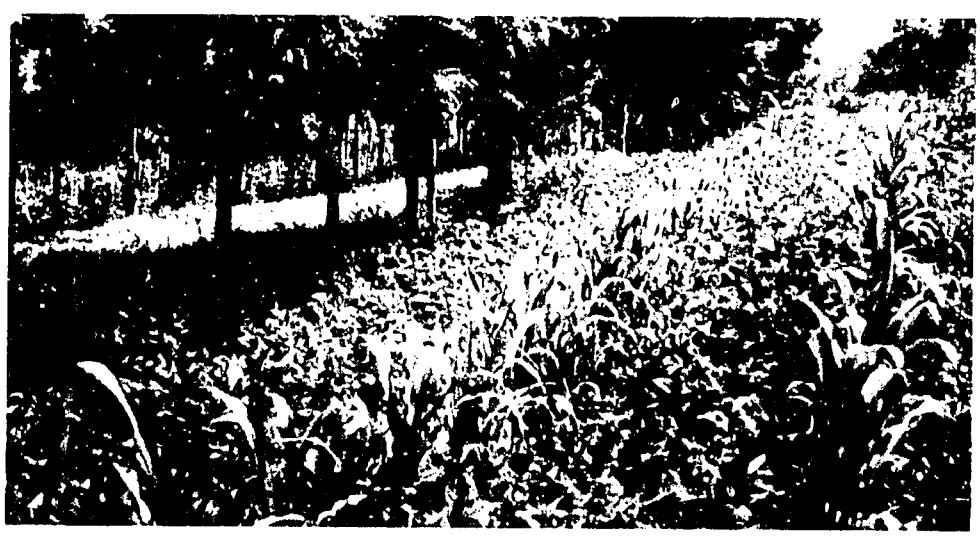

Fig. 12B Another manifestation of the concept of hedgerow intercropping in the agroforestry demonstration/trial plots at "Projet Agro-pastoral" in Rwanda in the central African Highlands. The *Grevillea robusta* trees seen in lines at regular row distances on a maize-and-bean plot are five years old; the lower branches of the trees are pruned off to facilitate light penetration to the understorey crops, and to get good quality poles. Guinea grass (*Panicum maximum*) is planted along Grevillea tree lines, between the trees, for soil conservation. Other crops in the background include sweet potato and climbing bean.
Photo credit: P.K.R. Nair

conditions in the researchers' minds, the development of a simple and economical establishment procedure has received priority attention. Figure 13 shows the planting pattern for establishing leucaena with maize and maize/cassava. The initial phase of a 2-year rotation involving maize/leucaena followed by yam/leucaena was also established in a similar pattern. Crop yields and the growth of leucaena from a 2-year study from one of the plots are given in Table 18, which shows no serious disadvantages to the establishment of leucanea through intercropping. The use of leucaena tops maintained maize

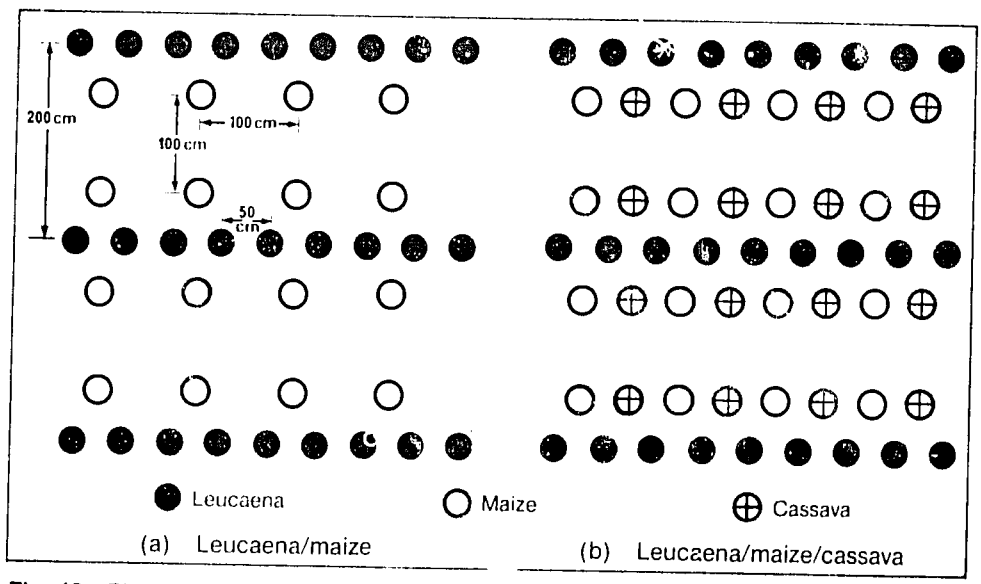

Fig. 13 Planting patterns of hedgerow intercropping (alley cropping) of Leucaena with maize and cassava (*Wilson and Kang, 1981*)

Table 18 Yields of maize, cassava and yam and development of leucaena in hedgerow intercropping (alley cropping) establishment of leucaena

Crop	Year 1 Maize	Year 2 Cassava	Leucaena Height	Leucaena Girth	Yam
	(kg ha^{-1})		(cm)		(kg ha^{-1})
Maize	2512	—	—	—	—
Maize/cassava	3058	20 187	—	—	—
Maize/leucaena	2857	—	375	2.72	14 905
Maize/cassava/leucaena	1840	29 229	370	2.62	12 333
Leucaena	—	—	445	3.14	13 690
LSD 0.05	NS	NS	74	0.25	NS

Source: Wilson and Kang (1981)

NS = not significant

grain yield at a reasonable level, even with no additional nitrogen input on a low-fertility sandy Inceptisol. The effect of nitrogen contributed by the leucaena mulch on maize grain yield was equivalent to about 100 kg ha^{-1} for every 10 t ha^{-1} of fresh prunings (Table 19).

Table 19 Effect of application of Nitrogen and leucaena prunings on grain yield of maize variety TZPB grown in alleys between leucaena hedgerows*

Nitrogen rates (kg N ha^{-1})	Leucaena prunings added at time of planting (fresh weight, t ha^{-1})		
	0**	5***	10***
		Maize yield (kg ha^{-1})	
0	2109	2732	3221
50	2572	3166	3256
100	3377	3450	3432
LSD 0.05	296		

Source: Kang et al. *(1981)*

* Leucaena tops from two prunings carried out during maize-growing season were applied as mulch to all treatments.

** Prunings were removed from this treatment at planting.

*** Supplemented with Leucaena prunings from outside experimental area.

The hedgerow intercropping system offers the advantages of incorporating a woody species within an arable farming system without impairing soil productivity and crop yields. The potential of nutrient (nitrogen) contribution by several candidate species of woody legumes (Table 20) suggests that a wide range of such species could be integrated into crop production systems. By adjusting the interrow spacing of the woody species, mechanized equipment could be used, wherever deemed desirable, for various field operations connected with cropping. Moreover, the trees can be cut back and kept pruned during the cropping period and leaves and twigs applied to the soil both as a

Table 20 Nitrogen contribution by various leguminous woody species interplanted with maize in alley cropping trials at IITA, Ibadan, Nigeria

Shrubs	Leaf yield dry weight (kg ha^{-1})	N content	
		%	kg ha^{-1}
Gliricidia sepium	2300	3.7	84
Tephrosia candida	3067	3.8	118
Cajanus cajan	4100	3.6	151
Leucaena leucocephala	5000-8000	3.2-3.5	180-250

Source: Kang et al. *(1981), Wilson and Kang (1981)*

mulch (see section 4.2) and a nutrient source, with the bigger branches being used as stakes or firewood.

The extent to which the potential benefits of the hedgerow intercropping system can be exploited will depend, however, on a number of factors. In addition to the species of crops and trees, and the environment (climate, soil), tree management aspects, such as method of planting, species admixture pattern and the pruning regime, are also extremely important factors. Moreover, the effectiveness of the practice will also depend on the general level of production of the crop. For example, based on an analysis of leucaena hedgerow intercropping in maize production using published data, Torres (1983) postulated that the potential for hedgerows was highest where soil fertility and the difficulty of adding fertilizer nitrogen limited average maize production to the order of 1,000 kg ha^{-1}. He also computed that in the lowland humid tropics (altitude less than 750 m with an annual rainfall >1,250 mm and length of dry season not exceeding 6 months per year), the productivity of organic nitrogen by leucaena hedgerows planted at distances of at least 150 cm, and plants cut approximately every 8 weeks at 15 to 30 cm height, was 45 g yr^{-1} for every metre length of the hedgerow. This would amount to a hypothetical maximum of 297 kg ha^{-1} yr^{-1}. In actual practice, the amount realised is likely to be less than this figure. In areas with a less favourable rainfall pattern, the number of cuttings will be much less and a wider spacing between hedgerows may be necessitated in order to avoid competition for moisture between the hedgerows and the interplanted crops. Thus, assuming a cutting frequency of 4 to 5 times per year and a row distance of 2 m, and also accounting for the expected unevenness in plant stand in most such situations, the present author's view is that a modest estimate of expected nitrogen contribution from leucaena hedgerows in low-input arable crop production systems in the lowland humid tropics will not usually exceed 100 kg ha^{-1} and will be about half of that in the semi-arid to sub-humid climates (where cutting frequency will be less and interrow distances more).

4.2 Mulch farming

Mulching with crop residues and other vegetative matter has been a consistently successful practice in shifting cultivation. Mulching has also been readily and profitably adopted in horticultural and plantation crop husbandry near market outlets where there are ready opportunities for a cash income.

Several benefits have been attributed to the practice of adding mulch. For example, Lal (1973, 1975) has shown experimentally 46, 55 and 22 percent yield responses of maize to mulch at IITA, Nigeria over the period 1970 to 1972. Such yield increases represent the net effect of a number of favourable effects ranging from seedling emergence and growth aspects to nutrient relations. Moreover, the presence of organic cover on the soil not only reduces the raindrop impact on the soil, but also improves both the physical conditions (Lal, 1979) and fertility status of the soil (Abu Zeid, 1973). Some data on the effect of mulching on runoff losses at Ibadan, Nigeria are given in Tables 21A and 21B. A live mulch cropping system, which involves the planting of an arable crop, such

Table 21A Effect of crop cover and mulching on runoff and relative soil loss, IITA, Ibadan, Nigeria September-December 1970

Slope (%)	Runoff losses (mm)			Relative soil loss - relative to natural vegetation plot of 1% slope		
	Unmulched maize	Mulched maize	Bush regrowth (forest fallow)	Unmulched maize	Mulched maize	Bush regrowth
1	19	6	5	329	2	1.0
5	119	23	4	374	24	1.5
10	125	17	5	352	0.5	2.0
15	52	5	6	348	0.8	2.0

Source: Lal (1976, 1977)

Total rainfall during the period: 295 mm

Table 21B Effect of mulch rate on runoff and soil loss on uncropped land at IITA, Ibadan, Nigeria.

Mulch rate ($t\ ha^{-1}$)	Runoff (%)	Soil loss ($t\ ha^{-1}$)
0	50.0	4.83
2	19.7	2.48
4	8.0	0.52
6	1.2	0.05

Source: Lal (1977)

as maize, directly in a living cover of a low-growing plant (legume or grass), is a further development in this direction. This system incorporates the soil conservation features of organic mulch and no-tillage and has the advantage of smothering weeds and adding nitrogen to the soil.

These principles of mulching are very relevant to agroforestry systems. Loppings from fast-growing and quickly-regenerating woody perennials grown with agricultural crops in either zonal or mixed cropping schemes could be added as mulch on crop production fields. The hedgerow intercropping (alley cropping) system described earlier (section 4.1) is an excellent illustration of the possibility. In these situations, the most readily available form of mulch is likely to be woody residues; besides, there will often be difficulties in obtaining enough quantities of grasses and other leafy mulches for which there is an alternative use as cattle feed. In a recent diagnostic survey of the farming system practices in Machakos District, Kenya conducted by ICRAF to identify the major constraints that limit farm production and to suggest the potentials for improvement through agroforestry practices, the likely benefit from mulching was identified as one of the important aspects of the agroforestry approach to land management in the semi-arid, low-input crop production systems of that region (J.B. Raintree, 1982: personal communication).

However, the use of woody mulch in agroforestry has its own problems. In

IITA experiments during 1975 and 1976 (IITA, 1976; 1977), legume residues were the most effective mulching materials from the point of view of yield response of maize. Mulching with mixed twigs, although effective, did not give the best grain yields at any time. Secondly, even if farmers are ready to allocate land for growing mulch crops, the farm operations connected with growing, cutting, carrying and spreading the mulch can constitute a set of the costliest farm operations. Then there is likely to be the problem of obtaining the mulch in adequate quantities. Most experiments indicate that some 5 to 10 tonnes per hectare of air-dried mulch are needed annually in order to realize the beneficial effects to any discernible extent; getting that much quantity of material could be a problem, especially in semi-arid climates. Other disadvantages of inefficient mulching, such as termite problems, mechanical damage to emerging crop seedlings, the possibility of weeds thriving in gaps left by woody mulch, and the creation of anaerobic conditions during rainy periods, have to be taken into account, as Huxley (1982) has pointed out.

Nevertheless, in those agroforestry systems in which multiple benefits are obtained from fast-growing woody species, there are distinct possibilities for using some parts of such species as woody mulch. A prudent way could, perhaps, be to use such mulch on a part of the farm only - depending on the availability of the mulching materials.

4.3 Intercropping systems involving plantation crops

As mentioned earlier (section 2.3), a sizeable percentage of the total production of most of the plantation crops is obtained in smallholdings, where it is customary to integrate crops and animal production with perennial crops. Most of such intensive land-use systems consist of some form of *crop* combination (see Fig. 14A), although there are other possibilities for intimate *plant* associations leading to more efficient use of land and other available resources (Nair, 1983c). Some of the prominent examples of integrated plantation crop systems include:

- cacao + food crops in Ghana, Nigeria and Trinidad;
- integrated farming (food crops + poultry) systems in rubber smallholdings in Malaysia, Thailand, Nigeria, India and Sri Lanka;
- coffee smallholders in East Africa, Colombia, Ivory Coast and Madagascar;
- intercropping and cattle raising with coconuts in India, The Philippines, Sri Lanka and the Pacific Islands; and
- cashew holdings in India, Tanzania and Mozambique.

Then there are other systems - like the home gardens of Indonesia (Wiersum, 1981) and other thickly populated countries and the mixed plant communities around dwellings in South America (Wilken, 1977). See Fig. 15 for an example.

Research efforts to improve these systems have so far been meagre. One notable example of research input in this direction, though not dealing exclusively with agricultural plantation crops, is the agroforestry trials conducted at CATIE (Centro Agronomico Tropical de Investigacion y Ensenanza), Turrialba, Costa Rica, where trials are in progress with different timber species, such as *Cordia alliodora, Eucalyptus deglupta, Gmelina arborea*

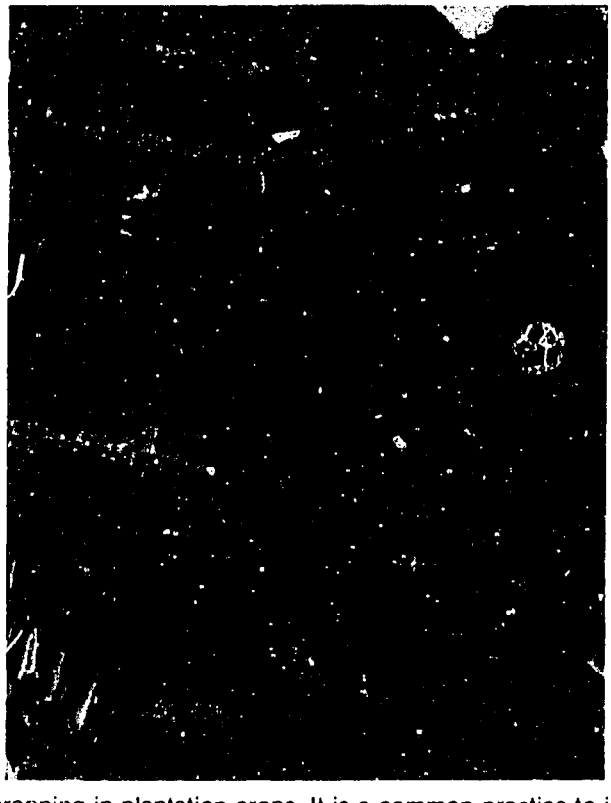

Fig. 14A Intercropping in plantation crops. It is a common practice to interplant one or more other species in the interspaces of woody plantation crops. Picture above shows cloves (*Zyzygium aromaticum*) trees interplanted with cacao, black pepper and papaya, in Bahia State, Brazil. The picture below is a multi-storey crop combination of coconut, black pepper, cacao and pineapple in Kerala State, India. (See also Fig. 4B and 4C). *Photo credit: P.K.R. Nair*

Fig. 14B Plantation crop agroforestry: field of tea interplanted with *Albizzia moluccana* shade trees in Sri Lanka.
Photo credit: Tea Research Institute of Sri Lanka

Fig. 15 Home gardens. Very intimate association of a large number of economically useful plants in the homesteads in thickly populated regions. Picture shows such a scene (Northern Thailand) in which banana, sugarcane and cucurbits feature prominently. Woody perennial species often form an essential component of such systems.
Photo credit: P.K.R. Nair

and *Terminalia ivorensis*, together with various food crops as understorey species. Silvopastoral systems involving *Cordia alliodora* and *Alnus acuminata* with pastures of *Pennisetum purpureum*, *P. clandestinum* and *Axonopus scoparius* (see Fig. 16), and three-layer canopies consisting of coffee or cacao at the lower storey, *Erythrina poeppigiana* as the intermediate canopy and *Cordia alliodora* as the upper layer, are also being investigated at CATIE (Budowski, 1983).

Soil productivity considerations under intercropping with plantation crops have already been briefly discussed (section 2.3.2 and 3.2.2). An important aspect that has been brought out from a unique study on a coconut-based system in India (Nair, 1979; Khanna and Nair, 1980) is that the presence of more plant cover on the plantation floor increases the fraction of nutrients that is cycled within the soil-plant system. Khanna and Nair (1980) estimated that out of a total annual K input of 353 kg ha^{-1} to the soil-plant system in a pure stand of regularly fertilized and well managed coconut palms in the west coast of India, 150 kg was returned to the soil after being taken up by the plant through cycling within the plant system (unavoidable "loss"). In a crop combination system of coconuts plus cacao under similar environmental conditions, this plant cycling fraction was increased to 237 kg and the direct loss by percolation beyond the root-absorbing zone was 55 kg ha^{-1} as compared with 114 kg ha^{-1} yr^{-1} in a sole crop coconut system. These plant cycling fluxes represented 33 and 35 percent of the total fertilizer addition from the sole and mixed (with cacao) plantings of coconuts under the climatic conditions prevailing in the study area.

The increase in the proportion of the plant-cycling fraction of nutrients as a consequence of increased plant cover on the ground facilitates not only a reduction in the direct loss of nutrients, but also enables the plants to meet the demand for highly mobile nutrients, like potassium, when the plants' metabolic needs are not fully met through external inputs, as, for example, in seasons of continued heavy rains (Nair and Khanna, 1978). One of the ways in which this phenomenon operates in a mixed community of plants is through a larger rooting volume. Since the transport of nutrients below the rooting zone is a major avenue for the direct loss of nutrients in sedentary agriculture, the rate of that process can be considerably reduced in mixed plant community systems where the total soil volume of root exploitation will be larger (also see section 3.1) - and consequently the amounts of nutrient loss less.

There is also evidence of complementarity in the interactions between compatible plant species, resulting in the build-up of soil fertility under a mixed crop community as compared to the sole crop (Nair and Khanna, 1978; Nair, 1979; Khanna, 1981). One example from the coconut intercropping system is given in Table 22. One of the reasons that contribute to this complementarity could be the increased activity of beneficial microorganisms, such as the free living di-nitrogen-fixing bacteria, *Beijerinckia* sp.; phosphate-solubilizers, such as *Aspergillus niger*, *Pseudomonas* sp.; and others producing growth promoters, such as glycerine-like substances (GLS) and indole acetic acid (IAA), in the rhizosphere of the crop combination, as discussed by Nair and Rao (1977).

Fig. 16A Silvopastoral system. Cattle grazing on *Pennisetum clandestinum* pasture under *Alnus acuminata* in Costa Rica's highlands.
Photo credit: CATIE, Turrialba, Costa Rica

Fig. 16B Silvopastoral system. Picture shows one-year-old *Dalbergia nigra*, a leguminous woody species of high timber value, with an understorey leguminous pasture species, *Desmodium ovalifolium*, in Manaus State, Brazil.
Photo credit: P.K.R. Nair

Table 22 Biological complementarity of crop combinations - yield of coconut in the coconut + cacao mixed cropping experiment at CPCRI, India

Cropping system	No. of plants/ha			Annual yield of coconuts per palm	
	Coconut	Cacao	Pre-experimental period (average for 2 years)	Experimental period (1972-1978) average for 6 years	Increase over pre-experimental period
Coconut alone	175	—	63	122	54
Coconut + cacao as single hedge between coconuts	175	350	57	121	64
Coconut + cacao as double hedge between coconuts	175	600	39	101	62

Source: Nair and Varghese (1980); Nelliat and Bhat (1979)

The plots were irrigated in the dry months during the experimental (but not during the pre-experimental) period.

Cacao was under-planted in 1970 when coconuts were 20 years old.

4.4 Integration of trees on farmlands in dry regions

A notable example of successful integration of trees on farmlands can be found in the semi-arid regions of West Africa where trees, such as *Acacia* spp., form an essential part of the traditional farming systems (see Fig. 17). Although the basic system of the bush-fallow remains the same throughout the dry savanna regions, several variations are found in different places, as described by Seif-el-Din (1981). One typical example is the system practised in the Sudan in the production of gum arabic (*Acacia senegal*). Gum arabic is combined with agricultural crops in a well defined rotational practice such that the gum is produced during the dry season when the farm labour requirement is at its lowest. Another example is the Bougage land rotation system in Niger, which is a stable bush-fallow system where farmers practise crop and livestock production along with tree planting for wood and fodder supplies. Similarly, in the peanut and millet areas of the Sahelian zone of West Africa, trees form an essential component of the farmland: *Acacia albida, Adansonia digitata* (the baobab tree), *Borassus aethiopum, Parkia biglobosa, Parinari macrophylla, Combretum micranthum, Euphorbia* spp., *Balanites aegyptiaca, Prosopis* spp., *Ficus* spp., *Acacia tortilis*, and others are very commonly found on the

Fig. 17 Agroforestry in the dry zones. *Acacia albida* intercropped with millets in Upper Volta. Note that the Acacia trees are beginning to shed their leaves, and hence offering little shade at this growth stage of the cereal crop. Moreover, crop growth is better nearer the tree than away from it, thus indicating the effect of micro-site enrichment by the tree. The tree will be in full foilage during the dry season when there will be no crop, and they provide valuable fodder to livestock.
Photo credit: Neill McKee, IDRC

farmlands. Since a detailed discussion of all the tree species would be rather lengthy, and because *Acacia* and *Prosopis* are the two most important economic species in the dry regions of the tropics and the sub-tropics (Griffith, 1961), information on these species can be used to illustrate the example.

One of the most comprehensive accounts of the farming system practices involving such trees in the Sahelian region has been done by Felker (1978) for *Acacia albida*. After an evaluation of available literature, he concluded that in the infertile sandy soils of the peanut basin of Senegal, crop yields of peanuts and millet increased from 500±200 kg ha^{-1} to 900±200 kg ha^{-1} directly under *Acacia albida* foliage. In addition to a 50 to 100 percent increase in soil organic matter and nitrogen content as mentioned earlier in sections 3.2.1 and 3.2.2, a marked increase in soil microbiological activity and water-holding capacity was also observed beneath the trees. Jung (1966, 1967) compared soil microbiological changes under and away from *A. albida* trees. Under *A. albida* he found clear increases in invertase, dehydrogenase, asparaginase and respiratory CO_2. Bacteria counts under and away from the tree were the same but under the *A. albida* tree there was a marked increase in the fungi and actinomycetes population, indicating thereby that soil under *A. albida* could more quickly degrade leaf litter to release plant nutrients.

As a result of the increased organic matter content of the soil under the trees, cation-exchange capacity and water-holding capacity were also found to have increased and a better soil structure was obtained (Charreau and Vidal, 1965). As a combined result of these effects, *A. albida* is known to increase soil fertility and consequently crop yields in the small farm holdings in the Sahelian zone. It has been further postulated (Felker, 1978) that the presence of *A. albida* on farms could increase land carrying capacity from 10 - 20 to 40 - 50 persons per square kilometre and enable the farmers to have more sedentary, permanent agricultural settlements by eliminating the need for fallow periods.

Another very useful multipurpose leguminous tree for the dry regions is mesquite (*Prosopis* spp.), of which there are 43 species indigenous to North and South America, Africa and Asia. Excellent reviews on its taxonomy (Burkart, 1976), physiology and ecology (Simpson, 1977) and multipurpose uses (Felker, 1979) are available. The main advantages of the tree are its deep root system and low requirement for water, nitrogen, and plant management, and thus the ability to grow in arid and semi-arid marginal environments (250-500 mm annual rainfall), and yet produce pods rich in protein (13 percent) and carbohydrate (up to 30 percent sucrose) for human and animal consumption (Felker and Bandurski, 1977). It can also prevent soil erosion caused by wind and water, and it yields high-quality fuelwood. There are several reports on the successful adaptation of mesquite trees in arid environments and in poor soils (Gupta and Balera, 1972; Ahmed, 1961; Kaul, 1970; Rao, 1964; Bhimaya *et al.*, 1964).

With regard to intercropping with food- and fodder-crops and soil fertility improvement, *Prosopis cineraria* is a far more useful species than *P. juliflora*. There is a long-standing tradition of growing pearl millet (*Pennisetum glaucum*) (or *Bajra* in the local language) under *P. cineraria* (*Khejri* in the local language) in the arid zones of India. Results of investigations conducted at the Central Arid Zone Research Institute, Jodhpur, India over the past 20 years on the *Khejri* tree have been compiled in an excellent monograph (Mann and Saxena, 1980). In short, *Khejri* supports good growth of understorey pearl millet and a large number of forage species, whereas grass growth under *P. juliflora* was

poor (Ahuja, 1980; Saxena, 1980). These studies have substantiated the scientific basis of the traditional Hindu belief that *Khejri* is sacred whereas *Babul* (*Prosopis juliflora*) is a "resort for demons". This preference for "Khejri" is attributed to the high amount of leaf litter it adds to the soil, increase in soil organic matter and nitrogen content, an increased availability of micronutrients (Zn, Mn and Cu), and higher moisture availability in the surface soil layer in comparison with the soil under *P. juliflora* or the open field conditions (Aggarwal, 1980; Lahiri, 1980). Because of its economic, cultural and socio-religious values, the *Khejri* tree has been acclaimed as the Pride of the Desert (Kaul and Ganguli, 1962), and "Tree of Heaven" (*Kalpa Taru*) in the arid areas of north-west India (Purohit and Khan, 1980).

There are also several other beneficial multipurpose species of trees and shrubs that are found in the arid and semi-arid regions of the world (Felker and Bandurski, 1978). Examples include *Acacia aneura* in the low woodlands of Australia, several other species of *Acacia*, *Balanites aegyptiaca*, *Zizyphus nummularia*, *Cassia auriculata*, *Azadirachta indica*, *Salvadora oleoides*, *Albizzia lebbeck*, *Tocomella undulata*, and others in the dry regions of the Indian sub-continent (see Singh, 1982), *Parkia clappertonian* in the higher (>700 mm per annum) rainfall savannas of Africa, the carob (*Ceratonia siliqua*) in the Mediterranean, the honey locust (*Gleditsia tricanthos*) of southern Africa, and *Prosopis alba*, *P. nigra*, and *P. chilensis* of Argentina. Table 23 gives a list of leguminous trees and shrubs most commonly found in the major agroforestry systems and practices in different ecological regions of the tropics and the sub-tropics. Even without any supplementarity - not to mention complementarity - with associated agricultural species, several of these woody species, with all their multiple uses and ability to grow in environments that are too poor and harsh for other species, play an important role in the life of countless numbers of farmers in their respective regions, and that, in itself, is a sustainable agroforestry possibility in the wider sense of the term.

Table 23: Some characteristics and uses of a few leguminous woody perennials with agroforestry potential *(Nair et al. 1984)*

MAJOR ECOLOGICAL ZONE	SPECIES	ECOLOGICAL ADAPTABILITY: ALTITUDE (m asl)	RAINFALL RANGE (mm/yr)	MAXIMUM DRY PERIOD (months per year)	SOIL CONDITIONS	GROWTH FORM	MANAGEMENT ASPECTS: ESTABLISHMENT	SEED TREATMENT	CARE	COPPICING ABILITY	SEPCIAL FEATURES
HUMID/SUB-HUMID	*Acacia auriculiformis*	up to 600 m	1000 - 1800	6-8	Wide range including Uranium and tin mining spoils. pH 3-9	Tree, 30 m	Direct seeding or seedlings	Boiling water & soak 24 hours	Weeding	Poor	Shallow roots
	Calliandra calothyrsus	up to 1500 m	1000 - 2000	3-4	Wide range of soils. Very good tolerance to flooding	Shrub, 5-10 m	Direct seeding or seedlings	Boiling water & soak 24 hours	Good tolerance to weeds	E cel-lent	1-2 year rotations
	Casuarina equisetifolia	up to 1500 m	200 - 5000	6-8	Most soils except clay. Tolerant to salinity and waterlogging	Tree, 30-50 m	Seedlings	Ant repellant on seed	Weeding	Poor	N-fixing Actinomycete
	Derris indica	up to 1200 m	500 - 2500	4-6	Most soils including limestone. Very good tolerance to salinity	Tree, 5-8 m Deciduous	Direct seeding/ cuttings	None	Good tolerance to weeds	Good	Shade tolerant
	Gliricidia sepium	up to 1600 m	2300	2-3	Moist or dry soils even when very alkaline	Tree 5-10 m Open crown	Seedlings or large cuttings	Hot water (80°C) & soak 24 hours	?	Good	Deciduous
	Leucaena leucocephala	best below 500m	250 - 1700	5-6	Poor growth on acid soils (pH 5). Poor tolerance to waterlogging	Shrub/tree, 5-20 m	Direct seeding or seedlings	Hot water (80°C) & soak 48-72 hours	Weeding	Good	Frost sensitive
	Mimosa scabrella	up to 2400 m	1000 - 2000	?	Most well drained soils. Poor tolerance to waterlogging	Shrub/tree 10-12 m	Direct seeding	?	?	?	3-1 year rotations
	Samanea saman	up to 1000 m	600 2500	5-6	Wide range of soils	Tree, 30-40 m Spreading crown	Seedlings	Feed pods to cattle	Good tolerance to weeds	?	Shallow roots
	Sesbania bispinosa	up to 1200 m	550 - 1100	5-6	Most soils. Very good tolerance to alkalinity, salinity, and waterlogging	Shrub-like, 4 m	Direct seeding	None	Very good tolerance to weeds	-	An annual
	Sesbania grandiflora	up to 800 m	1000 - 2000	2-3	Wide range of soils. Good tolerance to waterlogging	Tree, 10 m	Direct seeding seedlings/cuttings	None	Little maintenance	Good	Frost sensitive

* FAIR
** GOOD
*** EXCELLENT

FUNCTIONS/USES

SPECIES	FOOD: Fruit/Pods	Nuts/Seeds	Vegetables	Oils/Fats	Starch	Spices (S)/ Condiment (C)	FODDER: Leaves	Fruit/Pods/Seeds	Shoots	Raw Forage	WOOD: Fuel Wood	Charcoal	Building Material	Wood for Utensils & Tools	Sawn Timber	Others	SERVICES: Windbreak	Live Fence	Soil Conservation	Dune Fixing	N Fixing	Organic Manure	Mulch	Others	MISCELLANEOUS: Waxes	Essential Oils	Tannins (T) Dyes (D)	Gums	Fibres	Medicinal/Drugs	Cultural, Ritual Social	Ornamental	Other	OTHER REMARKS
Acacia auriculiformis											**	**				pulp			**		**						(T) *	-				**		Outgrows *Imperata cylindrica*
Calliandra calothyrsus							**			*	**								**		**	**										*		Combines well with agric. species
Casuarina equisetifolia											***	***	**	**		pulp	***		**	**	*						(T) *							Fire sensitive
Derris indica							**				**			*					**	**	*					*			-	*				Insecticide properties
Gliricidia sepium							**			**	**						**	***	**		*	**												Coffee/cocoa shade
Leucaena leucocephala							***		**	**	**	**	*			pulp	**		**		**	***												Combines well with agric. species
Mimosa scabrella											**					pulp	*	**			*	**										**		Coffee shade
Samanea saman	*							**						**	**						**							*				**		Pasture shade
Sesbania bispinosa							**				*					pulp	*		**		**	**							**					Combines well with agric. species
Sesbania grandiflora	*		**				**	**			*					pulp	**		**		**	***					(T) *	-		*				Combines well with agric. species

Table 23 (continued)

MAJOR ECOLOGICAL ZONE	SPECIES	ECOLOGICAL ADAPTABILITY: ALTITUDE (m a.s.l.)	RAINFALL RANGE (mm/yr)	MAXIMUM DRY PERIOD (months per year)	SOIL CONDITIONS	GROWTH FORM	MANAGEMENT ASPECTS: ESTABLISHMENT	SEED TREATMENT	CARE	COPPICING ABILITY	SEPCIAL FEATURES
ARID/SEMI-ARID	*Acacia albida*	up to 1200 m	300 - 800	6-8	Sandy silty well drained soils. Good tolerance to salinity	Tree to 30 m	Seedlings	Hot water (80°C) & soak 24 hours	Weeding	Poor	Leafless in rains
	A. senegal	up to 1700 m	200 - 800	8-11	Sandy well drained soils pH 5-8 poor tolerance to waterlogging	Tree 5 to 15 m	Seedlings	Hot water (80°C) & soak 24 hours	Weeding	Good	Browse susceptible
	A. tortilis	up to 1500 m	100 - 1000	10-12	Alkaline and sandy soils. Good tolerance to salinity	Tree flat top 4-30 m	Seedlings	Hot water (80°C) & soak 24 hours	Weeding	Good	Bruchids eat seeds
	Albizia lebbeck	up to 1600 m	500 - 2000	4-5	Prefers drained loams. Good tolerance to salinity	Tree 20-30 m spreading crown	Direct seeding root shoot cuttings	Boiling water & cool & soak 24 hrs	Weeding	Good	Browse susceptible
	Cajanus cajan	up to 3000 m	400 - 2500	5-6	Light sandy soils and loams. Poor tolerance to waterlogging	Shrub 1-4 m	Direct seeding	None. Use fresh seeds	Weeding for first 4-6 weeks	Good at 0.15 m	Shade intolerant
	Cassia siamea	up to 1200 m	500 - 1000	4-5	Most soils including limestone & laterite. Poor tolerance to waterlogging	Tree 15-20 m dense crown	Direct seeding	Hot water (80°C) & soak	Weeding for first 2 years	Good	Browse susceptible
	Cordeauxia edulis	300 - 1000 m	200 - 500	10-12	Sandy soils pH 7-8.5, very poor tolerance to frost	Shrub 1-3 m	Direct seeding	None. Short seed viability (3 mths)	-	-	Frost sensitive
	Pithecellobium dulce	up to 1500 m	400 1600	4-5	Most soils including clay. Good tolerance to salinity and waterlogging	Tree 15-20 m	Seedlings or cuttings	None. 6 month seed viability	Very good tolerance to weeds	Very good	Insects eat seeds
	Prosopis chilensis	300 - 2900 m	200 - 600	8-11	Most soils. Good tolerance to salinity	Tree 6-15 m	Seedlings	Hot water (80°C) & soak 24 hours	Weeding in first year	?	Frost susceptible
	Prosopis cineraria	up to 1000 m	75-850	8-10	Sandy/rocky soils. Tolerates pH 9, salinity and waterlogging	Tree 5-9 m open crown	Seedlings or root suckers	Scarified & boiling water & soak	Good tolerance to weeds	Good	Tolerates slight frost

* FAIR
** GOOD
*** EXCELLENT

FUNCTIONS/USES

SPECIES	FOOD: Fruit/Pods	Nuts/Seeds	Vegetables	Oils/Fats	Starch	Spices (S)/Condiment (C)	FODDER: Leaves	Fruit/Pods/Seeds	Shoots	Bee Forage	WOOD: Fuel Wood	Charcoal	Building Material	Wood for Utensils & Tools	Sawn Timber	Others	SERVICES: Windbreak	Live Fence	Soil Conservation	Dune Fixing	N Fixing	Organic Manure	Mulch	Others	MISCELLANEOUS: Waxes	Essential Oils	Tannins (T) Dyes (D)	Gums	Fibres	Medicinal/Drugs	Cultural, Ritual Social	Ornamental	Other	OTHER REMARKS
Acacia albida							**	*			*		*	*					**		**	**					(T) *							
A. senegal		*					**	**			***	**							**	*	*							***	**	*		*		Combines well with agric. crops
A. tortilis							**	**	*	**	***	**	**	**					**	**	*													Yields Gum arabic
Albizia lebbeck							**		*	**	**		*		**				**		**	*						*				*		Widely used for livestock pens. Termite resistant
Cajanus cajan		**	**				*	**	*		*								**		***								*			*		Fast growing
Cassia siamea							*	*	*		***				**		**		**			**							*			*		Sericulture, shellac
Cordeauxia edulis		***		**	**		**												*		*						(D) *							Very toxic to pigs
Pithecellobium dulce	*			*			**	**		**	*		*		*		*	**			*						(T) *	*				*		Subsistence food
Prosopis chilensis		*					*	*		*	*		**	*					**		*													Presscake makes good stock feed
P. cineraria							**	**		*	***	**	*	*					**	**	**													High biomass yielder. Combines well with agric. species

Table 23 (continued)

MAJOR ECOLOGICAL ZONE	SPECIES	ECOLOGICAL ADAPTABILITY: ALTITUDE (m a s l)	RAINFALL RANGE (mm/yr)	MAXIMUM DRY PERIOD (months per year)	SOIL CONDITIONS	GROWTH FORM	MANAGEMENT ASPECTS: ESTABLISHMENT	SEED TREATMENT	CARE	COPPICING ABILITY	SEPCIAL FEATURES
TROPICAL HIGHLANDS	*Acacia mearnsii*	up to 2000 m	500 - 1200	4-6	Wide range except calcareous soils	Tree to 25 m	Direct seeding	Immerse in boiling water	Good tolerance to weeds	Poor	Mod. frost tolerant
	Albizia stipulata	2000 - 3000 m	500 - 2500	3-5	Well adapted to infertile and shallow soils	Tree 15-20 m	Seedlings, root/shoot cuttings	None	Weeding	Good	Highlands - Nepal
	Alnus acuminata	1200 - 3200 m	1000 - 3000	3-5	Well drained loams and loamy sands. Also on gravelly and clayey soils	Tree 15-40 m	Seedlings or root cuttings	None 2-3 weeks seed viability	Weeding	Good	Actinomycete Frankia sp
	A. nepalensis	300 - 3000 m	500 - 2500	3-5	Wide range. Best on alluvial loams and loamy sands.	Tree 30-40 m	Seedlings/cuttings	None	Good tolerance to weeds	Fair	Shade tolerant
	Lespedeza bicolor	up to 2000 m	500 - 2500	3-5	Most types including infertile rocky soils	Shrub 2-3 m	Direct seeding or seedlings	None	Good tolerance to weeds	Good	Korean species
	Casuarina oligodon	up to 2300 m	700 - 4000	6-8	Most soil types	Tree 20-35 m	Seedlings	Ant repellant	Weeding	?	Mod frost tolerant
	Erythrina poeppigiana	up to 2000 m	1000 - 3000	3-5	Most soils, dry to wet	Tree 10-15 m	Seedlings/cuttings	?	?	Good	-
	Gleditsia triacanthos	up to 1500 m	500 2500	6-8	Most soils, acid to alkaline, sandy to clay	Tree to 45 m flat topped	Seedlings/cuttings	Immerse in hot water (80°C)	Good tolerance to weeds	Good	Frost tolerant
	Inga jinicuil	up to 1400 m	500 - 3000	5-6	Most soils including limestone	Tree, 10-20 m	Seedlings	Short seed viability	?	Good	Termite susceptible
	Trema orientalis	up to 2000 m	1000-3000	3-4	Wide range including denuded infertile soils	Tree, 10-15 m	Seedlings/cuttings	Refrigerate 2°C for 3-4 months	Good tolerance to weeds	Good	Shade intolerant

* FAIR
** GOOD
*** EXCELLENT

FUNCTIONS/USES

SPECIES	FOOD: Fruit/Pods	Nuts/Seeds	Vegetables	Oils/Fats	Starch	Spices (S)/Condiment (C)	FODDER: Leaves	Fruit/Pods/Seeds	Shoots	Bee Forage	WOOD: Fuel Wood	Charcoal	Building Material	Wood for Utensils & Tools	Sawn Timber	Others	SERVICES: Windbreak	Live Fence	Soil Conservation	Dune Fixing	N Fixing	Organic Manure	Mulch	MISCELLANEOUS: Others	Waxes	Essential Oils	Tannins (T) Dyes (D)	Gums	Fibres	Medicinal/Drugs	Cultural, Ritual Social	Ornamental	Other	OTHER REMARKS
TROPICAL HIGHLANDS																																		
Acacia mearnsii											***	**				pulp			***		**	***					(T) ***							Combines well with agric. species
Albizia stipulata							***														**	**						*				**		Coffee/tea shade
Alnus acuminata											**		**	**	*	pulp			***		**	*												Pasture trees
Alnus nepalensis							*				*			**					***		**											*		Outgrows and suppresses most weeds
Casuarina oligodon											***	**	**				***		**		*													Common fuelwood in Papua New Guinea
Erythrina poeppigiana							**							*				**	**		**	**	*											Coffee shade
Gleditsia triacanthos	*						**	*			**		**	**	*		**		**													*		Could become a weed
Inga jinicuil											*		**						**		***	**												Coffee shade
Lespedeza bicolor							**			**	**								***		**	**												Nurse/fallow species
Trema orientalis							**				**	**	**			pulp			**		?													Cacao/coffee shade

5

Soil productivity and soil management in agroforestry: some postulations and suggested research approaches

5.1 Soil productivity

Although there are many variations in agroforestry practices - both in their types, and in the conditions under which they are practised - some hypotheses about expected soil changes under agroforestry can be made in the light of the evidence that has been collated. In doing this, the emphasis is on those systems where trees and other woody perennials do not form a significant component of the existing land-use system(s), but where such species are likely to be integrated without unduly modifying the production patterns of the main existing enterprises.

1. The inclusion of compatible and desirable species of woody perennials on farmlands can result in a marked improvement in soil fertility. There are several possible mechanisms for this, which include:

- an increase in the organic matter content of the soil through addition of leaf litter and other plant parts;
- more efficient nutrient cycling within the system, and consequently more efficient utilization of nutrients that are either inherently present in the soil or externally applied;
- biological di-nitrogen fixation, solubilization of difficultly available nutrients, for example, phosphate, through the activity of mycorrhizas and phosphate-solubilizing bacteria;
- an increase in the plant cycling fraction of nutrients, with a resultant reduction in the loss of nutrients beyond the nutrient absorbing zone of the soil;
- complementary interactions between the component species of the system, resulting in a more efficient sharing of nutrient resources among the components;
- an enhanced nutrient economy because of different nutrient-absorbing zones of the root systems of the component species;
- a moderating effect of additional soil organic matter on extreme soil reactions and, consequently, improved nutrient release/availability patterns.

2. The improvement in the organic matter status of the soil can result in an increased activity of the favourable microorganisms in the root zone. In addition to the nutrient relations mentioned earlier, such microorganisms may also

produce growth-promoting substances through desirable interaction and cause commensalistic effects on the growth of plant species.

3. The inclusion of trees and woody perennials on farmlands can, in the long run, result in marked improvements in the physical conditions of the soil - in permeability, water-holding capacity, aggregate stability, and soil temperature regimes. Although these improvements may be slow, their net result can be that the soil is made a better medium for plant growth.

4. The role of trees in soil conservation and erosion control is one of the most widely acclaimed and compelling reasons for including trees on farmlands that are prone to erosion hazards. The beneficial effects of trees in this regard are limited not only to protecting the immediate farmland under consideration, but also to imparting stability to the ecosystem and reducing the rate of siltation of dams and reservoirs.

5. The influence of trees on hydrological characteristics can extend from the micro-site level to the farm and regional levels. Although the effect of water use by the tree component on water availability to crop plants in different climatic conditions is not yet fully understood, there is evidence that the hydrological characteristics of catchment areas are favourably influenced by the presence of trees.

It should be remembered, however, that agroforestry is only *one* potential approach to land use, which, if adopted properly, *may* prove superior to some other approaches in *some* situations. It is not an approach to replace or substitute other profitable and stable production systems, nor is it a means to do away with nutritional input to soil through manures and fertilizers if sustained productivity at higher levels is to be achieved. Properly practised, the system is likely to use the nutrients more efficiently and cost-effectively, and to increase the sustainability of production from the land. Thus, it may be pointed out again that these suggested benefits are still hypothetical. The magnitude of the benefit that can be derived will depend upon a number of factors, including the environmental conditions, tree and crop characteristics and soil conditions and, above all, management practices. The results are, therefore, likely to differ from farm to farm.

5.2 Soil management

The mechanisms described above, insofar as they are operative, would mean that the incorporation of soil-improving and compatible woody species on the farmlands can considerably retard the rates of various undesirable processes of soil degradation and productivity decline that are brought about in many tropical farmlands by current arable farming practices. However, these likely advantages are still conceptual, if not speculative, and our knowledge of soil conditions in agroforestry is much less than that of these conditions in other well researched agricultural and forestry land-use systems. Validation of these conjectures through appropriate research is essential before the practices based on them can be recommended for adoption with any reasonable expectation of assured benefits. Nevertheless, in order to circumvent the difficulty of experiencing a considerable time-lag in generating research data from well conducted experiments, it seems justifiable, as mentioned in section 1, to consider some expedient measures, however *ad hoc* these might appear to

be at present. Hedgerow intercropping (alley cropping) is one example that illustrates how technically feasible and socially acceptable farming systems involving trees can impart sustainability of production to fragile and easily degradable soils. Similarly, the evidence of the soil-improving qualities of some multipurpose tree species (e.g. *Acacia albida* and *Prosopis cineraria*) in the dry regions, and their complementarity with the understorey agricultural species (section 4.4) would seem to confirm the distinct promise held out by these species. It may not, therefore, be merely wishful thinking to expect possibilities for devising or improving soil management systems for other marginal areas and "wasted" lands in different ecological situations involving a wide range of useful woody perennial species. Brewbaker *et al.* (1983) and Table 23 provide lists of multipurpose woody perennials with a potential role in agroforestry under different conditions.

In the circumstances, some technology components of low-input soil management systems can be suggested for agroforestry situations.

1. Trees and other woody perennials can be incorporated on farmlands, preferably without causing significant changes in conventional agricultural practices. These include alley planting, other zonal systems, and contour strips. Similarly the intercropping of agricultural species can be undertaken in tree stands in a number of ways. Several approaches have also been proposed to increase crop production in shifting cultivation systems without substantially changing the structure of such systems: the corridor system, shortening of the fallow period planted fallows and other ways of improving the quality of fallows.
2. Methods of land clearing and preparation are of crucial importance because certain mechanical operations can result in serious damage to soil physical properties, leading to compaction and degradation of soil structure or the removal of topsoil by erosion. Similarly conventional land preparation methods, especially for agricultural species, can aggravate soil erosion and impair soil physical conditions. The choice of land clearing and preparation methods depends on the soil properties, the species, and the level of management. The magnitude of effort needed to control weeds decreases as the proportion of the soil surface that is left unprotected by a plant canopy over a specified time span decreases.
3. When relatively short-duration agricultural species are continuously cultivated in sole stands or in combination with perennial species, the fertility status of the soil will change, necessitating frequent external inputs of nutrients as manures and fertilizers in order to compensate for such a frequent "export" of nutrients from the soil through harvests. However, in many areas the cost and/or availability of fertilizers make heavy fertilization uneconomical and impracticable. It is in this context that it becomes convenient and important to exploit the desirable soil-enriching and/or restoring characteristics of woody perennials to the fullest extent. Biological di-nitrogen fixation, efficient nutrient cycling, maintenance of higher organic matter status through litter fall and the addition of dead biomass, the complementary sharing of nutrients, and a reduction of leaching loss of nutrients because of more root spread in the soil profile are some of the phenomena that could be advantageously manipulated.
4. A combined stand of plants of different growth habits and forms can be of considerable advantage in protecting soil also. The presence of a greater plant cover on the soil, either as living plants or as mulch, reduces the impact of raindrop on the soil surface and thus minimizes splash and sheet erosion.

Moreover, a higher organic matter content and a larger root volume in the soil impart better physical conditions, thus causing increased infiltration and decreased runoff. These advantages of species diversity of plants in soil productivity and protection are little understood and hence often overlooked.

Considering the vastness and complexity of situations under which agroforestry could be adopted as a viable land-use system (Table 1; Nair *et al.*, 1984), it is inevitable that the soil management considerations outlined above have to be of a general nature. The specific management practices for a given set of conditions will depend upon the prevailing soil conditions, climate, plant species, level of management and other local situations. It would therefore appear worthwhile to aim at a soil quality categorization for grouping soils and soil conditions according to the nature of problems they present, and suggest an agroforestry solution to the management of their physical and chemical properties. While the different categories so developed could indicate the main soil-related constraints, it might be possible to examine ways of overcoming such constraints by appropriate agroforestry technologies. When the necessary data become available, the scheme would be directly applicable to land evaluation exercises, and serve as a useful tool for soil constraint analysis vis-a-vis agroforestry solutions and alternatives.

5.3 The systems approach to the study of soil conditions in agroforestry

As already mentioned, agroforestry situations are more complex than many other land-use systems. The limiting process and regulatory mechanisms are many and varied, and they all have to be studied simultaneously and continuously over a long period of time in order for the system to be understood in its totality. But weaknesses exist in our ability to effect a detailed integration of the various processes and their relations. Therefore, the holistic analysis offered by approaches like 'systems analysis', which can enable us to predict the net results from different interacting processes, appears very promising for research in agroforestry (Loomis and Whitman, 1983). Some examples of the successful application of the procedure in biological fields are found in studies both of farming systems *per se* (Zandstra, 1977, 1980; Zandstra *et al.*, 1980; Collinson, 1980), and of the studies on components of these systems, such as in nutrient cycling in agro-ecosystems (Frissel, 1977) and forest ecosystems (Ulrich *et al.*, 1977; 1979), grazing studies (Innis, 1978), integrative physiology (Loomis, *et al.*, 1979) and pest management (Ruesink, 1976).

The term 'systems analysis', originally taken to mean an analysis of the interrelationships among significant components of a system, is now used to refer to the analysis of relationships - mostly in quantitative terms - among the components, on the basis of convenient and abstract models. Systems analysis has come to have two connotations: analysis of the cause-effect pathways in a complex system (Watt, 1966), and the construction and use of simulation models of complex systems (de Wit and Goudrian, 1974). Since most scientific disciplines are structured around some sort of conceptual models, it is convenient to analyse the system based on such models. Simple models include qualitative hypotheses and easy mathematical statements, which deal

with one or two important processes at a time. But in complex agroforestry situations, discrete measurements at defined times, as are usually possible in individual experiments, are of little value since they neglect the dynamic nature of the processes involved. Therefore it becomes necessary to assemble all the relevant processes and state variables (variables that describe the 'state' of the system, for example, amounts of nutrients in plants and soils), and iterate the assembled model frequently until a final result is simulated. That is how computers have come to play increasing roles in these exercises - to retain very large amounts of information and make very large numbers of calculations.

Systems analysis should not, however, be considered as limited to the formal aspects of model conception and development. Modelling is only a tool or a means in the systems analysis approach to put things together holistically and aim at a cause-effect assessment of a complex system. The analysis will lead to identification of missing information and to establishing research priorities. With the example of their work aimed at characterizing the growth development of *Medicago* sp. (lucerne, alfalfa), Loomis and Whitman (1983) have described how the effort at cause-effect analysis, coupled with quantitative budgets, leads to a well defined set of hypotheses and research objectives.

Khanna and Nair (1980) and Nair and Khanna (1978) applied this procedure while evaluating the fertilizer practices of coconuts in sole and mixed (with cacao) stands. The results of that study have already been briefly discussed (sections 3.2.3 and 4.3). For this purpose, they considered a conceptual model of a unit of the coconut-based system, bordered by the surface of the vegetation and the lower end of the root zone; the system was subdivided into compartments of plant and soil, and each into different sub-compartments. The amounts of nutrients incoming (input) to and outgoing (output) from each sub-compartment were estimated in terms of mass per unit area per unit time (kg ha^{-1} yr^{-1}), which, when put together, revealed the nature of the turnover fluxes within the whole system. The types of field data that are required to be obtained for this type of approach were also indicated from the analysis. The nature of information obtained from the study, such as the magnitude of the recycling processes within the soil-plant system and the losses of nutrient from the system, would not have been obtained from any amount of conventional field experiments to study the plant's response to graded doses of nutrients.

Soils research in agroforestry is not an end in itself, but a means of facilitating the maintenance of stable and productive agroforestry systems under difficult and often harsh situations. From that point of view, the nature of soil studies that need to be undertaken urgently in agroforestry relates to the nutrient cycling, nutrient budgeting and soil conservation aspects that would lead to establishing both the productivity potential of the systems and the sustainability potential of the soil. However, both these aspects are interlinked with plant density-water-management interactions, which, in turn, are compounded by environmental factors and the dynamic nature of the processes. Moreover, the method, frequency and depth zone of soil sampling for these studies have to be different from conventional soil sampling in monoculture situations.

The complexity of these problems demands a total approach, and systems analysis seems to be the best methodology for tackling this. Specific problems that are identified by such a total approach and the critical field data required for the analysis can then be tackled easily with a succession of single- or two-factor experiments. This approach seems to be the most expedient one while dealing with such complex systems as agroforestry.

6

Summary and conclusions

Although the *art* of agroforestry is old, the *science* is new. There is no substantial body of knowledge on any of the operational aspects of agroforestry, including soil management. However, in the context of the increasing awareness about the potential value of agroforestry as an approach to sustainable land use, especially in low-input situations and marginal lands, it is necessary to develop the scientific premises about agroforestry by a synthesis of the existing knowledge from situations similar and relevant to agroforestry. The procedure would be similar to the one adopted in the case of multiple cropping when it emerged as a scientific activity over a decade ago. An evaluation of the relevant land-use systems *per se* and an understanding of the role of trees in enriching and/or conserving the ecosystem are the two aspects to be considered in this context.

Shifting cultivation, the taungya system, woody perennial plantation agriculture, plantation forestry and multiple cropping are the important land-use systems of relevance to agroforestry. Research results on the productivity and management of soils under these systems have been collated and evaluated. Scientific evidence on the productive and protective value of trees on farmlands has also been gathered to indicate the beneficial effects of trees on nutrient relations and soil fertility, nutrient cycling, soil conservation, soil physical properties and ecosystem stability. A few field examples of the successful integration of trees on farmlands have also been given. These include hedgerow intercropping (alley cropping), mulch farming, intercropping in plantation crops, and the integration of trees on farmlands in dry regions.

Based on the available evidence, some postulations are made on the advantages that can be expected if compatible species of trees are properly incorporated on farmlands. Soil fertility advantages could be brought about by the addition of organic matter and nutrients through the input of litter and various plant parts from living trees; the mechanisms involved could be more efficient nutrient cycling, biological di-nitrogen fixation by tree legumes, the solubilization of difficultly available plant nutrients, and a reduction in the leaching losses of nutrients due to more plant cover on the soil and the consequent increase in the plant cycling fraction of nutrients in the soil-plant system. Improvements in the organic matter status of the soil can also result in an increased activity of favourable microorganisms, which, in addition to the effect on nutrient relations, may also have beneficial interactions with higher plants, thus resulting in their better growth. The physical conditions and hydrological characteristics of the soil can also be improved in the long run by the presence of trees, making the soil a better medium for plant growth. The beneficial effects of trees with regard to soil conservation and soil erosion are not limited only to farmlands in the immediate vicinity, but will also extend to the whole ecosystem of the area.

Although these likely advantages are still conceptual, and the concepts have to be validated by field research before site-specific soil management practices can be recommended, it seems necessary to suggest some expedient technology components of low-input soil management systems, however ad hoc they might appear to be. The incorporation of trees on farmlands can be accomplished in a number of ways without causing significant changes in conventional agricultural practices. Some of the soil management considerations of particular value in this context are: combining desirable methods of land clearing and land preparation, exploiting the soil-enriching and restoring characteristics of woody perennials to the fullest extent, making use of the advantages of species diversity in producing adequate soil cover by the plant canopy and/or mulch, and improving the efficiency of nutrient utilization. It would also be worthwhile to have a soil quality categorization for grouping soils and soil conditions according to the nature of the problems they present, and so be able to suggest agroforestry solutions or alternatives to tackle them. Such a scheme would be valuable in land evaluation exercises and for soil constraint analysis vis-a-vis agroforestry.

It has to be emphasized that several of the desirable qualities of trees are manifested to any discernible extent only in a community of trees. But in many farmlands, the farmer's primary objective of, say, food production sets limits to the number of trees than can be included on a farm. Therefore postulations of possible advantages and management considerations should not be interpreted to lead to exaggerated claims and conclusions, nor should agroforestry be considered a panacea for all the defects of currently practised soil management measures. The magnitude of soil management benefits that can be derived from agroforestry will depend on a number of factors and, therefore, will vary from farm to farm.

Intensive research efforts are needed to validate these concepts and devise appropriate soil management practices suitable for different agroforestry systems in diverse agroecological situations. Owing to the sheer complexity of the system, the multiplicity of the regulatory mechanisms and limiting processes, and the dynamic as well as long-term nature of the soil changes, the conventional experimental approaches of a cause-effect nature are unlikely to be of much value in soils research in agroforestry. The holistic, integrated approach of systems analysis, which is increasingly and effectively being made use of in the study of complex biological systems, appears to be very useful in many aspects of research in agroforestry, including soils.

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