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Review article

Fertiliser trees for sustainable food security in the maize-based production systems of East and Southern Africa. A review

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Abstract – The negative effects of soil fertility depletion on food security, especially among smallholder farmers in Africa, is of economic importance, and may be worsened by climate change and rising global fertiliser prices. Substantial efforts and investment have gone into development of alternative soil fertility management options. These include vigorous research and development of N-fixing plants or "fertiliser trees", that has been on-going in the last two decades in East and Southern Africa. In this paper, we review several studies conducted both on-station and on-farm and synthesise the results in terms of improvements in soil physical, chemical and biological properties, and crop yield in response to fertiliser trees. Our major findings are that (1) fertiliser trees add more than 60 kg N ha^{-1} per year through biological nitrogen fixation (BNF); (2) nutrient contributions from fertiliser tree biomass can reduce the requirement for mineral N fertiliser by 75%, translating to huge savings on mineral fertilisers; (3) fertiliser trees were also shown to substantially increase crop yield. A meta-analysis has further provided conclusive evidence that with good management, fertiliser trees can double maize yields compared with local farmer practices of maize cultivation without addition of external fertilisation. (4) Financial analyses showed that fertiliser tree systems are profitable and also have higher net returns than the farmers' de facto practice, i.e. continuous maize cropping without fertiliser. We conclude that widespread adoption and scaling up of fertiliser trees can reduce the amount of mineral fertiliser needed, maintain the soil ecosystem, and positively impact on the livelihoods of farm households in southern Africa.

agroforestry / integrated soil fertility management / N-fixing legumes / scaling up

Contents

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1. INTRODUCTION

Sub-Saharan Africa is often described as food-insecure (Conway and Toenniessen, 2003). The 2007–2008 food price crisis has not only increased food insecurity around the globe, but also exposed long-term failures in the functioning of the world food system (von Braun, 2009). Food shortage has nearly reached challenging dimensions and may become more crippling in the near future than anything the world has ever seen, unless efforts are geared toward improving productivity. At the centre of the imminent food catastrophe is maize, one of the main inputs in biofuel production as well as a staple food in most parts of Africa. Driven by a rapid rise in petroleum prices and, in response, a massive global expansion of biofuel production from maize (Cassman, 2007), the price of maize rose by over 50% from 2001–2007 (FAO, 2008). The rise in maize price not only impacts on the price of food products made from grains, but also the price of meat due to increased prices of livestock feed. Both food crops and feed demand are estimated to double in the next half century (Gowing and Palmer, 2008). The trends in southern Africa are worse than those in other parts of sub-Saharan Africa as population growth, dietary change and land-use pressures have driven prices of food and agricultural inputs to new heights. The prospects for meeting food demand in sub-Saharan Africa, which depends mainly on rain-fed and smallholder agriculture (Conway and Toenniessen, 2003), will likely remain bleak without major efforts to reverse current trends.

The focus of this work is the maize-based mixed farming system, which is the most important food production system in East and Southern Africa. It extends across plateau and highland areas at altitudes of 800–1500 metres, from Kenya and Tanzania to Zambia, Malawi, Zimbabwe, South Africa, Swaziland and Lesotho (Dixon et al., 2001). Maize accounts for 60% of the cropped area in some countries such as Malawi, Zimbabwe and Zambia, and it is almost a dominant crop in other countries including Kenya and Tanzania. In Malawi, maize is estimated to be grown on over 70% of the arable land and nearly 90% of the cereal area, making Malawi the world's highest consumer of maize at 148 kg per capita per year (Smale and Jayne, 2003). Thus, maize will remain a central crop in the food security equation even if the agricultural economy is diversified (Sauer et al., 2007). Crop-livestock integration is strong in the maize mixed farming system, where cattle are the most important livestock species. This farming system accounts for 10% of the land area and 19% of the cultivated area (Dixon et al., 2001). The climate varies from dry sub-humid to moist sub-humid. The most typical areas have unimodal rainfall, but some areas experience bimodal rainfall. The maize mixed farming system is currently in crisis (Dixon et al., 2001). Average farm sizes have fallen to under 0.5 ha in several areas (Dixon et al., 2001), while opportunities for expansion of cultivated land are limited as rapid population growth has led to progressive encroachment upon marginal lands (Bojo, 1996). Most farmers in the maize-based farming systems are crowded out of the agricultural input market and can hardly afford optimal quantities of inorganic fertiliser (Sauer et al., 2007).

The rapid deterioration of soils in this farming system directly affects productivity and it perpetuates rural poverty. Malawi alone loses US$350 million worth of nitrogen and phosphorus through erosion each year, which translates to a gross annual loss of income equivalent to 3% of the agricultural Gross Domestic Product of Malawi (Bojo, 1996). If the situation is to be improved, agricultural production needs to be intensified through the application of agro-ecological technologies that do not require large amounts of capital and labour; a development paradigm termed the "Doubly Green Revolution" (Conway and Toenniessen, 2003). The fertiliser tree system is one of such innovations. A range of fertiliser tree options have been developed and several publications have documented individual studies (Kwesiga et al., 2003; Akinnifesi et al., 2008). There is need for an updated evidence-based review on the lessons learnt from about two decades of Research for Development on fertiliser tree technologies in terms of the science and their adoption and impact. Therefore, the objective of this review is to synthesise experiences in the development, scaling up and impact of fertiliser tree systems in the last two decades in southern Africa.

2. FERTILISER TREE SYSTEMS

Fertiliser tree systems involve soil fertility replenishment through on-farm management of nitrogen-fixing trees (Mafongoya et al., 2006). They represent a new paradigm because they use a completely different approach to land-use management by smallholder farmers. First, fertiliser tree systems capitalise on biological N fixation by legumes to capture atmospheric N and make it available to crops. Secondly, they permit growing of trees in association with crops in space or time to benefit from complementarity in resource use (Gathumbi et al., 2002). Thirdly, they address most of the biophysical and socioeconomic limitations identified with the earlier technologies based on using N-fixing tree legumes such as green manures (Kwesiga et al., 2003; Akinnifesi et al., 2006, 2008). The different fertiliser tree systems that have been developed and promoted in East and Southern Africa in the last two decades are briefly discussed below.

2.1. The *Faidherbia albida* system

The potential of faidherbia (*Faidherbia albida*) for improvement of soil fertility and crop yields has been demonstrated in many parts of Africa (Saka et al., 1994; Kang and Akinnifesi, 2000). This species has a unique phenology in that it sheds its leaves during the wet season and resumes leaf growth during the dry season. This makes it possible to grow crops under its canopy with minimum shading on the companion crop. About 20 to 30 mature trees are needed to completely cover one hectare of land and maintain optimum crop response (Kang and Akinnifesi, 2000). Several studies in Africa showed yield benefits when crops were grown under the canopy of Faidherbia. Saka et al. (1994) reported 100–400% increase in maize yield in the Lakeshore plain of Malawi.

However, it takes a long waiting period (up to 20 years) for the tree to reach maturity and have an impact on the understorey crop (Kang and Akinnifesi, 2000). Recent development has shown that with closer spacing, 10 × 10 m, earlier impact can be achieved at 12–15 years (Dutch Gibson, pers. comm.). A major improvement of this system is integration with other sustainable land management options, such as use of short rotation fallow species in the first 10–15 years.

2.2. Sequential tree fallow

Sequential tree fallow, often known as 'improved fallow', is a practice whereby a piece of land is planted with fast-growing nitrogen-fixing trees or shrubs for 2–3 years' fallow (Mafongoya et al., 2006). Tree fallows have distinct advantage over herbaceous fallows, particularly in seasonally dry climates, because they have the ability to tap nutrients from deeper soil layers and are capable of accumulating large quantities of biomass through which nutrients are recycled back for crop use. Nitrogen-fixing trees also add large quantities of N through biological nitrogen fixation and improve crop yield.

Improved fallows have been widely tested on farmers' fields in Zambia and this technology has now spread to other parts of southern Africa (Kwesiga et al., 2003). Several studies reviewed by Akinnifesi et al. (2008) showed that planted fallows of sesbania (*Sesbania sesban*) in Zambia, Malawi and Zimbabwe had doubled or tripled maize yield compared with control plots.

2.3. Annual relay intercropping

In relay intercropping, fast-growing nitrogen-fixing legumes are planted in a crop field at a time when annual crops such as maize have already been well established, usually within 2–4 weeks of crop sowing (Phiri et al., 1999). The legumes continue to grow after the crop harvest throughout the off-season. Legumes such as sesbania, tephrosia and pigeon pea (*Cajanus cajan*) are recommended. As farmers prepare land for the next season, they clear-cut the legume and incorporate the biomass into the soil. Although the yield levels are usually less than those of intercropping and 2-year improved fallow systems, it works well on small farms, and the benefit of trees can be seen immediately after one season of tree growth. Additionally, farmers do not lose any cropping year of maize. The main limitation of this technology is that the legumes need to be replanted every year.

2.4. Gliricidia intercropping

The intercropping of gliricidia (*gliricidia sepium*) with crops is an improvement building on the characteristics and advantages of alley cropping but minimising its biophysical limitations such as the "hedge effect", "competition" and tree management (Akinnifesi et al., 2006). A detailed description of this innovation has been published elsewhere (Akinnifesi et al., 2008). Gliricidia-maize intercropping has formed an important part of on-station and on-farm research in Malawi since the early 1990s (Akinnifesi et al., 2006). The socioeconomic and biophysical conditions in southern Malawi seem to meet most of the broadly defined criteria for the success of intercropping of crops with trees (Akinnifesi et al., 2006). The fact that land is scarce, labour is relatively cheap, fertiliser is costly in Malawi and the country is highly nitrogen-deficient, coupled with the fact that maize is a high nitrogen-demander, creates the prospect for adoption of gliricidia-maize intercropping in southern Malawi.

The main advantage of gliricidia intercropping is that once established it can be managed to continuously supply nutrients to crops year in, year out. Although gliricidia requires labour to establish seedlings and tree management, this is not yet a bottleneck as land holdings are less than a hectare and less than a quarter of a hectare is put to gliricidia-maize intercropping in the southern region of Malawi. Additionally, labour is cheap in Malawi due to high population density. Farmers appreciate that coppicing trees need to be established only once and can then be used for many years, despite low initial returns.

2.5. Biomass transfer

Biomass transfer is essentially moving green leaves and twigs of fertiliser trees or shrubs from one location to another, usually in the wetlands to be used as green manure. Recent studies (Kuntashula et al., 2004) have shown that biomass transfer using fertiliser tree species is a more sustainable means for maintaining nutrient balances in maize and vegetable-based production systems. The advantage is that synchrony between nutrient release and crop uptake can be achieved with well-timed biomass transfer. The management factors that can be manipulated to achieve this are litter quality, rate of litter application, and method and time of litter application (Mafongoya et al., 1998).

Although it has been argued that biomass transfer technologies require a lot of labour for managing and incorporating biomass, economic analyses have concluded that it is unprofitable to invest in biomass transfer when labour is scarce and its cost is thus high (Kuntashula et al., 2004, 2006). In addition to increasing yields of vegetables such as cabbage, rape, onion and tomato, and maize grown after vegetable harvests, biomass transfer has shown potential to increase yields of other high-value crops such as garlic (Kuntashula et al., 2004, 2006).

3. RATIONALE FOR PROMOTING FERTILISER TREES

What is the evidence base for promoting fertiliser tree systems? The benefits of fertiliser tree adoption include significant increase in crop yield, improvement in soil health, and savings on mineral fertiliser costs and labour. Significant benefits are also derived from fertiliser trees in terms of other

Table I. Average maize yield and yield increase (t ha^{-1}) with fertiliser trees relative to the control (unfertilised maize grown continuously) in southern Africa.

Species	Country	Number of sites	Yield (t ha^{-1})	Yield increase (t ha^{-1})	Percentage increase
gliricidia	Malawi	5	3.9	2.9	345.6
	Tanzania	2	2.3	0.8	55.8
	Zambia	4	2.8	1.8	349.7
sesbania	Malawi	7	2.5	1.3	161.4
	Tanzania	2	1.2	0.7	171.4
	Zambia	9	3.2	2.2	480.0
	Zimbabwe	4	3.0	1.9	583.1
tephrosia	Malawi	9	2.0	1.1	232.7
	Tanzania	2	2.0	0.9	80.1
	Zambia	8	1.7	0.8	198.4
	Zimbabwe	5	3.6	0.2	17.7

Note: yield increase is the yield difference between the treatment (T) plot and the unfertilised control (C) plot, which is farmers' de facto practice. Percentage increase (%I) was calculated as follows: %I = 100((T-C)/C).

ecosystem services, including provision of fuelwood and fodder, reduction of erosion and carbon sequestration. The state of knowledge on the various ecosystem services of agroforestry has been reviewed by Sileshi et al. (2008). In the following sections we will briefly describe improvement in crop yields and soil health.

3.1. Improvement in crop yield

One of the direct benefits of fertiliser trees is the maize yield response, as discussed in the next section. In an effort to fill the long-standing knowledge gap and conundrum of "marginal versus high impact" arguments regarding the effect of fertiliser trees on crop yield, a meta-analysis was undertaken using 94 peer-reviewed publications across sub-Saharan Africa (Sileshi et al., 2008). The results of the analysis provided a solid perspective for making recommendations about fertiliser trees to policy-makers, investors and scientists. Table I presents maize yields achieved using fertiliser trees across a range of sites in Malawi, Zambia, Zimbabwe and Tanzania. On average, gliricidia gave 55–350% yield increase over the control, while sesbania gave 160–583% increase. Yield increases with tephrosia spp were modest, and ranged from 180% to 233% (Tab. I).

In a long-term trial in Makoka, gliricidia intercropping with maize increased maize yield in the range of 100 to 500%, averaging 315% over a ten-year period (Akinnifesi et al., 2006). Increase in yield is more apparent from the third year after tree establishment and onwards (Akinnifesi et al., 2006). The unfertilised plots not amended with gliricidia had steadily declining yield, and amendment with N and P could not sustain high maize yield over time (Fig. 1). Continuously cropped maize plots without gliricidia or fertiliser declined steadily from 2 t ha^{-1} at the start of the experiment in 1992 to half a tonne in 2006. Unfertilised maize under gliricidia maintained yield at 3 to 4 t ha^{-1}. When the intercrop plots were amended with 46 kg N ha^{-1} and 40 kg P_2O_5 ha^{-1} (representing 50% N and 100% P, respectively), there was a 79% increase in grain yield over the recommended practice, indicating complementarity between the applied fertiliser and organic inputs from gliricidia (Akinnifesi et al., 2007).

Similarly, in an on-farm experiment, 30% of the 40 on-farm type II farmers (farmer-managed trials) experienced increase in yield in the first two years, and 90% of these experienced yield increases in the subsequent two years (Akinnifesi et al., 2008). Yield increases in the third and fourth years averaged 69%. The authors observed that farmers with low yields in these early years were associated with poor field management conditions. Similarly, Makumba and Maghembe (1999) reported yield increase in Makoka of 126% over three years for type I farmers' fields (researcher-managed), and an increase of 37% in on-farm type II averaged over five years. They attributed low response to erratic rainfall during the period.

3.2. Soil health

Soil health has been broadly defined as the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain biological productivity and diversity, maintain or enhance water and air quality, and promote plant and animal health (Doran, 2002; Sileshi et al., 2006a, b, 2008). In a global context, soil quality affects not only soil productivity but is also a significant factor governing environmental quality, and human and animal health and food safety and quality. Soil health is enhanced by management and land-use decisions that weigh the multiple functions of soil, and is impaired by decisions which focus only on single functions, such as crop productivity. Trees have been known to contribute to soil health in a number of ways: (i) enhancing soil physical structure and water regimes, (ii) improving soil chemical properties and nutrient input, (iii) increasing biological (microbial and faunal) communities, and (iv) suppressing soil pests. Several of these aspects of fertiliser tree management on soil health have been addressed in various studies in

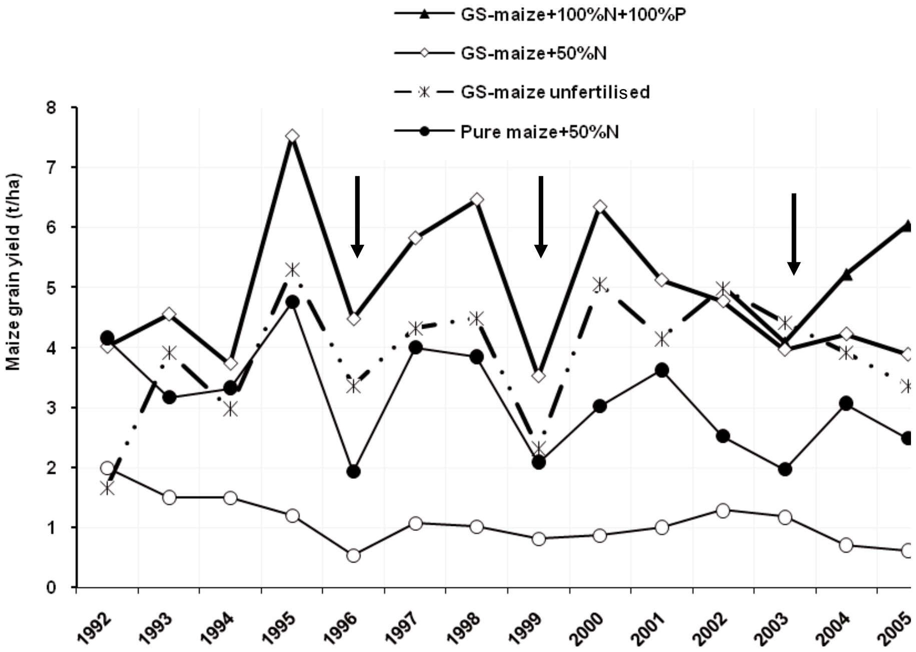


Figure 1. Long-term maize grain yield as affected by fertiliser and pruning incorporations in a gliricidia-maize intercropping in Makoka, Malawi. Arrows indicate flood due to excessive rainfall in 1996/97, and droughts in the 1999/00 and 2003/04 seasons (Akinnifesi F.K., unpublished). Gs = *Gliricidia sepium*; N = nitrogen, P = phosphorus.

southern Africa. In the following section we will discuss these in detail.

3.2.1. Improvement in soil physical properties

Among the commonly used indicators of soil physical health are soil depth and rooting, infiltration, bulk density, water-holding capacity, aggregate stability, and penetration resistance. Fertiliser trees improve soil physical properties due to the addition of large quantities of litter fall, root biomass, root activity, biological activities, and roots leaving macropores in the soil following their decomposition (Rao et al., 1997). In studies conducted in eastern Zambia, sesbania fallows significantly increased the percentage of water-stable aggregates (>2 mm) compared with continuous maize cultivation without fertiliser (Sileshi and Mafongoya, 2006a). In the same experiment after two years of cropping, significantly lower bulk density and higher porosity ($P < 0.05$) was recorded in pigeon pea and sesbania fallows than a monoculture maize (Fig. 3). Similarly, bulk density was higher under monoculture maize compared with maize grown in association with gliricidia and *L. leucocephala* (Sileshi and Mafongoya, 2006a). The fact that fertiliser trees consistently improve soil physical properties is seen from measured increases in infiltration rates (Fig. 2), soil penetration resistance (Fig. 3), and reduced runoff and soil losses (Nyamadzawo et al., 2007; Phiri et al., 2003). Treatments involving fertiliser trees (leucaena, gliricidia, sesbania) have consistently shown significantly higher infiltration rates than monoculture maize (Fig. 2). Increased water infiltration implies reduced water runoff and thus low soil erosion. Generally, plots under fertiliser trees had lower resistance compared with continuously cropped maize plots (Chirwa et al., 2003; Fig. 3).

In a study conducted in Kagoro in eastern Zambia, the soil in maize planted following improved fallows had lower penetration resistance compared with monoculture maize at all soil depths (Fig. 3). The lower values following planted fallows could be attributed to the high amounts of litter biomass left on the surface by the fallow species. The lower infiltration and high penetrometer resistance in the monoculture maize indicate soil compaction as a result of degradation of soil structure. The improvement in soil structure under fertiliser trees was evident, as reflected by the results from time-to-runoff studies (Phiri et al., 2003). Rainfall simulation studies (Nyamadzawo et al., 2007) also indicated that sesbania and gliricidia mixed with Dolichos increased infiltration rates significantly compared with continuously fertilised maize plots.

In another study, Chirwa et al. (2007) reported that gliricidia did not compete with maize in a gliricidia-maize intercropping system in Makoka. The water-use efficiency (WUE) was higher in the agroforestry system than sole maize or pigeon pea.

3.3. Improvement in soil chemical properties

Among the chemical indicators of soil health, total soil organic matter, the carbon to nitrogen ratio, carbon and nitrogen mineralisation rates, pH, electrical conductivity, and extractable N, P and K are commonly used. A recent study (Beedy, pers. comm., 2008) indicates that soil organic matter balance under gliricidia intercropping is positive following 14 years of continuous cropping. The study concluded that

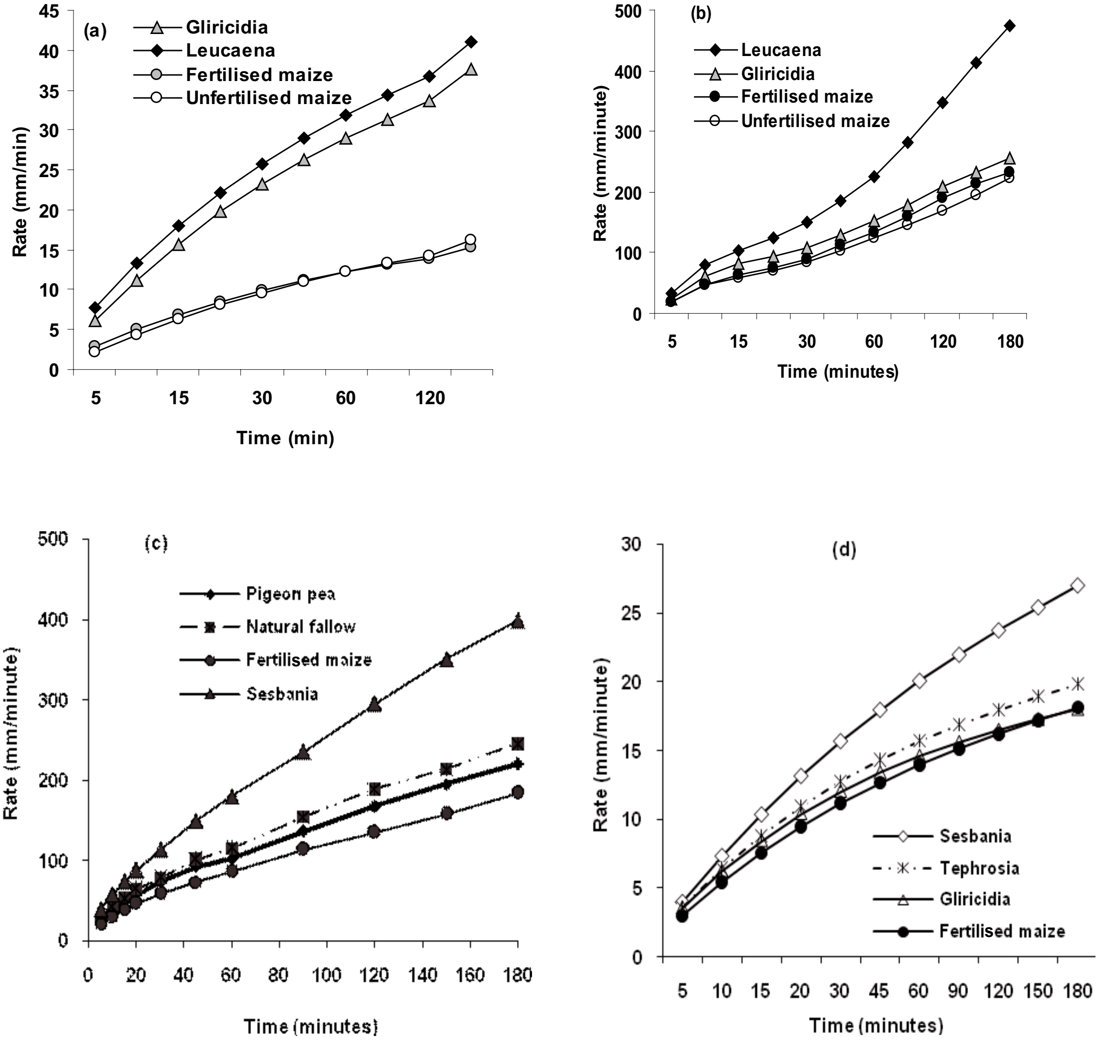
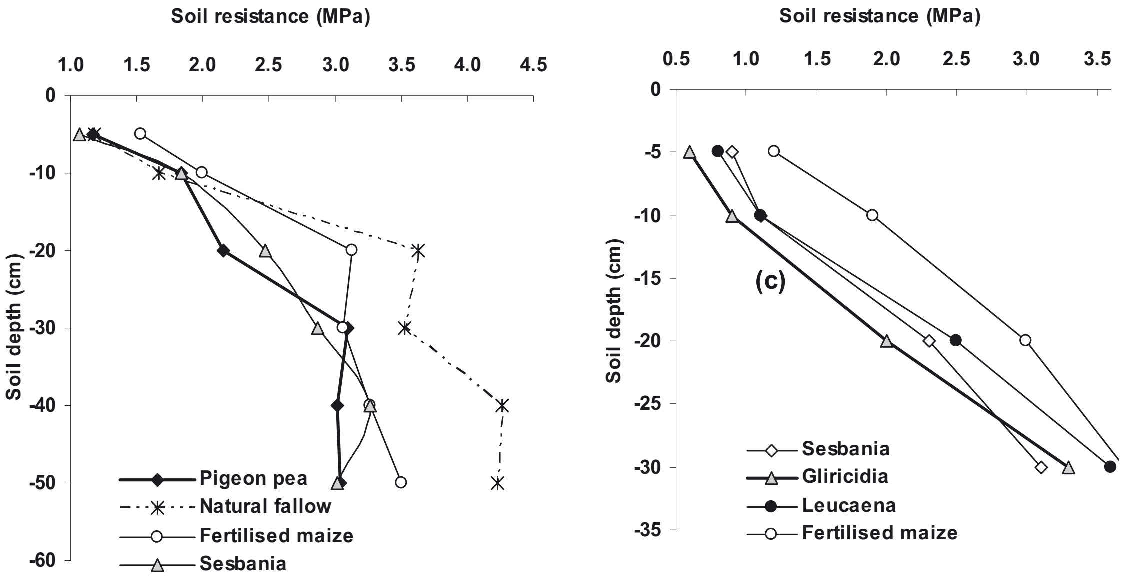


Figure 2. Cumulative water intake in different treatments: (a) experiment 99-2, (b) experiment 2000-3, (c) experiment 92-2 in Masekera and (d) experiment in Kagoro (adapted from Sileshi and Mafongoya, 2006a and b; Chirwa et al., 2003).

after 14 years, predictors of soil fertility and supporting soil organic matter fractions were significantly greater under the gliricidia-maize intercrop than under sole maize (Beedy, pers. comm., 2008). Both gliricidia intercrop and N fertiliser had a significant positive effect on dry season available N (Ikerra et al., 1999).

The legumes used in the sequential (e.g. fallow, relay) and simultaneous (e.g. intercrop) systems described above contribute to soil N through BNF and capture of subsoil N (otherwise unutilised by crops). Estimates of the amounts of N accumulated by fertiliser trees are given in Table II. Out of the N accumulated, 55–84% is N derived from the atmosphere (Tab. II). A series of multi-location trials were set up to measure the amount of N_2 fixed by different tree genera and provenances using the ^{15}N natural abundance method in Zambia. The data shows high variability among species and varieties of the same species in percent N derived from the atmosphere (Ndfa). So the measurement task is still a challenging one (Mafongoya et al., 2006). Two-year tree fallows of the non-coppicing species sesbania and tephrosia are able to replenish soil N to levels sufficient to grow three subsequent high-yielding maize crops in southern Africa (Kwesiga and Coe, 1994). Unlike non-coppicing species, coppicing trees such as gliricidia and *Leucaena* spp. cause increases in residual soil fertility beyond 2–3 years because of the additional organic inputs that are derived each year from coppice re-growth that is cut and applied to the soil. The fertiliser value of total N was estimated to exceed 60–75 kg N ha^{-1} (Akinnifesi et al., 2008), which can replace the current need for mineral N. Some legumes were more effective in improving soil productivity and maize yield than others, probably due to differences in biomass production, N_2 fixation and recovery of leached nutrients.

Legumes can also have other beneficial effects on crop yield as they can improve availability and uptake of nutrients such as phosphorus. In small-scale farming systems in Africa, crop harvesting removes almost all of the P accumulated by cereal crops (Sanchez et al., 1997). Application of plant biomass



(a) (b)

Figure 3. Soil penetrometer resistance in different treatments: (a) in the 1999 cropping season in experiment 92-2 in Msekera (adapted from Sileshi and Mafongoya, 2006a) and (b) in Kagoro (adapted from Chirwa et al., 2003). Treatments significantly differed in 1998 ($P = 0.004$) and 1999 ($P = 0.018$).

from fertiliser trees as green manure can contribute to P availability, either directly by releasing tissue P during decomposition and mineralisation or indirectly by acting on chemical processes that regulate P adsorption-desorption reactions (Mweta et al., 2007). Table III presents the P and K input from biomass for different fertiliser tree species. Soil organic matter contributes indirectly to raising P in soil solution by complexing certain ions such as Al and Fe that would otherwise constrain P availability (Li et al., 2003; Mweta et al., 2007). Decomposing organic matter also releases anions that can compete with P for fixation sites, thus reducing P adsorption. The more extensive root systems that trees and shrubs have compared to crops increase the exploration of larger soil volumes, which results in enhanced uptake of P and other nutrients (Schroth, 1999).

Rotation of maize with legume fallows can result in more effective subsoil nitrate and water utilisation than maize monoculture (Chirwa et al., 2007; Nyamadzawo et al., 2007; Phiri et al., 2003). Where both soil organic matter and phosphorus are very poor, legumes may not accumulate a significant amount of biomass and will fix little N. To maintain positive nutrient balances for N and P in these environments, organic resources need to be combined with low rates of mineral fertiliser amendment (Sileshi et al., 2009).

The retrieval and cycling of nutrients from soil below the zone exploited by crop roots is referred to as nutrient pumping. Deep capture is favoured when perennials have a deep rooting system and a high demand for nutrients, when water or nutrient stress occurs in the surface soils, and/or when extractable nutrients occur in the subsoil (Buresh and Tian, 1997). These conditions were observed in eastern Zambia where nitrate accumulated in the subsoil during periods of maize growth. Fertiliser trees grown in rotation with maize could effectively retrieve the nitrate in the subsoil that is not accessible to maize (Mafongoya et al., 2006). Intercropping rather than rotating fertiliser trees with crops appears to improve the long-term efficiency of nutrient use in deep soils. The nutrient balance has been shown to be positive after 8–12 years of continuous cultivation with fertiliser trees such as gliricidia in Malawi and Zambia (Akinnifesi et al., 2007; Mafongoya et al., 2006). Intercropping with fertiliser trees such as gliricidia may be more effective for pumping of soil nutrients than a fallow legume-maize rotation. The introduction of gliricidia with maize rotation has a great potential for deep capture of Ca and Mg compared with continuously fertilised monoculture maize.

3.3.1. Soil biological processes and functions

Soil biological processes, mediated by roots, flora and fauna, are an integral part of the functioning of natural and managed ecosystems. Soil biota have been identified as potential indicators of soil health and sustainability at the farm level (Sanginga et al., 1992). These include microflora numbers, microbial biomass, enzyme activity and respiration, and soil fauna (abundance, diversity and community structure of soil arthropods, earthworms, etc.), as they respond sensitively to land management practices and correlate well with beneficial soil functions including water storage, decomposition and nutrient cycling, and suppression of pestiferous organisms.

Table II. Amount of N fixed (kg/ha) and the percentage of nitrogen derived from the atmosphere (% Ndfa range) by fertiliser trees in southern Africa.

Species	N fixed	%Ndfa	Site (Country)	References*
Acacia anguistissima	122	56–79	Chikwaka (Zimbabwe)	1
	210		Chipata (Zambia)	2
Pigeon pea	NA	65–84	Chikwaka (Zimbabwe)	1
	64	96–99	Nyambi (Malawi)	3
	85	94–97	Ntonda (Malawi	3
	34	66–96	Gairo (Tanzania)	3
	54	95–99	Babati (Tanzania)	3
Gliricidia sepium	212	NA	Chipata (Zambia)	2
Leucaena collinsii	300	NA	Chipata (Zambia)	2
Sesbania sesban	84	55–84	Chikwaka (Zimbabwe)	1
Tephrosia candida	280	NA	Chipata (Zambia)	2
Tephrosia vogelii	157	NA	Chipata (Zambia)	2

* References: 1. Chikwko et al. (2004); 2. Mafongoya et al. (2006); 3. Adu-Gyamfi et al. (2007).

Table III. Annual inputs of the major nutrient (kg/ha) from biomass‡ from fertiliser trees added to the soil.

Tree species	Tree management	Nutrient input			Site	Reference
		N	P	K		
G. sepium	Coppicing	33.7	2.0	21.4	Muheza (Tanzania)	1
	Pollarding	71.9	4.4	45.8	Muheza (Tanzania)	1
L. leucocephala	Coppicing	65.6*	3.6	30.9*	Msekera 1 (Zambia)	2
	Coppicing	44.3†	2.5†	20.6†	Msekera 2 (Zambia)	2
G. sepium	Coppicing	69.9*	4.6*	26.2*	Msekera 1 (Zambia)	2
	Coppicing	69.2†	4.6†	25.9†	Msekera 2 (Zambia)	2
	Coppicing	72.1	-	-	Kagoro (Zambia)	3
	Coppicing	67.3	-	-	Kalunga (Zambia)	4
	Coppicing	74.4	5.2	42.5	Makoka (Malawi)	5
S. sesban	Non-coppicing	38.0	-	-	Chikwaka (Zimbabwe)	6
Pigeon pea	Non-coppicing	82.0	-		Chikwaka (Zimbabwe)	6
G. sepium	Coppicing	-	2.2	13.2	Msekera 3 (Zambia)	4
	Coppicing	-	4.3	25.3	Kalunga (Zambia)	4

‡ In the case of coppicing species this represents only coppice biomass, while in non-coppicing species both litter and standing leaf biomass are considered.

* Averaged over 9 years.

† Averaged over 5 years. Msekera 1 and 2 represent experiments 92-3 and 97-3, respectively.

†† References: 1. Meliyo et al. (2007); 2. Sileshi and Mafongoya (2006a); 3. Chirwa et al. (2003); 4. Sileshi and Mafongoya (2006b); 5. Akinnifesi et al. (2006); 6. Chikowo et al. (2004).

Soil microflora such as fungi and bacteria are responsible for the breakdown of plant litter and most soil activities. Very few studies have examined the effect of fertiliser trees on soil biological properties. In a study conducted in Zimbabwe using leaf biomass of various fertiliser trees, microbial biomass carbon and nitrogen did not differ among treatments. However, fungal Actinomycetes populations differed with the biomass of legume species used as well as the method of biomass application (Mafongoya et al., 1997).

Among the macrofauna essential in soil processes in agroecosystems, probably the most important ones are the so-called ecosystem engineers (termites, earthworms and some ants), and the litter transformers including millipedes, some beetles and many other soil-dwelling invertebrates. Earthworms can be used as an integrative measure of soil health, assuming their importance in regulating soil processes which are vital to the continued formation of soil and as protection against soil degradation. These have been used to monitor changes in soil quality and to provide early warning of adverse trends and identify problem areas. In five separate experiments conducted in eastern Zambia, the number of invertebrate orders per sample and the total macrofauna (all individuals per square metre) recorded were higher when maize was grown in association with tree legumes than under fertilised monoculture maize. Similarly, densities of earthworm and millipede were also higher than under monoculture maize (Sileshi and Mafongoya, 2006a, b). Cumulative litter fall, tree leaf biomass, and re-sprouted biomass under legume species appeared to explain the variation in macrofauna densities (Sileshi and Mafongoya, 2007). Litter transformer populations were higher under gliricidia, which produced good quality organic inputs, than among the other fallow species. On the other hand, a higher population of ecosystem engineers was found under trees that produce poor quality organic inputs (Sileshi and Mafongoya, 2006a, b).

3.3.2. Reduction in weed problems

Declining soil fertility, along with the concomitant problems of weeds, pests and diseases is now a significant constraint to Africa's aspiration for sustainable development and food security (Sanchez, 2002). The declining soil resource base has also contributed to loss of biodiversity and persistent soil pest problems and weeds such as *Striga* spp. (witchweed). The effect of fertiliser trees on weeds and soil insects has been studied in eastern Zambia (Sileshi and Mafongoya, 2003; Sileshi et al., 2005, 2006). Abundance of *Striga asiatica* was significantly influenced by the quantity and the interaction effect of quantity and quality of biomass. Species that produce low to medium quantities of slow-decomposing biomass tended to reduce *striga* abundance in maize, while fast-decomposing ones did not (Sileshi et al., 2006). Similarly, in East Africa, reduction of another witchweed (*Striga hermontica*) by legume fallows depended on the rate of decomposition and nitrogen mineralisation of organic residues, which in turn was determined by quality in terms of carbon to nitrogen + polyphenol ratios (Gacheru and Rao, 2001). This indicates that the mechanism by which legume fallows influence striga is much more complicated than just by soil fertility improvement. Among the legumes tested, sesbania appeared to be the best in reducing striga infestation in maize in eastern Zambia (Sileshi et al., 2006).

Fertiliser trees have also reduced arable weed problems (Sileshi and Mafongoya, 2003; Sileshi et al., 2006). The mechanism by which legumes suppress arable weeds varies. Rotational fallows can modify the chemical ecology of the soil by releasing a range of volatile and water-soluble compounds that may act as germination stimulants or inhibitors. Chemicals such as nitrate and ethylene stimulate germination of numerous agricultural weeds. These compounds also sensitise weed seeds to other environmental factors such as changes in soil temperature and exposure of weed seeds to light (Sileshi et al., 2006).

3.3.3. Reduction in soil insects

Although termites are generally essential ecosystem engineers, some are also crop pests. Few, if any effective methods exist to control pestiferous species. Fertiliser tree systems generally reduce insect pests such as termites (Sileshi and Mafongoya, 2003; Sileshi et al., 2005). In a study conducted in eastern Zambia, Sileshi and Mafongoya (2003) recorded lower termite damage (% lodged plants) on maize planted after tephrosia + pigeon pea, sesbania + pigeon pea and pure sesbania compared with maize grown after traditional grass fallow. Monoculture maize grown after traditional grass fallow had about 11 and 5 times more termite damage compared with maize grown after tephrosia + pigeon pea and sesbania + pigeon pea, respectively. In another set of experiments, Sileshi et al. (2005) monitored termite damage on maize grown in coppicing fallows. Those studies showed that fully-fertilised monoculture maize suffered higher termite damage compared with maize grown in gliricidia and *L. leucocephala*.

4. ADOPTION, SCALING UP AND IMPACT

Given the biophysical performance and relevance of fertiliser trees in southern Africa, since the mid-1990s, emphasis on the system has shifted from purely on-station field trials to on-farm research, which allows incorporation of socioeconomic studies of adoption, profitability, labour, farmer perception and acceptability of different fertiliser tree systems under farmers' field conditions (Ajayi, 2007). The research for development efforts has therefore been expanded to address questions on farmer uptake, determinants of adoption and factors influencing farmers' decisions to adopt fertiliser trees, impacts of the technological innovations, and constraints and obstacles against adoption.

4.1. Adoption

A number of empirical studies have been carried out to gain insights into the factors influencing farmers' decisions to adopt fertiliser trees and the impacts that the technology has made on livelihoods and the environment in southern Africa. Using a logistic regression approach, Thangata and Alavalapati (2003) investigated the adoption of mixed inter-cropping of *Gliricidia sepium* and maize in Malawi. Their results suggest that age of the farmer, frequency of contact with extension, and the effective number of household members who contribute to farm work are important variables determining the adoption of agroforestry. A study in Zambia (Keil et al., 2005) found that 75% of farmers who initially tested fertiliser trees eventually adopted the technology. Their study shows that scarcity of capital, inadequate access to markets for fertiliser and relatively low population density are the conditions that enhance the adoption of the technology. Studies on the use of labour in agricultural field plots in Zambia show that over a five-year period, the total quantity of labour used in fertiliser tree plots was 13% lower than unfertilised maize, and far less compared with fertilised monoculture maize plots (Franzel et al., 2002; Franzel, 2004). A study by Ajayi et al. (2007) found that aggregated over a five-year cycle, the total quantity of labour input used in fertiliser tree plots (improved fallows) was lower than in fertilised continuously cropped maize fields, but higher than in non-fertilised maize. These results do not lend credence to the notion that fertiliser trees are more labour-intensive given that the quantity of labour inputs used per unit of fertiliser tree plot area is not higher than in fertilised maize. Given the small plot sizes of fertiliser trees, estimated at an average of 0.2 ha only, farmers' decision to test fertiliser tree systems or not may not be attributed to the quantity of labour requirements. Rather, the popular perception regarding labour constraints and adoption of fertiliser trees in fertiliser trees may be due to the fact that some field operations may coincide with operations in other fields (especially cash crops) that are managed by the same households, and which depend on the same labour supply drawn from household members (Ajayi et al., 2009; Ajayi, 2007). This suggests that both the quantity and temporal distribution of labour input requirements are important factors in farmers' decision to adopt fertiliser trees. It is expected that as the land area that farmers cultivate to agroforestry increases, the temporal distribution of labour requirement for tree establishment and management may become more significant than it is presently. A modification to the agronomic practices of the technology to shift some of the labour inputs away from the main cropping season to the "off peak" labour demand season is expected to enhance the acceptability of fertiliser trees among farmers. Based on these and several other studies, the main factors that affect the adoption of fertiliser trees have been identified. These can be grouped into four categories: household-specific, technology-specific, institution and policy, and geo-spatial factors (Ajayi et al., 2007), further elaborated below.

Household-specific factors: These include farmer perceptions, resource endowment, household size (a proxy for household labour supply),risk, and access to information on inputs and output prices. These factors vary widely across households, resulting in different levels of uptake of fertiliser trees by different typologies of farm households. Those households who have access to a larger pool of labour supply, e.g. higher household size or land and other production inputs tend to have higher levels of adoption (Ajayi et al., 2006; Keil et al., 2005). While economic performance and short-term profitability of fertiliser trees enhance the probability of farmers' uptake, these alone do not provide an exclusive explanation for farmers' adoption patterns. Key attitudinal issues such as farmers' perceived usefulness of the technology (Ajayi, 2007), and household resource endowment are important for adoption. Although most options of fertiliser trees have positive net present values over time, some of them attain break-even point only after two years, implying that farmers make an upfront investment for a couple of years before receiving returns to their investment in the technology. This poses challenges to some types of farm households in southern Africa, who may not be sufficiently well off to absorb the initial investment and/or who may want to derive immediate benefits from the technology (Ajayi et al., 2007). For some farmers, a long "waiting period" can forestall the adoption of certain fertiliser tree technologies that guarantee high net returns in future.

Technology-specific factors: The technology-specific factors that affect farmers' uptake of fertiliser trees include the management regime required under some options as well as characteristics of particular fertiliser tree technology. Smallholder farmers more readily adopt specific options of fertiliser trees if such options produce grain that could be consumed or sold for cash income, in addition to replenishing their soils (Ajayi, 2007). Different types of fertiliser trees require varying amounts of labour and this plays an important role in their acceptability to farm households, depending on their internal labour endowment or ability to command additional labour from outside the household. In general, species that can be directly sown are much more preferred by farmers than those which require nursery establishment, transplanting, and other operations that add to the complexity of the options. Apart from the quantity of labour required to manage fertiliser trees, the temporal distribution of the same is also important for adoption (Ajayi et al., 2007). Fertiliser trees are an emerging technology relative to conventional agricultural practices that farmers have known, been used to, and have received training on for a much longer period. Unlike annual crop production technologies and conventional soil fertility management options, fertiliser tree systems require skills in terms of management of the trees.

In terms of profitability, fertiliser tree systems are profitable and have positive net benefits (Franzel et al., 2002; Franzel, 2004). A field study in Zambia (Ajayi et al., 2009) found that the net present value of maize plots amended with only fertiliser tree systems (US$233–309) compared well with a full fertiliser dose (US$349), and performed better than a continuous unfertilised maize plot; US$130 (Tab. IV). In addition, the return to labour in fertiliser trees is two times higher than in unfertilised fields (Franzel, 2004). Improved fallows require 13% less labour inputs per hectare than unfertilised maize and 33% less labour inputs than fertilised maize (Franzel, 2004).

Policy and institution factors: The policy and institution context within which fertiliser trees are disseminated plays an important role in affecting decision-making regarding the technology. Such factors include input and output prices, customary land-use practices, land tenure and property rights. Policy and institutions are cross-cutting and affect several farmers because the adoption of a relatively long-term technology such as fertiliser trees depends on incentives created by market and non-market institutions (Ajayi et al., 2007). National policies may modify the profitability of fertiliser trees, thereby altering their attractiveness and potential adoptability by farmers. Lack of access to quality seeds is one of the greatest constraints to fertiliser trees. Private sector organisations have not yet engaged in the multiplication and distribution of fertiliser tree seeds as done for the seeds of food crops such as maize. One of the reasons is that the market size and potential returns on investment in the latter is expected to be more rewarding for private entrepreneurs because more farmers currently grow maize than fertiliser trees. A profitability analysis conducted on fertiliser trees in Zambia showed that the four factors that most influenced the financial attractiveness and potential adoptability of the technology are external to the household, and most smallholder farm households have very little or no control over them (Ajayi et al., 2009).

Some local customary practices affect the nature of risk and potential adoptability of fertiliser trees. Field studies in Zambia show that bush fires and browsing constrain

Table IV. Financial profitability of maize production systems using tree fallows, fertiliser and farmers' practices in Zambia[†††].

Description of system	Benefit-cost ratio	Net present value (US$ /ha)	% increase in net profit over unfertilised maize
Continuous maize – non-fertilised	2.01	130	0
Continuous maize – subsidised fertiliser[†]	2.65	499	284
Continuous maize – fertiliser priced at market rate[††]	1.77	349	168
2-yr *Gliricidia sepium* fallow	2.91	269	107
2-yr sesbania fallow	3.13	309	138
2-yr tephrosia fallow	2.77	233	79

[†] Fertiliser subsidised by government at 50%.
[††] Fertiliser at market rates.
[†††] Figures are on a one hectare basis, at prevailing costs & prices and annual discount of 30%.

widespread adoption of certain fertiliser technologies (Ajayi and Kwesiga, 2003). Extensive browsing by livestock led to the discontinuation of the promotion of pigeon pea-based fertiliser trees in Zambia (Franzel et al., 2002). In addition, local customary practices and institutions (especially incidence of bush fires and browsing by livestock during the dry season, and absence of perennial private rights over land) prevailing in southern Africa limit widespread uptake of some agroforestry technologies (Ajayi and Kwesiga, 2003). Collaborative efforts initiated by traditional rulers, and research and development organisations to respond to these challenges have contributed to solving some of the constraints posed by these customary practices, e.g. through the enactment of bye-laws against the practices, but have not completely resolved them. Short-term customary land tenure creates a disincentive to longer-term investment in tree-based technologies.

Geo-spatial factors: There is a spatial dimension to the adoption of fertiliser trees in southern Africa, as the performance of the technologies varies with location, across crops and with time. Geo-spatial factors focus on the performance of species across different bio-physical conditions and site or village location. They include the type and characteristics of soils, which determine the bio-physical limits of technologies, access to roads and markets, and location of a village relative to institutions promoting fertiliser trees. The choice of species used for fertiliser trees is critical as the biophysical performance and social-economic needs of different communities vary from one region to another. The establishment of proper targeting of fertiliser trees to geographic and social niches is an important factor that affects the relevance of the technology to farmers and that they create the desired impact among smallholder farmers.

The fertiliser tree system is financially profitable, but its widespread uptake by smallholder farmers may be constrained by challenges posed at the farm, household and policy levels as enumerated above. One of the important lessons learnt is that scaling up of fertiliser trees requires both vertical processes (to influence policies and institutions that are conducive for farmer adoption) and horizontal processes (to quicken the spread of the technology across communities and geographic boundaries). In addition, there is the need for appropriate structures that support the uptake of fertiliser trees. Such structures include the existence of strategic partnerships with several research, education and development institutions, and viable seed and output markets.

4.2. Biophysical and socioeconomic considerations for proper targeting

After two decades of research, it is known that the technical performance of fertiliser trees is important but not an exclusively sufficient condition to guarantee their adoption by smallholder farmers. A substantially large volume of new knowledge has been generated on where these legume-based technologies fit best within spatially heterogeneous landscapes. The most important considerations include:

1. Landholding size: In areas where landholding is a problem such as in the southern region of Malawi, Gliricidia is best suited as a permanent system where fallowing and cropping are concurrent. Improved fallows are not appropriate where landholding is small, such as southern Malawi where average holding is less than one hectare. The two- to three-year waiting period may also be a disincentive in land-pressured areas as farmers may be unable to allocate a separate field for fallows for such long periods. A well-designed simultaneous intercropping or relay fallow cropping system is ideal for such situations.
2. Waiting period: Where landholding size is bigger, many fertiliser trees and shrubs can be practised. For instance, faidherbia is recommended where a farmer can afford to wait for at least 12–15 years before getting soil fertility benefit. To reduce this period, we recommend that short-duration species be used as fertiliser during the first 10–12 years. Gliricidia and faidherbia are not recommended for farmers without permanent lands. On the other hand, farmers without permanent ownership of land, but access for a few years, would prefer short-duration species.
3. Land and tree tenures: Where the small landholding problem is also coupled with land tenure due to tree tenure, especially in matrilineal matrilocal systems, annual relay fallow intercropping with short-duration fallow species such as sesbania, *Tephrosia* spp. and pigeon pea become more

Table V. Assessment of the impact of agroforestry adoption on livelihoods of farmers in Malawi, Mozambique and Zambia (Schueller et al., 2005).

Impact indicator	Malawi (n = 31)	Zambia (n = 184)	Mozambique (n = 57)
Increase in area under Agroforestry	55	87	65
Yield increases (>quarter to tripled)	70	90	71
Significant food security (>2 months of hunger reduction)	94	84	54
Increase in income	58	68	53
Firewood availability	90	nd†	59
Increased savings	87	94	71
Change in wealth	77	84	77
Strong reduction in *Striga* spp.	90	93	88
Soil improvement	84	82	59
Other benefits	65††	nd	24

† nd, not determined.
†† Malawi, seed sale; Mozambique, tree stakes.
* Figures in table represent % of respondents.

attractive. In such matrilineal systems men are less motivated to plant permanent trees. Faidherbia and gliricidia are not recommended where land and tree tenures are a problem.

4. Nursery investment: *Tephrosia* spp. has the advantage that it could be sown directly without nursery investment. Because gliricidia is planted once, farmers who are not interested in annual or bi-annual nursery establishment will prefer gliricidia. However, because of the shortage of seeds and need for nursery establishment, many farmers are encouraged to use *T. candida*. This also means that planting of gliricidia, and especially faidherbia, must be started early before the season, as these require 6–8 weeks for gliricidia and sesbania and 9–12 weeks for faidherbia before transplanting. Where the season has already begun, only pigeon pea or *Tephrosia* spp. are feasible as they could be sown in the field directly.
5. Germplasm availability: Availability of tree seeds may limit the type of fertiliser tree technology to embrace. Gliricidia is more expensive and difficult to obtain in large amounts. On the other hand, *Tephrosia* spp., faidherbia, pigeon pea and sesbania are prolific seed producers. However, gliricidia can be established from stem cuttings.
6. Soil type and catena positions: The fertiliser trees have specific niches they perform best. The survival of gliricidia on wetlands is generally poor. Well-drained soils are better for gliricidia. Sesbania is well suited to both well-drained and wetlands. However, it does not perform well on sandy soils. *Tephrosia* spp. performs well on flat to upper slopes, like gliricidia.
7. The results from the meta-analysis indicate that they are generally best-performing in low to medium potential sites in terms of rainfall and fertility.
8. Pests and disease: Some species (e.g. sesbania) are susceptible to pests during the seedling stage.
9. Grazing problem: where livestock grazing is a chronic problem, sesbania, pigeon pea and gliricidia may not be successful. In that case, *Tephrosia* spp. is ideal. Also, communities could formulate bye-laws to deal with animal encroachment during and after cropping seasons.
10. In some cases, the biomass produced by fallows could be constrained by low soil fertility and a supplement with micro-doses of inorganic fertilisers, especially P, is worthwhile. The use of P fertilisers from inorganic fertiliser or rock phosphate has been recommended for poor P-deficient soils (Sanchez, 2002).

4.3. Impact of fertiliser trees on livelihoods

A large body of literature has been generated since the 1990s, and new results, innovations and challenges have emerged. Conclusions from these clearly indicate that agroforestry is making a positive impact on the livelihoods of people who adopt the technologies, although much remains to be done in quantifying the impact. One of the major impacts of fertiliser trees is on food security through the increase in maize yield (see Sect. 3.3). For example, an extra increase in yield equivalent to between 54 and 114 extra-person days of maize consumption reduced the hunger period by 2–3 months per household in Zambia (Ajayi et al., 2007).

A monitoring and evaluation framework used with partners in five countries showed that the number of farmers benefiting from the technology increased from a few hundreds in the mid-1990s to more than 400 000 by 2007 in the region (Schuller et al., 2005). An impact assessment in the region also indicated that farmers have generally increased the land under agroforestry, and appreciated that the fertiliser tree technologies have improved soil fertility for 59–84% of farmers, increased maize yield for 70–90% of practising farmers, improved food security and reduced hunger months by at least 2 months for 54–94% of farmers, and contributed to fuel wood availability for 54–90% of farmers, income generation for 53–68% of farmers, and other livelihood indicators (Tab. V) as shown below.

Empirical studies in Zambia show that farmers appreciate fertiliser tree technology for its ability to respond to the critical problems of poor soil fertility, its effects on food security, and the additional benefits obtainable from fertiliser trees to households (Ajayi, 2007). They mentioned, however, challenges to the widespread uptake of the technology to include land constraints, land tenure rights, lack of tree seeds, and the knowledge-intensive nature of the technology.

5. CONCLUSION

From the discussion above it can be concluded that the fertiliser trees can sustain crop yield and deliver a range of other benefits that enable farmers to produce adequate food to feed their families. A variety of fertiliser tree systems have been developed to fit into different farming systems and farmers' socioeconomic circumstances. Although the technical performance of fertiliser trees is important, it is not exclusively sufficient to guarantee their adoption by smallholder farmers. Compared with technologies based on annual crops, the adoption of fertiliser trees will be slower because the technology involves multiple components and the multi-years through which testing, modification and uptake of the technology by farmers take place. Moving fertiliser trees to the mainstream requires approaches that overcome the major adoption hurdles discussed above: robust technology that fits farming systems, clear economic benefits from farmers' perspective, establishment of a sustainable germplasm base and input supply system, and a supportive macro-economic policy environment.

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