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Agroforestry: Fertilizer Trees

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Glossary

Coppicing   Cutting trees close to the ground level to produce regrowth from the remaining stump.
Deep capture   The extraction of nutrients by tree roots from soil depths beyond the reach of crop roots.
Pollarding   Cutting back the crown of a tree but leaving the main trunk with the objective of harvesting wood and browse, producing regrowth beyond the reach of animals, or reducing the shade cast by the crown.
Protein (fodder) bank   Stands of trees or shrubs established within a farm or pasture area to serve as a supplementary source of protein-rich fodder for livestock.
Silvopastoral   Land use system in which trees are integral part of pasture land.

Introduction

Much of the world's agricultural land is degrading rapidly, and losing its productivity due to soil erosion and nutrient mining associated with continuous cropping without nutrient inputs and soil conservation. An estimated 24% of the world's land area has been degrading over the past 25 years, directly affecting the livelihoods of 1.5 billion people (Bai et al., 2008). Approximately 19% of the degraded land is cropland (Bai et al., 2008). According to the Global Assessment of Human-induced Soil Degradation, soil erosion affects 83% of the global degraded area (Bai et al., 2008). Soil degradation by erosion alone affects 1966 million hectares worldwide (Lal, 2007). In Africa, the annual average nutrient (NPK) loss is estimated at 9–58 kg ha^{-1} year^{-1} in 28 countries and 61–88 kg ha^{-1} year^{-1} in the remaining 21 (Chianu et al., 2012). Recent global analyses show that N limitation is particularly widespread in all ecosystems (LeBauer and Treseder, 2008; Liu et al., 2010). The global average N recovery rate is 59%, indicating that nearly 41% of N inputs are lost in ecosystems (Liu et al., 2010). Almost 80% of African countries experience N deficit or N stress problems, which, along with poverty, cause food insecurity and malnutrition (Liu et al., 2010). In total, 29% of the global cropland area experiences P deficits (MacDonald et al., 2011).

Conventionally in modern agriculture, increased productivity has been achieved mainly through application of synthetic inorganic fertilizers. However, the increasing price of synthetic fertilizers and the inability of poor farmers to gain access to them pose severe constraints on their widespread use. Although organic matter may be an alternative source of nutrients, neither animal manure nor green biomass is usually found in adequate quantities to meet the high application rates (10–40 Mg ha^{-1} year^{-1}) required to meet the nutrient requirements of crops (Mafongoya et al., 2006). Some authors have therefore argued that improving fertilizer use efficiency by a combination of organic and inorganic nutrients is vital to the long-term sustainability of global agriculture. Within this important goal there is great potential for the more effective utilization of biological N-fixation (BNF), which is virtually without cost. BNF accounts for 60% of N production (Zahran, 1999) and 16% of the current global N input (Liu et al., 2010). However, in Africa and South America, BNF is the single largest N source, accounting for 32–34% of the N input (Liu et al., 2010). In this respect its further use would, at the least, ease the pressure for land through the rehabilitation of degraded areas (Herridge et al., 2008). However, BNF can also play a greater role in sustainable agriculture as it increases N recovery rates in addition to reducing the need for synthetic fertilizers. In this article, the authors present a review of options for more efficiently harnessing BNF for improved food security within the important debate about the future of global agriculture. They specifically explore the potential role that N-fixing trees can play in land rehabilitation for food crops and pastures and the improved productivity of saline and impoverished soils. In this context it is interesting that with the advent of high-yielding crop varieties requiring full sunlight, the tendency has been to remove trees including N-fixers from many food and cash cropping systems.

Fertilizer Trees: Definition

The term 'fertilizer trees' is commonly used to refer to the utilization of N-fixing leguminous trees in cereal production systems to improve the availability of N to crops (Ajayi et al., 2011; Akinnifesi et al., 2010; Mafongoya et al., 2006), but this usage has generally excluded the use of such trees in pastures

Table 1   Cereal yield response to fertilizer trees summarized from studies across sub-Saharan Africa

Cereal crop	Species	Number of studies (N)	Mean yield (Mg ha^{-1} ± SE)	Yield increase (Mg ha^{-1} ± SE)	Increase[f] (% ± SE)
Maize	Pigeon pea[a,b]	24 (69)	2.1 ± 0.2	0.7 ± 0.1	89.8 ± 13.2
	Tephrosia[a,b]	28 (177)	2.1 ± 0.1	0.9 ± 0.1	206.3 ± 42.6
	Leucaena[b,c]	6 (78)	2.5 ± 0.2	1.0 ± 0.1	94.5 ± 12.2
	Sesbania[a,b]	42 (262)	3.0 ± 0.1	1.7 ± 0.1	318.1 ± 82.5
	Gliricidia[d]	15 (127)	3.2 ± 0.1	2.2 ± 0.1	295.9 ± 27.8
	Faidherbia[e]	12 (88)	4.5 ± 0.2	2.5 ± 0.2	184.6 ± 33.9
	Synthetic fertilizer	72 (384)	3.8 ± 0.1	2.2 ± 0.1	383.8 ± 40.5
Sorghum	Gliricidia[d]	4 (10)	1.5 ± 0.1	−0.1 ± 0.1	93.8 ± 5.3
	Faidherbia[e]	5 (14)	1.0 ± 0.2	0.3 ± 0.1	144.4 ± 22.8
	Sesbania[a,b]	2 (24)	1.8 ± 0.1	0.6 ± 0.1	180.44 ± 19.1
Millet	Vachellia[e]	3 (11)	0.7 ± 0.1	−0.04 ± 0.1	107.8 ± 14.4
	Faidherbia[e]	5 (13)	1.2 ± 0.1	0.4 ± 0.1	149.3 ± 14.4

[a]Relay cropping.
[b]Improved fallow.
[c]Alley cropping.
[d]Intercropping.
[e]Parkland.
[f]Increase over the no-input control.
Abbreviation: N = number of data points representing either sites or years within a study.
Note: The yield increase is the difference between the treatment and the control (no input) on the same site. The percent increase is increase in yield over the control in percentage terms, and this was calculated as 100*(yield increase)/control yield.

and for the rehabilitation of degraded land. The so-called 'N-fixing tree' is a tripartite symbiotic system involving an association between the plant, N-fixing bacteria, and mycorrhizae-forming fungi (Nygren et al., 2012). Atmospheric N-fixation by symbiotic, single-celled bacteria (Rhizobium) in root nodules is common in 340 species of the family Leguminosae. N-fixation also occurs in over 200 nonleguminous plants species in 25 genera of 8 families associated with Frankia (Actinomycetes), which are filamentous bacteria (Franche et al., 2009; Russo, 2005). The broader definition of 'fertilizer' trees used here includes the legume–Rhizobium as well as nonlegume–Frankia symbioses.

There are a large number of agroforestry practices that capitalize on BNF from fertilizer trees for the supply of N and organic matter to annual and perennial crops. These include alley cropping, improved fallows, cereal-tree legume intercropping, relay cropping, biomass transfer, fodder banks, multistrata agroforestry, parklands, and silvopastoral systems. Among the widely used fertilizer trees are acacia (Acacia spp.), acaciella (Acaciella spp.), albizia (Albizia spp.), alder (Alnus spp.), calliandra (Calliandra calothyrsus), casuarina (Casuarina equisetifolia), erythrina (Erythrina spp.), faidherbia (Faidherbia albida), flemingia (Flemingia spp.), gliricidia (Gliricidia sepium), inga (Inga edulis), leucaena (Leucaena spp.), sesbania (Sesbania spp.), parkia (Parkia biglobosa), tagasaste (Chamaecytisus palmensis), tephrosia (Tephrosia spp.), tamarind (Tamarindus indica), and vachellia (Vachellia spp.). Hereafter reference will be limited to these common names.

Benefits of Fertilizer Trees

Increased Crop Productivity

Several studies have reported the beneficial effects of fertilizer trees on yields of food crops. According to a meta-analysis of 94 peer-reviewed publications across sub-Saharan Africa (Sileshi et al., 2008a), maize yields increased by 0.7–2.5 Mg ha^{-1} over the no-input control, which translates to an 89–318% increase (Table 1). Under similar conditions, the recommended rate of synthetic fertilizer led to 384% increases over the control (Table 1). Robust estimates indicate that the 95% confidence intervals of maize yield increased by faidherbia (2.0–2.7 Mg ha^{-1}), gliricidia (1.8–2.4 Mg ha^{-1}), and synthetic fertilizer (1.9–2.3 Mg ha^{-1}) overlap completely. Recent analyses (Sileshi et al., 2011, 2012) also showed that maize yields are more stable in maize intercropped with leucaena and gliricidia than in fully fertilized sole maize at sites in Malawi, Zambia, and Nigeria. In terms of increased crop yields, synergistic effects of synthetic fertilizer and fertilizer trees were noted. Yield increases from fertilizer trees were substantial even when associated with 25–50% of the recommended dosages of synthetic fertilizer (Sileshi et al., 2011, 2012).

Although fewer data are available for millet and sorghum (mostly short term in nature), increases in yields relative to the control have been substantial with fertilizer trees (Table 1). An important gain that is usually under-reported is the stover yield. Stover is a critical fodder in cereal-livestock mixed farming systems in Africa. Using empirical distributions of stover to grain fresh weight ratios of 0.8:1.0 the authors estimate that an additional 0.2–2.0 Mg ha^{-1} year^{-1} of stover can be produced by the use of fertilizer trees (Table 1), an important contribution to livestock feed when grass is in short supply. These yield increases are also associated with large variability attributable to tree species, site conditions (soils, rainfall, elevation), and management factors (Bayala et al., 2012; Sileshi et al., 2008a, 2010). Although in the short term crop yields may be reduced due to tree competition, in the long term favorable soil conditions are expected to improve crop productivity.

Through biomass transfer, fertilizer trees can also be used to increase vegetable productivity. Biomass transfer is

Table 2   Vegetable yield[a] response to biomass transfer using fertilizer tree prunings from sub-Saharan Africa

Crop	Tree species (biomass)	Country	Mean yield (Mg ha^{-1})	Yield increase[b] (Mg ha^{-1})	(%)	References
Cabbage[c]	Gliricidia (8 ton ha^{-1})	Zambia	43.1	26.1	154	Kuntashula et al. (2004)
	Gliricidia (12 ton ha^{-1})		53.6	36.6	215	Kuntashula et al. (2004)
	Leucaena (12 ton ha^{-1})		32.6	15.6	92	Kuntashula et al. (2004)
	Fertilizer (800 kg ha^{-1} NPK)		57.6	40.6	239	Kuntashula et al. (2004)
Onion[d]	Gliricidia (8 ton ha^{-1})		68.3	40.2	143	Kuntashula et al. (2004)
	Gliricidia (12 ton ha^{-1})		79.8	51.7	184	Kuntashula et al. (2004)
	Fertilizer (800 kg ha^{-1} NPK)		57.1	29	103	Kuntashula et al. (2004)
Cabbage	Gliricidia (8 ton ha^{-1})		51.1	28.4	125	Kuntashula et al. (2006)
	Fertilizer (800 kg ha^{-1} NPK)		55.0	32.3	142	Kuntashula et al. (2006)
Onion	Gliricidia (8 ton ha^{-1})		49.7	26.7	116	Kuntashula et al. (2006)
	Fertilizer (800 kg ha^{-1} NPK)		40.8	17.8	78	Kuntashula et al. (2006)
Cabbage	Gliricidia (8 ton ha^{-1})	Zambia	59.7	27.9	88	Kuntashula et al. (2006)
	Synthetic fertilizer		80.8	48.9	153	Kuntashula et al. (2006)
Rape	Leucaena	South Africa	7.6	6.7	784	Muchecheti et al. (2012)
	Vachellia		5.0	4.1	481	Muchecheti et al. (2012)
	Calliandra		3.0	2.1	249	Muchecheti et al. (2012)
	Fertilizer (150 kg N ha^{-1})		10.0	9.1	106	Muchecheti et al. (2012)
Paprika	Gliricidia (8 ton ha^{-1})	Malawi	0.32	0.10	43.1	Sileshi et al. (2011)
	Gliricidia+50% Synth fertilizer		0.41	0.19	84.2	Sileshi et al. (2011)
	Synthetic fertilizer (100% recom.)		0.24	0.02	9.4	Sileshi et al. (2011)

[a]This represents fresh weight in the case of cabbage, rape, and onion, whereas dry weight in the case of paprika.
[b]Increase over the no-input control.
[c]Average of 31 farmers' fields.
[d]Average of 12 farmers' fields.
Note: The yield increase is the difference between the treatment and the control (no input) on the same site. The percent increase is increase in yield over the control in percentage terms, and this was calculated as 100*(yield increase)/control yield.

essentially moving tree biomass (prunings) produced in one part of the farm (e.g., in protein banks, fallows, etc.) to another (e.g., a vegetable garden). Usually 4–12 Mg ha^{-1} of the leafy biomass (on dry matter basis) is applied to crops, and this has been shown to increase yields of cabbage, rape, onion, tomato, and garlic in trials on research stations as well as farmers' fields in Africa (Table 2).

Increases in productivity have been demonstrated in cash crops associated with fertilizer trees. For example, shade trees reduce the stress on crops such as coffee and cacao by ameliorating adverse climatic conditions and nutritional imbalances, thus increasing overall system productivity in multistrata agroforestry (Beer et al., 1998). In Western Ghana, Isaac et al. (2007) found higher above ground cocoa biomass (39.6 Mg ha^{-1}) under albizia canopies compared to 22.8 Mg ha^{-1} for sole cocoa. Above-ground dry matter of cocoa also declined along a spatial gradient away from albizia trees (Isaac et al., 2007). In India, the agronomic yield of large cardamom doubled under 5–15-year-old alder stands and peaked between 15 and 20 years of age (Russo, 2005).

Soil Rehabilitation Services

To understand how the above yield benefits are achieved one needs to examine how adding fertilizer trees into the agricultural landscape restores soil fertility and promotes the biological processes and ecological functions that together rehabilitate degraded land. These are the critical processes that benefit the farmer in particular and society in general. Among these important services are nutrient cycling, increased

availability of macronutrients (extractable N, P, and K), cations and improvement in soil pH, increased organic matter (SOM), enhanced biological activity, improved soil physical properties, and better water relations.

Improvement in soil nutrient cycling

Fertilizer trees have potential to provide N in quantities sufficient to support moderate crop yields through (1) N inputs from biological N_2 fixation and retrieval of nitrate from deep soil layers and (2) cycling of N from plant residues and manures (Buresh and Tian, 1998). However, fertilizer trees cannot produce new resources of other nutrients, although they can increase their availability and uptake by crop plants through different mechanisms. The cycling of P from organic materials is also normally insufficient to meet the P requirements of crops (Buresh and Tian, 1998). As they access deep water reserves beyond reach of annual crops, tree roots act as a safety net to capture nutrients leached from the topsoil and return these to the soil surface as litter. The presence of trees improves nutrient use efficiency by providing a safety net to recover nutrients leached from the topsoil during intense rainfall and return them to the surface horizons on which crop roots primarily depend, in a manner analogous to the hydraulic lift of water.

N availability and uptake

The percentage of N derived from the atmosphere (NDFA) is more than 59% according to a recent analysis of 38 cases using N isotopic analyses (Nygren et al., 2012). Under humid and sub-humid conditions, on average NDFA was 69% in

young trees and 63% in periodically pruned trees compared to 54% in free-growing (nonpruned) trees (Nygren et al., 2012). The average N-fixation for 16 variable fertilizer tree species was found to be 246 kg N ha^{-1} year^{-1}, but much higher (300–650 kg N ha^{-1} year^{-1}) in improved fallows and protein banks where trees are managed by pruning or coppicing (Nygren et al., 2012). These values are much higher than the global estimates (23–176 kg N ha^{-1} year^{-1}) for food legumes and herbaceous pasture and fodder legumes (Herridge et al., 2008). Among the nonlegume–*Frankia* associations, N-fixation has been estimated at 40–320 kg N ha^{-1} year^{-1} for alder (Russo, 2005) and casuarina 73 kg N ha^{-1} year^{-1} (Nygren et al., 2012). Although the annual N inputs vary widely between species and even among provenances of the same species across different locations and stand age, the amounts reported are enough to fulfill crop N needs for sustained yield (Nygren et al., 2012).

In Latin American coffee and cacao agroforestry, pruning residues and litter fall from shade trees have been shown to contribute 60–340 kg N ha^{-1} year^{-1} (Beer et al., 1998). In coffee plantations in Costa Rica, erythrina contributed over 300 kg N ha^{-1} year^{-1} (Kass et al., 1997). Various studies across the globe have documented significant increases in N stocks under fertilizer trees compared to crop monocultures (Table 3). According to a study on cacao agroforestry in Ghana the ammonium sulphate fertilizer equivalent of albizia leaves is 21–72 kg N ha^{-1}; thus, the leaves could substitute 29–63% of fertilizer when applied to soil at 2.5 Mg ha^{-1} (Anim-Kwapong, 2006). In a silvopastoral system with king

grass in Costa Rica, erythrina contributed 266 kg N ha^{-1} year^{-1} (Kass et al., 1997). Direct below-ground transfer of N fixed by legume trees to associated non-N-fixing crops and forage grass has been widely documented (Nygren et al., 2012; Sierra and Nygren, 2006). This can take place via root exudates or common mycorrhizal networks (Nygren et al., 2012). In coffee agroforestry approximately 30% of the N effectively fixed by leucaena, calliandra, and erythrina was transferred to the associated coffee trees (Snoeck et al., 2000). In Sri Lanka, up to 21% of N in grass was derived from transfer of N fixed by gliricidia and leucaena (Jayasundara et al., 1997).

A review of studies in parklands across Africa shows that N availability is higher under faidherbia than in the open field (Table 3). N availability can also be increased significantly under improved fallows and alley cropping of fertilizer trees compared to control plots without trees (Table 3). In gliricidia-maize-pigeon pea intercropping in southern Malawi 191–302 kg N ha^{-1} could be realized from gliricidia prunings (Akinnifesi et al., 2010).

Although N inputs from fertilizer trees may be high, the N recovery by crops is usually 10–30% of the N applied as prunings per season, depending on the quality of residues. Much of the N from organic inputs (50–80%) is not used by the crop. Low N recovery is partly caused by a lack of synchrony between the N release and demand by the associated crop. Nevertheless, N use efficiency by cereals is higher from fertilizer trees than from synthetic fertilizer. For example, in alley cropping in Nigeria, N use efficiency of synthetic fertilizer was 10–22% compared to 49% in gliricidia and 59% in albizia

Table 3 Increase (%) in N and P stocks due to fertilizer and nutrient uptake by crop relative to crop monoculture or areas outside tree influence

	Agroforestry (crop)	Tree species	Increase (%)	Country	Reference
N stocks	Cacao	Albizia	5–10	Ghana	Isaac et al. (2007)
	Parkland	Faidherbia	15–156	Sahel	Boffa (1999)
			200	Niger	Kho et al. (2001)
			50–90	Sudan	Rhoades (1995)
			100–150	Ethiopia	Kamara and Haque (1992)
			5–29	Malawi	Rhoades (1995)
		Tephrosia	20	Viet Nam	Fagerström et al. (2002)
N uptake	Parkland (millet)	Faidherbia	139.2	Niger	Kho et al. (2001)
	Alley cropping (maize)	Albizia	126.6	Nigeria	Okogun et al. (2000)
		Gliricidia	159.6	Nigeria	Okogun et al. (2000)
		Leucaena	170.4	Nigeria	Okogun et al. (2000)
		Leucaena	50–114	Nigeria	Akinnifesi et al. (1997)
	Alley cropping (sorghum)	Albizia	100–300	USA	Rhoades et al. (1997)
	Intercropping (maize)	Gliricidia	156	Malawi	Mweta et al. (2007)
	Improved fallow (maize)	Sesbania	299	Zambia	Mafongoya (unpublished)
		Tephrosia	76	Zambia	Mafongoya (unpublished)
		Gliricidia	160	Zambia	Mafongoya (unpublished)
		Leucaena	99	Zambia	Mafongoya (unpublished)
P stocks	Cacao	Albizia	2.3–4.5	Ghana	Isaac et al. (2007)
	Parkland	Faidherbia	18–134	Sahel	Boffa (1999)
			30	Niger	Kho et al. (2001)
			44–125	Ethiopia	Kamara and Haque (1992)
			5–29	Malawi	Rhoades (1995)
	Intercropping	Gliricidia	160.7	Malawi	Mweta et al. (2007)
P uptake	Intercropping	Gliricidia	92	Zambia	Mafongoya (unpublished)
		Leucaena	110	Zambia	Mafongoya (unpublished)
		Gliricidia	121	Malawi	Mweta et al. (2007)

(Okogun et al., 2000). N uptake by crops is usually improved when cereals are associated with fertilizer trees (Table 3). Soil amendment with small dosages of inorganic fertilizer (25–50% of recommended rate) further increases N uptake. For example, N uptake increased by over 245% when the maize crop in the alleys between these trees was amended with 40–80 kg N ha^{-1} of synthetic fertilizers in Nigeria (Okogun et al., 2000). Similarly, N uptake significantly increased when gliricidia plots were amended with synthetic N and P fertilizers (Mweta et al., 2007).

The question arising from all of the above is: To what extent can fertilizer trees substitute for inorganic N fertilizers? The answer it seems depends on the desired crop yield. Typically, smallholder farmers in SSA have maize yields of 1–2 Mg ha^{-1}. 1 Mg ha^{-1} maize crop requires 20 kg N ha^{-1}. Tree pruning applied at 5 Mg ha^{-1} provides N input of 60–150 kg ha^{-1} (Palm, 1997), and this can support maize yields of up to 4 Mg ha^{-1} without any added synthetic fertilizer. In gliricidia-maize intercropping in Malawi, it is possible to reduce synthetic fertilizer use by 48 kg N ha^{-1} year^{-1} (Dong-Gill, 2012) while still maintaining yields of up to 4 Mg ha^{-1} (Akinnifesi et al., 2010). For higher yields, although BNF may supply adequate N, supplementation with inorganic fertilizers may be required to provide sufficient P and K.

P availability and uptake

Fertilizer trees can contribute to P availability, either directly by releasing tissue P during decomposition and mineralization or indirectly by acting on chemical processes that regulate P adsorption–desorption reactions. Compared to annual crops, tree root systems are more extensive. This increases the exploration of larger soil volumes, resulting in enhanced uptake of P and other nutrients. Trees may also access soil P from relatively recalcitrant pools not utilized by crops (Buresh and Tian, 1998). The symbiotic association between fertilizer trees and mycorrhizal fungi can also improve the capacity of the plant to take up P. A number of empirical studies have documented higher soil P concentrations and uptake by crops in the presence of fertilizer trees (Table 3). However, it is important to note that fertilizer tree innovations will not eliminate the need for P inputs in P deficient soils. Plant materials, even when added in large amounts, may provide less P than that required to obtain adequate crop yields. This inadequacy is due to a low concentration of P (<3 g kg^{-1}) in plant residues. For example, >18 kg P ha^{-1} is required to produce maize yield of 2 Mg ha^{-1}. However, application of even high-quality residues at 5 ton ha^{-1} adds only 15 kg P ha^{-1} crop (Palm et al., 1997). Therefore, soil amendment with soluble mineral P fertilizers or phosphate rocks is required to obtain adequate crop yields in P-limited soils (Buresh and Tian, 1998). The added P can be recycled through fertilizer trees in their leaf litter and root turnover.

Cation concentrations and improvement in soil pH

Increases in cations and soil pH and decrease in aluminium saturation and improvement in the conditions for plant growth in acid soils have been associated with application of tree prunings (Mafongoya et al., 2006). Increases in soil cation concentrations usually results from recycling through the biomass fertilizer trees. Several studies in parklands in the Sahel indicate that exchangeable K in the 0–10 cm soil is

43–133% higher under faidherbia than in the open (Boffa, 1999). Similarly, Ca was 2–270% higher, while Mg was 0–78% higher under faidherbia than in the open. In Ethiopia, Kamara and Haque (1992) found that K concentrations were higher by 150–178% beneath faidherbia than in the open. Fertilizer trees could minimize nitrate leaching and soil acidification both by decreasing drainage and recycling leached nutrients. Thus, in acid soils fertilizer tree prunings could be used as a 'liming' material, thus providing resource-poor farmers with an inexpensive biological means for alleviating soil acidity.

Increased soil organic matter

Fertilizer trees enhance soil organic matter (SOM) both through production of SOM and reducing losses due to erosion. A compilation of studies in parklands of West Africa (Boffa, 1999) indicates 11–100% higher SOM under faidherbia trees than in open areas. In Ethiopia, SOM under faidherbia was 69–107% higher than in the open (Kamara and Haque, 1992). Increased soil organic carbon (SOC) content, particularly in the light fraction, is known to improve aggregate stability, porosity, hydraulic conductivity, and soil structures that resist erosion.

Improvement in soil biological properties

The impact of fertilizer trees on soil biological properties may be assessed by changes in abundance, diversity, and community structure of soil fauna and flora, microbial biomass, enzyme activity (e.g., respiration), and soil pests and weeds. Soil fauna play a key part in litter decomposition through their interactions with plants and soil microbial communities. During decomposition, the organic forms of nutrients in the litter are converted to inorganic forms that can be absorbed by the growing plants. In addition, the activities of soil fauna improve soil water infiltration and storage, which is becoming increasingly important in agricultural sustainability in arid climates (Sileshi and Mafongoya, 2006; Tian et al., 2001).

Even in highly degraded soils, fertilizer tree species have been shown to restore soil fauna in a relatively short time (Sileshi and Mafongoya, 2006; Sileshi et al., 2008b; Tian et al., 2001). At two sites in eastern Zambia, earthworm densities were found to be significantly higher in maize intercropped with vachellia, calliandra, gliricidia, and leucaena compared with fully fertilized sole maize (Sileshi and Mafongoya, 2006). In another study in eastern Zambia, earthworm abundance was 2–3 times higher in maize planted after sesbania +tephrosia and pure pigeon pea fallows compared with sole maize (Sileshi et al., 2008b).

N-fixing trees have been shown to modify populations of microflora, microbial biomass, and enzyme activity (Mafongoya et al., 1997; Tian et al., 2001; Wick et al., 1998). For example, at Domboshawa in Zimbabwe, fungal and actinomycetes populations differed with the quality and quantity of fertilizer tree biomass as well as the method of application. Actinomycetes populations were six to nine times higher where vachellia and calliandra biomass was surface-applied than when incorporated in the soil (Mafongoya et al., 1997).

The microbial biomass is also part of the active SOM pool, and has been proposed as an indicator of state and change of total SOM. Enzyme activity in the soil is an indicator of soil

biological status. For example, phosphatases are important in the P cycle because they provide P for plant uptake by releasing PO_4, and acid phosphatase can provide a potential index for a soil to mineralize organic P. β-glucosidase catalyzes the conversion of cellulose to glucose, and as such important energy sources for micro organisms. In long-term experiments carried out at three sites in southern Nigeria (Wick et al., 1998), β-glucosidase increased by 41–119% with leucaena relative to continuous cropping of maize/cassava (Wick et al., 1998). Alkaline phosphatase increased by 24–149% with leucaena relative to the control (Wick et al., 1998).

Fertilizer trees in certain agroforestry practices can also reduce soil insect pests and weeds (Sileshi et al., 2008c). For example, termite damage to maize was reduced by improved fallows involving fertilizer trees in Zambia (Sileshi et al., 2005). One of the most important aspects is the control of problematic weeds such as spear grass (Imperata cylindrical). In Nigeria, hedgerows of leucaena and gliricidia reduced the population of spear grass by 51−67%, above-ground biomass by 78−81%, and below-ground rhizomes by 90−96% compared to a bush fallow (Anoka et al., 1991). In a study at Pucallpa in the Peruvian Amazon, weed biomass was 40–63% less in inga fallows compared to natural fallows (Lojka et al., 2012). In alley cropping, albizia and gliricidia have been shown to reduce weed in Nigeria (Okogun et al., 2000).

Fertilizer tree fallows have also been shown to reduce the parasitic witch weeds (Striga spp.) problem, which is usually associated with low soil fertility in Africa (Gacheru and Rao, 2001; Sileshi et al., 2008c). Sesbania was better than many other species in reducing Striga asiatica infestation in maize in eastern Zambia (Sileshi et al., 2008c). The reduction in infestation was significantly influenced by the quantity of biomass from fertilizer trees (Sileshi et al., 2008c). In East Africa, reduction of Striga hermontica infestation by legume fallows depended on the rate of decomposition and nitrogen mineralization of organic residues (Gacheru and Rao, 2001). Reduction in weed problems is due to shading and smothering of the weeds by trees and the thick mulch layer formed by the leaf litter from the trees subsequently depleting the weed seed-bank. Many legume species release a wide range of allelochemical compounds, which can inhibit weed seed germination or reduce weed vigor (Sileshi et al., 2008c).

Improvement in soil physical properties

Among the commonly used indicators of soil physical properties are soil depth, bulk density, aggregate stability, infiltration rates, water-holding capacity, and penetration resistance. Soil bulk density is a direct measure of soil compaction. Soils with low bulk density, although open-textured and porous, are susceptible to erosion, poor water retention, and oxidation of SOM and loss of SOC. In contrast, soils with high bulk density have lower porosity. Various studies indicate improvement in bulk density, aggregate stability, and porosity due to fertilizer trees. In sandy loam soil in the pre-Amazon region of Brazil, bulk density, total porosity, and soil aeration were substantially improved in alley cropping with leucaena, pigeon pea, acacia, and their mixtures over a period of three years (Aguiar et al., 2010). In gliricidia, leucaena, Vachellia, and sesbania rotational fallows in Zimbabwe and Zambia soil bulk density was up to 12% lower and aggregate stability was

higher by 18–36% compared to sole maize crops (Table 4). Pore density was also significantly higher in vachellia and sesbania fallows (285–443 m^{-2}) compared to continuous maize (256 m^{-2}). The pore density was significantly higher in Vachellia and sesbania fallows (4521–8911 m^{-2}) compared to continuous maize (2689–3938 m^{-2}). The mean pore sizes were lower in continuous maize and higher in the fertilizer tree fallows (Nyamadzawo et al., 2008a). The mean pore sizes at 5 cm tension were 0.07–0.12 mm in fallows relative to continuous maize, which were 0.03 mm.

The improvement in soil structure was also associated with increased drainage, especially during wet periods. In eastern Zambia and Zimbabwe, steady-state infiltration rates were 42–600% higher when maize was rotated with gliricidia, leucaena, vachellia, sesbania, and tephrosia compared to continuously grown sole maize (Table 4). Time to water runoff was also longer by 40–133% and drainage was improved by 88–900% compared to continuous sole maize. The soil in maize planted following improved fallows had lower penetration resistance compared with monoculture maize at various sites in eastern Zambia (Table 4).

Reduced penetrometer resistance and increased water infiltration imply reduced water runoff and soil erosion. The improvement under fertilizer trees was evident from the longer time to runoff measured in maize fertilizer tree rotations compared to sole maize in Zambia and Zimbabwe (Table 4). Land under fertilizer trees has been shown to be less susceptible to runoff and erosion than continuous maize. According to Fagerström et al. (2002), in an upland rice cropping system in northern Vietnam, tephrosia fallows and hedgerows effectively prevented nutrient losses by erosion. Runoff and soil losses were also lower in maize grown with fertilizer trees compared to continuous maize in Zimbabwe (Table 4). Soil loss was 30–100% higher under continuous maize than under fertilizer tree fallows (Nyamadzawo et al., 2006; Nyamadzawo et al., 2012).

As they increase hydraulic conductivity and reduce runoff losses, fertilizer trees improve water retention, storage, and availability to associated crops. At Domboshawa in Zimbabwe 75–80% of the total available water was retained at suction <33 kPa in the top 0–15 cm depth under vachellia fallows (Nyamadzawo et al., 2012). Soil water stored in 2-year sesbania-improved fallows was greater than in continuously cropped fertilized or unfertilized maize in eastern Zambia (Phiri et al., 2003). In parklands in Ethiopia, the amount of available water under faidherbia was twice that outside the tree canopy (Kamara and Haque, 1992). Similarly, in Malawi, soil moisture in the 0–15 cm soil was 4–53% higher under faidherbia than outside the tree canopy (Rhoades, 1995). The trees canopy also intercepts water and channels it down to the soil, thus contributing soil water recharge through macropores created by roots and increased microbial activities. Phiri (2002) recorded greater rainfall interception by sesbania tree canopies indicated by increased moisture storage and sub-soil moisture recharge.

The role of fertilizer trees in improving water use efficiency (WUE) has recently been demonstrated with long-term field studies in Africa (Sileshi et al., 2011). In rain-fed agriculture, rain use efficiency (RUE) defined as the ratio of above-ground net primary production to annual rainfall provides

Table 4   Changes in soil physical properties (0–20 cm) due to fertilizer trees (FT) in improved fallow and the control (sole maize) and the % change (%Δ) at Msekera, Kagoro, and Kalunga sites in Zambia and Domboshawa in Zimbabwe

Variable	Tree species	Site	FT	Control	(%Δ)	Reference
Bulk density (Mg m^{-3})	Gliricidia	Msekera	1.39	1.53	−9.2	Sileshi and Mafongoya (2006)
			1.40	1.42	−1.4	Mafongoya et al. (2006)
	Leucaena		1.35	1.53	−11.8	Sileshi and Mafongoya (2006)
	Vachelia	Domboshawa	1.33	1.41	−5.7	Nyamdzawo et al. (2008)
	Sesbania	Msekera	1.35	1.42	−4.9	Mafongoya et al. (2006)
			1.59	1.66	−4.2	Phiri (2002)
		Domboshawa	1.36	1.41	−3.5	Nyamdzawo et al. (2008)
Aggregate stability (mm)	Sesbania	Msekera	83.3	61.2	36.1	Chirwa et al. (2004)
			65.0	55.0	18.2	Phiri (2002)
			38.0	32.0	18.8	Phiri (2002)
	Pigeon pea		80.0	61.2	30.7	Chirwa et al. (2004)
Infiltration rate (mm hr^{-1})	Gliricidia	Kagoro	4.4	2.9	51.7	Chirwa et al. (2003)
		Msekera	16	4.0	300.0	Mafongoya et al. (2006)
	Leucaena	Kagoro	3.7	2.9	27.6	Chirwa et al. (2003)
	Vachelia	Kagoro	5.5	2.9	89.7	Chirwa et al. (2003)
		Domboshawa	>35	5.0	600.0	Nyamdzawo et al. (2007)
	Sesbania	Msekera	20.0	4.0	400.0	Mafongoya et al. (2006)
			0.13	0.08	62.5	Phiri (2002)
			4.4	2.1	109.5	Chirwa et al. (2004)
		Kagoro	9.5	2.9	227.6	Chirwa et al. (2003)
	Sesbania	Kalunga	21.0	7.0	200.0	Nyamadzawo et al. (2006)
		Msekera	8.0	5.0	60.0	Nyamadzawo et al. (2006)
		Domboshawa	12	5.0	140.0	Nyamadzawo et al. (2007)
	Pigeon pea	Msekera	5.2	2.1	147.6	Chirwa et al. (2004)
	Tephrosia	Kalunga	16.0	7.0	128.6	Nyamadzawo et al. (2006)
		Msekera	7.1	5.0	42.0	Nyamadzawo et al. (2006)
Time to runoff (min)	Vachelia	Domboshawa	30.0	15.0	76.5	Nyamadzawo et al. (2006)
	Sesbania	Kalunga	21.0	9.0	133.3	Nyamadzawo et al. (2006)
		Msekera	7.0	3.0	133.3	Nyamadzawo et al. (2006)
		Domboshawa	21.0	15.0	40.0	Nyamadzawo et al. (2006)
	Tephrosia	Kalunga	14.0	9.0	55.6	Nyamadzawo et al. (2006)
	Tephrosia	Msekera	7.0	3.0	133.3	Nyamadzawo et al. (2006)
Drainage (mm)	Sesbania	Msekera-1a	56.4	15.8	257.0	Phiri (2002)
		Msekera-1b	10.9	1.0	990.0	Phiri (2002)
		Msekera-2a	61.1	7.6	703.9	Phiri (2002)
		Msekera-2b	10.7	5.7	87.7	Phiri (2002)
Penetrometer resist (Mpa)	Gliricidia	Kagoro	0.6	1.2	−50.0	Chirwa et al. (2003)
	Leucaena	Kagoro	0.8	1.2	−33.3	Chirwa et al. (2003)
	Vachelia	Kagoro	1.0	1.2	−16.7	Chirwa et al. (2003)
	Sesbania	Kagoro	0.9	1.2	−25.0	Chirwa et al. (2003)
		Msekera	2.2	3.2	−31.3	Chirwa et al. (2004)
	Pigeon pea	Msekera	2.9	3.2	−9.4	Chirwa et al. (2004)
Runoff loss (%)	Vachelia	Domboshawa	0	57.0	−100.0	Nyamadzawo et al. (2006)
	Sesbania	Domboshawa	21.0	57.0	−63.2	Nyamadzawo et al. (2006)

information similar to WUE. Sileshi *et al.* (2011) analyzed variations in RUE with leucaena in three long-term experiments conducted in Zambia and Nigeria. At the two sites in Zambia, maize intercropped with leucaena achieved 191–197% higher RUE compared to sole maize continuously cropped without nutrient inputs. At the Nigerian site, RUE was 139–202% higher in maize planted between leucaena hedgerows compared to the control (Sileshi et al., 2011). According to another study at Makoka (Chirwa et al., 2007), WUE was higher in maize intercropped with gliricidia than in the sole maize and maize+pigeon pea intercropping. At another site in eastern Zambia, WUE was 202% higher in sesbania fallows compared to continuous sole maize (Phiri, 2002).

Carbon Sequestration and Greenhouse Gas Mitigation Potential

A growing number of studies have also demonstrated that fertilizer trees can sequester significant amounts of C both in the soil and in their woody biomass and mitigate greenhouse gas (GHG) emissions. In Mali, Takimoto et al. (2008) estimated 70.8 Mg C ha^{-1} in the top 40 cm of the soil in parklands dominated by faidherbia. SOC increases of 3–70% under faidherbia canopy have also been reported in the Sudan (Rhoades, 1995). At several sites in Malawi, SOC was 3–30% higher under faidherbia canopy than in the open (Rhoades, 1995). According to Sierra and Nygren (2006), gliricidia trees

in pastures contributed 16–18 Mg C ha^{-1} to soil over 12 years. In a 19-year-old gliricidia alley cropping in Costa Rica, the SOC pool was 16–23% higher than the sole crop (Oelbermann et al., 2004). In the 19th year of alley cropping, SOC was significantly higher in the alley crop (3.2%) compared to the sole crop (2.4%) (Oelbermann et al., 2004). Similarly, in a 19-year-old alley cropping with erythrina in Costa Rica, C inputs from tree prunings were 4.01 Mg C ha^{-1} year^{-1} (Oelbermann et al., 2006). The input from crop residues was significantly greater in the erythrina alley crop for maize (1.34 Mg ha^{-1} year^{-1}) and beans (0.35 Mg ha^{-1} year^{-1}) compared to the sole crop (Oelbermann et al., 2006). Nygren (1995) showed that C input from prunings of erythrina in Costa Rica ranged from 2.3 to 5.2 Mg ha^{-1} year^{-1} at a tree density of 625 trees ha^{-1}. In alley cropping with leucaena in Nigeria, SOC increased by 108% in the 0–15 cm soil as compared to the control without a hedgerow (Kang et al., 1999). In Zimbabwe, SOC was 1.7 times higher in Vachellia fallows than continuous sole maize (Nyamadzawo et al., 2008b). SOC stocks within 0–30 cm depth under 5-year-old rotational woodlots (15.8–25.6 Mg ha^{-1}) were higher than in soils that had been continuously cropped for the same time period (13 Mg ha^{-1}) in Tanzania (Kimaro et al., 2011). According to Kaonga and Coleman (2008) SOC stocks under tephrosia, sesbania, and pigeon pea were higher (27.3–31.2 Mg ha^{-1}) than under fully fertilized sole maize (26.2 Mg ha^{-1}) and unfertilized sole maize (22.2 Mg ha^{-1}) in eastern Zambia. The above-ground plant C input was estimated at 2.8 Mg C ha^{-1} year^{-1} for tephrosia, 2.7 Mg ha^{-1} year^{-1} for sesbania, and 2.5 Mg ha^{-1} year^{-1} for pigeon pea, which was comparable to 2.7 Mg ha^{-1} year^{-1} recorded for fully fertilized sole maize (Kaonga and Coleman, 2008). In Malawi, Makumba et al. (2007) found that soil C in a gliricidia–maize intercropping roughly doubled after 7 and 10 years compared to sole maize. A more recent reanalysis of the data from Makumba et al. (2007) found an annual net gain of 3.5 Mg C ha^{-1} year^{-1} in the soil (Dong-Gill, 2012). With the potential for N$_2$O mitigation of 0.12–1.97 kg N$_2$O–N ha^{-1} year^{-1}) the gliricidia–maize intercropping was estimated to mitigate 3.5–4.1 Mg CO$_2$ eq. ha^{-1} year^{-1} (Dong-Gill, 2012).

Estimates of above-ground C storage are also substantial. In cacao agroforestry in Indonesia, C stock in biomass was estimated at 31.4 Mg C ha^{-1} in 15-year-old gliricidia (Simley and Kroschel, 2008). Similarly, in Costa Rican cacao agroforestry, erythrina stored 40 Mg C ha^{-1} (Oelbermann et al., 2006). In 5-year rotational woodlots in Tanzania, carbon sequestered in wood of fertilizer trees ranged from 11.6 to 25.5 Mg ha^{-1} (Kimaro et al., 2011). Wood C accumulation rates ranged from 2.3 to 5.1 Mg C ha^{-1} year^{-1} in acacia species (Kimaro et al., 2011). A 6-year stand of faidherbia in Tanzania accumulated 9.4 Mg ha^{-1} of wood C at a 5 m by 5 m spacing (Okorio and Maghembe, 1994). In parkland in Mali, faidherbia accumulated 20.3 Mg ha^{-1} (Takimoto et al., 2008). This can play a critical role in mitigation of climate changes as they favor nutrient recycling and C sequestration in crop and pasture land. However, the potential for accumulation of ecosystem C by fertilizer trees depends on site characteristics and planting densities. Therefore, accurate methods are required to determine change in C with the inclusion of fertilizer tree innovations in the various farming systems.

Provision of Products

Most N-fixing trees provide various products including wood, fruits, edible seeds, and fodder that are rich in protein and increase pasture productivity.

Wood and Wood Products

Several studies have indicated production of substantial amounts of firewood and timber from fertilizer trees planted on farmland (Table 5). In acid soils in Peru, inga produced up to 8–12 Mg ha^{-1} year^{-1} of wood (Lojka et al., 2012). Russo (2005) reported wood production of 15–20 m^3 ha^{-1} year^{-1} in alder. A stand of 30-year-old trees with a density of 35 trees ha^{-1} yielded 70 m^3 ha^{-1} of timber, 18.3 Mg ha^{-1} of dry fuelwood (Russo, 2005). Several studies have also indicated production of substantial amounts of firewood in Africa (Table 5). Assuming per capita dried firewood consumption of 486 kg (0.67 m^3) year^{-1} (Ndayambaje and Mohren, 2011), wood yields of the various species would be sufficient to meet the household fuelwood demands for 1–17 families of 6 people (Table 5). Such high wood yields exemplify the potential of fertilizer trees in meeting local firewood demands, especially in Africa where the population depends on extraction of wood from forests due to lack of alternatives in energy supply. As forest resources continue to degrade, access to firewood declines, and rural women have to walk increasingly longer distances in search of firewood. Planting of fertilizer trees on farmland can increase access to firewood by women, and thus the time and labor spent in search of firewood can be reallocated to food production and childcare.

Fruits and Edible Seeds

Some fertilizer trees (e.g., tamarind, parkia, pigeon pea, Tetrapleura tetraptera, etc.) produced edible seeds or kernels. For example, pigeon pea seeds are a rich source of protein, carbohydrates, minerals, and vitamins, making it an ideal supplement to the traditional starch-based diets of Africa and Asia, which are generally protein-deficient (Odeny, 2007). The edible pulp of tamarind is consumed fresh or used to make syrup, juice concentrates, and exotic food specialities such as chutney, curries, pickles, and meat sauces. In the Sahel, parkia seeds are a valuable source of condiment locally called 'soumbala,' which is an important source of protein (Kalinganire et al., 2008).

Fodder and Pasture

Scarcity of forage and lack of access to high-quality feed are major constraints to livestock productivity, especially in the semiarid areas. Silvopastoral management including protein (fodder) banks and grazing systems involving fertilizer trees may partly overcome these problems. Protein banks allow animals to be stall-fed with fodder from trees such as gliricidia, calliandra, or various species of leucaena, pterocarpus, and others grown in blocks on farmland. Alternatively, grazing systems allow livestock to graze on pasture under widely

Table 5 Potential annual harvestable fuelwood produced from fertilizer trees planted in contour strips, woodlots, or rotational fallows

Tree species	Age (years)	Quantity (Mg ha^{-1} yr^{-1})	Sufficient for N families of 6	Country	References
Calliandra	4.5	3.2	1.1	Tanzania	Mwihomeke and Chamshama (2004)
Casuarina	4.5	1.8	0.6		Mwihomeke and Chamshama (2004)
Acacia crassicarpa	5	22.4	7.7		Otsyina (1999)
A. crassicarpa	4	19–24.0	8.2		Otsyina (1999)
Vachellia nilotica	7	1.2	0.4	Tanzania	Nyadzi *et al.* (2003)
Senegalia (Acacia) polycantha	7	10.1	3.5		Nyadzi *et al.* (2003)
Leucaena	7	12.7	4.4		Nyadzi *et al.* (2003)
Acacia crassicarpa	5	51.0	17.5	Tanzania	Kimaro *et al.* (2007)
A. mangium	5	40.0	13.7		Kimaro *et al.* (2007)
Senegalia (Acacia) polycantha	5	39.0	13.4		Kimaro *et al.* (2007)
Vachellia nilotica	5	27.0	9.3		Kimaro *et al.* (2007)
Gliricidia	5	30.0	10.3		Kimaro *et al.* (2007)
Leucaena	3	9.7	3.3	Zambia	Ngugi (2002)
Sesbania	3	8.0	2.7		Ngugi (2002)
Gliricidia	3	7.0	2.4		Ngugi (2002)
Sesbania	1–3	7.3	2.5		Kwesiga and Coe (1994)
Sesbania	Na	2.0	0.7	Rwanda	Ndayambaje and Mohren (2011)
Alder	Na	7.0	2.4		Ndayambaje and Mohren (2011)
Casuarina	Na	11.0	3.8		Ndayambaje and Mohren (2011)
Leucaena	Na	10.0	3.4		Ndayambaje and Mohren (2011)
Tagasaste	Na	11.0	3.8		Ndayambaje and Mohren (2011)
Leucaena single row	2.7	21.2	7.3	Kenya	Jama and Getahun (1991)
Leucaena double row	2.7	18.2	6.2		Jama and Getahun (1991)

spaced trees (e.g., alley farming) or scattered trees (e.g., parklands).

In the more extensive grazing areas of South America, Asia, Australia, and Africa, fertilizer trees are increasingly being planted in association with improved grasses to increase carrying capacity and/or enhance the productivity of grazing cattle. In high-elevation areas of Centra1 America and the Andean region, alders are prominent components of such systems. For example, in Costa Rica, alder stands in pasture grasses cover over 50 000 ha (Kass *et al.*, 1997), whereas the drier espinales of Chile (2 million ha), Bolivia, and Argentina are dominated by *Vachellia* (*Acacia*) *caven* (Muñoz *et al.*, 2007). Similarly, in the over grazed, semi arid chaco of Argentina, Bolivia, and Paraguay (more than 1.2 million km^2) fertilizer trees in the legume genera *Vachellia* and *Acaciella* (formerly *Acacia*), *Leucaena*, *Mimosa*, *Prosopis*, *Pithecellobium*, and *Sesbania* provide N for grass growth and browse (Abril and Bucher, 2001; Muñoz *et al.*, 2007). In the more intensively managed areas in Brazil, Venezuela, Colombia, Mexico, parts of Central America, and the Caribbean, trees such as leucaena are planted in pasture or protein banks (Argel *et al.*, 1998). In Southeast Asia, leucaena and gliricidia are widely used in silvopastures. In Indonesia alone leucaena occurs in > 79 000 ha of pasture land (Shelton *et al.*, 2005). In Queensland in Australia > 100 000 ha of leucaena in pastures provides valuable forage for large-scale beef production (Shelton *et al.*, 2005). In Western Australia, > 50 000 ha of tagasaste is grown in wide-spaced alleys or dense plantations to both provide fodder and reduce salinity by lowering the water table (Lefroy *et al.*, 1992). These are used as the sole source of feed during seasonal periods of nutritional shortage even on commercial farms.

In the parklands and in African savannahs, trees act as 'islands of fertility,' and grass growing under the canopy has better quality and yield than in the open areas (Treydte *et al.*, 2007). For example, grass productivity under faidherbia and parkia canopies was two to six times higher than in open areas in West African parklands (Boffa, 1999). Similarly, in Kenya grass productivity under acacia (now *Vachellia tortilis*) canopies was 1.5–2.3 times higher than outside the tree canopies (Weltzin and Coughenour, 1990). At Pakchong in Thailand, dry matter yield over 840 days was 30–41.5 Mg ha^{-1} in a mixture of grass and leucaena compared to 25–36.8 Mg ha^{-1} in grass alone (Tudsri *et al.*, 2002). Similarly, at Turrialba in Costa Rica, production of star grass was 16.9 Mg ha^{-1} year^{-1} with Erythrina compared to 11.7 Mg ha^{-1} year^{-1} in grass monoculture (Kass *et al.*, 1997).

In the parklands in the Sahel, pods of faidherbia provide a valuable source of dry season fodder. Parkia, locally called Néré, is also a valuable source of fodder in the Sahel, where its branches are lopped by farmers and fed to livestock in the dry season when grass is scarce. Supply of protein, which is the most important nutrient for cattle production on rangelands, can also be improved through fodder supplements from the legume genera *Acacia*, *Vachellia* (*Acacia*), *Leucaena*, etc. (Lefroy *et al.*, 1992; Mapiye *et al.*, 2011). As a result, meat and milk production is significantly improved. An analysis of results from experiments in Latin America and Australia indicated > 70% increase in live weight gain and beef production using leucaena pastures (Jones, 1994).

Trade-offs

Under certain circumstances, the benefits of fertilizer trees could be offset by tree-crop competition for light, nutrients and other resources, soil acidification, or gaseous emissions

(Dick *et al.*, 2006). For example, root competition between trees and crops is a major problem, especially where fast-growing tree species are used without knowledge of optimum planting densities and management requirements. In a study on root development in a cassava-based cropping system in southern Bénin, Lose *et al.* (2003) compared annually planted pigeon pea alleys, perennial alleys, and blocks of gliricidia, flemingia, parkia, and millettia mixture. Annual alleys of pigeon pea had less interference with cassava, whereas block arrangement of the tree mixtures had detrimental effects on the cassava growth in the adjacent rows (Lose *et al.*, 2003). Even with intimate mixtures, competition may not be a problem under optimum tree densities and appropriate management such as pruning, lopping, and coppicing. Pruning offers one of the most direct and adaptable methods of controlling competition. Pruning intervals and intensities can be modified to regulate above- and below-ground competition and to match various production goals. For example, deleteriously competition for water did not exist in gliricidia-maize-pigeon pea intercropping when gliricidia was pruned before and during the cropping season in southern Malawi (Chirwa *et al.*, 2007). Water use studies in southern Africa also show minimal or no competition for moisture between the tree and crops. However, these studies have mostly been restricted to areas with relatively high rainfall (>900 mm) in normal years. In drier areas, competition may be severe.

Agroforestry has great potential for optimizing nutrient cycling and managing soil acidity under appropriate management. However, continuous removal of plant biomass (depending on ash alkalinity) may result in soil acidification. The amount of acidity generated by product removal is equal to the ash alkalinity carried by the product. If the bulk of the leguminous plant biomass is allowed to decompose on site after harvest, then the ash alkalinity is released and soil acidification minimized (Wong *et al.*, 2002). Management of soil acidification under legumes in low-input agroecosystems should therefore minimize the removal of biomass from the site of production and nitrate leaching. Localized acidification may be beneficial in circumstances where alkalinity accumulates down in the soil profile or in localized parts of the landscape. In these circumstances, the use of acidifying legume allows the alkalinity to be accessed and made available in the form of biomass with high ash alkalinity. The acid-ameliorating effect of this biomass can then be used in more acid parts of the landscape or in the more acid top soil. Using low-acidifying fertilizer tree species (provenances) may also reduce the risk of acidification. High genotypic variability within tropical legumes allows selection of genotypes.

Some of the N from legume biomass not taken up by plants and microbes in the soil can contribute to N_2O emissions (Chikowo *et al.*, 2004; Hall *et al.*, 2006), especially after rainfall events. As N addition rates progressively increase beyond the capacity of soil microbes to utilize N, the rate of N_2O production would slow down and finally reach steady state; under this stage, soil C availability would presumably control N_2O production and emission (Dong-Gill *et al.*, 2012). In a semi arid condition in Mali, Hall *et al.* (2006) found six times more N_2O emission from gliricidia plots than from continuous cultivation of sorghum without fertilizer. In a wet tropical soil, Seneviratne and Van Holm (1998) found over 5900 times more N_2O emission from soil without mulch than from plots that received gliricidia mulch. In the same experiment, N_2O emission from urea fertilizer was over 25 000 times higher than from plots that received gliricidia mulch (Seneviratne and Van Holm, 1998).

Conclusions

This review suggests that diversification of agro-ecosystems with fertilizer trees can optimize indigenous soil N supply and increase productivity of the land. Fertilizer trees have an added advantage: ensuring a multifunctional agriculture that provides timber, fodder, shade, soil improvement, and watershed management. Unlike synthetic N sources, fertilizer trees ensure greater internal nutrient recycling and water availability, thus contributing to greater nutrient use efficiency. Therefore, they can make a major contribution to sustainable agriculture by minimizing external inputs, particularly N fertilizers, increasing resource and land use efficiency, and slowing down erosion. The savings on synthetic fertilizer costs and GHG mitigation potential could also be substantial. Unlike synthetic fertilizers, fertilizer trees may play a significant role in reducing N leaching, which is particularly important during periods of reduced ground cover by herbaceous plants, such as between cropping seasons. The advantage of organic inputs over synthetic fertilizers is that much of the N from organic inputs not used by the crop is usually incorporated into various SOM pools, or assimilated by the associated trees, thus remaining in the system for other uses. N from inorganic pools not taken by the crop is subjected to higher levels of leaching and denitrification. Thus, the accumulation of N in SOM pools over time is more sustainable compared to synthetic N fertilizer, which releases nutrients rapidly. The potential of inorganic fertilizers to ameliorate the physical and biological degradation of poorly buffered soils is limited. Synthetic fertilizers, however, will remain a necessary input to agriculture to feed the increasing human population. Therefore, the focus of this article is not just whether fertilizer trees are better or worse than mineral fertilizers, because both play an important (and complementary) role in food production. The authors strongly believe that smallholder farmers would benefit if development planners were to emphasize the merits of different fertility replenishment approaches and take advantage of the synergy between fertilizer trees and mineral fertilizers rather than focusing on the 'organic versus inorganic' debate.

Although the rate of adoption of fertilizer trees has been lower than anticipated in many regions of the world, there have been notable successes in other parts. In the traditional production systems, the adoption of fertilizer trees has been driven by local tradition, economic factors, and land ownership. These traditional systems are being degraded and losing their productivity, but they may be a source of inspiration in the design of new land management practices where fertilizer trees can play a greater role in increasing food, forage, and fibre production. However, a longer-term vision and significant investment in research and development are needed. Screening of candidate tree species and development of innovations appropriate to specific conditions are important where these do not exist.

Where appropriate innovations already exist, barriers to adoption and risks that the adoption presents need to be identified.

Acknowledgment

See also: Agroforestry: Complex Multistrata Agriculture. Agroforestry: Fodder Trees. Agroforestry: Hydrological Impacts. Agroforestry: Practices and Systems

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