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Appropriate technologies to replenish soil fertility in southern Africa

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Abstract In southern Africa, soil nutrient reserves are being depleted because of continued nutrient mining without adequate replenishment. The consequent downward spiral of soil fertility has led to a corresponding decline in crop yields, food insecurity, food aid and environmental degradation. The central issue for improving agricultural productivity in southern Africa is how to build up and maintain soil fertility despite the low incomes of smallholder farmers and the increasing land and labour constraints they face. Under this review five main options namely: inorganic fertilizers, grain legumes, animal manures, integrated nutrient management and agroforestry options appropriate to smallholder farmers are presented. Issues addressed in the use of inorganic fertilizers are reduction in fertilizer costs, timely availability and use efficiency. Legumes can be used to diversify farm system productivity but this requires P and lime application to support better legume growth and biological nitrogen fixation (BNF) as well as development of markets for various legume products. Manure availability and quality are central issues in increasing smallholder farm productivity and increasing its efficiency through proper handling and application methods. Integrated nutrient management of soil fertility by combined application of both inputs will increase use efficiency of inputs and reduce costs and increase profitability; but the challenge is often how to raise adequate amounts of either inorganic or organic inputs. Issues such as quality of inputs, nutrient balancing, labour to collect and transport organic inputs and their management need to be optimized. These are the challenges of adoption as are the scaling up of these options to millions of small-scale farmers.

Keywords Agroforestry · Grain legumes · Inorganic fertilizers · Integrated nutrient management and Organic inputs

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Introduction

Low soil fertility is increasingly recognized as a fundamental biophysical cause for declining food security among small-farm households in sub-Saharan Africa (SSA) (Sanchez et al. 1997). At present, aggregate maize yield in southern Africa is about 1.0 t ha^{-1} excluding South Africa. In most cases, nitrogen is the main nutrient that limits maize productivity, with phosphorus and potassium being occasional constraints. Low nutrient holding capacities, high acidity, low organic matter, poor soil structure and low water-holding capacity are other constraints to soil productivity. These constraints are in some cases exacerbated by over exploitation through continuous cropping and low nutrient application rates. Stoorvogel et al. (1993) estimated annual nitrogen losses from arable land to be 31 kg ha^{-1} in Zimbabwe and 68 kg ha^{-1} in Malawi. Swaziland, Mozambique and Madagascar have annual NPK losses >60 kg ha^{-1} with Lesotho falling somewhere between 30 and 60 kg ha^{-1} (Nandwa, 2003). The estimates of nutrient mining for some South African countries reported by (Henao and Baanante 1999) reflect similar losses (Table 1). Traditionally maintenance of soil fertility in agricultural systems relied largely on bush fallows (Blackie and Jones 1993). Today, fallowing in arable areas of Malawi, Zimbabwe and other countries has almost disappeared and continuous cropping is the norm. In Zambia and Mozambique where fallowing is still widely practiced, the length of the fallow period is decreasing and often insufficient to maintain soil fertility.

The critical issue for improving agricultural productivity in southern Africa is how to build up and maintain soil fertility despite low incomes, increasing labour and land constraints faced by smallholder farmers (Kumwenda et al. 1997).

Table 1 Annual nutrient depletion in agricultural soils in countries of Southern Africa

Country	Nutrient depletion (kg ha^{-1} $year^{-1}$)			Total fertilizer use (kg ha^{-1})
	N	P	K	
Tanzania	–38	–6	–25	4.5
Malawi	–48	–7	–37	14.6
Mozambique	–23	–4	–19	3.5
Zambia	–13	–1	–12	5.7
Zimbabwe	–20	–1	–21	49.3

Source: Henao and Baanante (1999)

(FAO 2003)

Following research from the 1950s, approaches for soil fertility replenishment have been proposed and these range from recurring fertilizer applications to low external input agriculture based on organic sources of nutrients. Although the strategies work well in specific circumstances, they pose major limitations for most smallholder farmers in southern Africa. In this review the focus is on some of the options which are appropriate and available to farmers namely: inorganic fertilizers, animal manures, grain legumes, agroforestry options, and integrated nutrient management options. The socio-economic challenges and constraints that limit the adoption of these options are also presented.

Inorganic fertilizer inputs and their management

Fertilizer use has been responsible for a large part of sustained increases in per capita food production that have occurred in Asia, Latin America as well as for commercial farmers in southern Africa (Sanchez et al. 1997). However, although most small-scale farmers in southern Africa appreciate the value of fertilizers they rarely apply them at the recommended rates and at the appropriate time because of high cost (Kazombo-Phiri 2005), lack of credit, delivery delays and low and variable returns (Heisey and Mwangi 1996). The high prices prohibit fertilizer use among subsistence farmers (Kazombo-Phiri 2005). Such constraints are likely due to lack of enabling policy environment in rural areas aggravated by poor market infrastructure.

Since the 1960s fertilizer use has been growing in SSA at around 6.7% annually but growth in application rates per hectare has slowed down since the 1990s. In Southern Africa, current fertilizer use varies from 3.5 kg ha^{-1} in Mozambique to 49.3 kg ha^{-1} in Zimbabwe as compared to 80 kg ha^{-1} $year^{-1}$ in the rest of the world. According to Ahmed et al. (1997) and Rusike et al. (2003) as quoted by ICRISAT (2006) <5% of farmers commonly use fertilizers in Zimbabwe for instance and this is due to the fear to risk investment in fertilizer. Recent estimates showed that a little over one-third of the maize, the most important staple food in the southern Africa region receives some inorganic fertilizers. Much less is applied for

Table 2 Nitrogen maize price ratio of some countries in southern Africa and other developing region

Country or Region	Nitrogen maize price ration
Malawi	7.7
Zimbabwe	6.4
Mozambique	4,3
Zambia	5.4
Lesotho	4.8
Swaziland	4.9
Asia	2.7
Latin America	3.8

Source: Waddington and Heisey (1996)

other crops. One of the main factors underlying low fertilizer use in southern Africa is the relatively high nutrient to grain price ratio (Table 2). High price ratios lead to unfavorable benefit cost ratios. For example, the benefit: cost ratio in Malawi is 1.8 for fertilizer use on hybrid maize (Conroy and Kumwenda 1995) and this is substantially below the ratio 2.0 usually assumed necessary for widespread adoption of fertilizer by smallholder farmers. Greater variability in policy, prices and climate especially in drier areas increase the risk of fertilizer use in southern Africa compared with Asia and other parts of the world. There is therefore a need to improve fertilizer use efficiency so that the use of fertilizer is financially attractive to farmers and thus expand its use.

Low fertilizer use efficiency also reflects inappropriate fertilizer recommendations promoted by research and extension services. For >50 years research on inorganic fertilizers in Zimbabwe and Malawi was geared towards commercial farmers who could afford large amounts of fertilizers on commercial crops. Thus, researchers have often ignored climatic and soil conditions of small-scale farmers in most southern Africa countries. For instance, although work has been done since independence on appropriate types, amounts, timing and placement of inorganic fertilizers for food crops produced by smallholder farmers (Hikwa and Mukurumbira 1995) fertilizer recommendations in Zimbabwe and other countries still fail to take sufficient account of cash constraints and risks affecting resource poor farmers in marginal areas. Recent work in the region to tailor inorganic fertilizers types, amounts, timing and placement to the conditions under which smallholder farmers produce maize and other cash crops is yet to be used in fertilizer recommendations. In Malawi for example, recommendations for improving maize yield include supplementation of basal NP fertilizer with Zn and S, reduction in P application rates, band application of basal and top dress fertilizer (compared with the current method), and earlier application of basal fertilizer and top dress N fertilizer (Jones and Wendt 1995; Kumwenda et al. 1995). Kumwenda et al. (1995) already showed that Zn and S supplementation targeted to deficient soils improved N fertilizer efficiency and increased maize yields by 40% over standard NP recommendations alone. Similarly, in Zimbabwe all compound fertilizers must contain S, Zn or Boron by law to deal with similar deficiencies.

Limited soil moisture in the drier areas is a frequent constraint to maize production and response to fertilizer application. Existing fertilizer recommendations are too risky in these areas and need to be adjusted to evolving rainfall pattern in order to increase their profitability (Piha 1993). An experiment on adjusting fertilizer recommendations to respond to rainfall in Zimbabwe gave 25–42% more yield and 21–41% more profit than existing application recommendations. By concentrating fertilizer applications in basins ('potholes'), along with liming and emphasis on timely planting and weeding, the maize yield of farmers practicing conservation farming has been raised from 1 t ha^{-1} to six or more. But the general fertilizer recommendations prove the best options compared to common farmer practices in the absence of area specific recommendations (Sakala 1996) indicating that these general recommendations may not be completely irrelevant.

The use of small quantities of fertilizer for crop production was assessed during the 1990s based on the premise that farmers may initiate investments in small quantities of fertilizer. The results suggest that farmers could increase their average yields by 50–100% by applying as little as 9 kg N ha^{-1} directly to the base of the plant (ICRISAT 2006). The response depends on the rainfall received, crop grown and the zone. According to Bwalya (2005), success in increasing yields will also depend on improved access to seed besides fertilizer inputs.

The challenge of generating and availing fertilizer technology and knowledge that are usable and affordable to small scale farmers must consider the diversity of the southern Africa agro-ecosystems. For instance, within-field and within-farm variabilities are sometimes greater than mean differences across districts and have potentially profound effects for extension recommendations (Carter and Murwira, 1995). The diversity of farmer reality, including access to resources implies that solutions need to be site-specific and requires emphasis on farmer experimentation and participatory learning, and building of partnerships between stakeholders (farmers, credit providers, input dealers, research and extension agencies, government) at village, regional, and national levels. This will require clear understanding of the socioeconomic contexts/constraints of farmers, agro-dealers, private and public sectors across regions in southern Africa, and identification of opportunities and constraints for increasing fertilizer use. These constraints include limited access to credit, poor infrastructure in rural areas, high risks and transaction costs of distant markets, weak purchasing power of the poor farmers, limited access to fertilizer information among the poor, limited number of trained rural fertilizer stockists, lack of inputs in affordable sizes, low and irregular supply of inputs, lack of appropriate fertilizers fit for local conditions among others.

Use of animal manures

Animal manure is an important soil fertility replenishment component in the mixed crop-livestock farming systems that are characteristic of Southern Africa. Animal manure has traditionally been used as a source of nutrients and can improve crop yields considerably. This has been shown in several studies and reviews (Probert et al. 1995; Haque 1993; Murwira et al. 1995). Murwira et al. (2002) observed per cent fertilizer equivalencies of manure across four sites in Zimbabwe to vary between 10 and 35%. In some cases, a yield reduction is observed when N-poor manure is applied due to immobilization effect when the C:N ratio is greater than 23. Within Fundikila (grass-mound) system in Zambia, there was no difference in finger millet yield between grass mounds only treatment and grass-mounds plus kraal manure treatment and this was due to N immobilization effect from poor quality grass (Goma, 2003). Other demonstrated benefits of manure include increase in soil pH, water holding capacity, hydraulic conductivity and infiltration rate and decreased bulk density. Manure can be an important source of nutrients, especially nitrogen (N), phosphorus (P) and potassium (K). In Zimbabwe, for instance, estimates from the Mutoko communal area suggest that over 80% of the N applied to field and garden crops is derived from kraal manure and about 10% from leaf litter (Scoones and Toulmin 1985).

Quantity and quality of manure

Inadequate availability of manure is a problem faced by farmers in southern Africa. The amount of manure available to a farmer is dependent on several factors such as breed, herd size, management system and seasonal rainfall conditions. Probert et al. (1995) estimated manure production levels of 1 t per livestock unit per year for unimproved local cattle breed in maize-livestock system in the semi-arid parts of eastern Kenya. Similar production levels have been reported in Zimbabwe. According to Murwira et al. (2004), farmers value manure quantity as being more important than quality and farmers usually augment quantity by adding anthill soil, crop residues and leaf litter. But not all farmers with cattle use manure in crop production. In Zimbabwe, 60% of households owning cattle did not use cattle manure as an amendment for crop production (ICRISAT 2006).

In spite of the low levels of manure production, recommended manure application levels are often as high as 10–15 t ha^{-1} $year^{-1}$ (Grant 1981) and sometimes upto 40 t ha^{-1} (Murwira et al. 1995). The manure used in trials where the recommendations are drawn often emanates from feedlots and ranches with higher feed quality than communal areas. The quality of kraal manure from livestock in communal areas is highly variable, with N levels as percentage of dry matter (DM) ranging from 0.46 to 1.98% (Tanner and Mugwira 1984; Mugwira and Mukurumbira 1985; Mureithi et al. 1994). The effectiveness of manure depend on its N content and the application rate (Murwira et al. 1995) yet nutrient content data is often not cited and quality varies considerably from farmer to farmer (Murwira 2003). For high yielding maize crops, manure alone is unable to supply continuously large amounts of readily available N especially in clay soils where mineralization is often lower than in sandy soils due to its shielding effect (Murwira et al. 1995). The P concentration also can vary greatly depending on the source, the diet of the animal, storage and management (Guar et al. 1984) but quite often, its supply is low requiring supplementary P fertilizer application (Murwira et al. 1995). Additionally, communal area cattle manure contains high fractions of sand due to the mixing of manure with soil during trampling by the livestock (Mugwira 1985).

One way to improve manure quality is to supplement livestock with nutrient rich concentrates and fodder. Many trees and shrubs used in agroforestry systems provide fodder that can improve the quality of manure produced. Jama et al. (1997) showed that high P-content manure (0.49% P) can be obtained if the grass fed to zero-grazed improved breed dairy cows is supplemented with the fresh leaves of *Calliandra calothrysus*. The effect of the resultant high quality manure increased crop yield both during the season of application as well as during the subsequent season due to residual effects.

The problem of low manure availability in smallholder farms is also addressed through increasing its use efficiency. One such strategy is placement of the manure in the planting hole instead of broadcasting, a common practice among farmers in the region. Spot application also reduces leaching and volatilization effects and maximizes yield. Spot placement or dribbling of manure into the planting furrow each year, rather than broadcast application at high rates every few years, are promising ways of increasing the recurrent crop yields benefits from cattle manure (Munguri et al. 1995). Spot placement however requires farmer knowledge, skills, labor inputs as we as good manure preparation (Ransom et al. 1995). Although data on losses of nutrients during manure management in smallholder farming is generally lacking some recent estimates, suggest that up to 60% N and 10% of P can be lost through poor manure management. Since 40 to 60% of the N excreted by livestock (ruminants) is in the form of urine, the potential for nutrient loss can be greater under stall-feeding than range grazing systems where only excreta is captured and applied to crop fields (Powell and Williams, 1995).

To increase manure use however, some myths surrounding the use of manure should be addressed. For example, application of raw manure in the planting holes leads to crop 'burning' as often reported by farmers, calling for extension and farmer education. Empowering farmers through greater understanding and application of principles is paramount (Murwira 2003). Murwira et al. (2004) and Bwalya (2005) also highlight the need to consider short-term and long-term effects, economic and environmental factors, farmer perceptions and other limiting nutrients to make manure recommendations. Socio-economic factors of importance are labour availability, cash income, livestock ownership and farmers indicators of manure quality, transport of manure, competitive use such as fuelwood and family headship. Simple indicators of manure quality used by farmers have been used to develop a decision guide, and present a valuable tool for farmer training (Murwira et al. 2004).

Grain legumes

Legumes play a central role in maintaining soil productivity in smallholder agriculture in southern Africa. Mixed intercropping of cereals with grain legumes such as groundnuts (*Arachis hypogaea*) soybeans (*Glycine max* [L] Merr) and *Phaseolus* beans or tree legumes such as pigeonpeas (*Cajanus cajan*) has been advocated (MacColl 1989). Grain legumes are also used as sole crops in rotation with cereals, are intercropped and occasionally used as green manures. Self-nodulating promiscuous types of soyabean, pigeonpea, groundnut, bambara nut and cowpea are the most promising legumes in Malawi, Zambia and Zimbabwe. Perennial legumes are sometimes retained in farmer's fields and are being incorporated in agroforestry interventions as improved fallows and fodder banks. Late maturing pigeonpea is especially promising as an intercrop with maize in densely populated areas where land is scarce and animals are few such as southern Malawi.

Biological nitrogen fixation (BNF) makes a significant contribution to N supply (Table 3) and for many poor farmers, BNF is an essential, cost effective alternative or complementary solution to industrially manufactured N fertilizers particularly for staple crops. Tropical grain legumes can certainly fix substantial amounts of N given favourable conditions, but the majority of this N is often harvested in the grain. Legumes such as soybean that have been subject to intense breeding efforts are very efficient at translocating their N into the grain, and even when the residues are returned to the soil there is generally a net removal of N from the field (Giller et al. 1994). Some promiscuous soybean varieties that are leafier, have a greater potential to add N to the soil, and are potentially more appropriate for cultivation by smallholder farmers than the recommended varieties grown on commercial farms in southern Africa (Mpepereki et al. 1996). Soybean residues at harvest are lignified (10% lignin) with C/N ratios around 45:1 and these tend to immobilize N when they are added to the soil (Toomsan et al. 1995). By contrast, groundnut (*Arachis hypogaea* L.) residues can contain >160 kg N ha^{-1}, are less lignified (5% lignin), and are rich in N, as the crop is harvested while still green.

Table 3 N fixed on smallholder farms in southern Africa by various legumes

Legume	N_2 fixed kg ha^{-1}	Source
Bambara nut	52	Rowe and Giller (2003)
Cowpea	47	Rowe and Giller (2003)
Groundnut	33	Rowe and Giller (2003)
Pigeonpea	39	Rowe and Giller (2003)
Pigeonpea	3–82	Mapfumo et al (2000)
Pigeonpea	97	Chikowo et al. (2004)
Cowpea	28	Chikowo et al. (2004)
Acacia angustissima	122	Chikowo et al. (2004)
Sesbania sesban	84	Chikowo et al. (2004)
Gliricidia sepium	212	Mafongoya PL
Acacia angustissima	210	Mafongoya PL
Leucaena collinsii	300	Mafongoya PL
Tephrosia candida	280	Mafongoya PL
Tephrosia vogelii	157	Mafongoya PL

For many years rotation of maize with groundnut has been the most common crop sequence on smallholder farms in sub-humid parts of Zimbabwe (Shumba 1983; Metelerkamp 1987). Under favourable management and when groundnut residues are incorporated on sandy soils, groundnut in rotation with maize can double the yield of the following maize, particularly when the maize is grown with little or no N fertilizer (Mukurumbira 1985). Another success is the use of a sole pigeon pea crop that can drop up to 40 kg N ha^{-1} in fallen leaves during its growth (Kumar-Rao et al. 1983) and its small N harvest index means that a relatively large proportion of the fixed N remains in the field and can be of substantial benefit to subsequent crops as observed in Malawi (Kumwenda, 1996). In addition, the rooting habit of pigeon pea has an added advantage of mining nutrients from deeper soil horizons thereby enriching the upper surface of the soil through leaf fall and litter decomposition (Van Noordwijk 1989; Mekonnen et al. 1997).

Intercropping of grain legumes generally results in the legume deriving a greater proportion of its N from N_2 fixation than when grown alone, but legume dry-matter production and N accumulation are usually reduced because of competition from the companion crop (Table 4) so that the overall amount of N_2 fixed is less than that of sole crop of a legume. Cowpea intercropping was advantageous with maize or millet in seasons with adequate rainfall, but the cowpea competed strongly with the cereal crop for soil water when

Table 4 Maize grain yields in intercropping systems with *Tephrosia candida* and *Cajanus cajan* in Chipata, Zambia

Treatment	Grain yield t ha^{-1}		
	Year 1	Year 2	Total
Fertilized maize	2.3	0.7	3.0
Unfertilized maize	0.6	0.7	1.3
Tephrosia candida (provenance 02970 + Maize	0.9	0.8	1.7
Tephrosia candida (provenance 02971 + Maize)	0.8	1.0	1.8
Tephrosia candida (provenances 02972 + Maize)	1.0	1.1	2.1
Tephrosia candida + Maize	1.3	1.0	2.3
Cajanus cajan + Maize	0.8	0.8	1.6

rainfall was limiting (Shumba et al. 1990). One notable exception again is traditional pigeonpea, which has a phenology complementary to that of most cereal crops. Its initial aboveground growth and development is very slow, hence there is little direct competition between the two crops (Natarajan and Mafongoya 1992). The long duration growth habitat and its ability to root deeply allow the pigeonpea to grow on after the companion cereal crop has been harvested, utilizing residual moisture in the soil (Table 4). However, although sole pigeonpea produced clear residual effects in the growth of subsequent maize, the residual effects of maize and pigeonpea intercrops were not substantial, presumably because of reduced inputs of N. Benefits are more likely to accrue to subsequent crops as the main transfer pathway is due to root and nodule senescence and fallen leaves (Ledgard and Giller 1995).

But virtually all the information that is available on legume N contributions is from research conducted on experimental stations where the crops have been adequately fertilized with P and other nutrients, and sometimes irrigated. As biomass and yields of sole-cropped grain legumes under smallholder conditions in Africa are often small (<500 kg ha^{-1} of grain), the amounts of N_2 fixed are also little. For example, in the Usambara Mountains in northern Tanzania, where bean (*Phaseolus vulgaris* L.) is the staple grain legume, most farmers' crops lacked nodules because of severe P deficiency, and amounts of N_2 fixed were estimated to be 2–8 kg N ha^{-1} (Amijee and Giller 1998).

Much of the work on legume based technologies has been done on research stations with little attention to tailor these technologies to smallholder conditions where labor is a problem. The fertilizer which is needed to jump start the system may be too costly or not available and some legume seeds are often difficult to obtain. It may also be difficult to release land from staple food crop production to produce legumes that are efficient in N_{2-} fixation but have a low food value. The legume market is also not very well developed and farmers will not give up cereal production for legumes. Other issues that need to be addressed are early planting of legumes which is necessary although it brings competition for labour at the onset of rains; time of legume biomass incorporation is also important to avoid being eaten by animals but incorporating immediately after harvest may also interfere with marketing; legume pests and diseases which present a bottleneck to produce sufficient legume biomass (Kabambe 1996).

Agroforestry options

Planted tree fallows with leguminous trees or shrubs that accumulate N in the biomass through biological nitrogen fixation (BNF) (Table 5) and capture of subsoil N (otherwise unutilized by crops) have been found to be an excellent option to replace natural fallows and increase maize yields on N deficient sites (Ajayi et al. 2004; Kwesiga et al. 1999; Kwesiga and Coe 1994). Two-year tree fallows of *Sesbania* (*Sesbania sesban* [L] Merr.) or *Tephrosia* (*Tephrosia vogelii* Hook. F.) are able to replenish soil N to levels sufficient to grow three subsequent high-yielding maize crops in N-depleted but P-sufficient soils in southern Africa (Kwesiga and Coe 1994; Kwesiga et al. 1998). In general, woody fallows accumulate larger N stocks than herbaceous ones because of their larger and continuing biomass accumulation. The residual effects of tree fallows are therefore longer than herbaceous fallows and grain legume crops. Large-scale adoption of fertilizer trees by farmers is now taking place across southern Africa.

Using non-coppicing species

Since the work of Kwesiga and Coe (1994) on *Sesbania* fallows, much has been learned about the performance of improved non-coppicing fallows such as *Sesbania sesban*, *Tephrosia vogelii*, *Tephrosia candida*, *Cajanus cajan*, and *Crotalaria* spp. The performance of *Sesbania* and *Tephrosia* under a wide range of biophysical conditions for example is shown in Table 6. These improved fallows of 2 year duration significantly increased maize yields well above those of unfertilized maize, the most common farmer practice in the region. The problem demonstrated in these trials was that the residual effects of these improved fallows on maize yield declined after the second year of cropping (Table 5). In the third year of cropping, maize yields following fallow were similar to those of unfertilized maize. The marked decline of maize yields two or three seasons after a non-coppicing fallow is probably related to depletion of soil nutrients and/or to deterioration in soil chemical and physical properties. In Zambia, *Sesbania sesban* was found to perform poorly in areas where soils were poor and rainfall was low but fairly well in better soils (Goma, 2003).

Using coppicing species

Unlike non-coppicing species, coppicing species such as *Gliricidia sepium*, *Leucaena leucocephala*, *Calliandra calothyrsus*, *Senna siamea* and *Flemingia macrophylla* show increases in residual soil fertility beyond 2–3 years because of the additional organic inputs that are derived each year from coppice regrowth that is cut and applied to the soil. An experiment was established in the early 1990s at Msekera Research Station to examine these relationships. These plots were cropped for 10 years during which both maize yields and coppice growth were monitored (Fig. 1). The species showed significant differences in their coppicing ability and biomass production, with *Leucaena*, *Gliricidia* and *Senna siamea* having the greatest coppicing ability and biomass production, while *Calliandra* and *Flemingia* performed poorly over all 10 years. There were no significant differences in maize grain yield between *Gliricidia* and *Leucaena* fallows over the seasons. In experiments conducted in other different sites in Malawi, however, *Gliricidia* seemed to be the most effective species in increasing maize yield but its use was constrained by seed availability and its growth was limited to some parts of the country only (Phombeya et al. 1996). In Zambia, the growth of both *Gliricidia* and *Leucaena* was improved by liming and P application (Goma, 2003).

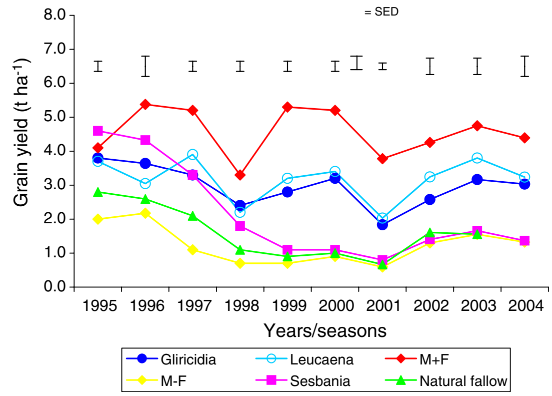

Fig. 1 Grain yield (t ha^{-1}) obtained from various fallow species for ten seasons at Msekera Research Station, Zambia

Species such as *Leucaena* and *Gliricidia* which have good coppicing ability produce large amounts of high-quality biomass, with high nitrogen content and low contents of lignin and polyphenols thereby contributing to higher maize yields (Mafongoya and Nair 1997; Mafongoya et al. 1998). While *Sesbania* produces high quality biomass, its lack of coppice regrowth means that it cannot supply nutrients for an extended period of cropping. Species such as *Flemingia*, *Calliandra* and *Senna siamea*, on the other hand, produce low-quality biomass, high in lignin and polyphenols and low in nitrogen. Their use as fallow species leads to N immobilization and reduced maize yields.

Biomass transfer using fertilizer-tree biomass

Biomass transfer using fertilizer-tree species is shown as a sustainable means for maintaining

Table 5 Maize yields for two season following soyabean in a sandy loam soil in a smallholder farm Hurungwe Zimbabwe (1998/99)

Soyabean variety	N fixed (kg ha^{-1})	Soyabean biomass incorporated (t ha^{-1})	Maize yield (t ha^{-1}) 97/98	98/99
Magoye (promiscuous)	90	5.4	2.3	1.2
Local (promiscuous)	90	4.9	2.1	1.4
Roan (Specific)	88	3.2	1.8	0.9
Nyala (Specific)	82	2.8	1.4	0.8
Maize control	Nil	Nil	0.2	0.2

Source: Adapted from Mpepereki and Pompi (2002)

Table 6 Maize grain yield after *Sesbania sesban* and *Tephrosia vogelii* fallows on farmers' fields in eastern Zambia during 1998–2000

Fallow species	Maize grain yield t ha^{-1}			
	Land use system (LUS)	Year 1	Year 2	Year 3
Farmers testing *Sesbania sesban* fallows	Sesbania fallow	3.6	2.0	1.6
	Fertilized maize	4.0	4.0	2.2
	Unfertilized maize	0.8	1.2	0.4
	LSD (0.05)	0.7	0.6	1.1
	Number of farmers	8	6	4
Farmers testing *Tephrosia vogelii* fallows	Tephrosia fallow	3.1	2.4	1.3
	Fertilized maize	4.2	3.0	2.8
	Unfertilized maize	0.8	0.1	0.5
	LSD (0.05)	0.5	0.6	0.9
	Number of farmers	17	9	5

nutrient balances in maize and vegetable-based production systems, as the tree leafy materials are able to supply N to the soil (Kuntashula et al. 2004). The transfer involves producing high-quality biomass through the establishment of on-farm 'biomass banks' from which the biomass is cut and transferred to crop fields in different parts of the farm. Synchrony between nutrient release from tree litter 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, method and time of litter application (Mafongoya et al. 1998).

Biomass transfer technologies require a lot of labor for managing and incorporating the leafy biomass. If used for the production of low-value crops like maize, the higher maize yield from biomass-transfer technologies may not be enough to compensate for the higher labor cost. Most economic analyses have concluded that it is unprofitable to invest in biomass transfer when labor is scarce and its cost is thus high. However, when prunings are applied to high-value crops like vegetables, the technology becomes profitable (ICRAF 1997). For instance, farmer participatory experiments conducted in 2000–2004 by Kuntashula et al. (2004) have shown that biomass transfer using *Leuceana leucocephala* and *Gliricidia sepium* is tenable for sustaining vegetable production in seasonal wetlands (dambos). 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 (Table 7). At Bunda college in Malawi, it was found that 10 t ha^{-1} of Leucaena leaf biomass is just as effective as 100 kg ha^{-1} of inorganic fertilizer N (Kazombo-Phiri 2005).

Whether copping or non-coppicing fallows or biomass transfer systems, work done for many years has shown how organic matter decomposition and nutrient release are affected by the levels of polyphenol (P), lignin (L) and nitrogen (N) content of the organic inputs (Mafongoya et al. 1998). Recently studies have also shown that maize yields after fallows with various tree legumes were negatively correlated with the (L + P): N ratio and positively correlated with recycled biomass. Fallow species with high N, low lignin and low polyphenols such as *Gliricidia* and *Sesbania* gave higher maize yields compared to species such as *Flemingia*, *Calliandra* and *Senna*. Mafongoya et al. (2000) has shown that it is not the quantity of polyphenols that is critically important, but rather their quality as measured by their protein-binding capacity.

Where land is limiting, the feasibility of fallow systems is yet to be proved. In such situations trees are grown simultaneously with crops (Kazombo-Phiri 2005). This mixed system is being adopted by farmers in southern Malawi using *Gliricidia sepium*. When trees are associated with crops they can compete for moisture, nutrients and light. But *Faidherbia albida*, usually intercropped with crops increases yields of cereal by 50–250% and is perhaps the most important agroforestry species in Malawi (Kazombo-Phiri 2005).

Table 7 Selected vegetable yields (t ha^{-1}) in dambos using inorganic fertilizers or organic inputs from manure, tree leaf biomass in Chipata district, Zambia

Treatments	Cabbage yield (n = 31); (2000)	Green maize cob yield after onion (t ha^{-1})	Onion yield (n = 12) (2001)	Green maize cob yield after cabbage (t ha^{-1})	Garlic yield (n = 6); (2004)
Manure 10 t +1/2rec. fertilizer	66.8	11.6	96.0	11.7	9.1
Recommended fertilizer	57.6	8.4	57.1	10.4	7.2
12 t Gliricidia sepium	53.6	12.4	79.8	17.3	–
8 t Gliricidia sepium	43.1	10.9	68.3	14.9	10.3
12 t Leucaena leucocephala	32.6	–	–	13.0	–
Non-fertilized	17.0	6.4	28.1	7.8	4.2
SED	5.3***	2.06***	11.2*	3.04*	1.2***

– treatment not evaluated, *significant at $P < 0.05$; **significant at $P < 0.01$; ***significant $P < 0.001$

The adoption of agroforestry options is quite low compared to grain legumes. Factors which affect adoption include, land tenure, labor shortage availability of seed and waiting for 2–3 years without benefits. However, current work of ICRAF and non-governmental organizations (NGOs) in southern Africa is showing encouraging results in adoption of various agroforestry options. Case studies on scaling up agroforestry options have been summarized by (Franzel et al. 2004).

Combined inorganic and organic inputs

Many reports in the literature have showed that continuous use of sole fertilizers may lead to shortage of nutrients not supplied by the chemical fertilizers and may also lead to chemical soil degradation. Chemical fertilizers are also too costly for farmers to apply the recommended rates. On the other hand, sole application of organic matter is constrained by low availability of N to the current crop (Haggar et al. 1993) low or imbalanced nutrient content, unfavorable quality and high labour demands for transporting bulky materials (Palm et al. 1997). The low P content of most organic materials indicates that in the long term addition of external sources of P will be needed to sustain crop productivity. The alternative is to combine application of organic matter and fertilizer so that improved crop yields are maintained without degrading soil fertility status (Swift et al. 1994).

There is substantial evidence demonstrating gains in crop productivity from nutrient additions through mixtures of organic and inorganic sources of nutrients compared with inputs alone (Swift et al. 1994). Combination of animal manure with inorganic fertilizers for instance is a common practice among smallholder farmers in Zimbabwe. Supplementation of 5 t ha^{-1} with 40 kg N ha^{-1} (inorganic fertilizer) in Zimbabwe resulted in a statistically higher yield than sole manure treatment (Murwira et al. 2002). Studies by (Murwira and Kirchmann 1993) showed that synchrony between N release and crop uptake was best achieved by applying combinations of manure and mineral N and having it in such a way that the N is applied a little later. Late application of mineral N reduced the amount N lost through leaching. Similar results were also reported in biomass transfer systems using manure and fertilizer on vegetables (Table 7, Kuntashula et al. 2004) and improved fallows when combined with small amounts of inorganic fertilizers (Fig. 2). This could be attributed to P addition from inorganic fertilizers or K or N which may not be supplied in sufficient amounts by organic inputs alone leading to better synchrony of nutrient release and uptake.

There are lots of technologies available to manage soil fertility in southern Africa and the range available to farmers is summarized in Table 8. The current challenge is how to increase small-holder farmer adoption of these soil fertility replenishing options. The paradox between profitability and contribution of agricultural technologies to soil fertility should be unraveled through appropriate integrative and more participatory research.

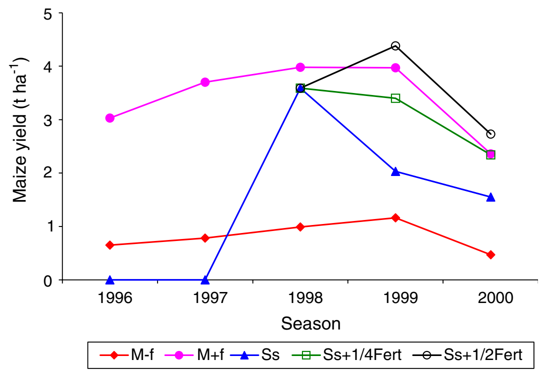

Fig. 2 Interaction of inorganic fertilizer and sesbania fallows on maize grain yield

Conclusions

Smallholder farmers in southern Africa have adopted high yielding maize varieties and other crops such as cotton, sunflower and grain legumes with some success. However, increases in crop yields have been disappointing. This is largely as result of declining soil fertility among many other factors. This problem is widespread and is becoming worse with market liberalization in southern Africa. Most nutrient budgets show a negative balance due to soil mining and little use of inorganic fertilizer and organic inputs.

The question to be posed is how to build up and maintain soil fertility under the poverty faced by many farmers. The need for added external nutrients is imperative. However, inorganic fertilizers are expensive, their use is sometimes unprofitable especially because of blanket recommendations. The solution to soil fertility problems will not depend on use of inorganic fertilizers alone. More attention should be directed to the use of organic inputs especially better integration of legume crop into cropping systems through legume rotation and intercropping, use of improved fallows in agroforestry as well as animal manures.

The paradigm of research and development on soil fertility options must change. The approaches

Table 8 Soil fertility options available and appropriate to farmers in southern Africa

Contribution to soil fertility	Soil fertility option	Rank	Remarks/Constraints	Ease of adoption by farmers
Low ↓	Crop rotation with legumes	1	- Food security concerns	High ↓
	Intercrop with legumes		- Limited land	
			- Little N contribution to subsequence crop - Poor legume growth	
	Inorganic fertilizer	2	- Insufficient cash to buy - Untimely distribution - Scarcity of input markets in rural areas - Risk environment and profitability issues	
	Use of livestock manure	3	- Unavailability, farmers some do not have livestock, problems of weed - Poor quantities of manure - Higher labour requirements	
	Agroforestry technologies	4	- Opportunity cost of leaving land fallow for 2 years is too higher - Immediate food concern - Variable performance agroforestry of options is highly degraded soils	
High				Low

Source: Various surveys conducted by Soil Fertility Network Scientists in Malawi, Zambia and Zimbabwe. Ranking was done by farmers.

need to move from rigid and prescriptive approach to flexible, problem solving format with a lot of farmer participation. There is need for social science research to deal with issues of adoption and scaling up of the available options. Potential synergies to address soil fertility problems can be gained by combining technical options with farmer's knowledge as well as new approaches to farmer training and policy dialogue. Policy issues touching on the soil resource base, as well as product markets need to be addressed to ensure use of agricultural technological innovations.

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