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Nutrient Cycling in Agroforestry Systems of the Semi-arid Tropics of Africa

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Abstract: Trees integrated with crops in time and/or space mediate nutrient cycling on farms by increasing the supply and availability of nutrients in the crop root zone and reducing nutrient losses. However, quantitative information is lacking on biological nitrogen fixation and nutrients recycled in semi-arid agroforestry due to the control of losses by trees, and most information available is on nutrients recycled through their above- and below-ground biomass. The potential for exploiting nutrient cycling in simultaneous agroforestry systems is constrained by a low and erratic water supply in the semi-arid areas of Africa. In parkland systems, there is a limited scope for increasing nutrient cycling because of the small quantity of biomass added into soil from low tree density in the system. However, trees in these traditional systems are more important for economic products in terms of poles, timber, fruits, etc., and have ecological benefits such as the reduction of nutrient and water losses. Although hedgerow intercropping uses high tree density and increases the nitrogen (N) supply in the soil, crops nevertheless fail to benefit due to competition between trees and crops for water. Contour hedgerows can conserve nutrients by arresting soil erosion on moderately sloping lands and are worthy of consideration for both soil conservation and fodder production. Mixed intercropping of *Gliricidia sepium* and maize with efficient tree management appears to be promising in some areas and needs further testing before widespread dissemination. Sequential systems with short-duration leguminous trees and shrubs, exemplified by 2-year *Sesbania sesban* rotated with crops, and biomass transfer systems are both efficient in nutrient cycling and increasing crop yields. Therefore, these systems can be considered for dissemination depending on the socio-economic conditions. The potential for using biomass transfer systems is constrained by the availability of biomass outside the farms, land for its production on farms and labor for its application. Although these agroforestry systems provide an adequate quantity of N for moderate cereal yields, they cannot meet the phosphorus (P) requirements of crops in P-deficient soils, which should be supplemented through inorganic P sources. Nutrient cycling using livestock is less efficient due to N losses by volatilization and leaching than direct use of biomass as green manure. The use of palatable and high quality biomass as fodder is three to five times more economical than green manure. While agroforestry clearly has a definite role to increase nutrient cycling in low input systems, no single technology can guarantee controlling nutrient depletion in the long term. The choice of different technologies to suit different niches of the farm and their integration with inorganic nutrients is important for sustainable production even on smallholders' farms in the semi-arid Africa.

Key words: Alley cropping, biomass transfer, fallows, fodder, hedgerows, integrated nutrient management, intercropping, livestock, parklands, soil fertility.

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Semi-arid tropical (SAT) area accounts for about 18% of sub-Saharan Africa (SSA), but it has the burden of supporting about 40% of human and 27% of livestock (cattle, goat and sheep) populations of the region. SSA is characterized by an annual rainfall that varies from 500 to 1000 mm, a crop growing period from 75 to 180 days, and well-established mixed farming systems. Sorghum [*Sorghum bicolor* (L.) Moench], maize [*Zea mays* L.] and pearl millet [*Pennisetum glaucum* (L.) R. Br.] are the major cereal food crops and cowpea [*Vigna unguiculata* (L.) Walp.], pigeonpea [*Cajanus cajan* (L.) Millsp.], groundnut (*Arachis hypogea* L.) and bean (*Phaseolus vulgaris* L.) are the principal leguminous food crops grown in this region. Residues of all these crops are removed from the fields to feed livestock. Although the average rural population in the semi-arid SSA may appear low (14.6 persons km^{-2}) relative to the SAT Asia, in contrast there are areas of very high population density (over 300 persons km^{-2}). Livestock plays a significant role contributing to farm income by 10 to 40% and its importance generally increases with lower rainfall. In the more favorable wetter areas, where sedentary agriculture has been practised for decades, nutrient depletion is a major cause of low crop yields. Nutrient depletion observed at 20 kg N, 2 kg P and 14 kg K ha^{-1} y^{-1} in southern Africa is typical of the semi-arid areas (Stoorvogel and Smaling, 1990). Although fallowing is still commonly practised as a means of restoring soil fertility, the fallow periods have decreased over the years due to increased population pressure and a declining per capita food production. Farmers may leave land under fallow for 3 to 5 years in low population density areas (e.g., eastern Zambia) but fallowing has been abandoned in areas of high population density (e.g., southern Malawi).

In the semi-arid parts of SSA, Alfisols, Aridisols, Entisols and Vertisols are the major soils, but the first two orders predominate, each covering about 30% of the region. Soils are generally low in organic C and total N contents primarily because of low biomass production and the high rate of decomposition. Soil P stocks are also low, but as the P fixing capacity of most soils is rather low, small quantities of P could be adequate for good crop yields. Nitrogen and phosphorus are the two most limiting nutrients, though the extent of their deficiency varies widely in the three geographic regions (East, West and southern Africa). While N and P deficiencies are most common in West and East Africa, N deficiency is more widespread in southern Africa. Significant crop responses to commercial fertilizers have been reported in all the three geographic regions, although the magnitude of response varied from year to year depending on the rainfall. Many studies have emphasized the need for a combined use of organic residues with fertilizers for sustaining higher production and efficient use of nutrients (Bekunda *et al.*, 1997). The use of commercial fertilizers has been minimal and with the removal of subsidies following structural adjustment programs, their use has declined even further throughout the continent in recent years. Neither the use of crop residues nor the collection, storage and use of manure is managed efficiently. In many regions cattle herders graze the croplands after the harvest of crops that deprives the land-holders of nutrients in the crop residues. Soil erosion

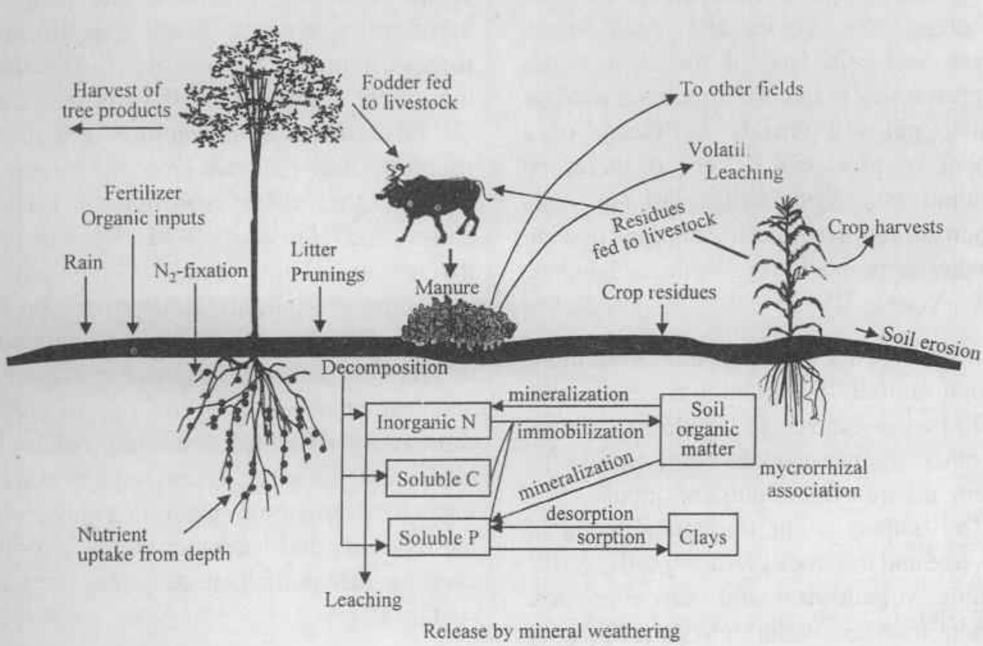


Fig. 1. Main pathways of nitrogen and phosphorus cycling in agroforestry systems (adapted from Sanchez et al., 1997). Fertilizer inputs are negligible in smallholders' farms in the semi-arid Africa.

by wind in the Sahelian zone, and by water on hill slopes and undulating plateaus further contributes to the loss of nutrients from arable lands and degradation of the soil resource base.

Nutrient Cycling

In natural and derived ecosystems, living things interact with the abiotic environment in clear tropic structures enabling the flow of nutrients. The efficiency with which nutrients are captured by and flow through living things is directly related to biomass production in natural systems and harvested products in managed systems. Nutrient cycling refers to transfer of nutrients from one component to another in the soil-plant-animal-environment system. In semi-arid agroforestry systems the plant component includes crops, trees and pasture. Nutrient transfers occur through livestock if they are an integral part of the systems. Nutrient cycling in natural ecosystems (tropical rain or savannah forests) is tight with limited nutrient losses. This contrasts with agricultural or managed systems, which lose a considerable quantity of nutrients by leaching, erosion, volatilization and animal movement, and through crop harvests. Agroforestry systems are intermediate between natural and agricultural systems, and their relative status depends on several factors including the spatial and temporal arrangement of trees and crops, tree species and management, climate and soil. One of the basic tenets of agroforestry is that trees increase nutrient cycling and soil fertility by means of a number of processes. There is increased quantitative evidence in the last ten years supporting the agroforestry nutrient cycling hypotheses proposed by Young (Sanchez, 1995; Young, 1997).

In agroforestry systems, nutrient additions through rainfall, biological nitrogen fixation (BNF) by trees and crops, fertilizers, manure and other organic residues from outside the system all constitute nutrient inputs (Fig. 1). The outputs occur through removal of crop, tree and livestock products, soil erosion, leaching, volatilization and other processes. Nutrient transfers within a system occur by litterfall, root decay, and the internal recycling of nutrients through the return of tree prunings, crop residues and manure produced within the system, and those nutrients recycled by trees from deep soil horizons to the soil surface. The nutrient transfers that occur at farm level between plots and systems have to be distinguished from the transfers that take place within a system. Nutrient transformations also occur, whereby nutrients change form, for example, from unavailable to plant available forms or vice versa (Fig. 1). Soil fertility benefits of trees go beyond nutrient cycling by favorably modifying soil physical and biological processes and in turn of their effects on water and nutrient availability to crops (Buresh and Tian, 1998; Rao *et al.*, 1998).

A quantitative understanding of nutrient cycling processes is essential to exploit the potential benefits and determine the constraints of trees for sustainable production in the currently practised and proposed agroforestry systems. Trees in agroforestry mediate nutrient cycling by (1) increasing the supply of nutrients in the crop root zone, (2) increasing the availability of nutrients to crops and (3) reducing the losses of nutrients from the system through leaching and erosion (Nair *et al.*, 1999). Trees increase the nutrient supply through BNF and the recycling of nutrients at depth to the soil surface. They increase the nutrient availability to crops by decomposition of the biomass and leaf litter added to the system and by improving soil structure and enhancing biological activity. Trees reduce nutrient losses by arresting soil erosion and intercepting the nutrients that leach out of the crop root zone by means of their deep and extensive root systems.

Many researchers have reviewed nutrient cycling in agroforestry in recent years. Some have dealt with specific aspects of nutrient cycling such as BNF by agroforestry trees (Dommergues, 1995; Sanginga *et al.*, 1990), soil improvement by trees (Rhoades, 1997; Buresh and Tian, 1998), biophysical interactions in tropical agroforestry (Rao *et al.*, 1998) and decomposition of organic residues (Mafongoya *et al.*, 1998; Palm *et al.*, 1997). Other researchers provided a general discussion of the potential of agroforestry for soil fertility management (Sanchez, 1995; Cooper *et al.*, 1996; Sanchez *et al.*, 1997; Young, 1997). The emphasis in all these reviews was on the sub-humid and humid tropics. This paper examines nutrient cycling and soil fertility benefits in the traditionally practised and recently proposed agroforestry systems, and their potential for sustainable crop production in semi-arid Africa. Our review focuses on the semi-arid region where there is an urgent need to increase productivity on smallholders' farms with limited external inputs. A great expectation, therefore, exists for agroforestry to meet that challenge.

Simultaneous Systems

Trees in croplands

Trees in croplands, also known as 'parkland systems', are common to all the three geographic regions of the semi-arid SSA. In West Africa, the parkland systems differ following a climatic gradient. Generally karité (*Vitellaria paradoxa*) and néré [*Parkia biglobosa* (Jacq.) R.Br.ex G.Don] dominate in the areas of high rainfall (800 to 1000 mm), balanites (*Balanites aegyptiaca*), faidherbia [*Faidherbia albida* (Del.) A. Chev.] or their mixtures with others in the intermediate rainfall (600 to 800 mm) and pure faidherbia dominate in the lower range of rainfall (400 to 500 mm). The other important parkland trees are *Sclerocarya birrea*, *Borasus aethiopum*, *Prosopis africana*, *Adansonia digitata* and *Hyphaene thebaica*. In eastern and southern Africa, the most important trees in croplands include faidherbia, mango (*Mangifera indica*), *A. digitata*, melia (*Melia volkensii* Gurke), *Sclerocarya birrea*, *Parinari curatellifolia* and *Acacia* species. These trees have ecological functions of nutrient cycling, arresting soil degradation, improving the microclimate and or economic functions by providing several products for both human and livestock use (food, medicines, fodder). The tree density varies from 2 to 50 trees ha^{-1} depending on the tree species. Farmers rarely plant the trees in parkland systems, with the exception of exotic species such as mango, eucalyptus (*Eucalyptus* spp.) or neem [*Azadirachta indica* (A.) Juss.].

It is important to note that a number of parkland trees are not N fixers (karité, néré, balanites, melia, *A. digitata*) and for those that fix N (most *Acacia* spp. and *Faidherbia albida*), the extent of BNF is not clearly known. However, among those N_2-fixing species studied including *Faidherbia*, there are wide provenance differences indicating the promise for selection of superior germplasm (Sanginga *et al.*, 1990). The limited understanding of BNF is due to methodological difficulties in estimating BNF in mature trees and the long-term measurements needed (Danso *et al.*, 1992). Nitrogen input through BNF could be small in dry areas (Dommergues, 1995). Nitrogen leaching could be expected in sandy soils of some areas and BNF was thought to be the source of N for leaching in such soils (Deans *et al.*, 1994). In soils posing no restriction to root growth, tree roots extend deep into the soil (up to 32 m) and capture the N at depth, as indicated by *Acacia senegal* and neem in Senegal (Deans *et al.*, 1994). Nutrient export from trees in parklands occurs through the removal of tree products (fruits, nuts, foliage and pods for feeding livestock, and branches for firewood).

Several processes contribute to an increased nutrient supply and water availability beneath trees (Breman and Kessler, 1997). In the SAT zone, processes such as BNF, nutrient capture from depth, interception of wind blown material, reduced wind erosion, and deposition by animals may each contribute to small increases of N (1 to 5 kg ha^{-1}). Reduction of water erosion and internal and external recycling could each contribute 5 to 10 kg N ha^{-1}, but that of decreased leaching

Table 1. Effect of single trees of parkland systems on the topsoil properties and crop yields below their canopy compared with those in the open area in the semi-arid sub-Saharan Africa

Tree species	Location	Total C (%)	Total N (%)	Ca	Mg	K	pH	Crop response[a]
				----------(cmol$_c$ kg^{-1})----------				
North-central Senegal (Dancette and Populain, 1969)								
Faidherbia albida	canopy	3.70	0.40	1.61	0.71	0.10	5.7	Groundnuts: +37%
	open	2.70	0.30	1.13	0.62	0.07	5.5	Sorghum: +200%
Central Plateau, Burkina Faso (Depommier *et al.*, 1992)								
F. albida	canopy	1.10	1.30	5.80	2.08	0.65	6.7	Sorghum grain: +115%
	open	0.78	0.90	5.05	2.00	0.38	6.6	
Lakeshore Plain, Malawi (Rhoades, 1995; Saka *et al.*, 1994)								
F. albidia	canopy	2.50	0.22	5.71	1.50	0.98	63	Maize grain: +100 to 400%
	open	2.20	0.19	6.84	1.78	0.87	63	
South-eastern Mali (Kater *et al.*, 1992)								
VP	canopy	0.66	0.06	1.68	0.67	0.27	6.0	Cotton: VP: -2%
PB	open	0.51	0.05	1.45	0.42	0.16	6.0	PB: -65%
								Sorghum: VP: -44%
								PB: -66%
								Millet: VP: -60%
								PB: -60%
Morogoro, Tanzania (Okorio, 1992; Okorio and Maghembe, 1994)								
F. albida	canopy	0.70	0.06	3.95	1.19	0.44	6.1	Maize: 0%
	open	0.64	0.05	3.56	1.15	0.43	6.0	

VP: *Vitellaria paradoxa*, PB: *Parkia biglobosa*, [a]Yield under tree canopy as % of open tree-less area.

contributes over 10 kg N ha^{-1}. The magnitude of P increase by each of the above processes and mycorrhizae was estimated to be in the order of 10% of N increases.

Trees increase water availability by improving soil structure and infiltration and consequently reduce run off and improve microclimate by lowering the supra-optimal temperatures common in the SAT to favorable levels. The positive effect of trees on crop yields under trees, is the cumulative result of improvements in soil fertility, microclimate and water availability, which outweigh the negative effects of nutrient exports. The maximum effect of all these changes on a millet crop under faidherbia trees in the Sudan zone was expected to be a yield increase of 200 to 400 kg ha^{-1} (Breman and Kessler, 1997).

Many researchers have reported increased nutrient status under trees in croplands and grass savannahs in SSA compared with open areas (Rao *et al.*, 1998; Rhoades, 1997). Nutrient changes under trees were noted in terms of increased mineral nitrogen at the beginning of the season, extractable P, organic C, and cations Ca and K (Table 1). The magnitude of changes was greater with increased size or age of the trees. Crop yield increases were substantial under faidherbia (known as 'albida effect'): for example, maize yields increased by more than 100% in Malawi (Saka *et al.*, 1994) and by 76% in Ethiopia (Poschen, 1986); sorghum yields increased by 36% in Ethiopia (Poschen, 1986) and 125% in Burkina Faso (Depommier *et al.*, 1992). Many *Acacia* spp. have open canopies and do not shade the crops underneath. In fact, faidherbia drops its leaves during the rainy season. In a study in Niger, increased millet yield under faidherbia trees was ascribed predominantly to higher soil fertility and only a small extent to other factors including such as improved microclimate. About 60% of higher soil fertility was attributed to increased N availability and 40% to increased P availability (ICRAF, 1997). Although these results must be considered as specific to the site, they indicate the importance of soil fertility for crop production in the SAT. In contrast to the case of faidherbia, substantial crop yield decreases were noted under the canopies of large, evergreen and unmanaged trees relative to those in the open areas. In Burkina Faso, sorghum yields under karité and néré trees were reduced on average by 50 and 70%, respectively (Kessler, 1992). In Mali, Kater *et al.* (1992) observed 44 to 65% lower sorghum yields under the canopies of these trees relative to those in the open areas. The decline of crop yields under these trees was primarily due to the reduced light and water competition (Kater *et al.*, 1992; Kessler, 1992), but sometimes combined with increased pathogenic organisms (Kater *et al.*, 1992).

Can nutrient cycling, and in turn crop yields, be improved by higher tree density or choice of tree species in parkland systems? A distinction should be made between trees that improve soil fertility and crop yields, and trees that may increase soil fertility, but actually reduce yields under their canopies. Trees of the latter category (karité, néré, neem), are mostly non-N_2 fixing, and grown primarily for their products (fruits, nuts, bark, wood) and generating income from their sale, which more than compensates the reduction in crop yields. Although nutrient cycling by these trees is of limited consequence to crop yields, the yields can be improved by reducing competition through tree canopy management (pruning, lopping) and the selection of less competitive species and provenances. If trees improve soil fertility as a result of BNF and/or capture of nutrients from depth, increasing tree density will probably improve nutrient cycling. Increasing tree density will have a more positive effect on crops if trees improve the microclimate without altering the competition with crops. However, such a situation is rarely feasible. There seems to be little opportunity for increasing tree density beyond 30 to 40 trees ha^{-1} even for faidherbia because several factors other than BNF such as capture of nutrients leaching, reduced soil erosion, and uptake from surrounding area, are responsible for soil improvement and increased yields under faidherbia (Rao *et al.*, 1998). Parkland systems with faidherbia or similar species may maintain crop yields at a low level in N-deficient sites, but they cannot sustain the necessary yield increases required for the growing populations without external inputs.

Hedgerow intercropping

Hedgerow intercropping (HI, synonymous with alley cropping) has been considered for three purposes: (1) improving soil fertility and crop yields, (2) controlling soil erosion on sloping lands and (3) production of fodder for livestock. The performance of the system

Table 2. Nitrogen and phosphorus budgets in hedgerow intercropping at a drier- and a wetter-bimodal highlands in sub-Saharan Africa

System	Leucaena/ manure applied t ha^{-1}	N (kg ha^{-1} season^{-1})			P (kg ha^{-1} season^{-1})		
		Input/ recycled	Export	Balance	Input/ recycled	Export	Balance
Machakos (Kenya)[1SC]							
Maize-F		0	38	-38	0	6	-6
HIg	1.4	52	37	15	3	7	-4
HIm	1.2	20	72	-52	4	8	4
Maize+F		40	53	-13	15	9	6
Debre Zeith (Ethiopia)[2SC]							
HIg 0	0.0	0	13	-13	0	-8	-8
1	0 7	22	14	8	2	10	-8
2	2.2	90	18	72	8	9	-1
+m	3.0	78	18	60	34	12	22

HIg = Hedgerow intercropping with prunings used as green manure but crop residues removed; HIm = Hedgerow intercropping with prunings and crop residues fed to cattle and manure recycled; F = fertilizer at 40 kg N and 18 kg P ha^{-1} season^{-1}; +m = Manure added from external source.

Source: 1. Mathuva *et al.* (1998); soils: Alfisols; seasonal rainfall: 350 mm. Results averaged over six seasons. 2. Lupwayi and Haque (1990); soils: Alfisols; seasonal rainfall: 730 mm; 0, 1 and 2 in HIg represent none, one and two leucaena prunings applied to soil, respectively. Results averaged over two seasons.

with regard to the first two objectives is discussed in this section and the latter is considered subsequently. The initial promise of HI in the sub-humid and humid tropics has prompted many researchers to explore its potential for improving soil fertility in the semi-arid tropics too.

In the mid-eighties, some developmental agencies tried to disseminate the technology among farmers despite the inadequate experimental basis. However, results of many studies that evaluated the biophysical potential and socio-economic constraints of the system in SAT are now available. HI was experimented in SAT mostly with leucaena (*Leucaena leucocephala*), spectabilis (*Senna spectabilis* DC), siamea (*S. siamea*), gliricidia [*Gliricidia sepium* (Jacq.) Walp.], neem, albizia [*Albizia lebbeck* (L.) Benth.], calliandra (*Calliandra calothyrsus* Meissner), pigeonpea [*Cajanus cajan* (L.) Millsp.], and flamingia (*Flamingia macrophylla*), using 4 to 6 m alley widths and pruning hedgerows at 0.5 to 1 m height.

None of the studies to our knowledge quantified all the processes of nutrient cycling to determine the complete nutrient balance of HI in semi-arid Africa. Information is lacking particularly on BNF, so inferences on the potential contribution of BNF and sustainability of HI have to be based on studies conducted in other environments. Among the species used for HI, leuacena, gliricidia, albizia and pigeonpea are known to have a high to medium BNF capacity (50 to 60% N derived from fixation). Flamingea and calliandra are assumed to have similar BNF potential, while *Senna* spp. and neem do not fix N (Danso *et al.*, 1992; Dommergues, 1995). There will eventually be N mining of soils if there is no N input through BNF, which is the case with non-N_2 fixers such as *S. siamea* and *S. spectabilis* or poorly-nodulated legumes. In studies conducted at Machakos (Kenya), N deficiency was observed in alleycropped maize between hedgerows of *Senna* spp. in above-normal rainfall seasons after about three years, indicating that the technology with non-N_2 fixing species defeats the very purpose of nutrient replenishment. The biomass produced by hedgerows varied from as low as 1.1 t in the unimodal rainfall areas of southern and west Africa to 3.5 t ha^{-1} y^{-1} in the bimodal highlands of east Africa. Assuming an average nutrient concentration of 3% N and 0.2% P, the amounts of N and P recycled with the above quantities of biomass range from 33 to 105 kg N and 2.2 to 7 kg P ha^{-1}. With only 10 to 20% of N in organic residues being available to crops in a given season (Palm, 1995), the impact of N recycled through prunings on crop yields was minimal. Biomass production was low because of limited and erratic rainfall in SAT and hedgerows failed to extract all the subsoil water due to confinement of most roots in the top 0.75 to 1.0 m as a consequence of repeated pruning. This has often resulted in the competition of hedgerows with crops for water in the same soil layers and restricted the response of crops to the increased nutrients in HI (Rao *et al.*, 1998).

The extent of soil changes under HI depends on the quantity of biomass returned to the alleys, but in any case significant soil changes are unlikely to be detected within a short period. In a six-year study at Machakos in the semi-arid eastern Kenya, N and P recycled to soil through leucaena prunings averaged 52 and 3 kg ha^{-1} season^{-1}, respectively (Table 2). This has resulted in a positive balance of 15 kg for N but a negative balance of 4 kg for P ha^{-1} per cropping season. Consequently, soil available P declined by 44% over a five-year period. In another study in Ethiopia, the removal of hedgerow prunings left a negative balance of 13 kg N and 8 kg P ha^{-1} y^{-1}. Although the return of prunings removed N depletion and increased N balance in proportion to the quantity of prunings applied, P balance remained negative unless manure was applied from an external source (Table 2). In another HI study with sorghum and *Acacia saligna* (Labill.) H. Wendl. in northern semi-arid Kenya, nutrient input through rainfall was generally low and nutrient export with the harvest was high for N and K, being reversible only with the return of tree prunings (Lehmann *et al.*, 1999). These studies clearly indicate that although N replenishment is possible with N fixing trees in HI, other nutrients are necessary from external sources.

A synthesis of many studies indicates that HI has not shown encouraging results in the semi-arid Africa (Rao *et al.*, 1998). In five of seven long-term trials (4 or more years) cereal yields in HI were lower than in sole cropping (Table 3). In another long-term trial at Machakos, whereas annual legumes cowpea and pigeonpea increased the yields of maize intercropped or rotated with them by 17 to 24% over the yields of continuous sole maize, HI with gliricidia

Table 3. Grain yields of cereal crops in sole cropping and hedgerow intercropping in long-term experiments conducted in the semi-arid Africa

Site/country	Rainfall (mm)	Years of study	Mean sole crop yield (t ha^{-1} y^{-1})	Yield change in alley cropping (%)	Mean hedge prunings (t ha^{-1} y^{-1})	Source
Machakos, Kenya	740 (bm)	6	3.90 (m)	-15	2.82 LI	Mathuva *et al.*, 1998
		6.5	2.60 (m)	- 8	2.66 Ssi	Mugendi & Muthoka, 1991
Kagasa, Rwanda	836 (bm)	5	0.52 (m)	+29	3.80 Sse	Balasubramanian & Sekayange, 1991
Chitedze, Malawi	900 (um)	3	1.23 (s) 0.78	+84 +55	na Sse	Buderson, 1992
Central Burkina Faso	830 (um)	5	0.78 (m) 0.69 (s)	+49 -16	na Gs 1.11	Tilander *et al.*, 1995
Lilongwe, Malawi	865 (um)	4	0.39 (m)	-21	1.80 LI	Chiyenda & Materechera, 1989
Gairo, Tanzania	500 (um)	4	0.71 (m)	- 2	na LI	Chamshama *et al.*, 1998
Cinzana, Mali	690 (um)	4	0.51 (pm)	+25 +12	1.89 Gs 0.49 LI	Sidebe *et al.*, 1997

bm = bimodal, um = unimodal, s = sorghum, LI = *Leucaena leucocephala*, Sse = *Senna spectabilis*, Ssi = *S. siamea*, Gs = *Gliricidia sepium*, A1 = *Albizia lebbeck*, na = not available, m = maize, s = sorghum, pm = pearl millet.

decreased the yields by 5% (Rao and Mathuva, 1999). Chiyenda and Materechera (1989) observed a 21% decrease in maize yields in HI with leucaena compared with the sole crop control over the first four years in Malawi. However, Kwapata *et al.* (1995) later reported almost two-fold greater yields from HI in the fourth and eighth years from the same trial. Although crop yields may have increased in certain years due to above average rainfall, as was the case for example whenever seasonal rainfall exceeded 500 mm at Machakos, conclusions based on individual years would be misleading. HI did not increase crop yields over sole cropping in a number of other short-term experiments (2 to 3 years) conducted at ICRAF's Machakos Research station (Jama *et al.*, 1995; McIntyre *et al.*, 1997) and in Zambia (Akyeampong *et al.*, 1995). The poor performance of HI throughout these trials was the consequence of low biomass production by the hedgerows and their competition with crops for water, thus limiting the crops' response to hedgerow prunings. Obviously, the nutrient cycling potential of trees cannot be exploited for increasing crop yields through HI in semi-arid regions. Following the analysis of published literature, Young (1997) concluded that no strong evidence exists for HI to increase crop yields in dry sub-humid bimodal, sub-humid unimodal, and dry unimodal climates.

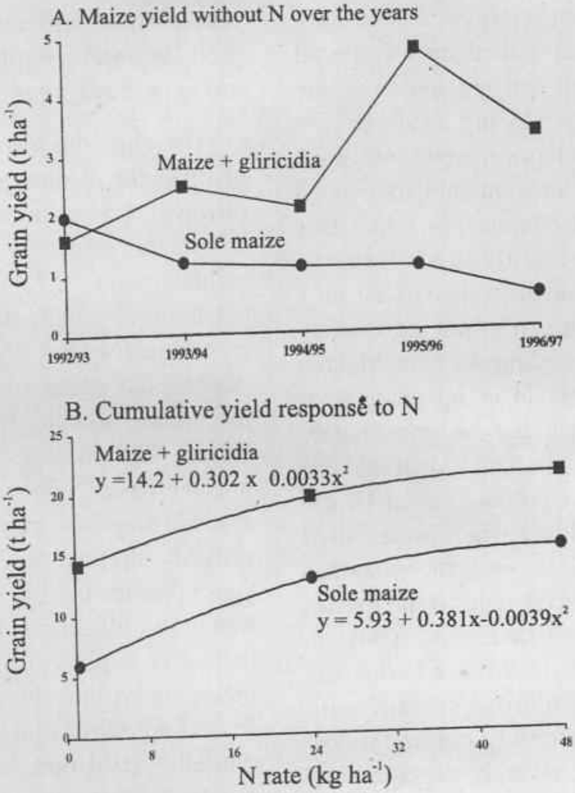


Fig. 2. Maize yields in continuous sole cropping and mixed intercropping with Gliricidia sepium at Makoka, Malawi, during 1993–1997. A. Yields without N fertilizer over the years and B. Cumulative yield response to 0, 25 and 50% of the recommended N fertilizer.

HI enhanced crop yields in three specific cases: (1) in the bimodal highlands (Rwanda), where biomass production by hedgerows was high and evapotranspiration was low, (2) in Mali, where the soils were extremely poor and probably the trees had access to the watertable and (3) in a short-term trial in Malawi, probably because of above average rainfall during the course of the study (Table 3). Interestingly, increased crop yields at the fore mentioned sites were obtained with non-N fixing *S. spectabilis* and N-fixing *G. sepium*; both these species grow slowly and the biomass of gliricidia is of particularly high quality. However, it is doubtful whether yield increases even with these species were sufficiently high for the technology to be attractive to farmers.

HI was evaluated for soil conservation on sloping lands on the premise that hedgerows serve as erosion barriers and the prunings applied as surface mulch further strengthens the conservation benefit and also improves soil fertility (Njoroge and Rao, 1998). Contour-planted hedgerows spaced 4 m apart controlled soil erosion to a safe level on moderately sloping lands (<15% slope). On steeper slopes, hedgerows alone cannot control soil erosion and they need to be considered in conjunction with other conventional mechanical structures. However, leucaena hedgerows spaced at 1 m intervals controlled erosion adequately on steep slopes exceeding 40% in Malawi (Banda *et al.*, 1994). The advantages of soil conservation may not be immediately apparent because of the small quantities of nutrients conserved. Contour-planted HI did not affect crop yields if the species used for hedgerows were less competitive (siamea or gliricidia), but reduced yields if the species used were competitive (leucaena). Only on the Ntcheu plateau in Malawi, did the contour-planted hedgerow system with leucaena increase soil fertility and crop yields, because the soil was severely degraded and a higher rainfall at the site together with the conserved water reduced hedgerow competition with the crops. In the context of soil conservation, hedgerows in combination with or without fodder grasses and other soil conservation structures (contour bunds, terrace risers) should be adopted for productive purposes, such as for fodder in the short-term, and for preserving the soil resource base in the long-term.

Other simultaneous systems

In relatively high populated and land-scarce southern Malawi (population density 180 to 360 people km^{-2} and average land holding = 0.50 ha per family) farmers cannot afford to grow tree fallows at the expense of crops. For such socio-economic conditions, systems that combine both trees and crops such as intercropping with gliricidia or sesbania have been proposed.

The gliricidia/maize mixed intercropping involves the planting of gliricidia in alternate furrows (1.5 m between rows and 0.9 m within the rows) of normal maize planted on the ridges (0.75 m between ridges and 0.3 between plants within rows). The trees are pruned at the beginning of each rainy season and again at about 6 weeks after the maize sowing to a height of 0.2 to 0.3 m. The prunings are then incorporated into the maize ridges as green manure. The system may not initially benefit maize or possibly slightly depress yields in the first year when the trees are not pruned. However, maize yields are substantially increased thereafter as gliricidia prunings are regularly incorporated into the soil twice per season. In a long-term trial at Makoka (average rainfall = 1034 mm, soils: Oxic Haplustalf), while yields of monocropped maize decreased with time, those of intercropped maize with gliricidia increased progressively by a 2- to 5-fold increase (Fig. 2). Gliricidia produced 2 to 5 t ha^{-1} (dry weight) of biomass annually which with an average N concentration of 3.9% recycled 78 to 195 kg N ha^{-1}. The application of gliricidia prunings substantially increased the topsoil inorganic N at the end of the dry season and during the early part of the rainy season. Maize yields in gliricidia/ maize mixed intercropping systems were highly dependent upon the pre-season inorganic N and the anaerobic N mineralization potential (Ikerra *et al.*, 1999).

In the closely related sesbania [*Sesbania sesban* (L.) Merr.]/maize relay inter-cropping, 4- to 6-week-old bare-rooted sesbania seedlings are interplanted in the standing maize 4 or 5 weeks after its sowing in alternate furrows (1.5 m between rows and 0.9 m within rows). After the maize harvest, sesbania is allowed to grow in the dry season using the residual water. The biomass produced during the post-rainy period is incorporated into the soil for the benefit of subsequent maize. In a long-term trial at Makoka, relay interplanted sesbania produced an average foliar biomass of 1.7 t ha^{-1} $season^{-1}$, which with an average N concentration of 3.4% recycled 58 kg N ha^{-1}. Maize under sesbania relay intercropping without any fertilizer produced significantly higher yields than that of sole maize in 4 out of the 5 years. Averaged over the trial period of 5 years, intercropped maize produced 110% more grain than sole crop (ICRAF, 1994). The potential benefits of sesbania relay intercropping were greater in the *dambo* valleys and *dambo* margins, where the deeper soils helped retain more water and produced more sesbania biomass than on the steep slopes (Phiri *et al*., 1999a). There may or may not be a need for supplemental N for moderate maize yields in high potential sites, but external N would be needed in low potential sites because of the small quantity of N recycled by the relay planted sesbania (Phiri *et al*., 1999b; Snapp *et al*., 1998).

Conceptually, both these intercropping systems function on the principle of a complementary use of growth resources by the tree and crop components over time and space. While the crop uses the rainy season resources, the tree (gliricidia or sesbania) exploits the post-rainy season residual water and nutrients that the crop could not use and thus produces biomass. The traditional maize/pigeonpea intercropping operates on the same principle. However, whereas pigeonpea produces a bonus yield of legume grain (for human use and sale) and contributes to a limited degree to soil fertility improvement, these 'dry season tree fallow systems' produce biomass for green manuring subsequent maize crops. In view of the short period of growth free from the crop competition, both the biomass produced by the intercropped trees and its relative effect on maize compared with pure tree fallows are small. However, gliricidia, a perennial with coppicing ability, avoids the need for re-planting every year and exploits the subsoil water and nutrients better with its deeper root system than sesbania. Consequently, gliricidia in mixed intercropping produces a greater quantity of biomass and recycles greater amounts of N compared with the annually planted sesbania in relay intercropping.

The biomass production by trees depends primarily on the residual water, which is in turn determined by the soil type, rainfall and soil depth (including position in the landscape). Thus, there is a need to test these technologies on a range of soil and climatic conditions to determine the biophysical conditions relevant for their use. How do these new technologies compare with intercropping of pigeonpea with maize or groundnut in terms of short and long-term productivity and income? Is replenishing soil fertility through the purchase of fertilizer with cash earned from pigeonpea better than nutrient cycling by these agroforestry systems? These questions must be answered to judge the suitability of either of the above strategies. The ongoing wide-scale on-farm testing indicates a greater potential for

Table 4. Above- and below-ground biomass, and nutrients recycled in the soil by 1- and 2-year *Sesbania sesban* fallows at Chipata, Zambia (Torquebiau and Kwesiga, 1996)

Year/ fallow length	Biomass (t ha^{-1})				Nutrients recycled (kg ha^{-1})			
	Wood	Litterfall[a]	Leaves & twigs	Roots	Above-ground[b]		Roots[c]	
					N	P	N	P
1992								
1-year	3.2	0.96	0.18	1.31	25.0	3.3	18.0	1.0
2-year	13.0	3.05	0.35	1.71	71.4	9.5	23.4	1.3
1993								
1-year	10.1	1.36	0.50	2.13	44.2	5.6	29.2	1.6
2-year	15.1	4.00	0.50	2.93	95.2	12.7	40.1	2.2

[a]Litterfall was measured in both the years only during May to September, so these under-estimate the actual content.
[b]Includes nutrient content of litterfall and leaves and twigs at harvest. Nutrient concentration of leaf litter was 1.93% N and 0.27% P, and of leaves and twigs 3.6% N and 0.37% P.
[c]Nutrient concentration of root biomass was 1.37% N and 0.07% P.

gliricidia/maize mixed intercropping than for sesbania relay intercropping. The potential of the relay system was in part lowered by defoliation of sesbania by the beetles, *Mesoplatys ochroptera* and *Exosoma* sp.

Gliricidia/maize mixed intercropping is a variant of HI. How is it possible that mixed intercropping increases crop yields and justifies further on-farm testing in contrast to that of HI? Gliricidia mixed intercropping differs from HI with other tree species in at least four respects: (1) as gliricidia is pruned severely and grows slowly, it does not compete with maize, (2) gliricidia prunings decompose rapidly and release N for immediate use by the crop, (3) in the process of land preparation and forming ridges and furrows every season, surface roots of gliricidia are pruned, further reducing tree competition with maize, and (4) the evenly distributed gliricidia throughout the field efficiently exploit the residual water to produce a greater quantity of biomass than do widely spaced hedgerows in HI.

Sequential Systems

Managing the natural vegetation with selective planting or retaining of trees for specific tree products and/or faster enrichment of soil has been in vogue in the humid and subhumid tropics. The concept of planted fallows with deep rooting, N_2-fixing and fast growing trees or shrubs for rapid soil fertility replenishment has gained momentum in SSA only recently, particularly after HI had indicated no success for SAT. If planted fallows are to be accepted by farmers, they should be of shorter duration and with species that can be established easily and fix biological nitrogen. Many woody species suitable for short-duration planted fallows (*Sesbania*, *Crotalaria* spp., *Tephrosia* spp., *Desmodium* spp., pigeonpea) are known to fix nitrogen to varying degrees (Giller *et al.*, 1997). There could be substantial N input of BNF in planted fallows as the trees grow in sole systems free from crop competition and without pruning (unlike in HI).

Planted tree or shrub fallows, now commonly referred to as 'improved fallows', have been experimented with a range of species such as sesbanias (*S. sesban*, *S. macrantha*), tephrosias (*Tephrosia vogelii* Hook. F., *T. candida*), pigeonpea, acacia [*Acacia angustissima* (Mill) Kuntze] in ICRAF's co-ordinated agroforestry research project for southern Africa (Zambia, Zimbabwe, Tanzania and Malawi). Of the different species tested, *S. sesban* and *T. vogelii*, followed by pigeonpea, were suitable for 1- to 2-year fallows. At Chipata in eastern Zambia (soils: Haplustalfs, average rainfall: 1000 mm y^{-1}), whereas 1-year planted fallows of sesbania and tephrosia increased maize yields immediately after fallows by 32 to 62%, 2-year fallows increased yields by 72 to 158% compared with 2-year grass fallow (Kwesiga *et al.*, 1994). The effect of 1-, 2- and 3-year fallows of sesbania, acacia and pigeonpea were evaluated on three subsequent maize crops with and without fertilizer at Domboshava in Zimbabwe (soils: sandy Ustalfs, average rainfall: 750 mm y^{-1}). The effects of tree fallows were in the following order sesbania >pigeonpea >acacia, mostly in relation to the quality of biomass of these species. The longer the duration of tree fallows, the bigger the residual effect on the subsequent maize, particularly in the second and third crops after the fallows of low quality acacia and pigeonpea (Mafongoya and Dzowela, 1999). The beneficial effect of fallows on crops in rotation was due to (1) the nutrients recycled through incorporation of above and below-ground biomass and (2) improved soil physical conditions from the combined effect of tree root activity and biomass incorporated in the soil.

Research has not distinguished between effects of nutrient cycling and improved soil physical conditions, but their combined effects in 1- and 2-year sesbania fallows were monitored at Chipata over two fallow – crop rotation cycles (Torquebiau and Kwesiga, 1996). The 2-year fallows produced 3.4 to 4.5 t ha^{-1} of foliar biomass and 1.7 to 2.9 t ha^{-1} of root biomass (Table 4). These fallows also produced 13 to 15 t ha^{-1} of wood, which was removed as firewood – an added value of fallows. Two-year sesbania fallows recycled 71 to 95 kg N and 10 to 13 kg P through above-ground biomass (leaves, twigs and litterfall) and 23 to 40 kg N and 1 to 2 kg P through roots (Table 4). The 1-year sesbania fallow recycled only about one-half of those by the 2-year fallow. Nitrogen added through biomass includes N input through BNF into the system and N captured from deep soil layers. This study did not measure BNF, but the observed profuse nodulation of sesbania infers that a substantial quantity of N was fixed. Root observations have indicated that although 45 to 54% of sesbania root mass was concentrated in the top 25 cm, many roots were also found in 1 to 2 m depth and some even extended to the water table at 7 m. Nitrogen leaching in this ecozone is expected to be negligible because of the lower rainfall compared to the east African highlands, thus the quantity of N at depth would be correspondingly low. Evidence from western Kenya indicates that sesbania can capture whatever N is available at depth beyond the crop root zone and recycles to the surface via foliage (Buresh and Tian, 1998). The high quality sesbania foliage (low C:N and lignin + polyphenol:N ratios) decomposes and mineralizes N rapidly

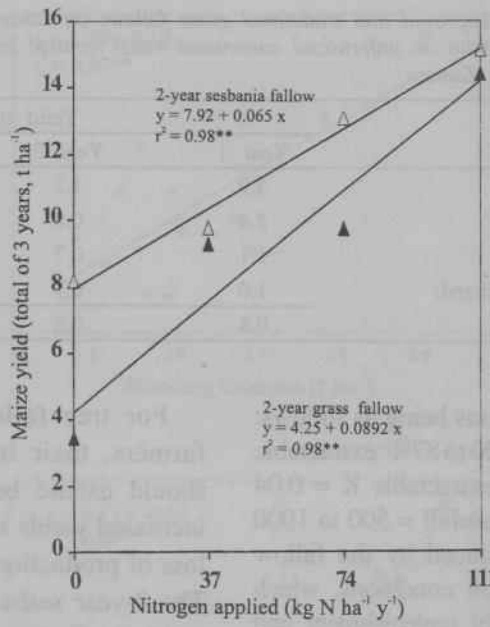


Fig. 4. Response of cumulative maize yield over three years (1993–1995) to nitrogen following two-year sesbania and grass fallows at Chipata, Zambia.

The improved fallow technology is suitable where the population density is low, the opportunity cost of labor is high, the soils have greater pH (>5.5) and clay (>20%), rainfall exceeds 700 mm per year, and the trees give additional products such as fodder and fuelwood. There is a need to expand the range of species suitable for planted fallows and to determine whether nutrient cycling can be improved with coppicing species such as gliricidia and leucaena or by mixed fallows.

Biomass Transfer

Foliar biomass of trees and shrubs grown on or outside the farm is an effective source of nutrients to increase food crop production in smallholders' farms. Although the 'biomass transfer' system practised in the name of 'green-leaf manuring' in many Asian countries has lost its significance in the wake of cheaper and more effective chemical fertilizers, it is still very relevant in SSA because of the high cost of fertilizers and their unavailability to small-scale farmers.

Collecting leaf litter from *miombo* woodlands and its application to croplands is a common practice in some southern African countries (Rao, 1994).The material is either directly applied, collected and stored during the dry season when the pressure for labor is less for use in the rainy season, or cured by mixing with manure before applying to crops. In Zimbabwe, farmers collect on average 0.5 t of litter per household per annum, most of which is cured in cattle pens and the manure-litter mixture is finally

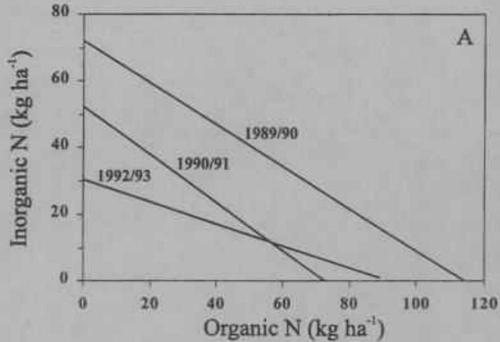
Table 6. Average concentration of major nutrients and secondary compounds in the foliage of trees and shrubs commonly employed in agroforestry in the semi-arid Africa

	N	P	K	Lignin	Soluble polyphenols	C:N
	(% of dry matter)					
Acacia angustissima	3.74	0.19	-	14.57	9.51	17.6
Albizia lebbeck	3.78	0.15	1.00	-	2.28	11.0
Azadirachta indica	2.92	0.17	1.96	13.50	3.68	20.7
Calliandra calothyrsus	3.29	0.16	0.76	17.68	10.50	17.6
Flemingia macrophylla	2.67	0.38	1.85	22.07	8.00	24.9
Gliricidia sepium	3.44	0.24	1.71	11.34	1.99	11.7
Leucaena leucocephala	3.93	0.24	2.30	10.62	6.42	8.5
Senna siamea	2.48	0.16	1.30	10.44	3.33	21.0
Senna spectabilis	3.56	0.21	1.56	10.48	1.24	16.0
Sesbania sesban	3.66	0.22	1.74	8.60	2.40	16.0
Tithonia diversifolia	3.71	0.37	4.48	6.50	1.60	12.02
Cajanus cajan	3.95	-	-	14.87	1.69	15.2
Manure	2.91	0.64	2.81	19.90	1.30	7.7
Miombo litter	1.07	-	-	28.27	2.67	44.0

Source: Several, including the Organic Inputs Database of the Tropical Soil Biology and Fertility Program, Nairobi, Kenya.

applied to maize and finger millet (*Eleusine coracana*) crops (Nyathi and Campbell, 1993). In many areas of SSA, tree/shrub vegetation exists in communal lands, along roadsides and as live fences around farms and home compounds, the biomass of which is essentially unused. For example, tithonia [*Tithonia diversifolia* (Hemsley) A. Gray], which grows throughout SSA in the vacant lands, is a high quality foliar biomass and can be exploited for crop production (Jama *et al.*, 1999). In SAT, special effort is required to collect and store the biomass of tithonia and other natural vegetation before it dries out in the dry season. If the biomass applied to crops is from outside the farms such as from savanna woodlands (*miombo*), it provides nutrient inputs to the croplands. However, the extent to which this technology overcomes nutrient mining depends on the quantity and quality of biomass applied.

Four issues need to be addressed in determining the feasibility and developing appropriate strategy for biomass transfer technology as follows: (1) How much biomass of a given species needs to be applied either alone or in combination with fertilizers for an economic impact on crop yields? (2) Can the trees or shrubs be integrated with crops to produce the material on farms for sustainable use? (3) Under what circumstances is the technology economical, given that extra labor is required for production or collection, transportation and application of biomass to arable fields? and (4) If biomass is palatable, is feeding it to livestock and recycling manure more economical than direct use as green manure? The last issue is discussed in the subsequent section. Research at ICRAF and many national programs in SSA have addressed these issues.



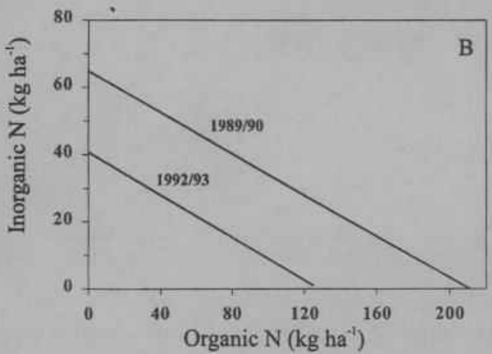


Fig. 5. Combination of inorganic and organic N required to produce 3 t ha^{-1} maize grain yield using gliricidia (A) and leucaena (B) green manures at Chipata, Zambia, based on fitted regressions of yields against inorganic and organic N rates in different years.

The response of crops to biomass depends on the quantity and quality of biomass applied and a number of other factors including the soil, climate and management. The quality of different tree/shrub biomass differs widely in terms of nutrient concentration and secondary compounds such as lignin and polyphenols, that bind proteins and resist decomposition and nutrient release to crops (Table 6). A moderate quantity of biomass can meet N and K requirements of cereal crops targeted for moderate yields, but not that of P because most materials have a low concentration of tissue P. For example, a 5 t (dry weight) ha^{-1} material of species listed in Table 6 supplies 124 to 198 kg N and 38 to 224 kg K ha^{-1}. The same quantity of biomass supplies only 8 to 19 kg P, which does not meet the P requirement of a maize crop that yields 2 t ha^{-1} grain. Generally, materials that contain a tissue concentration of <2% N, >15% lignin, >3% polyphenol and <0.25% P results in an initial net immobilization of N and P (Palm, 1995). Mafongoya *et al.* (1997) and Palm *et al.* (1997) reviewed the results of decomposition

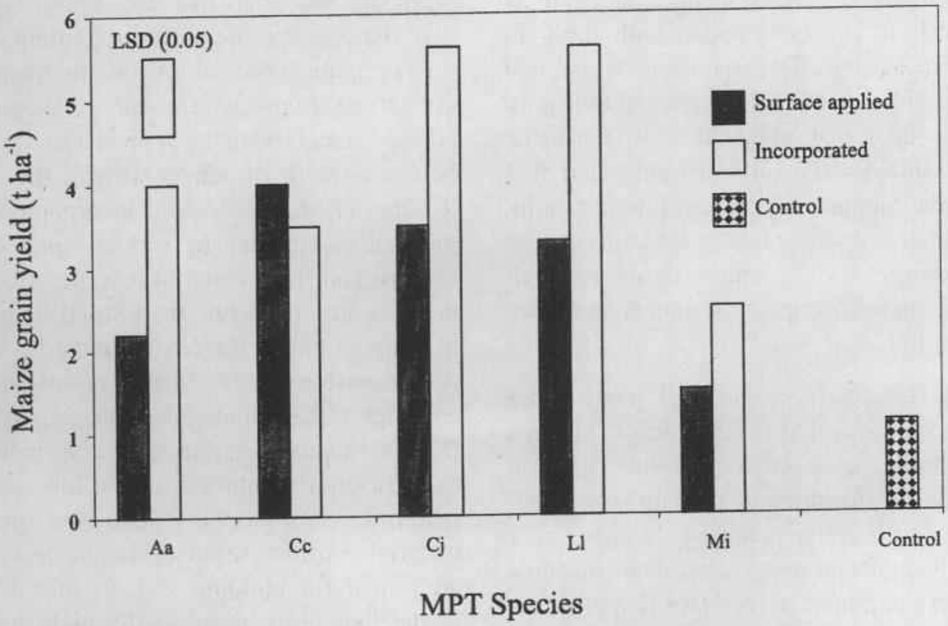


Fig. 6. Response of maize grain yields to different tree prunings and method of application at Domboshava, Zimbabwe (Mafongoya and Nair, 1997). Aa = Acacia angustissima, Cc = Calyandra calothrysus, Gs = Gliricidia sepium, Ll = Leucaena leucocephala, Mi = Bachystegia spiciformis (miombo litter), Control = no prunings.

of organic residues and nutrient release in relation to quality and management strategies for improving their efficient use.

At Chipata, Zambia, five rates (0, 5, 10, 15 and 20 t ha^{-1} fresh material) of gliricidia (22% dry matter, 3.36% N) or leucaena (28% dry matter, 3.85% N) biomass were evaluated in combination with five rates of N fertilizer (0, 30, 60, 90 and 120 kg N ha^{-1}) at a constant rate of P (18 kg P ha^{-1}) and K (16 kg K ha^{-1}) over four years. With the exception of one year when maize failed due to poor rainfall, significant responses were observed to both inorganic and organic N in the remaining three seasons. There was no significant interaction between inorganic and organic N sources in the first two seasons, but a significant interaction was observed for the material of both tree species in the fourth season following a drought. Maize yield responses to inorganic N were consistently greater than those obtained from organic N. Many previous studies also reported that organic N is less efficient than inorganic N, because of several factors affecting the synchrony of nutrient release with crop demand (Gutteridge, 1992; Cooper *et al*., 1996). Responses to current applications of both organic and inorganic N sources increased with time, probably as a result of the residual effect of previous applications. This implies that fresh applications of green manure as well as N fertilizer can be reduced with time. In all three seasons, the response to N supplied by gliricidia green manure was significantly greater than that obtained from leucaena. Other studies have also demonstrated that gliricidia biomass decomposes more rapidly than that of many other tree/shrub species (Gutteridge, 1992), emphasizing its high quality and the impact of such material on crop yields.

The results from this and many other studies confirm that foliar biomass of trees and shrubs, in biophysical terms; has the potential to substitute or partially substitute, for N fertilizer. In addition, because of a high K concentration, green-leaf manures reduce or eliminate the need for K application on soils that are marginal in K supply. The potential for N substitution of gliricidia and leucaena, based on the results of the Chipata trial, is illustrated in Fig. 5. Based on 1989-90 results, a maize crop that produces 3 t ha^{-1} would require 72 kg inorganic N (156 kg urea ha^{-1}) or 112 kg organic N of gliricidia (equivalent to 15 t ha^{-1} fresh material), or 210 kg organic N of leucaena (equivalent to 20 t ha^{-1} of fresh material) or any combination of the two sources lying on the curves of the respective species. At the 1997 prices in Zambia, 156 kg urea would cost about US$ 61. In contrast, about 0.5 ha would be required to produce adequate green manure for 1 ha of cropped land each year.

The efficiency of organic nutrients can be improved by management practices related to the use of organic source materials and crop husbandry practices aimed at achieving better synchrony between nutrient release and crop requirement. The high quality materials (gliricidia, leucaena) that decompose rapidly may have some flexibility regarding their time of application, but low quality materials (*Senna* spp., *Piliostigma thonningii*, flamingia, *miombo* litter) should be applied 1 to 2 weeks before sowing or when sowing the crop (Cooper *et al.*, 1996). Soil incorporation of material is superior to surface application (Fig. 6) and fresh material is more effective in releasing nutrients than dried material in terms of nitrogen recovery and crop yield responses (Rao, 1994). Mixing of low quality and high quality materials, and composting the low quality materials may help increase the efficiency of nutrient use in low quality materials (Palm, 1995). The low quality materials exhibit greater residual effects and are suited for building soil organic matter in the long-term, whereas the high quality materials are better for short-term N supply to crops.

In semi-arid Africa, water scarcity is a common feature. The foliar biomass of trees could be employed as mulch to increase the available water to crops by reducing soil evaporation. In the semi-arid areas of Burkina Faso, mulching with neem or albizia leaves was tested at rates equivalent to 25, 50 and 75 kg N ha^{-1} over a 3 year period. The material required for the highest rate was 3.7 t ha^{-1} dry weight of neem and 2.7 t ha^{-1} dry weight of albizia. Average sorghum yield response compared with an unmulched control increased from 91% at 25 kg N to 172% at 75 kg N mulch rate. Between the two materials, the slower decomposing neem gave 17% higher yields than albizia due to better water conservation (Tilander, 1993; Tilander and Ong, 1999). In a long-term trial at Machakos (Kenya),

Table 7. Promising indigenous and exotic fodder trees/shrubs in the three semi-arid regions of sub-Saharan Africa

West Africa	East Africa	Southern Africa
Ziziphus mauritiana	Melia volkensii	*Acacia angustissima* (FB)
Bauhinia rufescens	*Morus alba* (FB)	*Cajanus cajan* (FB)
Gliricidia sepium (FB)	*Cussonia holstii*	Leucaena pallida (FB)
Albizia gauchapele	*Grevillea robusta*	*L. diversifolia* (FB)
Pterocarpus erinaceus (FB)	*Cordia africana*	*Gliricidia sepium* (FB)
P. lucens	Leucaena leucocephala (FB)	*L. leucocephala* (FB)
Cajanus cajan (FB)	*Calliandra calothyrsus* (FB)	
Grewia bicolor	Ehretia cymosa	
Sesbania sesban (FB)	*Persea americana*	
Leucaena leucocephala (FB)	*Commiphora zimmermanii*	
Hardwickia binnata		
Caesalpinia ferrea		
Kigalia africana		

Source: ICRAF, 1997 & 1998; Species designated with (FB) are particularly suited for fodderbanks and others are pruned or lopped.

water conserved by tree mulches depended on the rate of decomposition (*S. siame* >gliricidia >grevillea), but the crop yield responses ultimately depended on the nutrients supplied by the materials (gliricidia >*S. siamea* >grevillea) (R. Chiti, pers. comm.). The lowest quality grevillea decomposed fastest due to termites.

As nutrient depletion is equally (if not more) severe as water scarcity in the semi-arid regions, materials that supply nutrients and contribute to water conservation (neem, *Senna* spp., gliricidia) should be preferred over those that provide few nutrients but conserve water (straw). The relative importance of the site problem (nutrient vs. water scarcity) and quality of the material determine the purpose and mode (soil incorporation vs. mulch) of use of organic residues. Palm *et al.* (1997) provided a simple decision tree to determine the suitability of organic materials for different objectives based on quality characteristics (tissue concentration of nutrients, lignin and polyphenols).

A positive aspect of biomass transfer systems, unlike simultaneous systems, is the absence of competition between the tree and crop components for growth resources. A negative aspect, however, unlike sequential systems, is that the crop cannot benefit from the soil-tree root interactions. As previously stated, biomass produced outside the farm constitutes a nutrient input to the system, but biomass (especially of non-N_2-fixing species) produced on the farm moved between different fields represents only transfer of nutrients. Such a practice may give short-term benefits, but cannot sustain the system in the long-term. To summarize, the biomass transfer technology has potential where high quality biomass is available freely near crop fields, the opportunity cost for labor is low, and biomass has no value (fodder) other than as a source of nutrients. If labor costs are high, then the technology is only relevant for high value crops such as vegetables.

Agroforestry Integrating Livestock

In mixed farming, there is competition between crops and livestock for the biomass produced on farms and complementarity through the return of manure to croplands. In addition to being a source of dietary products, income, draft power and manure, livestock are regarded as an insurance against the risk of crop failure in semi-arid Africa. Inadequate supply and poor quality of fodder, particularly in the dry season, is one of the major reasons for low livestock productivity in semi-arid SSA. Mixed farms, in contrast to those without livestock, gain nutrients through grazing of livestock on communal lands and crop residues of other farms. Although manure provides nutrients to crop plants in a readily available form, the livestock route of nutrient cycling also offers opportunities for accelerated loss of nutrients compared with green manures. The issues that should be considered in the context of improving livestock productivity and nutrient cycling in mixed farming systems are: (1) how to increase the production of high quality fodder, (2) which animal and what feeding systems are appropriate for any given agroclimatic and socio-economic conditions, (3) how the diet affects manure quality, and (4) how to manage manure to increase its use efficiency. Many previous publications have dealt with the role of livestock in sustaining nutrient cycling in mixed farming systems of sub-Saharan Africa (Powell *et al.*, 1995; Pell, 1999), so we limit our discussion here to increasing on-farm fodder production through trees and tree–animal interactions that affect nutrient cycling.

Leguminous tree/shrub fodders are high in crude protein and N, and can be used to supplement the low quality diet of ruminants and are alternatives to expensive commercial concentrates (Paterson *et al.*, 1996). Nitrogen in tree fodders, if not bound by tannins, can alleviate N deficiency problems. In addition to N, tree fodders contain minerals, vitamins, readily degradable organic matter and water, and their supply promotes multiplication of cellulolytic microorganisms to facilitate the breakdown of poor quality roughages. However, tree fodders may contain anti-nutritional compounds that limit their value (Reed *et al.*, 1990; Paterson *et al.*, 1996). Indigenous and exotic tree/shrub species suitable for increasing fodder production have been identified in different geographic regions of SSA (Table 7). These species can be grown on farms in different niches and systems as (1) regularly pruned hedgerows on internal and external field bunds, soil conservation structures (contour bunds and terrace risers), (2) upperstorey trees integrated with crops (i.e. parklands) which can be lopped periodically, and (3) sole fodderbanks. If HI is practised with fodder species, some proportion or all of the prunings can be used as fodder. Trees/shrubs are particularly better suited for SAT to increase fodder production than are herbaceous plants because of their resistance to drought.

Fodder production from hedgerows in SAT may vary from 2 to 5 kg dry matter

m^{-1} y^{-1}, depending on the rainfall and soil type. In the semi-arid areas of Zimbabwe, about 500 m of contour bund area is available ha^{-1} on sloping lands, where it was possible to produce 835 kg (dry weight) of *A. angustissima*, 560 kg of leucaena or 475 kg of pigeonpea fodder. The acacia fodder from bunds of one ha is adequate to sustain one animal for three months in the dry season at a daily ration of 9 kg (3% of body wt.), or to feed the whole year at a supplemental rate of 2 kg per day (ICRAF, 1995). In Mali, gliricidia and leucaena fodderbanks have been found to be highly productive for the year-round supply of high quality fodder. A gliricidia fodderbank two years after establishment produced on an average 12.7 t ha^{-1} of fresh fodder in the dry season (March to June) compared with 6 t by leucaena. The wet season production was nearly three times that of the dry season for both species (ICRAF, 1995). Leucaena and sesbania have been considered highly appropriate for dairy cows and small ruminants in east and southern Africa. At Machakos, a leucaena fodderbank was found to produce exceptionally high yields (dry weight) of 17 t ha^{-1} y^{-1}during 1989-1991 (Jama *et al.*, 1995). The arrival of leucaena psyllid (*Heteropsylla cubana*, Crawford) to Africa in the early nineties has severely affected the adoption of leucaena in agroforestry. However, a number of psyllid-resistant alternative *Leucaena* species [*L. diversifolia* (OFI53/88), *L. pallida* (K806, K376), *L. esculenta*] have now been identified with a similar agronomic potential to *L. leucocephala*. Given the essentiality of fodder and crops for mixed farms, whether land productivity is greater by intercropping trees and crops (as HI) than sole cropping was investigated. Studies confirmed that in SAT intercropping has no advantage over separate cropping of trees (as fodderbanks) and crops, and that mixing may be considered only if hedgerows have an over-riding soil conservation function (Jama *et al.*, 1995; Mathuva *et al.* 1998). Livestock productivity, measured in terms of milk yield or live weight gain, increased by supplementing the normal diets with tree fodders (Cooper *et al.*, 1996).

Should the biomass of palatable trees be applied as green manure or fed to livestock? From a nutrient cycling perspective, livestock feeding of biomass is inefficient because of nutrient losses through movement of livestock, sale of livestock products, and volatilization and leaching of N in urine and manure. However, the production of high value animal products and the 'composting effect' on biomass in the course of its passing through animals may more than compensate for the loss of nutrients. In a study at Machakos, Kenya, while green manuring of leucaena prunings recycled 40% more N than that exported through crop harvests, manure recycled only 27% of N exported. Both cattle feeding and green manure systems recycled similar quantities of P about 50% of that exported (Table 2). However, leucaena biomass as fodder was three times more profitable than green manure (Mathuva *et al.*, 1998). Other studies have also confirmed that the economic value of using harvested biomass as fodder is three to four times that of using the same biomass directly as green manure. If the value of manure was considered in the calculations, the ratio between these systems will be five times or more (Paterson *et al.*, 1996). It is important to recognize that there would

Table 8. Per cent nitrogen and phosphorus in the leaves of some fodder trees and in the respective manures obtained by feeding the leaves to goats in Zimbabwe (Mafongoya et al., unpublished data)

MPT species	Total N		Total P	
	Leaves	Manure	Leaves	Manure
Acacia karro	2.0	2.0	0.13	0.25
Acacia nilotica	2.4	1.1	0.16	0.46
Calospermum mopane	1.1	1.0	0.05	0.24
Gliridia sepium	2.9	0.9	0.14	0.43

be substantial nutrient depletion from fodderbanks with the removal of large quantities of biomass. This is true even for N fixing legume species, especially for P and other nutrients, which need to be replenished for sustainable production. Part of the income generated through livestock could be used to buy fertilizer to overcome the nutrient depletion from croplands.

About 95% of nutrients consumed by animals are excreted, N through urine and faeces, but others mostly through faeces. Soluble N in manure and urine N is almost immediately available to plants, but insoluble N in undigested plant residues mineralizes and will gradually be available to plants. The rate of N mineralization is faster and volatilization losses greater for N in manure than in prunings. Nitrogen in urine is particularly difficult to manage and is invariably lost. Stall-feeding of livestock through cut-and-carry system (zero grazing) ensures better utilization of fodder and crop residues and more efficient collection of manure. This method has become popular in the east African highlands. Unless such controlled feeding systems are introduced, free grazing animals pose a major threat to the establishment of trees in agroforestry systems in the semi-arid areas. Stall-feeding has the drawback of N losses because of the difficulty of managing urine. Increased bedding with organic residues and its frequent removal to a compost pit, or any mechanism that directly transfers urine to the nearby plots of the cattle-shed would probably reduce losses. Penning animals on croplands during the dry season is an efficient traditional practice for handling manure as it reduces N losses from both urine and manure, which are directly deposited on the croplands thus eliminating the need for transport and the distribution of manure.

The proportion of dietary N excreted in dung or lost through urine from livestock depends on the quality of forage and the site of catabolism in the digestive tract (Somda *et al.*, 1995). Tannins and related polyphenol compounds have a major effect on the amount and pathway of N excretion. A high correlation exists between the concentration of lignin and polyphenols in browse and concentration of insoluble-N in faeces. Reed *et al.* (1990) reported 2.1 to 2.6% N in the faeces of sheep fed with *Acacia cyanophylla, A. sieberiana* and *A. seyal*, which contain high polyphenols, compared with only 1.6% N in the faeces of sheep fed with sesbania leaves, which contain high N and low polyphenols. Under

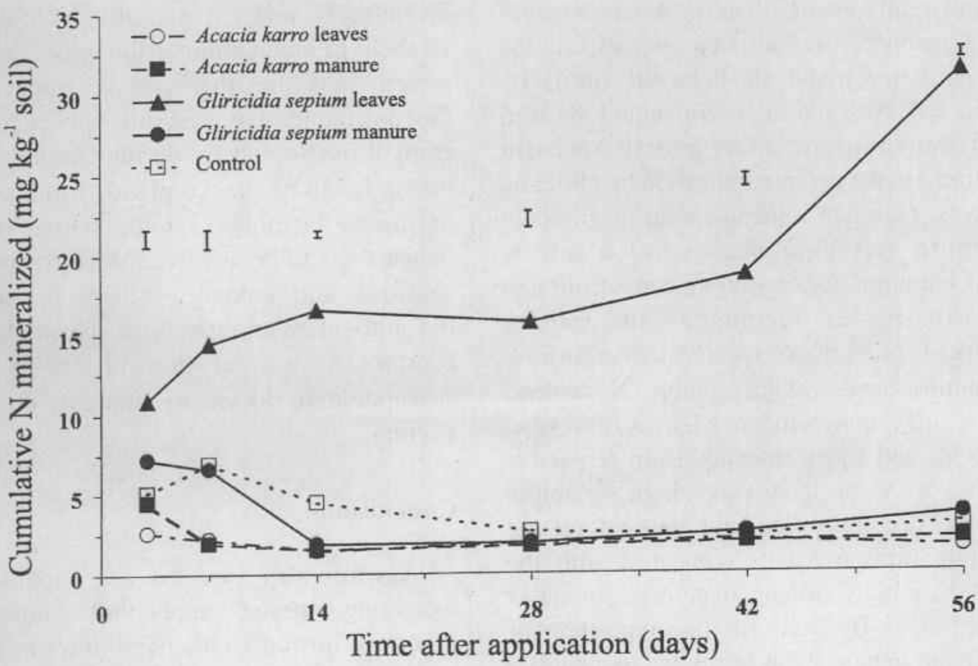


Fig. 7. Net nitrogen mineralized from tree leaves and respective manures compared to that of no input control at different incubation periods. Vertical bars at each observation are standard errors of difference of treatment means (source: Mafongoya et al., 1999).

stall-feeding conditions, the greatest faecal N content was from sheep fed browse leaves, followed by sheep fed cowpea leaves and then millet leaves. In a feeding trial in Niger, sheep fed with diets having a wide lignin:N (*Acacia trachycarpa*, *Guiera senegalensis*) excreted the highest amounts of total- and faecal-insoluble-N. This markedly contrasts with those fed diets with a wide polyphenol:N ratio (*Acacia trachycarpa*, *Guiera senegalensis* and *Combretum glutinosum*) that excreted the lowest urine and faecal soluble-N (Powell *et al.*, 1994). Nitrogen concentration and total carbon were generally higher in tree leaves, but P and lignin concentrations were higher in the respective manures. In Zimbabwe, while the N concentration of manures from goats fed on low quality *A. karro* and *C. mopane* was 90 to 100% of N concentration of their respective leaves, the N concentration of manure from high quality gliricidia was only 31% of its leaf N concentration (Table 8).

The secondary compounds (lignins and polyphenols) affect nutrient release from manures similar to their effects on tree leaves. Tannin-rich leaves and manures derived from such browse resist mineralization. Nutrients released from *Acacia karro* and gliricidia leaves, and manures obtained from goats fed with their leaves in Zimbabwe illustrate the typical pattern for low and high quality leaves, respectively (Fig. 6). Cumulative N release from gliricidia leaves was significantly greater than for *A. karro* leaves and manures of both tree species; all the three latter materials behaved similarly. Acacia leaves and the two manures showed net immobilization for several weeks in contrast to the net mineralization by gliricidia leaves. Nitrogen mineralization of gliricidia manure was poor because of a low N concentration. Generally, manures from low quality leaves decompose and release nutrients faster than respective leaves because manures have a high soluble N content. In a study that compared leaves of several species and sheep manures from respective leaves in Niger, there was a high variability in the decomposition and nutrient release among browse leaves compared with the low variability among manures (Somda *et al.*, 1995). The uniform decomposition of different manures was attributed to a narrow range of nutrient concentrations, the presence of endogenous microorganisms from the digestive tracts of animals and the similar size of undigested and lignified particles irrespective of the fodder materials. While browse leaves immobilized nutrients, between 15 and 50% of N and P in manures was mineralized in the first four weeks of application. Difference between leaves and manures was more apparent in the dry and cool seasons because of dry and unfavorable temperatures relative to the wet season. In terms of N utilization, it is more efficient to use surplus high quality prunings such as gliricidia directly as green manure to crops or as compost than to pass through animals.

These studies indicate that: (1) lignin, tannins and related phenolic compounds shift excretion of N from urine to the faeces and from faecal soluble- to faecal insoluble-N, and (2) it is not biologically efficient to include more rumen-degradable protein in a diet than can be trapped by the rumen microbes. The shift of N excretion from urine to faeces permits more N to be recycled to the croplands via manure in mixed farming systems. However, a balance has to be achieved through species selection and feeding strategy to satisfy the nutrient requirements of livestock and produce an animal excreta that is less susceptible to losses to improve nutrient cycling.

Conclusions

Agroforestry systems are capable of increasing nutrient supply and availability to crops through enhanced internal and external recycling and reducing nutrient losses. However, opportunities to exploit them for increasing production in the SAT are restricted by a low and erratic rainfall and the social constraints associated with land, labor and policy. There is a narrow scope for increasing nutrient cycling in parklands systems because of the low tree density. Trees in these traditional systems have other ecological and economic functions, and improvement of these systems should be by planting of quality tree germplasm. Changing policy that deprives ownership of trees to farmers may encourage them to new plantings. Hedgerow intercropping has little success in most areas influenced by low biomass production by trees and the competition with crops for water, restricting crop response irrespective of soil improvements achieved within the system. However, hedgerows have the potential to reduce soil erosion on moderate slopes as a long-term measure to protect the soil resource base. Gliricidia/maize mixed intercropping with intensive management of gliricidia is promising but needs further testing in a range of soil and climatic conditions prior to its dissemination in highly populated areas.

Short-duration fallows such as two-year sesbania rotated with two to three years of cropping are highly promising for replenishing soil nutrients and raising crop productivity in the semi-arid southern Africa, where population densities are moderate. Biomass transfer systems in which the biomass from external sources is transferred to croplands add nutrients to soils in proportion to both the quantity and quality of biomass applied. However, if biomass transfer is from one field to another within a farm, it only constitutes a nutrient transfer and does not eliminate nutrient depletion. The use of locally available and currently unused organic materials should be encouraged. For farmers practising crop and livestock enterprises, it is more economical to feed the palatable tree biomass to livestock and recycle nutrients to cropland through return of manure. Fodder supply can be increased through fodderbanks with adapted exotic species (gliricidia, *Leucaena* spp. *Acacia angustissima*) and indigenous species (*Pterocarpus* spp.). Confined feeding of livestock with cut-and-carry of fodderbanks will facilitate agricultural intensification in SAT and dispense with problems associated with uncontrolled grazing for the establishment of agroforestry systems. Efforts should be made to reduce nitrogen losses through urine in stall feeding systems.

While agroforestry systems can provide adequate N for moderate yields of cereal crops (2 to 4 t ha^{-1}), additional fertilizer N is needed to achieve the potential yields of the season and improved varieties. As agroforestry systems cannot recycle adequate P, inorganic P fertilizers have to be applied even for moderate yields where soil P availability is low. Thus an integrated approach of using agroforestry and organic residues to supply N and inorganic fertilizers to supplement additional N and P should be promoted (Palm *et al.*, 1997). The P could come through commercial fertilizers or locally available phosphate rocks. The latter are particularly relevant to east and West Africa where phosphate rocks are available (Bekunda *et al.*, 1997). Fallow systems are currently tested only in southern Africa but could be extended to other semi-arid regions, especially to West Africa that has a similar biophysical environment. It is not essential that the agroforestry systems described above be practiced as experimented by researchers. Rather, it is more appropriate for farmers to choose a mix of systems to suit the different niches on their farms, with multiple functions in time and/or space. For example, fodderbanks and biomass production plots could be rotated with crops over the years for the latter to exploit the improved soil fertility under the former, and to use tree biomass as green manure in the absence of any livestock on farms. HI is unimportant solely for the purpose of improving crop yields, but widely spaced and contour-planted hedgerows could become essential for the dual objective of soil conservation and fodder production.

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