Tropical Alley Cropping and Improved Fallows

6

Contents

Abstract

Alley cropping is an agroforestry practice of growing an arable crop between rows of trees or perennial shrubs. In tropical alley cropping, the perennial species, usually leguminous trees or shrubs, are planted and managed as hedgerows less than 10 m apart with the crop planted in the interspaces or alleys between the hedgerows. The trees are *pruned* at regular intervals during the cropping phase and the succulent biomass of leaves and twigs is added to the alleys as green manure (Temperate alley cropping, discussed in Chapter 10, is a form of intercropping between rows of trees where the trees are not pruned, and tree rows are spaced wider). The soil-improving attributes such as efficient nutrient recycling and soil-erosion control of the tree-based system create soil conditions comparable to those in the fallow phase of shifting cultivation. The choice of tree species is an important factor that determines the success or failure of the system. Improved Fallows was introduced as a new technology in the 1990s although its scientific basis is not different from that of tropical alley cropping: using fast-growing nitrogen-fixing trees and shrubs to support the growth and production of food crops growing simultaneously or sequentially with them. More than three decades of research and development experiences with these technologies

P. K. R. Nair et al., *An Introduction to Agroforestry*, https://doi.org/10.1007/978-3-030-75358-0_6

have shown that they perform well under conditions of adequate water availability during crop growing seasons but are unsuitable for dry areas. Despite their technical merits, however, farmer adoption of the technologies has been low, and it is attributed to administrative failures in creating an enabling environment for providing credit and financial support, seeds and other planting materials, and strategic failures in pushing the boundaries of testing to ecological regions that are way beyond the "safe" zones for these technologies.

6.1 Introduction

Alley cropping, initially developed for tropical situations, has since been adapted to temperate zones also. However, there are differences between tropical and temperate forms of alley cropping just like there are differences between tropical and temperate forms of other land-use systems of agriculture, forestry, and animal production. In tropical alley cropping, the perennial species, usually leguminous trees or shrubs, are managed as hedgerows at distances of usually less than 10 m between rows, and the crop is planted in the interspaces or alleys between the hedgerows. The trees are *pruned* during the cropping phase to limit their height to less than a meter from the ground to reduce shading of the interplanted crop and to stimulate the growth of new foliage [*Pruning* usually refers to "trimming off the smaller branches to stimulate new shoot growth" (see Figure 14.3); however, in the context of tropical alley cropping, pruning refers to trimming off the entire upper part of the shrub]. The succulent biomass of leaves and twigs (called *prunings*) obtained in the process is used as green manure or added to the alleys. Thus, tropical alley cropping is a form of hedgerow intercropping; it is also known as "avenue cropping" in some countries. Temperate alley cropping, on the other hand, is a form of intercropping between rows of trees or "tree-row intercropping" where the trees are not pruned, and tree rows are spaced much more widely than in the tropical form to allow the use of farm machinery. Both these forms of alley cropping involve zonal (as opposed to mixed) arrangement of components, in which the components occupy definite zones, usually strips of varying widths. At least until two distinctly different words become accepted universally to denote the two forms of alley cropping, they will continue to be designated as at present (tropical alley cropping and temperate alley cropping). This chapter deals with tropical alley cropping; temperate alley cropping is discussed in Chapter 10. It needs to be strongly emphasized, however, that the random tendency to portray alley cropping as a synonym of agroforestry (for example, Wolf and DeLucia 2018) is incorrect and confusing.

6.2 Tropical Alley Cropping

In (tropical) alley cropping, the woody perennial (tree or shrub) is usually planted in single rows, but sometimes in multiple rows too, and is managed to restrict its growth in the form of a hedge. Although pruning height is variable depending on species and locations, a height of 1 to 1.5 m, which facilitates profuse branching and abundant foliage production, is generally favored. The underlying hypothesis of (tropical) alley cropping is that by retaining the trees on farmlands and adding the nitrogen-rich, easily decomposable biomass to crops grown between tree rows, the nutrients – especially nitrogen (N) – that are released through the rapid decomposition of the prunings become available to the growing crop. The pruning schedule can be set in a way to synchronize N release from the decomposing prunings with N demand of the crop at critical physiological stages (the so-called "synchrony principle": see Chapter 16, Section 16.3.3) without the risk of nutrient loss that could happen in fertilizer applications. The application of fertilizer N in quantities larger than the absorbing ability of plants leads to its loss through runoff and leaching. The soil-improving attributes (such as efficient nutrient recycling, weed suppression, and soil-erosion control) of the tree-based system will create soil conditions comparable to those in the fallow phase of shifting cultivation. Thus, alley cropping retains the basic restorative attributes of the bush fallow system of Africa (Chapter 5) and combines them with arable cropping so that all processes occur concurrently on the same unit of land; this allows the farmer to crop the land for an extended period than under the traditional bush fallow system (Kang et al. 1990). Since it combines both the cropping and fallow phases of the traditional bush fallow system, it is sometimes referred to as an "improved bush fallow system." The technique is scale-neutral, implying its suitability for conditions ranging from smallholder family farms to large-scale mechanized farming situations (Kang 1997).

The basic steps involved in setting up a tropical alley cropping configuration include:

- Plant fast-growing, preferably nitrogen-fixing, trees and shrubs, which are usually propagated by large cuttings, on crop-production fields in rows 4 to 8 meters apart (depending on the crop, one or more rows of the crop may have to be compromised for establishing the trees)
- Once the trees are established (usually 18 to 24 months after planting), prune them periodically (at 4- to 8-week intervals depending on the species and its rate of regrowth) and place or "apply" (leave on the soil surface or incorporate) the succulent foliage between rows of interplanted crops
- Let the trees grow unpruned during the dry season when there are no crops in the field
- When the land is being prepared at the beginning of the cropping season (at the end of the dry season and onset of the rainy season), cut the tree hedgerow branches that would have grown tall, strip the leaves and small branches off the thicker branches and incorporate the foliage to the soil before sowing the crop, and set aside the thicker branches for use as firewood, yam stakes, and such other farm- and household uses.
- Repeat tree pruning and application of pruning as above year after year until the trees become senile as indicated by thickening stumps and declining coppicing ability resulting in low biomass (pruning) yields, which happen when they are 10 to 15 years old depending on species. At that stage, the field could be used for other farming operations or planted with a different hedgerow species to repeat alley cropping.

Pioneering work on this technology was initiated at the International Institute of Tropical Agriculture (IITA), in Nigeria, during the early 1980s. As a newly minted technology, alley cropping generated a lot of interest among researchers and development professionals and it was portrayed as a viable alternative to the traditional bush-fallow system. The practice has been tried and evaluated in many parts of the tropics under a variety of soil- and climatic conditions (Figures 6.1, 6.2, 6.3, 6.4, 6.5, and 6.6). The technology, originally developed as an approach to enhancing crop production in areas of West Africa dominated by the traditional bush-fallow system, was soon extended to fodder production systems (by using fodder tree and shrub species as hedgerows and for erosion control on sloping lands (by using contour-aligned hedgerows as live barriers to erosion: Figure 6.7). The potential of alley cropping for reaping such benefits have been investigated under several agroclimatic

Figure 6.1 Alley cropping: *Gliricidia* - Early (1980) trials at IITA, Nigeria. (Photo: PKR Nair 1984)

Figure 6.2 Alley cropping: *Gliricidia* - Early (1980) trials at IITA, Nigeria. (Photo: PKR Nair 1985)

Figure 6.3 Alley cropping: *Leucaena* – Machakos, Kenya. (Photo: PKR Nair 1984)

Figure 6.4 Alley cropping: *Leucaena* – Machakos, Kenya. (Photo: PKR Nair 1985)

Figure 6.5 Alley cropping: *Senna siamea* – Machakos, Kenya. (Photo: PKR Nair 1985)

conditions and numerous conceptual and research-based publications on the topic were produced during the 1980s and 1990s (Kang et al. 1990, 1999; Nair 1990; Kang 1993, 1997; Akeyampong et al. 1995; Sanchez 1995; Jama et al. 1995; Cooper et al. 1966; Rao et al. 1998). Biophysical aspects were the thrust of much of the research in alley cropping; these results are summarized in this chapter.

6.2.1 Hedgerow Species

Biologically, the effectiveness of alley cropping systems depends on the tree/shrub species used – which depends on soil type and agroecological characteristics of the location – and the management strategies adopted. Several factors such as the choice of tree species, row orientation, field layout, and manipulation of the hedgerows and

Figure 6.6 Alley cropping: Acid Soil at Yurimaguas, Peru – *Dactyladenia barterii*. (Photo: PKR Nair 1985)

Figure 6.7 Contour hedgerows of *Leucaena leucocephala* for soil conservation in Haiti. (See also Chapter 18, Figure 18.17 from Haiti, and Figures 18.9, 18.10, and 18.11, and 18.12 from other countries).
(Photo: PKR Nair 1988).

crop husbandry practices are important in determining the success of the alley cropping system.

The choice of tree species for alley cropping is perhaps the most important factor, and to a large extent, it determines the success or failure of the system. Kang and Gutteridge (1994) proposed several major attributes that should be considered when selecting tree species for alley cropping, including:

- fast growth rate
- ability to withstand frequent cutting
- good coppicing ability (regrowth after cutting)
- ease of establishment from seeds or cuttings
- nitrogen-fixing capacity
- deep-rooting habit
- multiple uses such as forage and firewood
- ability to withstand stresses (drought, waterlogging, soil pH extremes, etc.)
- high leaf-to-stem ratio
- small leaves or leaflets
- leaf-retention during the dry season
- non-susceptibility to pests and diseases.

A wide range of tree species has been used in alley cropping experiments or demonstrations in the tropics (Table 6.1), but *Leucaena leucocephala* (commonly known as leucaena) has been the most widely used (Kang et al. 1990). Numerous trials in different parts of humid and subhumid tropics have shown that leucaena performed comparatively better than other species in soils of relatively high base-status, whereas, in acidic, low base-status soils, leucaena was not as successful as some other species such as *Flemingia macrophylla* in Nigeria (Kang et al. 1990) and *Erythrina peoppigiana* in Costa Rica (Kass et al. 1993). Several of the species used in tropical alley cropping are used in “Improved Fallows” too as described later

Table 6.1 Common agroforestry tree and shrub species used for soil fertility improvement in Alley Cropping (AC) and Improved Fallows (IF) in the tropics and subtropics.

Species	Reported use in AC/IF	Short description	Ecological adaptability
Acacia angustissima	AC, IF	Legume, N_2 fixer; short duration; coppicing	Wide range, sub-humid
Cajanus cajan	IF	Legume, N_2 fixer; valuable grain legume, mostly short-lived; non-coppicing	Semiarid to sub-humid
Calliandra calothyrsus	AC	Legume, N_2 fixer; mildly coppicing, cattle fodder, firewood	Humid to sub-humid, Acid to neutral soils, medium elevations
Flemingia macrophylla	IF	Legume, N_2 fixer	Humid to sub-humid
Gliricidia sepium	AC, IF	Legume, N_2 fixer; fuelwood; shade tree for cacao	Wide adaptability
Inga edulis, *I. jinicuil*	AC, IF	Legume, N_2 fixer; coppicing	Humid to sub-humid lowlands
Leucaena leucocephala	AC, IF	Legume, N_2 fixer; vigorous coppicing, excellent cattle fodder	Basic to neutral soil, Wide range
Senna siamea	AC, IF	Legume, N_2 fixer; coppicing, fuelwood; mildly coppicing	Sub-humid to semiarid
Sesbania sesban, *S. grandiflora*	IF	Legume, N_2 fixer; short duration	Acid to neutral soils, Humid to subhumid
Tephrosia candida, T. vogelli	IF	Legume, N_2 fixer; non-coppicing	Acid to neutral soils, Sub-humid to semiarid
Non-Woody Species			
Calopogonium mucunoides,		N_2 fixer, short duration, green-manure/cover crop	Wide adaptability
Centrosema pubescens		N_2 fixer, short duration, green-manure/cover crop	Wide adaptability
Crotalaria spp. *(agatiflora, grahamiana, incana, striata)*		N_2 fixer, mostly short duration	Wide adaptability; dry climates preferred
Desmodium spp. *(discolor, distortum, uncinatum)*		N_2 fixer, fodder/cover crop	Wide adaptability

(Section 6.3) and indicated in Table 6.1; short profiles of some of them are also included in the Agroforestry Tree Species Profiles (Chapter 13, Annexure 13.I).

6.2.2 Nutrient (Nitrogen) Yield from Tree Species and Soil Fertility

The growing emphasis on the role of nitrogen-fixing trees in soil-fertility improvement in agroforestry systems, particularly alley cropping (Brewbaker et al. 1982; Dommergues 1987; Nair 1988), has encouraged the initiation of field trials in various places and varied conditions, and numerous research results have been published. The preponderant trend emerging from such studies is that legumes generally outperform non-legumes in terms of the productivity of the companion crops. For instance, on an Alfisol in southwestern Nigeria, Kang et al. (1999) showed that alley cropping systems involving gliricidia (*Gliricidia sepium*) and leucaena provided greater nutrient yields than those of non-legumes such as *Alchornea cordifolia* and *Dactyladenia (*syn. *Acioa) barteri,* and the former sustained moderate levels of maize yield (>2 t ha^{-1}) without exogenous nutrient inputs, implying a “saving” in the application of nitrogenous fertilizers under alley cropping situations.

There are, however, great variations in the estimates of nitrogen fixation by trees depending on methods of estimation (Chapter 17) as well as the nitrogen-fixing ability of different tree species. Given that, the nitrogen-fixation rates reported in the literature are, at best, only indicative and not necessarily accurate; but also are strictly location-specific. The nitrogen contribution of a woody perennial to a current season's crop (that usually means the amount of nitrogen made available from the decomposition of biomass added to soil and the sloughing off of legume root nodules) is the most important source of nitrogen for crops in unfertilized alley cropping systems. Obviously, the amount of nitrogen added varies, and largely corresponds to the biomass (and nitrogen) yield of trees, which in turn depends on the species and its management and site-specific factors. Simply stated, the higher the biomass yields, the greater will be the nutrient yield and cycling. As noted above, nitrogen contributions may also vary according to the rate of nitrogen fixation as well as the turnover rate of nodulated roots.

Some data on the biomass (and nutrient) yield of four woody species growing on Alfisols in Ibadan, Nigeria, under different management systems, are provided in Table 6.2. Kass (1987) reported similar data from alley cropping studies conducted in CATIE (The Tropical Agricultural Research and Higher Education Center), Costa Rica, in which *Erythrina poeppigiana* (commonly called erythrina) was grown as a hedgerow species. In one of the early reports on the topic, Torres (1983) estimated that the annual nitrogen yield of leucaena hedgerows, cut approximately every eight weeks, was 45 g per meter of hedgerow; if the hedges were planted 5 m apart, this amounted to 90 kg N ha^{-1} yr^{-1}. Higher nitrogen contributions have been reported from other field studies where the hedgerow species was leucaena or gliricidia (Yamoah et al. 1986a; Budelman 1988; Kang et al. 1999). In a comparative study of the effect of various pruning practices on leucaena, gliricidia, and *Sesbania grandiflora* (commonly called sesbania), Duguma et al. (1988) found that for all three species, the highest yields were obtained from biannual prunings at 100 cm pruning heights (245, 205, and 111 kg N ha^{-1} yr^{-1}, respectively).

The major focus of nutrient status and soil fertility studies under alley cropping was on nitrogen; however, hedgerow prunings are also reported to be an important source of nutrients other than nitrogen (Table 6.2). In studies conducted in Côte d'Ivoire, yields of 44, 59, and 37 kg of K ha^{-1} were obtained for three months from *G. sepium*, *L. leucocephala,* and *Flemingia macrophylla* (syn. *F. congesta*), respectively (Budelman 1988). Alley cropping has also been found to increase plant-available phosphorus (P), (Haggar et al. 1991; Hands et al. 1995). Other studies have shown that nutrient cycling through aboveground prunings is many times more than that which occurs through root turnover (Schroth and Zech 1995; Govindarajan et al. 1996).

The chemical aspects of soil fertility under alley cropping have received much attention in research during the 1980s to early 2000s. Based on a comprehensive review of available literature on the topic, Rao et al. (1998) concluded that the major mechanisms by which hedgerows increase or maintain nutrient status in the crop rooting zone are: (1) nitrogen input to the system through

Table 6.2 Estimated nutrient yield from hedgerow (4-m interrow spacing) prunings (not including woody material) of four fallow species grown in alley cropping on a degraded Alfisol in southern Nigeria

		Nutrient yield[a]				
	Biomass yield[a]	N	P	K	Ca	Mg
Species	t ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}				
Acioa barterii	3.0	40.5	3.6	20.4	14.7	5.4
Alchornea cordifolia	4.0	84.8	6.4	48.4	41.6	8.0
Gliricidia sepium	5.5	169.1	11.1	148.8	104.3	17.6
Leucaena leucocephala	7.4	246.5	19.9	184.0	98.2	16.2

[a] Fifth year after establishing of hedgerows; total of five prunings

Source: Kang and Wilson (1987)

biological nitrogen fixation in the case of N_2-fixing species, (2) reduced soil erosion, (3) reduced leaching loss of nutrients, and (4) uptake of nutrients from lower soil layers that are beyond the crop root zone and recycling them to the soil surface via prunings. Two aspects of this topic that received special attention were: biomass decomposition and nutrient cycling patterns, and dynamics of soil nutrient pool vis-à-vis soil chemical properties following mulch (pruning) application. These issues are of fundamental importance in hedgerow management for best results in alley cropping; both issues are considered in detail in Chapter 16.

An important criterion to judge the success of alley cropping at any location is the quantity of nutrient-rich mulch that can be produced for timely application during the crop-growing season. If the ecological conditions do not favor the production of enough quantities of nutrient-rich mulch for timely application, then there is no perceptible advantage in using alley cropping. Let us examine, for example, the quantity that could potentially be produced from 1 ha. Within a square configuration of 100 x 100 m, it is feasible to have 20 hedgerows of leucaena, each 100 m long and 5 m apart. If the hedgerows are pruned three times per cropping season (once just before the season and twice during the season), and if the rainfall conditions permit two crops a year, this results in six pruning events a year. Assuming a biomass yield of 375 g of dry matter (1.5 kg fresh matter) from each pruning per meter of hedgerow, the total biomass yield will be 4500 kg of dry matter (375 g x 2000 m x 6 cuttings). If the N content of this dry matter is 3% on average, the total N yield would be 135 kg ha^{-1} yr^{-1}, about half of which can be expected to be taken up by current season crops.

6.2.3 Soil Properties and Soil Conservation

Alley cropping, compared with annual crops, is reported to have improved soil physical conditions considerably. These include better soil aggregation, lower bulk density, and improved soil porosity, resulting in increased water infiltration and higher water holding capacity (Lal 1989; Jama et al. 1995; Yamoah et al. 1986b). These beneficial effects are primarily due to increased soil organic matter and root activity of perennial hedgerows, and secondarily due to increased activity of soil microorganisms. It is doubtful, however, if improved soil physical conditions will increase available soil water to alley crops under water-limiting conditions considering the presumed competitive dominance of the hedgerows over crops (Rao et al. 1998). An earlier study had indicated that competition for soil moisture between the hedgerows and crops made alley cropping less suitable for semiarid tracts (Singh et al. 1989).

Studies on the effect of alley cropping on other soil properties have been rare. Comparing the effect of three mulches – *F. macrophylla*, gliricidia, and leucaena – applied at the rate of 5 t ha^{-1} dry matter near Abidjan, Côte d'Ivoire, Budelman (1989) found that all three, particularly *F. macrophylla*, had favorable effects on soil temperature and moisture conservation (Table 6.3). The report by Lal

Table 6.3 Average temperature and soil moisture content over a 60-day period after adding three different mulches at a rate of 5000 kg dry matter ha^{-1}

Treatment/ mulch material	No of observations at 15.00 h	Average temperature at 5 cm (°C)	Average % soil moisture over 0–5 cm
Unmulched soil	40	37.1	4.8
Leucaena leucocephala	40	34.2 (-2.9)	7.1 (+2.3)
Gliricidia sepium	40	32.5 (-4.6)	8.7 (+3.9)
Flemingia macrophylla	40	30.5 (-6.6)	9.4 (+4.6)
LSD		1.20	1.84

Note: Values in parentheses is the difference relative to an unmulched soil
Source: Budelman (1989)

Table 6.4 Changes in some physical properties of an Alfisol under alley cropping and no-till systems at IITA, Nigeria

Cropping system	Infiltration rate at 120 min (cm h^{-1})			Bulk density (g cm^{-3})		
	Year 1	Year 3	Year 5	Year 1	Year 3	Year 4
Plow-till	24.2	23.2	21.4	1.36	1.51	1.42
No-till	18.0	12.4	5.0	1.30	1.47	1.62
Alley cropping						
Leucaena 4 m	39.8	13.0	22.2	1.26	1.44	1.50
Leucaena 2 m	13.6	22.4	22.8	1.40	1.39	1.65
Gliricidia 4 m	18.8	18.8	16.8	1.30	1.35	1.57
Gliricidia 2 m	13.8	21.0	19.6	1.33	1.45	1.55
LSD (0.1)	5.8			0.03		

Source: Lal (1989)

(1989) based on experiments at IITA indicated lower soil bulk density and penetrometer resistance and higher soil moisture retention and available plant water capacity under alley cropping compared to non-alley cropping (Table 6.4).

Soil biological activity is crucial in low-input systems where the major source of nutrient supply for crop growth is the decomposition of newly added organic residues and concomitant release of nutrients contained in them (see Chapter 16). The role of soil macrofauna, especially earthworms, is particularly important in improving soil structure and, in turn, soil water relations and nutrient availability to crops. Yamoah et al. (1986b) observed 46% higher soil microbial biomass C (a measure of biological activity) under alley cropping with gliricidia and senna (*Senna siamea;* syn. *Cassia siamea*) than under sole cropping in the 0–15 cm soil layer. Higher earthworm activity was also reported under hedgerows on Alfisols in Nigeria (Kang et al. 1990). In a 7-year trial, Hauser and Kang (1993) found nearly five times more worm casts under leucaena hedgerows (117 kg ha^{-1}) than in the middle of the alley (24 kg ha^{-1}). Similarly, higher populations of earthworms, ants, and termites were noted under alley cropping with gliricidia and erythrina in Costa Rica (Hands et al. 1995).

Reports on the long-term effects of alley cropping on soil physical and chemical properties and hence on crop production are limited to a few from IITA, the institution with the longest record of alley cropping research. Kang et al. (1989) and Kang and Wilson (1987) reported that, with the continuous addition of leucaena prunings, higher soil organic matter and nutrient levels were maintained compared to no addition of prunings. Atta-Krah et al. (1985) showed that soil under alley cropping was higher in organic matter and nitrogen contents than treeless soil. Yamoah et al. (1986a) compared the effect of senna, gliricidia, and *F. macrophylla* in alley cropping trials, and found that soil organic matter and nutrient status were maintained at higher levels with *S. siamea* (although it is not an N_2-fixing species). Another set of reports from IITA by Lal (1989) showed that over six years (12 cropping seasons), the relative rates of decline in the status of nitrogen, pH, and exchangeable bases of the soil were much less under alley cropping than under non-alley cropped (continuous cropping without trees) control plots.

Numerous field projects undertaken in various parts of the tropics have shown that contour hedgerows are an effective soil conservation measure (Figure 6.7; see also Chapter 18). Most such reports, however, are based on field observations that lack experimental rigor and therefore do not get into scientific literature (which is an important issue for many similar agroforestry studies). Apart from the review by Young (1989), which contains convincing arguments regarding the beneficial effect of agroforestry on soil conservation, two reports produced in 1989 are worth mentioning in this context. Ghosh et al. (1989) carried out a study in a 1700 mm yr^{-1} rainfall zone in southern India, with hedges of leucaena and *Eucalyptus* (species not reported) intercropped with cassava (*Manihot esculenta*), groundnuts or peanuts (*Arachis hypogaea*), and various vegetables in a field with 5% to 9 % slope; the leucaena hedgerows were pruned to 1 m at 60-day intervals after the first year. In the second year of study, the estimated soil loss from the bare fallow plot was 11.94 t ha^{-1} yr^{-1}, whereas, for the leucaena alone and leucaena + cassava, the estimated losses were 5.15 and 2.89 t ha^{-1} yr^{-1}, respectively. The other study conducted in Nigeria reported that soil erosion from leucaena-based plots and gliricidia-based plots were 85 and 73 percent less, respectively, than from plow-tilled control plots; leucaena contour hedgerows planted 2 m apart were as effective as non-tilled plots in controlling erosion and run-off. The study also showed that, during the dry season, the hedgerows acted as windbreaks and reduced the desiccating effects of the "*harmattan*" winds; soil moisture content at a 0–5 cm depth was generally higher near the hedgerows than in non-alley cropped plots (Lal 1989).

6.2.4 Crop Yields Under Alley Cropping

The criterion that is used most widely to assess the desirability and success of any agricultural technology is its impact on crop yields; alley cropping is no exception. Indeed, most alley cropping trials have reported little data other than crop yields, and that too from trials conducted over a relatively short period. The net effect of alley cropping on the various tree–crop interactions under several agroclimatic conditions expressed in terms of crop yield has been investigated/reviewed by several authors (Kang et al. 1990; Nair 1990; Kang 1993; Akeyampong et al. 1995; Sanchez 1995; Cooper et al. 1966). Rao et al. (1998) identified the major interactions that affect crop yields as those related to soil fertility, competition, weed control, and soil conservation (especially in sloping lands), and expressed the net effects of these on crop yields as presented in Table 6.5. Overall, many trials have produced promising results; but most of them have been under research conditions. Some of the results are mentioned here in the following paragraphs.

An eight-year alley cropping trial conducted by Kang et al. (1989, 1990) in southern Nigeria on sandy soil showed that using leucaena prunings only, maize yield could be maintained at a "reasonable" level of 2 t ha^{-1}, as against 0.66 t ha^{-1} without leucaena prunings and fertilizer (Table 6.6). Supplementing the prunings with 80 kg N ha^{-1} increased maize yield to over 3.0 t ha^{-1}. The effect of using fertilizer without the addition of leucaena prunings was, however, not tested in the study. Yamoah et al. (1986b) reported that to increase the yield of maize alley cropped with senna, gliricidia, and *F. macrophylla* to an acceptable level, it was necessary to add nitrogen. An earlier report by

Table 6.5 Net effect on crop yield of tree-crop-soil interactions in hedgerow intercropping systems in different climates, assuming a moderately fertile soil

Process	Semiarid	Subhumid	Humid
Nutrient availability to alleycrops	positive (S → L)	positive (L)	positive (L)
Soil chemical changes	positive (S)	positive (S)	positive (L)
Soil physical changes	positive (S → L)	positive (S → L)	positive (S → L)
Soil biological changes	neutral	positive (S → L)	positive (L)
Soil conservation	positive (S → L)	positive (L)	positive (L)
Water availability to alleycrops	negative (L)	Neutral/negative (S)	neutral
Shading	neutral	negative (S)	negative (L)
Microclimate changes	positive (S)/neutral	neutral	neutral
Weed suppression	positive (S)	positive (L)	positive (L)
Crop yield	negative (S → L)	positive (S → L)	positive (S → L)

S = small; L = large
Source: Rao et al. (1998)

Table 6.6 Grain yield of maize grown in rotation with cowpea under alley cropping at IITA, Nigeria (t ha^{-1})

Treatment†	Year						
	1979	1980	1981‡	1982	1983	1984§	1986
0N-R		1.04	0.48	0.61	0.26	0.69	0.66
0N+R	2.15	1.91	1.21	2.10	1.91	1.99	2.10
80N+R	2.40	3.26	1.89	2.91	3.24	3.67	3.00
LSD (0.05)	0.36	0.31	0.29	0.44	0.41	0.50	0.18

Note: § Plots fallowed in 1985

†N-rate 80 kg ha^{-1}; (-R) *Leucaena* prunings removed; (+R) *Leucaena* prunings retained. All plots received basal dressing of P, K, Mg and Zn

‡Maize crop affected by drought

Source: Kang et al. (1990)

Table 6.7 Grain yield and dry matter production from crops in different cropping systems at Yurimaguas, Peru

Cycle crop	Yield (kg ha^{-1}) under cropping system†							
	Cc	Ie	Nc	Fc	Cc	Ie	Nc	Fc
	Grain‡				Dry matter			
1. Maize	634a		390a	369a	1762b		2268b	4339a
2. Cowpea	778ab	526b	1064a	972ab	1972b	1791b	2597b	4766a
3. Rice	231a	211a	488a	393a	1138b	1160b	1723b	3718a
4. Rice	156c	205bc	386b	905a	929b	1151b	2121b	5027a
5. Cowpea	415a	367a	527a	352a	1398b	1353b	1404b	3143a
6. Rice		386b	382b	1557a		1054b	1037b	4897a

Note: For grain or dry matter, means within a row that are followed by the same letter are not significantly different, based on Duncan's test, $p = 0.05$

†Cc = *Cajanus cajan* alley cropping; Ie = *Inga edulis* alley cropping; Nc = nonfertilized, nonmulched control; Fc = fertilized, nonmulched control

‡Maize grain yield based on 15.5% moisture content; rice and cowpea grain yields based on 14% moisture content. *Inga* plots in cycle 1 and *Cajanus* plots in cycle 6 were not cropped

Source: Szott et al. (1991a)

Kang et al. (1981), however, had indicated that an application of 10 t ha^{-1} of fresh leucaena prunings had the same effect on maize yield as the addition of 100 kg N ha^{-1}, although to obtain this amount of leucaena leaf material it was necessary to supplement production from the hedgerows with externally-grown materials. Kang and Duguma (1985) showed that the maize yield obtained using leucaena leaf materials produced in hedgerows planted 4 m apart was the same as the yield obtained when 40 kg N ha^{-1} was applied to the crop.

Crop Yield Reductions under Alley Cropping: Results from all alley cropping trials have not always been promising, however. For example, in trials conducted on infertile acid soil at Yurimaguas, Peru (Figure 6.6), the yields of all crops studied in the experiment, apart from cowpea (*Vigna unguiculata*), were extremely low, and the overall yield from alley cropped plots was equal to or less than that from the control plots (Table 6.7). Szott et al. (1991a, 1991b) concluded from these data that the main reasons for the comparatively poor crop performance under alley cropping treatments were root competition and shading and that the competition increased with the age of the hedgerow. Other possible explanations are that the surface mulch physically impeded seedling emergence such that the decomposing mulch caused temporary immobilization of nutrients thus seriously reducing the availability of nutrients to young seedlings at a critical stage of their growth.

Moisture-stressed conditions as in low-rainfall areas form another environment where alley cropping experience has not been satisfactory.

Akyeampong et al. (1995) reviewed the results of 2- to 3-year-old experiments conducted by ICRAF in sub-Saharan Africa and found no benefit for alley-cropping at sites (50% of total sites) where rainfall was less than 1000 mm per year and concluded that under such situations, the negative effects of competition for water exceeded the positive effects of improved soil fertility. In a four-year study carried out at the International Crop Research Institute for the Semiarid Tropics (ICRISAT) near Hyderabad, India, the growth of hedgerow species was greater than that of the crops when there was limited moisture, resulting in reduced crop yields (Corlett et al. 1989; Rao et al. 1990). Similar observations have been reported from other semiarid areas too such as Kenya (Nair 1987; Jama et al. 1995). Comparing the relative performance of senna and leucaena as hedgerow species for alley cropping under the semiarid conditions (average rainfall 700 mm; bimodal distribution) at Machakos, Kenya during six cropping seasons, Jama et al. (1995) reported that maize grain yield was better when alley-cropped with senna than with leucaena (Table 6.8). Indeed, maize alley-cropped with leucaena yielded lower than under no-alley-cropping control. The results showed that senna was a better species for alley cropping than leucaena under those (semiarid) conditions, which emphasizes the importance of choosing appropriate species for alley cropping. Overall, low yields of hedgerow prunings (2 to 3 t ha^{-1} yr^{-1}) and competition for water between hedgerow species and crops were reported as the major reasons for negative yields in water-limited areas (Ong et al. 1991).

Some efforts have also been made to examine the general trends of results emerging from the numerous non-coordinated studies reported from different study locations. Reviewing the short-term results of alley cropping trials conducted on diverse soils in sub-humid and humid West Africa, Woomer et al. (1995) observed that on average (n = 44) 183% yield increase for alley-cropped maize over sole crop control. In a comprehensive analysis, Rao et al. (1998) assessed the performance of 29 alley cropping studies with no addition of nitrogen fertilizer to crops, conducted for four or more years over a wide range of soil and climatic conditions in the tropics (Figure 6.8). Experiments on sloping lands where the primary benefit is likely to be soil conservation were not included in the analysis. The tree species used were mostly leucaena ($n = 12$); others included senna ($n = 3$), gliricidia ($n = 2$), calliandra ($n = 3$), and erythrina ($n = 4$). Yields of sequential crops in bimodal rainfall sites are presented separately if crops involved were different (hence more than 29 observations in the figure). The results showed both positive

Table 6.8 Maize grain yield in *L. leucocephala* and *S. siamea* hedgerow intercropping systems with different hedge: crop land occupancy ratio at Machakos, Kenya. Values within a given proportion are means over the planting systems

Species	Hedge: crop land occupancy ratio	Maize yield (dry weight, Mg ha^{-1})						Average $crop^{-1}$
		1989		1990		1991		
		Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	
Leucaena	25:75	2.41	2.93	2.80	2.04	1.24	2.13	2.26
	20:80	1.82	2.61	2.94	2.13	1.05	2.50	2.17
	15:85	2.55	3.02	2.33	2.30	0.75	2.21	2.19
Senna	25:75	2.82	3.42	2.88	3.42	1.52	3.22	2.88
	20:80	2.45	3.77	2.93	3.04	1.44	2.93	2.76
	15:85	2.42	3.93	2.45	3.47	1.45	2.54	2.71
Sole maize	0:100	2.82	3.09	2.89	3.06	1.27	2.62	2.62
SED (Species at a given proportion)		0.34	0.49	0.52	0.41	0.36	0.29	0.15
SED (Proportions within a species)		0.21	0.35	0.29	0.36	0.28	0.21	0.26

Source: Jama et al. (1995)

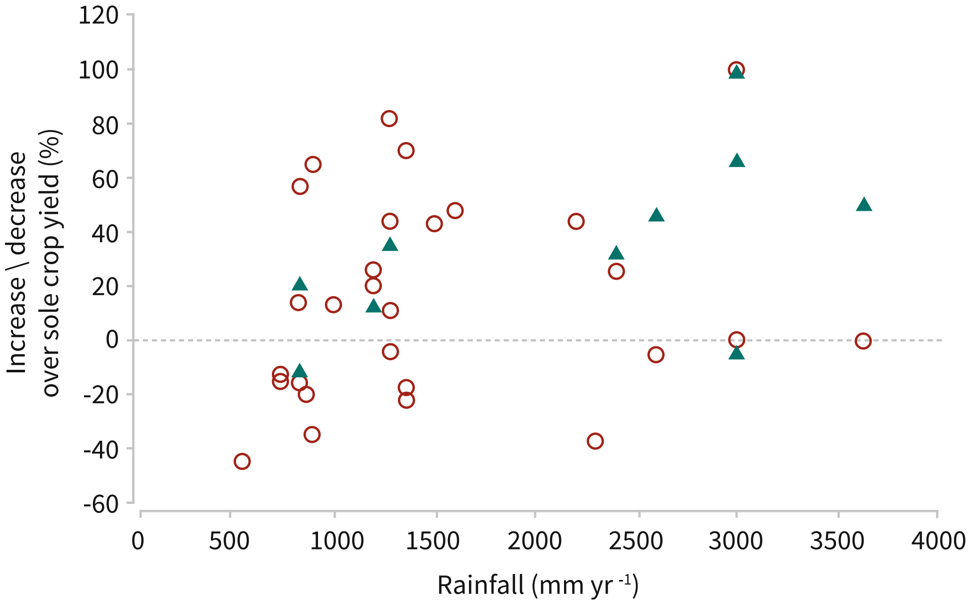

Figure 6.8 Crop yields in tropical alley cropping expressed as percent yields of same crops in sole stands in 29 experiments conducted throughout the tropics. Open circles represent the average relative yields of cereal alley crops: maize (*Zea mays*), sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glauca*) and rice (*Oryza sativa*). Closed triangles represent the average relative yields of non-cereal alley crops: taro (*Colocasia esculenta*), beans (*Phaseolus vulgaris*) and cowpea (*Vigna unguiculata*). Source: Rao, Nair, and Ong (1998)

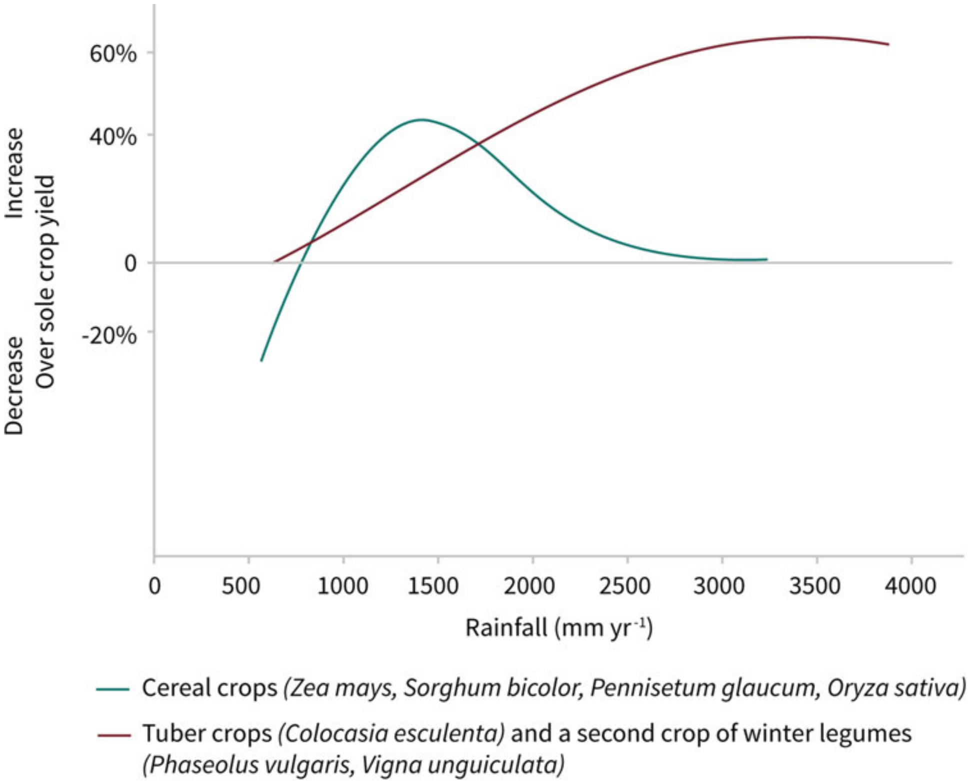

Figure 6.9 Location specificity of crop performance in tropical alley cropping: A generalized form of crop performance under tropical ally cropping showing the location specificity of annual crop response to interaction with hedge row species along productivity gradients and crop species, based on a further evaluation of the results synthesized by Rao et al. in Figure 6.8. Source: García-Barrios (2003)

($n = 15$ for cereals, and $n = 8$ for non-cereal crops) and negative (n = 13 for cereals and n = 2 for tuber crops). Considering that yield increase of < 15% may be unattractive to farmers, only two out of 10 studies in semiarid sites with < 1000 mm annual rainfall gave any substantial crop-yield increase. In sub-humid conditions (rainfall in the range of 1000 to 1600 mm), significant positive yield responses were observed in seven out of 11 studies. In the humid tropics (rainfall > 2000 mm), the crops (maize and taro: *Colocasia esculenta*) did not benefit from alley cropping in four out of eight trials. Those results synthesized by Rao et al. (1998) were further evaluated by García-Barrios (2003), who presented in a generalized form (Figure 6.9), showing that annual crop response to interaction with hedgerow species can change strongly along productivity gradients and differs according to crop species. Thus, the yield performance of alley cropped crops is so location-specific and management-sensitive that generalizations can be difficult and misleading. Alley cropping can be advantageous in relatively fertile but nitrogen-deficient soils in the sub-humid and humid environments where there is no competition for water between the hedgerows and crops; but in semiarid areas with annual rainfall < 1000 mm and acid infertile soils, hedgerows produce too little biomass and compete with crops and crop yields are substantially reduced.

Extensive but Not Rigorous Studies? While evaluating these results it needs to be acknowledged that there have been deficiencies in the experimental procedures followed in different situations. Indeed, because of the newness of agroforestry and alley cropping as research endeavors, rigorous and uniform research protocols and procedure may not even have been established. Many of these experiments suffered from the disadvantages of small plots, in which the sole crop yields could be underestimated because of the exploitation of nutrients and water by tree roots from the alley-cropped plots. Moreover, in alley-cropping experiments, as in other woody and herbaceous mixtures, crop yields are expressed per unit of gross area, i.e., the combined area of both the hedgerows and the crops. Crop yields are measured in transects across the hedgerows, i.e., from all crop rows extending from the row closest to the hedgerow to the farthest row (Rao and Coe 1992). Studies at IITA projected maize yields with cumulative soil losses under different fallow management systems (Ehui et al. 1990). When land in fallow and land occupied by the hedgerows (in shifting cultivation and alley cropping, respectively) were considered and maize yields were adjusted accordingly to account for these possible losses (due to reduced cropping area) in production, the highest yields would be obtained if alleys were spaced 4 m apart, whereas the lowest yields would be obtained from nine-year fallow treatments. Yet another issue is the end-use of hedgerow prunings. In some situations, the biomass is used as an animal fodder instead of being returned to the soil as a source for crop nutrition and soil organic matter. A six-year study in north-western India where maize, black gram (*Vigna mungo*), and cluster bean (*Cyamopsis tetragonoloba*) were alley-cropped with leucaena and the leucaena prunings were taken away as fodder, the crop yields under alley cropping were lower than when grown in pure stands; the fodder- and fuelwood yields of leucaena were also lower under alley cropping than under non-alley cropped hedgerows (Mittal and Singh 1989).

6.2.5 The Rise and Fall of Alley Cropping

By the early 1990s, after about two decades of experience, it became evident that alley cropping as originally conceived, wherein a heavy emphasis was given to such species as leucaena, was unlikely to be a promising technology in the semiarid tropics. Several factors could limit the realization of the potential of alley cropping. A major one is soil moisture. In many semiarid regions, the rainfall is of a unimodal pattern extending over four to five months. Therefore, the number of pruning events would be reduced to about three. The mulch yield and, therefore, nitrogen contributions will also be lower, implying that the nitrogen yield will not be adequate to produce any substantial nitrogen-related benefits for the crop. Additionally, there are shade effects caused by the hedgerows as well as the reduction of land available for crop production (in a square configuration, 20 hedgerows, each casting severe shade over an area 1 m wide and 100 m long, will cover 2000 m^2 per hectare, or 25% of total area). The additional labor that is required to maintain and prune the hedges is another limitation. Furthermore, farmers may choose to remove the mulch for use as animal fodder, rather than adding it to the soil, as is the case in Haiti (Bannister and Nair 1990). While all factors related to the biological advantages of alley cropping are important, social acceptability and adoption potential of the practice are equally – even more – important. In addition to common difficulties in popularizing an improved agricultural technology developed at research stations among target farmers, some features of alley cropping counterbalance its advantages and hinder its widespread adoption. These include the need for additional labor and skills that are required for hedgerow pruning and mulch application, loss of cropping area to the hedgerows, difficulty in mechanizing agricultural operations, and potential for the hedgerow species to become a weed and/or an alternate host for pests and pathogens or harbor grain-eating birds, and possibilities for increased termite activity, especially under dry conditions.

In retrospect, alley cropping is no exception to the all-too-common experience in agricultural development initiatives in the tropics – of excessive expectations and euphoria that accompany the introduction of any new initiative, followed by disappointment when the expectations are not fully met. The reasons are several and well-known from past experiences: the craze and race for finding immediate solutions to long-standing, complex, and multifaceted problems; simplistic and trivial nature of the proposed solutions; popularization of the solution (technology) without adequate testing; and so on. Exaggerated emphasis was placed (the “panacea” syndrome) on the advantages and expectations from agroforestry, and researchers and the development community were under severe pressure to bring out something like a “magic wand” that would erase all the massive problems of deforestation, land degradation, food scarcity and poverty, and all the related issues. Alley cropping, being one of the early technologies of agroforestry, was welcomed with such a wave of extreme enthusiasm. Although it was based on a sound land-management principle – biological means of maintaining and improving soil fertility – its limitations became evident when introduced to surroundings that are unfavorable and would later be acknowledged as beyond its limits (for example, dry areas). While some proponents of alley cropping took extreme positions of going to great lengths using only positive results and ignoring the not-so-positive ones, others just denigrated and dismissed the technology. Some played it “safe” by joining the bandwagon at first lest they should be counted out of any eventual benefit, and later (when it became clear that the going was rough) trying to become smart by criticizing that it was based on weak science and posturing with the acceptance of a vague philosophical consolation that “all-results-are-valuable” (Sanchez 2019). Others, however, argue that the results of tropical alley cropping datasets need further analyses before rushing to “throw out the baby with the bathwater” (Vandermeer 1998).

The results reviewed above show that alley cropping could be promising under conditions where the annual rainfall during cropping season/s is more than 1000 mm and the soils are reasonably fertile with no serious nutrient deficiencies and extreme soil reactions. Under these conditions, alley cropping results would even be better if the land is gently sloping (less than 10% slope), and there is no labor shortage during cropping seasons. Soil-health and environmental sustainability advantages arising from reduced use of chemical fertilizers would make alley cropping a winner in such situations. An important point to remember is that under conditions where alley cropping is appropriate such as in the lowland humid tropics, the technology can be adapted for both low and high levels of productivity. If higher levels of crop productivity are the goal, fertilizer application will be necessary under most conditions. In other words, alley cropping cannot be a substitute for fertilizers if high levels of crop production are to be realized. But under conditions of adequate and well-distributed rainfall as in many humid and some sub-humid areas, fertilizer-use efficiency could be substantially increased under alley cropping compared with no-alley-cropping situations.

6.3 Improved (Shrub and Tree) Fallows

For about 15 years from the early 1980s, alley cropping was the most-talked-about and researched topic in tropical agroforestry. By the mid-1990s, that was replaced by an ICRAF-promoted technology called "Improved Fallow." It refers to "deliberate planting of fast-growing, usually leguminous, species for rapid replenishment of soil fertility, and implies the use of improved tree and shrub species during the fallow phase" (Sanchez 1995). The technology attained prominence during the early 1990s when ICRAF under the leadership of its new director-general (Pedro A. Sanchez) started focusing its institutional efforts on improved fallow as the approach to soil fertility management for enhancing crop production in nutrient-depleted soils of sub-Saharan Africa. Faced with the frustrations about the failure of alley cropping to deliver the expected benefit of the soil-improvement potential of trees and shrubs – a major scientific principle based on which ICRAF was founded – the Centre started promoting improved fallow as a breakthrough in improving crop production and alleviating hunger and poverty (Sanchez 1999). It became the Centre's flagship program since the mid-1990s and, understandably, dominated the tropical agroforestry scene in sub-Saharan Africa, and generated a lot of expectations. Numerous publications (research reports, journal articles, conference proceedings, etc.) became available during the ensuing 10–15 years; a notable one was *The Science and Practice of Improved Fallows*, a book-length compilation of mostly experiential descriptions of improved-fallows from various countries published as a special issue of the journal *Agroforestry Systems* (Buresh and Cooper 1999). The flow of publications slowed down gradually, except for a few summaries and reviews (Ajayi et al. 2007; Sileshi et al. 2008). The sections below present a brief account of these results gleaned from these publications and the author's (P.K.R. Nair) decades-long personal field experiences, observations, and interactions in sub-Saharan Africa.

6.3.1 Improved Fallow: The Practice and Terminology

As discussed in Chapter 5, fallow is a practice probably as old as agriculture itself and has been an essential component of traditional agriculture globally. Kass and Somarriba (1999) observed that fallows have been the fundamental means by which farmers in tropical America maintained sustained food production without external inputs during more than five millennia of the practice of agriculture in the region. Similar experiences have also been reported from other parts of the tropics as well as the temperate regions (Chapter 5). As a traditional low-input farming activity of smallholder farmers, the practice had several forms and variants in terms of the species used, plant-stand density, fallow length, and such other management aspects depending on local conditions. Such variations in traditional fallows are common for improved fallows too even in research trials. Thus, the literature on improved fallows is replete with several planting and management procedures and various terms to reflect these differences (Table 6.9).

Table 6.9 Fallow Terminology

Fallow: Refers to an agricultural land lying idle, either abandoned or when cropping is deliberately skipped for a season or more to give "rest" to tired land.

Natural Fallow: The early stage of secondary vegetation after a cropping period. Natural fallows, known by different terms in different places, are an essential aspect of the shifting cultivation cycles in the tropics and are dominated by weeds and secondary vegetation. Sometimes grasses of various types, especially the obnoxious weed *Imperata cylindrica* (local names: *alang-alang*, cogon grass) in the tropics and grass leys in temperate regions dominate grass fallows.

Improved Fallow: Deliberate planting of fast-growing, usually leguminous, species for rapid replenishment of soil fertility, and implies the use of improved tree and shrub species during the fallow phase.

Sequential Fallow: When the same fallow species is repeated in every fallow cycle.

Rotational Fallow: When the fallow species are different in successive fallow cycles.

Enriched Fallow: Refers to fallows that are planted with economically useful trees at low stand-densities to provide fruits, nuts, timber, and other economic products.

Managed Fallow: A term used to refer to both improved fallow and enriched fallow.

Mixed Fallow: A fallow with more than one woody species planted simultaneously on the same land during the fallow phase.

Improved fallows are sometimes referred to by the tree species used, for example "sesbania fallow," "tephrosia fallow," etc.

Although the differences among these various terms are blurry for the general reader, the experts may find "major" differences among the various terms making "lack of uniformity" an intimidating issue in comparative studies as experienced by Sileshi et al. (2008) in their meta-analysis.

Compiled from: Sanchez (1995, 1999); Buresh and Cooper (1999)

A "typical" pattern of establishing an improved fallow would be as follows:

- Seedlings of the chosen tree species are planted in the crop production field and are let to grow as a *tree fallow* for "some" time (1, 2, or 3 years) that is designated as the *fallow length*.
- If the tree species is non-coppicing (i.e., if it does not grow back after its main stem and/or branches are cut), the trees are cut down at the end of the fallow length, and the biomass (leaves, twigs, branches) is incorporated into the soil while the land is being prepared for the food crop (mostly maize).
- The food crop is raised for one, two, or three consecutive seasons (known as the *post-fallow cropping* period).
- Sometimes, incremental doses of fertilizer (25, 50, 75, 100% of the recommended levels) would be applied to the crop following the fallow (the practice is called *fertilizer amendment* in improved-fallow literature).
- After the cropping period, the cycle of fallow- and cropping-phases are repeated. Improved fallows of non-coppicing species could be *sequential fallows* (when the same fallow species is used in successive fallow periods) or *rotational fallows* (when a fallow species used in one fallow period is replaced by another species in the subsequent fallow cycle); see Table 6.9.
- Fallow species that have the coppicing ability (i.e., re-sprout after it is cut back) are left to grow for 2 years. Then they are cut back and the crop (maize) is planted every year between the stumps. These are also called improved fallows, although, in the long run, they essentially become intercropping systems (Akinnifesi et al. 2007).
- As the stump re-sprouts, the biomass is cut back two to three times during the maize cropping season and incorporated into the soil (as in tropical alley cropping).

6.3.2 Improved-Fallow Species

As mentioned above, there are two types of fallow species: coppicing and non-coppicing. The coppicing fallow species are left to grow for some time, usually 2 years, then cut back, the foliage added/incorporated into the soil, and the crop planted every year between the stumps so that the system essentially becomes intercropping or alley cropping depending on the planting pattern of the tree/shrub (fallow) species. The species used for such "fallows" are the same as those used for tropical alley cropping too (Table 6.1). Several non-coppicing species of trees and shrubs, both legumes and non-legumes, are also used in improved fallows; even some herbaceous green-manure species that have traditionally been used in agricultural systems as green-manure crops are also listed as improved fallow species in some literature. Pigeon pea (*Cajanus cajan*) that is usually grown as an annual grain legume is also sometimes used, especially its biennial cultivars, as an improved fallow species (Figure 6.10). Table 6.1 lists the essential characteristics of the improved fallow species; more detailed species profiles of some of them are included in Chapter 13, Annexure 13-I.

6.3.3 Soil Fertility and Crop Yields Under Improved Fallows

Objective assessment of the merits and weaknesses of the Improved-Fallow practice for soil fertility improvement is difficult because of several reasons. First, soil fertility improvement is hypothesized as the primary means for improving crop production through improved fallow systems, but that has often been relegated to a supporting role in attaining the goal of crop-yield increase. Therefore, the two issues are usually mixed inseparably in most reports. Secondly, the results of rigorous, process-oriented, long-term studies are not available on the topic. Moreover, the literature on improved fallows is mostly experiential (reporting experiences of specific studies) or promotional (describing its possible virtues and potential as articulations of wishful thinking without rigorous supporting evidence). Above all, there is no uniformity in the practice in terms of the species used and their management, the nature and length of fallows, and other site-specific features. The summary of available information presented below may be seen in the backdrop of these limitations.

Most of the available reports are from sub-Saharan Africa. They have indicated a significant increase in soil organic matter under planted fallows, for example, under *Cajanus cajan* on degraded soils in western Kenya (Onim et al. 1990), and under *Tephrosia candida* and *C. cajan* in Nigeria (Gichuru 1991). The review by Mutuo et al. (2005) reported increased soil C stocks in the top 5 cm soil depth by about 1.5 t C ha^{-1} within a two-year fallow with *C. cajan* and increased soil C stocks in the top 15 cm depth by about 2.5 t C ha^{-1} under a 1.5-year

Figure 6.10 Improved fallow: One-year-old *Cajanus cajan* fallow, Zambia. (Photo: Ann Degrande, ICRAF)

fallow of *S. sesban* in western Kenya. Biomass productivity data of the fallow species are sometimes used as a surrogate for soil fertility. Table 6.10 shows some such results on biomass productivity on some fallow species in Kenya used by Albrecht and Kandji (2003). Mafongoya and Nair (1997) reported that nitrogen recovery by maize from tree biomass of improved fallows was higher when biomass was incorporated in soil rather than left on the surface in Domboshawa, Zimbabwe (Table 6.11). Mafongoya et al. (2006) prepared nutrient budgets based on data for three years under non-coppicing fallows (Table 6.12). Their results showed that during the three years, while N and P budgets (stocks) were positive under *Cajanus*- and *Sesbania* fallows and fertilized maize, they were in the negative for unfertilized maize. For P, the values were positive for all treatments except for unfertilized maize, where the values were marginally in the negative (-1 and -2 t ha^{-1}). Potassium stocks, however, were in the negative for all treatments except under *Cajanus* fallow. Ajayi et al. (2007) also found similar results from a review on the impact of improved fallows in Zambia. An 8-year study showed that there was a positive nitrogen balance in the two years of cropping after the fallow for all improved fallow species. Maize fertilized

Table 6.10 Biomass productivity of some improved fallow species in western Kenya

Fallow Species	**Biomass (Mg ha^{-1})**		
	Aboveground	**Belowground**	**Total**
12-month-old fallows			
Crotalaria grahamiana	8.5	2.7	11.2
Calliandra calothyrsus	21.0	7.0	28.0
Cajanu cajan	8.5	3.9	12.4
Senna spectabilis	7.0	4.8	11.8
Sesbania sesban	14.2	7.3	21.5
Tephrosia vogelii	10.8	4.0	14.8
18-month-old fallows			
Crotalaria grahamiana	24.7	10.9	35.6
Calliandra calothyrsus	19.8	13.6	33.4
Tephrosia candida	31.0	33.2	64.2
22-month-old fallows			
Calliandra calothyrsus	27.0	15.5	42.5
Sesbania sesban	36.9	10.8	47.7
Grevillea robusta	32.6	17.7	50.3
Eucalyptus saligna	43.4	19.1	62.5

Source: Albrecht and Kandji (2003)

Table 6.11 Nitrogen recovery by maize from improved fallows is higher when incorporated rather than left on the surface as mulch in a loamy Ustalf of Domboshawa, Zimbabwe

Species	Quality[a]	Nitrogen recovery (%)	
		Surface applied	Incorporated in soil
Leucaena leucocephala	High	21.1ab	35.7a
Cajanus cajan	High	23.4a	30.9ab
Acasia angustissima	High	12.1c	32.4ab
Callindra calothyrsus	Low	31.3a	26.0b
Brachystegia spiciformis (Miombo litter)	low	15.3bc	13.3c
Mean values		20.6	27.7

[a] High quality = >2.5% N and <15% lignin (Palm et al. 2001)

Source: Adapted from Mafongoya and Nair (1997)

Table 6.12 Nutrient budgets for land-use systems involving non-coppicing fallows in Zambia

	Nitrogen			Phosphorus			Potassium		
	1998	1999	2002	1998	1999	2002	1998	1999	2002
Cajanus fallow	44	17	84	21	8	33	37	9	27
Sesbania fallow	47	19	110	39	24	32	–20	–25	–20
Fertilized maize	70	54	48	14	12	12	-56	–52	–65
Unfertilized maize	–20	–17	–22	–2	–1	–2	–31	–30	–38

Source: Mafongoya et al. (2006)

Table 6.13 Maize grain yield after two-year *Sesbania sesban* fallow with and without recommended fertilizer in eastern Zambia during 1998–2000 (n=48). (From Kwesiga et al. 2003)

	Maize grain yield (t ha^{-1})		
Type of land-use system	Year 1	Year 2	Year 3
Sesbania fallow + no fertilizer	3.6	2.0	1.6
Sesbania fallow + 50% recommended fertilizer[a]	3.6	4.4	2.7
Sesbania fallow + 25% recommended fertilizer[a]	3.6	3.4	2.3
Continuous maize + 100% recommended fertilizer[a]	4.0	4.0	2.2
Continuous maize + no fertilizer	1.0	1.2	0.4
LSD (0.05)	0.7	0.6	1.1

[a]Recommended fertilizer rate is 112 kg N, 20 kg P and 16 kg K per ha
Source: Ajayi et al. (2007)

with 112 kg N ha^{-1} yr^{-1} had the highest, and unfertilized maize the lowest, nitrogen balance each year (Table 6.13). An important observation was that all land-use systems showed a negative balance for potassium, the highest negative balance being in fully fertilized maize fields, possibly due to higher maize grain- and stubble yields that required a high amount of potassium and fertilizer application was only for nitrogen and, unlike nitrogen, there was no potassium contribution by the fallow species.

In Malawi, Kwesiga et al. (1999) reported *Sesbania sesban* rotational fallow increased maize yields compared to plots fertilized with inorganic nitrogen. Sanginga (2003) reported that on an Alfisol in Nigeria, leguminous tree fallows of *Cajanus cajan*, *Crotalaria grahamiana*, *Sesbania sesban*, and *Tephrosia candida* accumulated 100–200 kg N ha^{-1} between six months and two years, and biomass transfer from those species increased maize yield by four times compared with unamended controls. A report from northern Ghana showed that improved fallow with *Calopogonium mucunoides* significantly increased the yield of rice compared with natural fallows and chemical fertilizer treatments (Langyintuo and Dogbe, 2005). Similarly, an improved fallow system with *Mucuna pruriens* is reported to have increased soil organic carbon and total nitrogen under nutrient-poor conditions in the semiarid tropics of Zimbabwe (Masikati et al. 2014).

One of the comprehensive evaluations of crop-yield performance under improved fallows is a meta-analysis (using a mixed linear model) by Sileshi et al. (2008) based on a total of 94 peer-reviewed publications from West, East, and southern Africa that evaluated the yield benefits from woody and herbaceous green manure legumes. A summary of some of the main results of the analysis are presented in Table 6.14. Mean maize yield increase over unfertilized maize was highest (2.3 t ha^{-1}) and least variable (CV=70%) in fully fertilized maize, while it was lowest (0.3 t ha^{-1}) and most variable (CV=229%) under natural fallows. The increase in yield over unfertilized maize was 1.6 t ha^{-1} with coppicing woody legumes, 1.3 t ha^{-1} with non-coppicing woody legumes, and 0.8 t ha^{-1} with herbaceous green manure legumes. Doubling and tripling of yields relative to the control (Response Ratio, RR > 2) was recorded in coppicing species

Table 6.14 Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. Summary statistics of maize yield differences (*D*, t ha^{-1}) in the different treatmentss

	Full fertilizer	Coppicing	Non-coppicing	Green manure	Natural fallow
Number of publications (*N*)	52	10	48	54	29
Number of pairs (*k*)	261	185	458	622	155
Minimum	−1.3	−0.9	−2.2	−2.8	−2.9
Maximum	7.5	6.3	6.7	5.2	2.6
Mean	2.3	1.6	1.3	0.8	0.3
Mode[a]	1.4	1.2	0.2	0.3	0.2
Coefficient of variation (CV in %)	69.7	92.4	113.0	135.7	228.9
Upper quartile (75%)	3.3	2.6	2.0	1.3	0.7
Median (50%)	2.2	1.5	0.8	0.6	0.3
Lower quartile (25%)	1.1	0.4	0.2	0.1	-0.1
Percent cases with $D<0$ t ha^{-1}	4.6	10.3	8.3	16.2	27.1
Percent cases with $D>1$ t ha^{-1}	77.0	62.7	43.7	31.3	14.2
Percent cases with $D>2$ t ha^{-1}	53.3	35.1	23.6	12.2	0.6

[a] The mode was estimated by kernel soothing of the empirical distribution
Source: Sileshi et al. (2008)

(67% of the cases), non-coppicing legumes (45% of the cases), herbaceous green manure legumes (16% of the cases) and natural fallows (19% of the cases). Amending post-fallow plots with 50% of the recommended fertilizer dose further increased yields by over 25% indicating that legume rotations may play an important role in reducing fertilizer requirements. The authors concluded that overall the global maize yield response to legumes is significantly positive and higher than unfertilized maize and natural vegetation fallows but was still lower than that of fertilized maize. The study also showed that 3-year fallows of non-coppicing woody legumes had no advantage over 2- or 1-year fallows of non-coppicing species. The analysis also suggested that amending legume fallows with inorganic fertilizer may be important to sustain productivity over several years, as yields normally decrease with the length of post-fallow cropping period. Amending post-fallow plots with 50% of the recommended fertilizer dose could increase yields by over 25%, indicating that legume rotations may only reduce but cannot substitute fertilizer requirements. The long-recognized synergistic effect between organic and inorganic fertilizer sources was another aspect that was evident from this analysis. The main conclusions from these reports are that improved fallows, preferably of leguminous species, could have advantages in improving crop production if the soils are not extremely low in organic matter and phosphorus contents, but could lead to potassium deficiency in the long run.

6.3.4 The Rise and Fall of Improved Fallows

Improved Fallows was introduced by ICRAF as a new technology in the early 1990s. The driving force behind its development was the search for new approaches to respond to soil fertility problems, primarily of sub-Saharan Africa, resulting from the breakdown of traditional farming systems that used to have the benefit of long fallow periods. Scientifically it is founded on the well-known principles that are not very different from the foundations of tropical alley cropping that planting fast-growing tree species, especially the nitrogen-fixing ones, produce easily decomposable biomass to provide nitrogen for food crops growing together with or following the tree species, increase soil organic matter, and improve soil physical conditions. The rather disappointing performance of tropical alley cropping provided a good background and incentive for presenting the soil improvement potential of trees as the new approach to the issue.

The technology being new to sub-Saharan Africa, research testing had to be conducted on various technical issues such as species screening and selection and fallow establishment/management. While efforts on these time-consuming procedures were continuing, the technology was taken, rather prematurely, to the dissemination stage based on its assumed promise and success potential. A noteworthy aspect of the technology development, however, was the realization that the success of such technologies crucially depended on their suitability to local conditions that could best be realized by farmers' participation in technology development and adaptation. Consequently, farmers were involved in assessing technology and making modifications based on their experiences. For assessing the extent of farmers' adoption of the improved fallow technology, farmers who planted trees for a second cycle were identified as "adopters" as opposed to those still in the first cycle of tree fallows, who were described as "users." Presenting the case study of Zambia, Ajayi et al. (2007) describe how the scaling up of the technology to different parts of the country was coordinated by a Network comprising representatives of ICRAF, government research and extension services, farmer organizations, and nongovernmental organizations (NGOs). From less than a hundred planters in the early 1990s, the number of farmers who planted improved-fallow trees reportedly increased each year by tens of thousands of farmers. Subsequent reports indicated, however, that the initial euphoria fizzled out and the number of adopters declined gradually to the extent that out of the nearly 700,000 smallholder farmers who were reportedly planting improved fallows in East and Southern Africa, only less than 50,000 (7 percent) continued to do so after four years. The major reason for the failure of the adoption of the technology that was acclaimed as "rock-solid" was attributed to the lack of a financial package to offset the opportunity costs for one or two years (Sanchez 2019). Strangely, however, the same author has attributed the failure of tropical alley cropping – the scientific foundation of which is basically the same as that of improved fallow – to the weakness of its science (". . . decades of research devoted to an agroforestry technology without fully taking into account the principles . . .")!

6.4 Concluding Remarks

In conclusion, what lessons can be learned from three decades of efforts in agroforestry technology development involving soil-improving trees and shrubs?

- Both alley cropping and improved fallows are two sides of the same coin; the scientific principles of both are fundamentally the same (although this is not unanimously accepted)
- Both technologies perform well under conditions of adequate water availability during crop growing seasons but are unsuitable for dry areas
- The artificial dichotomy between the two technologies perpetuated by some researchers should be eschewed and efforts should be focused on finding the best ways of incorporating the proven benefits of including fast-growing woody legumes and other species in smallholder farming systems of nutrient-poor tropical soils.
- It seems that the low level of adoption of the technologies by the targeted clientele of smallholder farmers of sub-Saharan Africa is due to two major reasons: 1. Administrative failures (in creating an enabling environment for providing credit and financial support, seeds and other planting materials, "fertilizer amendment" as needed, etc.), and 2. Strategic failures in pushing the boundaries of testing to ecological regions that are way beyond the "safe" zones for these technologies.

References

Ajayi OC, Place F, Kwesiga F, Mafongoya P (2007) Impacts of improved tree fallow technology in Zambia. In: Waibel H, Zilberman D (eds) International research on natural resource management: advances in impact assessment. CABI/Science Council/CGIAR, Wallingford/Rome, pp 147–168

Akeyampong E, Duguma B, Heineman AM, Kamara CS, Kiepe P, Kwesiga F, Ong CK, Otieno HJ, Rao MR (1995) A synthesis of ICRAF research on alley cropping. In: Kang BT, Osiname AO, Larbi A (eds) Alley farming research and development. IITA, Ibadan, pp 40–51

Akinnifesi FK, Makumba W, Sileshi G, Ajayi O, Mweta D (2007) Synergistic effect of inorganic N and P fertilizers and organic inputs from *Gliricidia sepium* on productivity of intercropped maize in Southern Malawi. Plant Soil 294:203–217

Albrecht A, Kandji ST (2003) Review of carbon sequestration in tropical agroforestry systems. Agric Ecosyst Environ 99:15–27

Atta-Krah AN, Sumberg JE, Reynolds L (1985) Leguminous fodder trees in the farming systems: an overview of research at the humid zone programme of ILCA in Southwestern Nigeria. ILCA, Ibadan

Bannister ME, Nair PKR (1990) Alley cropping as a sustainable agricultural technology for the hillsides of Haiti: experience of an agroforestry outreach project. Am J Altern Agric 5:51–59

Brewbaker JL, Van Den Beldt RR, MacDicken KG (1982) Nitrogen-fixing tree resources: potentials and limitations. In: Graham PH, Harris SC (eds) BNF technology of tropical agriculture. CIAT, Cali, pp 413–425

Budelman A (1988) The decomposition of the leaf mulches of *Leucaena leucocephala*, *Gliricidia sepium* and *Flemingia macrophylla* under humid tropical conditions. Agrofor Syst 7(33–45):47–62

Budelman A (1989) Nutrient composition of the leaf biomass of three selected woody leguminous species. Agrofor Syst 8:39–51

Buresh RJ, Cooper PJM (eds) (1999) The science and practice of short-term improved fallows. Special issue. Agrofor Syst 47:1–356

Cooper PJM, Leakey RRB, Rao MR, Reynolds L (1966) Agroforestry and the mitigation of land degradation in the humid and subhumid tropics of Africa. Exp Agric 32:235–290

Corlett JE, Ong CK, Black CR (1989) Modification of microclimate in intercropping and alley-cropping systems. In: Reifsnyder WS, Darnhofer TO (eds) Meteorology and agroforestry. ICRAF/WMO/UNEP/GTZ, Nairobi, pp 419–430

Dommergues YR (1987) The role of biological nitrogen fixation in agroforestry. In: Steppler HA, Nair PKR (eds) Agroforestry: a decade of development. ICRAF, Nairobi, pp 245–271

Duguma B, Kang BT, Okali DUU (1988) Effect of pruning intensities of three woody leguminous species grown in alley cropping with maize and cowpea on an Alfisol. Agrofor Syst 6:19–35

Ehui SK, Kang BT, Spencer DSC (1990) Economic analysis of soil erosion effects in alley cropping, no-till and bush fallow systems in southwestern Nigeria. Agric Syst 34:349–368

García-Barros L (2003) Plant–plant interactions in tropical agriculture. In: Vandermeer JH (ed) Tropical agroecosystems. CRC Press, Boca Raton, pp 11–58

Ghosh SP, Kumar BM, Kabeerathumma S, Nair GM (1989) Productivity, soil fertility and soil erosion under cassava-based agroforestry systems. Agrofor Syst 8:67–82

Gichuru MP (1991) Residual effects of natural bush, *Cajanus cajan* and *Tephrosia candida* on the productivity of an acid soil in southern Nigeria. *Plant Soil* 134:31–36

Govindarajan M, Rao MR, Mathuva MN, Nair PKR (1996) Soil-water and root dynamics under hedgerow intercropping in semiarid Kenya. Agron J 88:513–520

Haggar JP, Warren GP, Beer JW, Kass D (1991) Phosphorus availability under alley cropping and mulched and un-mulched sole-cropped systems in Costa Rica. Plant Soil 137:275–283

Hands MR, Harrison AF, Bayliss-Smith T (1995) Phosphorus dynamics in slash-and-burn and alley cropping systems of the humid tropics. In: Tiessen H (ed) Phosphorus in the global environment: transfers, cycles and management. Wiley, New York, pp 155–170

Hauser S, Kang BT (1993) Nutrient dynamics, maize yield and soil organic matter dynamics in alley cropping with *Leucaena leucocephala*. In: Mulongoy K, Merckx R (eds) Soil organic matter dynamics and sustainability of tropical agriculture. Wiley-Sayce, New York, pp 215–222

Jama BA, Nair PKR, Rao MR (1995) Productivity of hedgerow shrubs and maize under alley-cropping and block planting systems in semiarid Kenya. Agrofor Syst 31:257–274

Kang BT (1993) Alley cropping: past achievements and future directions. Agrofor Syst 23:141–155

Kang BT (1997) Alley cropping–soil productivity and nutrient recycling. For Ecol Manag 91(1):75–82. https://doi.org/10.1016/S0378-1127(96)03886-8

Kang BT, Duguma B (1985) Nitrogen movement in alley cropping systems. In: Kang BT, van den Heide J (eds) Nitrogen in farming systems in the humid and subhumid tropics. Institute of Soil Fertility, Haren, pp 269–284

Kang BT, Gutteridge RC (1994) (reprinted 1998) Forage tree legumes in alley cropping systems. In: Gutteridge RC, Shelton HM (eds) Forage tree legumes in tropical agriculture. Tropical Grassland Society of Australia, St. Lucia. http://www.fao.org/ag/AGP/AGPC/doc/Publicat/Gutt-shel/x5556e00.htm (also available at: http://www.tropicalgrasslands.asn.au/)

Kang BT, Wilson GF (1987) The development of alley cropping as a promising agroforestry technology. In: Steppler HA, Nair PKR (eds) Agroforestry: a decade of development. ICRAF, Nairobi, pp 227–243

Kang BT, Wilson GF, Sipkens L (1981) Alley cropping maize (*Zea mays* L.) and leucaena (*Leucaena leucocephala* Lam de Wit) in southern Nigeria. Plant Soil 63:165–179

Kang BT, van der Kruijs ACBM, Cooper DC (1989) Alley cropping for food production in the humid and subhumid tropics. In: Kang BT, Reynolds L (eds) Alley farming in the humid and subhumid tropics. International Development Research Centre, Ottawa, pp 16–26

Kang BT, Reynolds L, Atta-Krah AN (1990) Alley farming. Adv Agron 43:315–359

Kang BT, Caveness F, Tian G, Kolawole GO (1999) Longterm alley cropping with four hedgerow species on an Alfisol in southwestern Nigeria – effect on crop performance, soil chemical properties and nematode population. Nutr Cycl Agroecosyst 54:145–155. https://doi.org/10.1023/A:1009757830508

Kass D (1987) Alley cropping of annual food crops with woody legumes in Costa Rica. In: Beer JW, Fassbender HW, Heuveldop J (eds) Advances in agroforestry research: proceedings of a seminar. CATIE, Costa Rica, pp 197–208

Kass DCL, Somarriba E (1999) Traditional fallows in Latin America. Agrofor Syst 47:13–36

Kass DCL, Foletti C, Szott LT, Landaverde R, Nolasco R (1993) Traditional fallow systems of the Americas. Agrofor Syst 23:207–218

Kwesiga FR, Franzel S, Place F, Phiri D, Simwanza CP (1999) *Sesbania sesban* improved fallows in eastern Zambia: their inception, development and farmer enthusiasm. Agrofor Syst 47:49–66

Kwesiga F, Akinnifesi FK, Mafongoya PL, McDermott MH, Agumya A (2003) Agroforestry research and development in southern Africa during the 1990s: review and challenges ahead. Agrofor Syst 59:173–186

Lal R (1989) Agroforestry systems and soil surface management of a tropical Alfisol. Parts I–VI. Agrofor Syst 8:1–6; 8:7–29; 8:97–111; 8:113–132; 8:197–215; 8:217–238; 8:239–242

Langyintuo AS, Dogbe W (2005) Characterizing the constraints for the adoption of a *Calopogonium mucunoides* improved fallow in rice production systems in northern Ghana. Agric Ecosyst Environ 110:78–90

Mafongoya PL, Nair PKR (1997) Multipurpose tree prunings as a source of nitrogen to maize under semiarid conditions in Zimbabwe. 1. Nitrogen-recovery rates in relation to pruning quality and method of application. Agrofor Syst 35:31–46

Mafongoya PL, Kuntashula E, Sileshi G (2006) Managing soil fertility and nutrient cycles through fertilizer trees in southern Africa. In: Uphoff N, Ball AS, Fernandes E, Herren H, Husson O, Liang M, Palm C, Pretty J, Sanchez P, Sanginga N, Thies J (eds) Biological approaches to sustainable soil systems. Taylor & Francis, New York, pp 273–289

Masikati P, Manschadi A, Van Rooyen A, Hargreaves J (2014) Maize–mucuna rotation: an alternative technology to improve water productivity in smallholder farming systems. Agric Syst 123:62–70

Mittal SP, Singh P (1989) Intercropping field crops between rows of *Leucaena leucocephala* under rainfed conditions in northern India. Agrofor Syst 8:165–172

Mutuo PK, Cadisch G, Albrecht A, Palm CA, Verchot L (2005) Potential of agroforestry for carbon sequestration and mitigation of greenhouse gas emissions from soils in the tropics. Nutr Cycl Agroecosyst 71:43–54

Nair PKR (1984) Soil productivity aspects of agroforestry. Science and practice of agroforestry 1. ICRAF, Nairobi

Nair PKR (1985) Classification of agroforestry systems. Agrofor Syst 3: 97–128

Nair PKR (1987) Soil productivity under agroforestry. In: Gholz HL (ed) Agroforestry: realities, possibilities and potentials. Martinus Nijhoff, Dordrecht, pp 21–30

Nair PKR (1988) Use of perennial legumes in Asian farming systems. In: Green manure in rice farming. International Rice Research Institute, Los Baños, pp 301–317

Nair PKR (1990) The prospects for agroforestry in the tropics, World Bank technical paper no. 131. World Bank, Washington DC

Ong CK, Corlett JE, Singh RP, Black CR (1991) Above and below ground interactions in agroforestry systems. For Ecol Manag 45:45–47

Onim JFM, Mathuva M, Otieno K, Fitzhugh HA (1990) Soil fertility changes and response of maize and beans to green manures of Leucaena, Sesbania and pigeon pea. Agric Syst 12:197–215

Palm CA, Giller KE, Mafongoya PL, Swift MJ (2001) Management of organic matter in the tropics: translating theory into practice. Nutr Cycl Agroecosyst 61:63–75

Rao MR, Coe R (1992) Evaluating the results of agroforestry research. Agrofor Today 4(1):4–9. (cited in Nair, 1993)

Rao MR, Sharma MM, Ong CK (1990) A study of the potential of hedgerow intercropping in semiarid India using a two-way systematic design. Agrofor Syst 11:243–258

Rao MR, Nair PKR, Ong K (1998) Biophysical interactions in tropical agroforestry systems. Agrofor Syst 38:3–49

Sanchez PA (1995) Science in agroforestry. Agrofor Syst 30:5–55

Sanchez PA (1999) Improved fallows come of age in the tropics. Agrofor Syst 47:3–12

Sanchez PA (2019) Properties and management of soils in the tropics, 2nd edn 666p. Cambridge University Press, Cambridge

Sanginga N (2003) Role of biological nitrogen fixation in legume-based cropping systems: a case study of West Africa farming systems. Plant Soil 252:25–39

Schroth G, Zech W (1995) Above- and below-ground biomass dynamics in sole cropping and alley-cropping system with *Gliricidia sepium* in semi-deciduous rainforest zone of West Africa. Agrofor Syst 31:181–198

Sileshi G, Akinifesi FK, Ajayi OC, Place F (2008) Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. Plant Soil 307:1–19

Singh RP, Ong CK, Saharan N (1989) Above and below-ground interactions in alley cropping in semiarid India. Agrofor Syst 9:259–274. https://doi.org/10.1007/BF00141088

Szott LT, Palm CA, Sanchez PA (1991a) Agroforestry in acid soils of the humid tropics. Adv Agron 45:275–301

Szott LT, Fernandes ECM, Sanchez PA (1991b) Soil-plant interactions in agroforestry systems. In: Jarvis PG (ed) Agroforestry: principles and practices. Elsevier, Amsterdam, pp 127–152

Torres F (1983) Potential contribution of leucaena hedgerows intercropped with maize to the production of organic nitrogen and fuelwood in the lowland tropics. Agrofor Syst 1:323–345

Vandermeer JH (1998) Maximizing crop yield in alley crops. Agrofor Syst 40:199–208

Wolf KJ, DeLucia EH (2018) Alley cropping: global patterns of species composition and function. Agric Ecosyst Environ 252:61–68

Woomer P, Baja O, Atta-Krah AN, Sanginga N (1995) Analysis and interpretation of alley farming data from tropical Africa. In: Kang BT (ed) Alley farming research and development. International Inst Trop Agri, Ibadan, pp 189–202

Yamoah CF, Agboola AA, Mulongoy K (1986a) Decomposition, nitrogen release and weed control by prunings of selected alley cropping shrubs. Agrofor Syst 4:239–246

Yamoah CF, Agboola AA, Wilson GF (1986b) Nutrient competition and maize performance in alley cropping systems. Agrofor Syst 4:247–254

Young A (1989) Agroforestry for soil conservation. CABI, Wallingford/Oxford