Agriculture, Ecosystems and Environment 71 (1998) 185–200

Organic matter technologies for integrated nutrient management in smallholder cropping systems of southern Africa

S.S. Snapp[a,*], P.L. Mafongoya[b], S. Waddington[c]

[a] ICRISAT, P.O. Box 1096, Lilongwe, Malawi
[b] ICRAF, Chipata, Zambia
[c] CIMMYT, P.O. MP163, Harare, Zimbabwe

Abstract

One of the biggest challenges in the tropics is to develop organic matter technologies which are adopted by the farmers. Technologies must be effective within farmer resource constraints, increase food production, reduce risk and enhance the soil fertility. Results from on-farm participatory research were used to quantify the effects of agronomic practices on soil resources. Agricultural productivity is primarily nitrogen (N) limited throughout Malawi, and sub-humid Zimbabwe. Tightening economic constraints faced by farmers in the region have reduced inorganic fertilizer inputs and necessitate increased reliance on biologically-fixed N and N cycling. Three components of organic matter technology were evaluated: (1) the effects of residue quality; (2) the role of deep rooting systems; and (3) tradeoffs between legumes grown for grain versus soil regeneration. Perennial systems investigated include improved fallows, intercropping, and biomass transfer. Annual systems include intercrops and rotations of cereals with legumes. The most promising non-food legumes were *Tephrosia* and *Sesbania*. Interestingly, high quality residues of perennial legumes were most effective at supplying N in the short to medium term, whereas low quality residues immobilised N. Low quality residues were problematic for smallholder farmers who need immediately available N. Challenges to adoption of perennial system technologies include establishment costs, resource competition and delayed benefits. Farmer adoption of annual grain legumes is promoted by the simultaneous production of food; however, those species which have a high N harvest index add little to no net N to the soil. Species that combine some grain yield with high root and leaf biomass, thus a low N harvest offer a useful compromise of meeting farmer food security concerns and improving soil fertility. Promising genotypes include *Arachis*, *Cajanus, Dolichos* and *Mucuna* spp. On-farm N budgets indicate that legumes with high quality residues and deep root systems are effective ways at improving nutrient cycling. Areas of future research priority for smallholder farms in southern Africa were identified, including technologies which combine inorganic and organic fertilizer and improve legume growth and establishment on degraded soils. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Soil fertility; Residue quality; Grain legumes; Agroforestry

1. Introduction

Improving food production and soil resources in the smallholder farm sector of southern Africa is an enormous challenge. Historically periodic fallow per-

*Corresponding author. Tel.: +265-743-542; fax: +265-720-906; e-mail: icrisat-malawi@cgnet.com

PII: S0167-8809(98)00140-6

iods regenerated soil organic matter over the course of shifting cultivation systems used in the region. However, population pressure has increased to the point where fallows are rare and continuous cropping of maize the norm in southern Africa (Kumwenda et al., 1997).

Waddington and Heisey (1997) conclude the soil fertility challenge in southern Africa is so large that farmers will need to combine gains from improved germplasm with improvements in their management of soil fertility. Nutrient supply is widely constrained by the limited use of fertilizers in sub-Saharan Africa (less than 10 kg ha^{-1}, FAO, 1988). Current economic conditions such as subsidy removal, exchange rate devaluation and high inflation are not conducive to high use of external inputs for smallholder farmers (Heisey and Mwangi, 1996). Organic fertilizers inputs including animal manures, green manures, crop residues and agroforestry leguminous prunings are an important way of improving soil fertility. Combinations of several organic and inorganic fertilizer sources at practical rates are central to better management (Janssen, 1993).

There is debate over the extent of soil fertility degradation in S. Africa. Negative nutrient balances approaching 20–60 N kg ha^{-1} and 5–15 P kg ha^{-1} annually have been estimated for S. Africa countries (Smaling, 1993). In contrast, Scoones et al. (1996); Scoones and Toumin, 1998 (this volume) contend that the decline of soil fertility has been overstated for subsistence agriculture in the region, and that soil fertility is a dynamic concept, where degradation and buildup of soils occurs at different scales over space and time. The extent of on-going nutrient loss is difficult to quantify, but the existence of widespread N deficiency, and severe P and micronutrient deficiencies in specific areas is well documented (Kumwenda et al., 1997).

Table 1 presents the oil nutrient status from characterization studies of smallholder farms and research station sites in Malawi. Data presented are for Ferrasols (USDA Soil Taxonomy Oxisols), Acrisols (USDA Soil Taxonomy Ultisols) and Lixisols (USDA Soil Taxonomy Alfisols, Oxic Kandiudalfs), the major soil associations of arable smallholder farms in the region. Organic carbon levels are approximately one-half as high on small-scale farms as on research stations, reflecting continuous cropping with limited inputs. Soil N levels are about one-third as high on smallholder farms as on research stations.

Table 1
Soil characteristics presented for smallholder farm sector and neighboring research station sites of Malawi, from unpublished data, Snapp et al., 1996

Soil Characteristic	Malawi	
	Farm (n=1890)	Research Station (n=26)
Organic C (g kg^{-1})	14 (6)[a]	27 (8)
Organic N (g kg^{-1})	0.5 (0.4)	1.5 (0.9)
Texture (% sand)	75 (10)	73 (7)
pH (water 2:1)	5.7 (0.8)	6.1 (0.5)
P (Mehlich III)	19 (17)	25 (13)
Zn (Mehlich III)	1.3 (1.0)	1.5 (0.7)

[a] Standard error in parenthesis.

Low N, and high C/N ratios, have been reported previously for Malawi agricultural soils (Brown, 1962; Weil and Mughogho, 1993), and nearby sites in Zambia (Barrios et al., 1996). Available phosphorus, Zn and pH, in contrast, were not significantly different on-farm or on research stations (Table 1). Granite-derived sands which dominate much of Zimbabwe smallholder farm sector are low in organic C, whether in a cultivated or uncultivated state (Murwira and Kirchmann, 1993; Scoones et al., 1996). This is expected because of the high sand content of the majority of soils and consequently limited physical and chemical protection for C from oxidation. Confirming the limited N supply capacity of the low organic C soils on smallholder farms, on-farm trials in Zimbabwe and Malawi have shown marked response of crops to N fertilizer (Nleya and Mugwira, 1991; Snapp and Benson, 1995).

This paper presents case studies on the development of soil fertility strategies for Malawi and Zimbabwe. Together, these two countries capture the diversity of agroecozones, semi-arid to sub-humid, and farmer resources in S. Africa. Organic matter technologies are the focus, as smallholder farmers can afford little or no use of fertilizers. Technologies must be adoptable within the maize-based cropping systems which dominate Malawi and Zimbabwe smallholder farm sectors (Waddington, 1994). A unimodal rainy season and 600–1200 mm annual precipitation characterizes both countries. Rainfall in Zimbabwe is distinguished by high variability and scarcity, and much of the country experiences periodic droughts. High population density, low livestock numbers and widespread food insecurity occurs in Malawi. This contrasts with relatively low population density, livestock-based systems and use of some inputs by the majority of smallholder farmers in Zimbabwe.

Constraints to adoption of organic matter technology by smallholder farmers are considerable. Constraints include limited income, substantial risk aversion and the need to produce food crops on all or most arable land. Extension departments and non-governmental organizations (NGO) have promoted the use of organic matter technologies such as green manures for over 70 years in southern Africa (Blackshaw, 1921; Rattray and Ellis, 1952; Muza, 1995). Adoption of organic matter technologies has been nil (Kumwenda et al., 1997). The technologies promoted require considerable labor inputs, and have often not met criteria of farmers. Emphasis on organic matter technology which build soil reserves, for example, does not pay attention to immediate needs for calorie production.

To be successfully adopted in sub-Saharan Africa technologies must be rigorously assessed for short term N contributions in this N limited environment, and for effectiveness within farmer resource constraints. Organic matter technology must be targeted to windows of opportunity. Examples include extended rainfall environments in Malawi with potential for relay intercrops, and short season, high risk environments in Zimbabwe where farmers have livestock and sometimes small amounts of cash to invest.

2. Sustaining productivity in agricultural lands and the role of organic matter

The role of manures and plant residues as nutrient suppliers in highly weathered soils is well documented (Brown et al., 1994). Organic inputs are also major sources of energy and nutrients for soil microbial communities which promote soil aggregation and nutrient buffering capacity. However, the use of organic materials to increase the carbon reserves of soil under tropical conditions requires large amounts of annual additions. Approximately 7 t ha^{-1} year^{-1} dry matter of low quality residues (roots, stems) or 10 t ha^{-1} year^{-1} of high quality residues (green manure leaves) are required to maintain a 1.0% organic C level in a sandy loam soil in the sub-humid tropics (assuming 0.05 fraction decomposed per year, see Janssen, 1993). Typical biomass production in on-farm trials comparing agroforestry species is around 2–4 t ha^{-1} year^{-1}. Often biomass production is less than 1 t ha^{-1} year^{-1} in the first year of establishment and in drought years of hedgerow intercrop systems (Saka et al., 1995).

Thus it is difficult to produce adequate organic materials under smallholder farm conditions to build or maintain soil organic matter (SOM). The level of soil organic matter that is sufficient to support crop production is an area of intense debate. Long-term experiments conducted in the semi-arid zones of west Africa (Pieri, 1995) suggest that a "sufficient soil organic matter", below which severe physical degradation will occur is related to soil texture. For example, soils with sand <90% require a minimum of approximately 0.9% soil organic C, a condition fulfilled by the majority of soils in Malawi (Table 1). Slightly higher levels of organic C, 1–1.5%, have been suggested as agroecologically viable over the long-term in the sandy soils which dominate the southern Africa landscape (Araki, 1993).

Because of the difficulty of building organic matter, the research reported investigated organic matter management strategies which do not necessarily build soil C, but instead use biological processes to increase nutrient availability and cycling efficiency (Pieri, 1995). Biologically smart organic matter technology improves N inputs through biological N fixation (BNF); inclusion of grain legumes in smallholder farming systems can contribute net annual amounts from negative to around 70 kg N ha^{-1} (MacColl, 1989; Nleya and Mugwira, 1991; Giller and Cadisch, 1995). Production of high quality residues (narrow C/N ratios and low polyphenolic and lignin content) is also important to increase soil microbial activity, P and micronutrient availability, and soil buffering capacity (Mafongoya et al., 1997b; Snapp, 1994). Inclusion of deep rooted species in organic matter technologies is essential to recycle nutrients. For example, *Sesbania sesban* grown in rotation with maize enhanced recovery of subsoil N by an estimated 25 kg ha^{-1} year^{-1} in the highlands of Kenya, compared with continuous maize cultivation (Hartemink et al., 1996). To enhance production in the driest areas, nutrient cycling can be enhanced through livestock systems and the combination of manure plus small amounts of inorganic fertilizer (Murwira and Kirchmann, 1993; Haque et al., 1995).

2.1. Quality of organic inputs

Predicting nutrient contribution is a critical issue to developing organic matter technologies which have immediate impact and are farmer acceptable. Recent work has shown the value of chemical characteristics to assess quality of the organic resources and nutrient availability (Palm, 1995). The percent of N, lignin and polyphenols, C:N, lignin:N, polyphenol:N and (lignin + polyphenol):N ratios are the major determinants of chemical composition (Mafongoya et al., 1997b). High quality organic inputs are low in lignin and polyphenol and high in percent N with low quality materials having the opposite characteristics (Palm et al., 1996).

Quality of organic inputs is an important issue. Addition of low quality organic inputs may, over time, increase soil organic C, but without necessarily increasing the productivity of the cropping systems. A pioneering cropping system study in India, for example, showed that wheat straw combined with urea substantially reduced yields, whereas a N equivalent amount of *Sesbania* green manure combined with urea enhanced yields compared with a N equivalent amount of urea applied alone (Goyal et al., 1992).

Many crop residues and animal manure are of low quality as they fall below critical N content of 1.8–2.0% and immobilize N temporarily. Incorporation of maize stover in Kenya reduced maize yields by 3–30% in the first three seasons. The reduction of maize grain yield was the result of N immobilization of about 4 kg N ha^{-1} $season^{-1}$ (Nandwa, 1995). Similar results have been obtained with cattle manure and maize stover in Zimbabwe (Rodell et al., 1980; Tanner and Mugwira, 1984; Murwira and Kirchmann, 1993). Thus even if crop residues and other low quality organic materials can be obtained in sufficient quantities they will immobilize N exacerbating the nutrient deficiency. These negative effects can in some cases be off-set by combining organic inputs with inorganic N (Murwira and Kirchmann, 1993).

High quality agroforestry prunings with N content greater than 2% and lignin content less than 15% and polyphenol content less than 3% would mineralize N rapidly as shown by Mafongoya and colleagues, 1997b). However, when lignin content is greater than 15% and polyphenol are above 3% materials will immobilize N. Both lignin and polyphenols are important factors affecting N release from many leguminous organic inputs. As opposed to temporary immobilization resulting from low C:N ratios in cereal crop residues, immobilization resulting from polyphenolics may be much longer (Palm et al., 1996).

Residues of high quality organic inputs such as green manures and legume tree prunings decompose quickly and may release between 70% and 95% of their N within a season under tropical conditions (Giller and Cadisch, 1995). The recovery of this released N was between 9% and 28% by the first crop (Giller and Cadisch, 1995; Mafongoya et al., 1997b). Limited data indicates that legume N recovery in the second crop is small, between 2% and 10% (Mafongoya and Nair, 1997c). High maize grain yields and residual benefits were obtained from high quality residues, but not from medium or low quality residues (Table 2).

Low quality organic materials do not provide soluble C and N to enhance the soil microbial activity, and may immobilize N availability, markedly reducing crop production subsequent to incorporation of maize stover (Kamukondiwa and Bergstorm, 1994). Production of high quality biomass, in contrast, in combination with small amounts of inorganic nutrient inputs, can be used to enhance N fixation and nutrient cycling efficiency (Snapp, 1994; Kumwenda et al., 1997). Improving efficiency of N use from organic inputs is an important research area. Table 2 shows that simple management strategies such as incorporation of prunings can improve N recovery (Mafongoya et al., 1997b). This is attributed to reduced losses of N through ammonia volatilization which was completely eliminated through incorporation of prunings into the soil, as was shown by Costa et al. (1990); Glasner and Palm (1995).

2.2. Assessing promising organic matter technology systems and species

Adoption by smallholders of organic matter technologies is influenced by a complex trade-off between costs (labor, land), and perceived benefits on a short

Table 2
Effect of residue quality from a range of multipurpose trees, and method of placement and residual effect on maize grain yield (t ha^{-1})

Multipurpose tree species	Method of application				
	1993/94		1994/95		1995/96
	S[a]	I[b]	S	I	Residual effect
Acacia angustissima	2.2	4.0	1.8	2.4	2.3
Calliandra calothyrus	4.0	3.5	1.3	2.2	1.4
Cajanus cajan	3.5	5.6	2.5	2.8	2.2
Leucaena lecocephala	3.3	5.6	1.5	1.8	2.2
Miombo litter	1.5	2.5	1.6	1.6	1.3
Control (no organic inputs)		1.1		1.2	0.6
C.V. (%)	19.9		37.3		28.9

S[a]: Surface applied.
I[b]: Incorporated.
High quality residues: *Leucaena lecocephala, Cajanus cajan* and *Acacia angustissima*. Medium and low quality residues: *Calliandra calothyrus* and Miombo litter.

Table 3
Technologies for enhancing soil organic matter, nitrogen and productivity on smallholder farms in southern Africa: contributions and constraints

Organic matter technology	Long term contribution to raising soil fertility	Short term ability to raise crop yields	Competition for arable land	Labor requirement	Ease of adoption by farmers
Grain legume: rotations	Low–medium	Medium	Low–medium	Low	Medium
Grain legume: intercrops	Low	Low	Very low	Low–medium	High[a]
Perennial legume: intercrops and hedgerow systems	Medium–high	Low–medium	Medium	High	Low
Perennial legume: *Faidherbia albida* intercrop	Medium	Very low	Low	Low	Medium
Perennial legume: improved fallows	High	Low–medium	High	Medium	Low
Green manure: relay intercrops and rotations	Medium	Medium–high	High	Low–medium	Low–medium
Biomass transfer	Medium	High	High	Medium– high	Low
Animal manure	Medium	High	Nil–low	Medium	High

[a] An important point on high potential for adoption is that these technologies are likely to be adopted for other reasons – provide food, food security, weed control, etc. – and the soil fertility effect is primarily a spin-off.

and long term basis (Table 3). Benefits may include multiple uses such as food, fuel and weed suppression. These address immediate concerns of farmers, but ability to raise crop yields in the succeeding year through BNF contributions to available soil N will also be favorably noticed by the farmers. Longer term benefits not immediately observable such as contributions to soil quality and building organic matter are rarely perceived by the farmers (Kanyama-Phiri and Snapp, 1997). Technologies which are both easy for the farmers to adopt, and can raise crop yields in the short term often require resources which are in short supply (labor, land or cash). For example, participatory resource mapping exercises showed that the majority of farmers in a S. Malawi watershed were aware of the benefits of applying animal manure to soil, but over 85% of the farmers did not have access to significant amount of manure because of low livestock populations (Kanyama-Phiri and Snapp, 1997).

The question is how to solve the paradigm, whereby cereal production is limited by N, and farmers prefer cereals to legumes which could be addressing the N deficit through N fixation. Evaluating organic matter technology contributions on a N budget basis highlights the following issues. (1) Grain legumes can contribute net N to cereal crops grown in rotation, but the contribution varies tremendously. Growth and yield of the legume, indeterminate versus determinate growth habit, N partitioning patterns, effective versus ineffective BNF, and quality factors which influence N availability, taken together determine the N contribution. (2) Intercrops of food legumes with maize is an important subsistence strategy to minimize risk, but maize is a highly competitive crop and legume biomass production in this system is so inhibited that soil contribution is generally nil. (3) Perennial legume use as intercrops and improved fallows can potentially contribute substantially through BNF and deep uptake of nutrients, but land and labour requirements are high. (4) Green manures grown as a relay intercrop have a lower N contribution potential, but land and labour use may be more efficient and the system is flexible around farmer needs.

A promising system for Malawi is relay intercropping of a deep rooted legume (e.g., *Sesbania sesban*), which combines some of the best properties of improved fallows and green manures. Also promising is a rotational sequence which provides food security and, in some cases, soil regeneration and N inputs. This is a legume/legume intercrop of deep rooted, late maturing pigeon pea intercropped with a short statured grain legume (e.g., groundnut), rotated with maize. These systems and the benefits and challenges associated with all of the organic matter technologies with potential for wider adoption in southern Africa are discussed in detail below.

2.2.1. Grain legumes: rotations

Legume rotations are an important practice for maintaining soil fertility for the farmers with sufficiently large holdings of land (above about 1 ha). Many smallholder farmers in southern Africa already use grain legumes in rotation with maize. This is primarily because grain legumes provide grain and sometimes leaf for food (promoting farmer adoption) and as a spin-off can in some circumstances help soil fertility through net N contributions (Kumwenda et al., 1997). Self-nodulating promiscuous types of indeterminate soybean (*Glycine max*), and pigeon pea (*Cajanus cajan)*, groundnut (*Arachis hypogaea*), dolichos bean (*Dolichos lablab*) and cowpea are among the most promising in Malawi and Zimbabwe for that dual role. Grain legumes are grown mainly for home consumption of the seed and sometimes leaves. But the more productive high harvest index grain legumes add relatively little organic matter and N to the soil because most of the above-ground dry matter and almost all the N is removed from the field in the grain.

Research conducted on maize-grain legume rotations shows that substantial benefits to soil fertility can be demonstrated in a favorable environment with good management. In Malawi, MacColl (1989) showed that the grain yield of the first crop of maize following pigeonpea averaged 2.8 t ha^{-1} higher than that of continuous maize that received 35 kg N ha^{-1} each year. In Zimbabwe, Mukurumbira (1985) showed large increases in maize yields following groundnuts and bambara nuts (*Voandzeia subterranea*), without supplemental inorganic N. A pigeonpea rotation with maize increased the maize yields by about 50% compared with maize after maize in sub-humid Nigeria (Hulugalle and Lal, 1986). Hulugalle and Lal found that, in comparison to continuous maize, a pigeonpea/maize rotation enhanced soil organic C after four growing seasons.

Groundnut is the most common grain legume that is rotated with maize on smallholder farms in sub-humid parts of Zimbabwe. Work at Domboshava in Zimbabwe comparing a maize–maize–groundnut–maize rotation with continuous maize, with inorganic fertilizer (providing 92 kg N ha^{-1}, 17 kg P ha^{-1} and 16 kg K ha^{-1} per year) and without fertilizer, showed that the groundnut crop almost doubled the grain yield of the subsequent season maize crop as is clearly shown in Fig. 1 (Waddington, Karigwindi and Chifamba, unpublished). It was estimated that up to 86 kg of inorganic N ha^{-1} would have been needed to obtain that yield increase with continuous maize. The rotation gave even more additional grain yield when fertilizer was used on the maize (Fig. 1). These results were especially encouraging because fertilizer was not applied to groundnuts, groundnut grain was removed and most of the groundnut haulms and maize stover were grazed by animals, practices that occur on smallholder farms. Presumably much of the effect was from leaf fall and the root system of groundnuts.

Yet in many other cases, particularly on smallholder fields and with adverse weather (dry or very wet), the grain and biomass yields from grain legumes are low and the benefits of a grain legume rotation for the

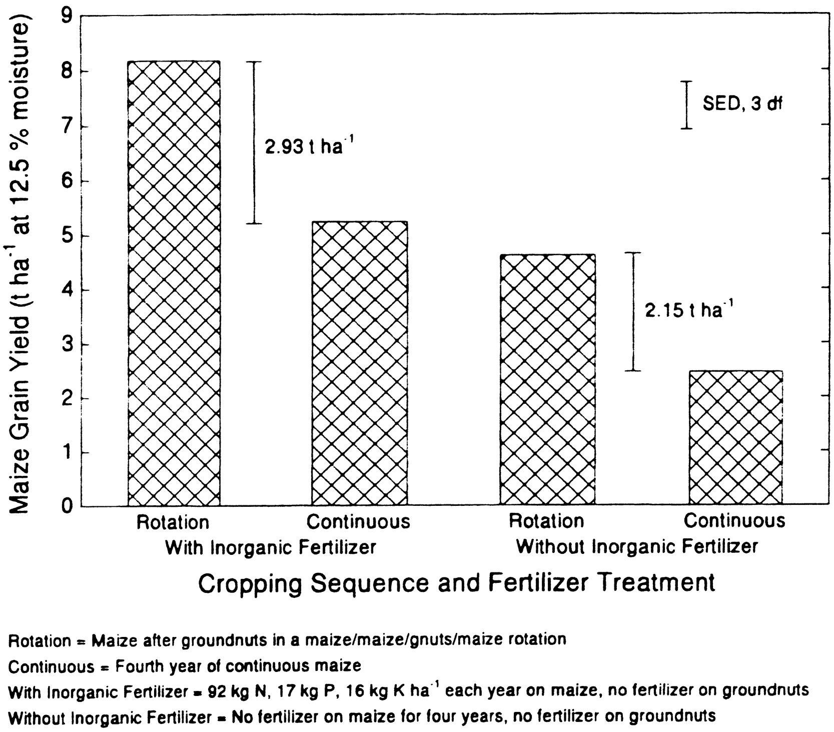

Fig. 1. The grain yield of maize with and without fertilizer in the fourth year of a long-term trial involving rotations with groundnuts at Domboshava, Zimbabwe, 1995/96.

subsequent maize crop are often small. For example at a different site in Zimbabwe, Marondera, in the same 1995/96 season as the experiment discussed above, there was little increase of maize yield with a groundnut rotation (L. Mukurumbira, unpublished). This may have been the result of heavy rains at that site. The amount of N returned from legume rotations depends on whether the legume is harvested for seed, forage or incorporated as green manure. Under smallholder conditions, where the legume grain and much of the legume stover may be removed from the field, there may be no net N contribution by the legume to the soil.

Research is needed on the yield and economic benefits from grain legume rotations on smallholder farm conditions, to raise knowledge of the causes of variation in response.

2.2.2. Grain legumes: intercrops

Grain legume intercrops with maize occupy a different niche from rotations. The low plant densities of legume found in most intercrops means they can input only modest amounts of N and organic matter each year to maintain soil fertility. However, because they do not take land away from cereals, farmers in land scarce areas may be willing to use them every year so that the aggregate effect may be important. Low growing legumes are shaded by taller cereals and under smallholder management in low soil fertility conditions, poor emergence and growth of the legume in the intercrop is common (Kumwenda et al., 1993). This limits the N and organic matter contribution of the legume on-farm to levels well below the potentials found on the research stations.

The importance of intercrops in densely populated regions is widely recognized. This arises from the stabilizing effect of intercrops on food security, and enhanced efficiency of land use. However, in semi-arid areas, plant densities (and thus potential growth and yield) have to be reduced (Shumba et al., 1990). These authors, working in southern Zimbabwe, found that cowpea–maize intercrops can greatly reduce the

Table 4
Nitrogen budget data from Zomba watershed in S. Malawi

Site charactistic low or high maize yield potential	N soil mineralized (estimate 1) soil nitrate (kg ha^{-1})	N soil mineralized (estimate 2) maize N (kg ha^{-1})	N Contribution *Sesbania sesban* relay intercropped (kg ha^{-1})	N Contribution pigeonpea/groundnut intercrop (estimate) (kg ha^{-1})	N needed to support 4.0 t ha^{-1} maize yield (in addition to Soil N) (kg ha^{-1})
(0 fertilizer added)					
Low (700 kg ha^{-1})	24	46	28	20	100
High (2100 kg ha^{-1})	42	140	63	53	40

Soil N mineralized per year is estimated in two ways, by monitoring soil nitrate at the beginning of the growing season plus estimate from N mineralization potential rate for the season, and measuring total N of maize biomass from 0 N treatment plots at the early cob development stage.
N contribution of legumes is estimated from total N of biomass at incorporation.

grain yield of maize in dry years. Late maturing pigeonpea is promising as an intercrop in areas where land is scarce and animals are few, such as southern Malawi (Kumwenda et al., 1997). Pigeonpeas continue to grow after the maize harvest and can potentially produce large quantities of biomass. In Malawi Sakala (1994) reported a pigeonpea dry matter yield of 3 t ha^{-1} from leaf litter and flowers when intercropped with maize. Pigeon pea growth is less under poor management, but N contribution from leaf abscission over the growing season has been estimated to be 10–40 kg N ha^{-1} (Table 4; Kumara Rao et al., 1981). Maize yield of a sole crop grown subsequent to a maize/pigeonpea intercrop is consistent with a pigeonpea contribution of about 25 kg N ha^{-1} ((Natarajan and Mafongoya, 1992; Versteeg and Koudokpon, 1993). These results were observed under farmer management and low to nil input conditions.

The multipurpose nature of pigeonpea is of considerable advantage, indicating that it is a prime candidate for higher density incorporation in intercrop systems. The leaves, stems, pods and grain (fresh or dried) are all edible and provide high quality fodder for livestock and human consumption. Stems are also gathered for fuel wood purposes. Pigeonpea grown under on-farm conditions of low fertility, and no inputs, produce about 0.2–0.8 t/ha grain, and 0.5–2 t of stems, whereas over 4 fold higher production is possible under favorable conditions (Ali, 1990; Natarajan and Mafongoya, 1992; El Awad et al., 1993; Sakala, 1994). Disadvantages of maize/pigeonpea intercrops include maize competitive effects limiting growth potential of pigeon pea and livestock browsing of pigeon pea.

Pigeonpea intercropped with an annual, short statured grain legume and rotation of this legume/legume intercrop with a cereal crop is a promising technology. Pigeonpea has limited effects on the yields of companion crops, because of its pattern of slow initial growth. This has been shown in Zimbabwe under dry (500 mm) as well as adequate (850 mm) rainfall conditions (Natarajan and Mafongoya, 1992), in semi-arid Sudan (El Awad et al., 1993), and in 1000 mm rainfall sites (Snapp, unpublished). Pigeonpea has a deep root system and substantial biological nitrogen fixation capacity under low fertility conditions (Kumara Rao et al., 1981). This is an important attribute as recent work has documented the existence of nitrate buildups about 1–3 m below the soil surface in semi-arid Saskatchewan, and Kenya highlands (Farrell et al., 1996; Hartemink et al., 1996). Reliance on short statured legume species alone will not allow recycling of nutrients from the subsoil, thus the need for technologies which include deep rooted species.

Inadequate growth of grain legumes in smallholder fields, in rotation and intercrop systems, severely limits soil fertility benefits. In P-deficient soils, grain legume growth can be reduced to a fraction of the potential. Smallholder farmers use little or no fertilizer on sole crop grain legumes, whereas fertilizer use on legume/maize intercrops is much more likely (Kanyama-Phiri and Snapp, 1997). Recent research has shown that targeted use of 30 kg P ha^{-1} on legume/maize intercrops can consistently increase productivity of both the legume and the maize by about 100% under on-farm conditions (Snapp, Aggarwal and Chirwa, unpublished, 1997). This suggests the need for more research on fertilizer targeting in intercrop and rotation systems.

2.2.3. Perennial legume: intercrops and hedgerow

A general assumption underlying much of hedgerow intercropping research is that superior tree ideotypes are those that produce the most leaf biomass under a pruning regime. For example, in Malawi screening trials were established for a range of agroecozones to evaluate tree biomass production in hedgerow intercropping systems, which was equated with contribution to soil fertility (Saka et al., 1995). Two promising tree species were identified using biomass productivity data, *Gliricidia sepium* and *Senna spectabilis* (Bunderson et al., 1991). However, to maximise benefits from trees grown with crops, residue quality must be high, and tree negative effects must be minimized.

Competition occurs between trees and associated crops for moisture, nutrients and light (Ong, 1994). Light competition can be managed by timely pruning of hedge-rows. Pruning has also been suggested to minimise competition for water and nutrients, but the effectiveness of this is disputed. In the short-term, yields will be influenced by competition during the growing season. It is also important to consider the consequences of the presence of trees over a long period on the soils. The influence of trees on soil fertility will be a function of where nutrients are extracted from, and the net effect of tree inputs on soil organic matter and nutrient supply. Benefits can not be inferred directly from quantity of biomass alone. Quality of biomass will determine how tree residues (above and below-ground) influence the soil fertility (Mafongoya and Nair, 1997a).

One test to evaluate the effects of technologies on soil fertility is to measure yields over the long-term. However, it takes years for yields to consistently reflect improved soil status, and farmers need improved technologies immediately. Methods are required that measure soil quality changes directly. New techniques have been developed recently for separating SOM into fractions that may be biologically meaningful, and that appear to have predictive value for agronomists and land managers (Biederbeck et al., 1994; Barrios et al., 1996). Physically-based isolation of SOM fractions can be achieved rapidly and easily by sieving soil and separating SOM on the basis of size and density. Use of SOM physically-based fractionation is in the process of being evaluated in Kenya and Zambia. Early indicators are that a fraction of SOM known as the light large fraction (which generally corresponds to the particulate organic matter POM fraction) and nitrogen associated with this pool is related to the readily available, mineralizable N pool (Barrios et al., 1996; Jones et al., 1996; Snapp et al., 1996).

Hedgerow intercropping systems have been evaluated for potential to contribute to soil fertility in medium-term trials conducted at four sites in central Malawi (Saka et al., 1995). Comparisons included three legumes (*Gliricidia sepium*, *Leuceana leucocephala* and *Senna spectabilis*) to a sole cropped maize grown with and without N fertilizer. Residue quality and yields varied considerably with treatment, about 0.5–2.0 t ha^{-1} $year^{-1}$ of leaf biomass compared with no organic inputs in sole maize where stover was removed in accordance with farmer practice. Soil organic C of whole soil was not altered by any treatment (Table 5). To alter organic C content in the top soil can take a considerable amount of time, and high rates of organic amendments, so these results are not surprising. For example, after 4 years of hedgerow fallow in the humid tropics, soil analysis showed that organic C was increased under *Gmelina arborea* compared with three other species, but not compared with initial soil organic C (Ruhigwa et al., 1993).

Soil fractionation, in contrast, provided biologically relevant differentiation (Table 5; Snapp et al., 1996). Organic C in a light large fraction (>53 μm) was enriched in treatments with intercropped tree species, compared with sole maize controls. All the three perennial species, *G. sepium*, *L. leucocephala* and *S. spectabilis,* had the same effect: organic C in the LL fractionated soil was enhanced, compared with C in the LL fraction of soil from sole crop maize (ANOVA p-value=0.001). However, maize yields were not increased in hedgerow intercrop treatments in years with below average rainfall (Saka et al., 1995), suggesting that competition by trees prevails over soil fertility benefits. Limited crop yield benefits from perennial intercrop systems have been shown on-farm, with the exception of highly eroded and steep sites (Ehui et al., 1990; Versteeg and Koudokpon, 1993).

Table 5
Carbon (g kg^{-1}) at four sites (Kasungu-Chipala, Chioshya, Tembwe and Lisasdazi) in central Malawi, comparison of sole maize treatments (0 and 92 kg ha^{-1} N) to hedgerow intercropped (G. sepium, S. spectabilis, L. leucocephala) maize treatments, 1995

Treatment	Whole soil (C g kg^{-1} soil)				Light large (>0.53 μm) fraction soil (C g kg^{-1} fraction)			
	KChipala	Chioshya	Tembwe	Lisasdazi	KChipala	Chioshya	Tembwe	Lisasdazi
Sole maize 0 N	10.4	10.0	6.2	4.8	80.0	88.0	49.3	128
Sole maize 92 N	11.9	10.3	6.3	4.9	78.1	97.7	51.4	127
G. sepium	10.5	9.4	6.4	5.1	122.7	111.1	75.9	150
S. spectabilis	11.5	9.9	6.0	4.3	126.1	133.9	91.5	157
L. leucoce.	10.9	10.6	5.7	5.3	124.3	116.1	52.7	120
F	0.66	1.78	0.07	0.66	9.98	1.55	4.00	5.39
Pr>F	0.63	0.21	0.99	0.63	0.002	0.261	0.03	0.01

In summary, intercrops of perennial legumes for soil fertility purposes have proved problematic because of the high management requirements and competitive nature of the system; the notable exception is *Faidherbia albida* which requires a long-term view, after 7–10 years enhanced grain yields occur under the tree canopy (Weil and Mughogho, 1993). The combination of grass species and perennials (hedgerow managed legumes or fruit trees) with physical conservation measures should be considered for the sites where erosion potential is high.

2.2.4. Perennial legume: improved fallows

In southern Africa shifting cultivation systems were important means of maintaining soil fertility until recently. Because of increased population pressures such systems are no longer sustainable. Shorter fallow periods of bush and grass of 1–5 years are common, and continuous cropping without fallows is widespread. Marginal lands are also increasingly under food crop production. Improved fallow systems utilizing fast growing leguminous trees have been identified as a means of restoring soil fertility and maize grain yields (Kwesiga and Coe, 1994). Yields of 5.5 t ha^{-1} were obtained with 2 year *Sesbania sesban* fallows compared with yields of 1.2 t ha^{-1} from continuously cropped fields. This research in eastern Zambia stimulated research in the region on improved fallows, including 2–3 year fallows of *Sesbania sesban*, pigeon pea (*Cajanus cajan*) and *Acacia angustissima*. Fig. 2 shows the results for maize response to N 2 years after fallowing in Zimbabwe. Maize yields in rotation with tree fallows were significantly higher than grass fallow at any given N fertilizer level. *Sesbania* spp. have been

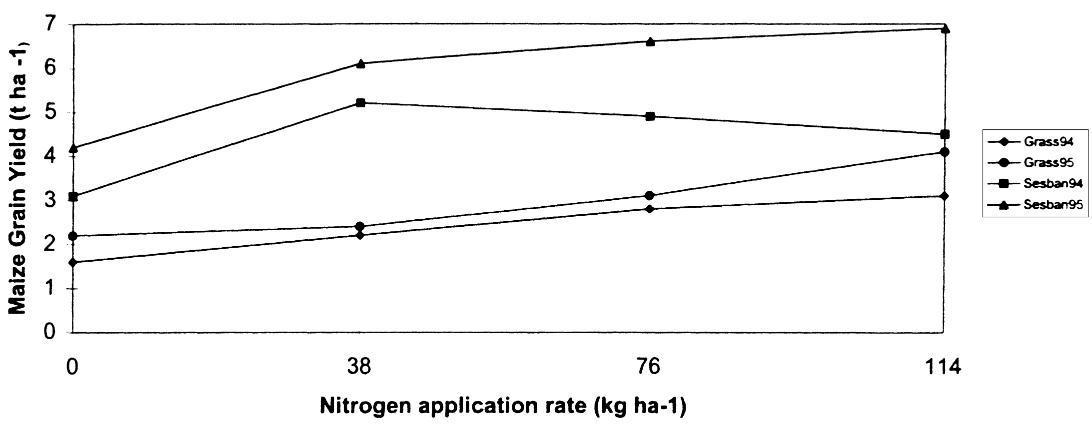

Fig. 2. The grain yield of maize in response to nitrogen (inorganic) when grown after a three year improved fallow with Sesbania sesban or after a natural grass fallow, Zimbabwe, 1995/96.

shown in other cropping systems to have the potential to contribute about 50–120 kg N ha^{-1} (Beri et al., 1989).

Leguminous tree fallows have the potential to improve soil fertility and crop yields in southern Africa agroecozones. Current research effort is being directed on where fallows will work and why they will work and screening perennial legume species for their suitability for fallowing. The socio-economic factors which determine adoption of improved fallows by small-scale farmers are under investigation.

2.2.5. *Green manure: relay intercrops and rotations*

A relay intercrop system is one of the technologies being tested by farmer-participatory methods in a S. Malawi watershed (Kanyama-Phiri and Snapp, 1997). In this system tree species (*Sesbania sesban* and *Tephrosia volgii*) are grown as annuals, relay intercropped between maize. The tree leaf biomass is incorporated at the end of the growing season, a system which is identical to green manure undersowing, only uses trees rather than annual green manure species. Preliminary results show that Sesbania is a promising species, producing 30–60 kg N ha^{-1} from 2–3 t ha^{-1} high quality leaf biomass plus fuel wood (stems) during 10 months of growth (January–October) (Table 4; Kanyama-Phiri and Snapp, 1997). *Tephrosia* growth was highly variable, often producing only 10% of Sesbania biomass (Kanyama-Phiri and Snapp, 1997).

Green manure legume species including *Crotelaria*, *Mucuna,* pigeonpea and *Dolichos* have been grown as relay intercrops with maize, or as a soil fertility improvement crop in rotation with maize, in on-farm tests in Malawi and Zimbabwe. The major challenge is establishment of the green manure and limited growth in degraded soils and drought-prone environments (Shumba et al., 1990; Muza, 1995; Kumwenda et al., 1997). Pigeon pea was the only consistent performer, growing vigorously on-farm in green manure trials conducted in the northern and central region in Malawi over 3 years (J. Kumwenda, personal communication, 1997).

There is a substantial body of literature addressing forage legume screening in sub-Saharan Africa, results which suggest that *Stylosanthes*, *Crotelaria*, pigeon pea and *Dolichos* are widely adapted and promising species for use as green manures (Blackshaw, 1921; Rattray and Ellis, 1952; Muza, 1995; Thomas and Sumberg, 1995). It must be borne in mind that historically forage germplasm screening has been conducted under relatively high input conditions, using the sole criterion of biomass production, whereas farmers place characteristics in order of priority, such as survival in a severe environment with minimal farm management input (Thomas and Sumberg, 1995).

A screening trial has been recently initiated by Zimbabwe and Malawi members of the Soil Fertility Network for southern and eastern Africa (Waddington, unpublished, 1997). This green manure trial includes evaluation of four species (*Crotelaria*, *Tephrosia*, *Mucuna*, and in some locations, pigeon pea) in the presence and absence of minimal P inputs, and quantifies the benefits to maize yield grown subsequent to the green manure. The results of this network trial should provide insight into adaptation of green manure over a range of agroecosystems, benefits to maize grown in rotation, and responsiveness of the system to addition of P fertilizer.

2.2.6. *Biomass transfer systems*

In Zimbabwe, on sandy soils farmers add organic inputs to sustain the crop production (Nyathi and Campbell, 1993). Traditionally farmers collect leaf litter from miombo woodland as source of nutrients to maize (Nyathi and Campbell, 1993). In the long term this practice is not sustainable for it mines nutrients from the forest ecosystem in order to build soil fertility in the croplands. Also, miombo tree prunings tend to be of very low quality with limited contribution to the maize yields (Table 3). An alternative means of producing high quality tree prunings through on-farm biomass banks and transfer to croplands may be sustainable.

The studies of Mafongoya and colleagues, 1997b have shown that the application of 5 t ha^{-1} of high quality residues of three perennial legumes gave a mean maize grain yield of 5 t ha^{-1} compared with 1.1 t ha^{-1} on control plots with no organic inputs. The results also showed that legume prunings were superior to miombo litter in their nutrient release characteristics (Mafongoya et al., 1997b). *C. cajan* and *L. lecocephala* proved to be the best tree prunings. Both the species had (lignin+polyphenols):N ratios of less than 10 and released N rapidly (Mafongoya et al., 1997b) and gave higher residual effect on subsequent maize crop (Table 3).

Current research effort is being directed at the sustainability of the biomass transfer systems in terms of nutrient mining and productivity on smallholder farm conditions. The economics of biomass transfer system, including labor requirements, are also being investigated.

2.2.7. Animal manures

Livestock manure is an integral component of soil fertility management in southern Africa. The beneficial effect of manure on soil fertility is well documented and crop responses often result more from the contribution of phosphorus and cations like Ca and Mg than from the addition of N (Grant, 1967). Crop responses to manure application observed in the farmers fields are highly variable because of the differences in chemical composition of manure, rates and frequency of manure application.

The nutrient contents of manure differ because of the variation in the animal diet and ways in which manure is collected and stored. The type of the diet may influence the partitioning of N between faeces and urine. Feeding high quality diets (low in lignin and polyphenols) results in more N being excreted in the urine than faeces (Somda et al., 1995). Feeds rich in tannins increased the amount of N excreted in the faeces as compared with urine where N is lost quickly through volatilization. Recent results indicate that the N in manure from animals fed with tannin rich diets is very resistant to mineralization in the soil (Mafongoya et al., 1997d).

The beneficial effects on N availability for maize grown in granitic sandy soil resulted from N released directly after application (Grant, 1967). The N was likely to be free mineral N in the form of NO_3 and NH_4, where ammonia may be lost rapidly by volatilization from the manures (Murwira, 1995). Nitrogen mineralization studies under field conditions have shown that poor quality manures in Zimbabwe can lead to prolonged period of N immobilization and N availability is increased by supplementing with inorganic N sources (Murwira and Kirchmann, 1993). Research to increase N use efficiency of low quality manure is being directed at reducing losses of N before manure is applied to fields and method of manure application.

2.3. Farmer participation and technology adoption

Effective ways of disseminating sources of soil fertility on smallholder farms has attracted considerable attention recently. There is broad agreement that an array of integrated research and extension tools ranging from basic process research, through widespread on-farm targeting and verification are required. All need to be organized in a more interactive institutional mode with the effective participation of the main client, the farmer (e.g., Versteeg and Koudokpon, 1993; Palm et al., 1996; Kumwenda et al., 1997). When interactions between the type of work and key players are included this can quickly become complex and difficult to maintain. Palm et al. (1996) have attempted to integrate process understanding and farmer appropriate recommendations. They describe the development of a decision support system to select organic inputs and their management for a given cropping system, soil type, and environment. It involves socioeconomic as well as biophysical characterization, and field testing of technology options as inputs into the model.

For both organic and inorganic sources of soil fertility, important practical questions for smallholders remain to be answered for many situations. Information is largely incomplete on the optimum use of small amounts of fertilizers, on the best combinations of organic and inorganic fertilizers for particular farm circumstances, on how to produce sufficient amount of organic inputs under poor fertility conditions, and on adjusting fertility management according to the seasonal rainfall. Farmers are looking for ways of combining inputs and employing them in ways that maximize output and minimize requirements for cash, labor and land (Thomas and Sumberg, 1995).

Flexible, conditional soil fertility recommendations that better address actual nutrient deficiencies, take advantage of cropping system opportunities, are efficient in the highly variable rainfall regime faced by most smallholders, and are compatible with the farmer's socio-economic circumstances are some of the solutions. Flexible approaches to recommendations (using 'decision trees'), not just area specific messages, are becoming available in Malawi for example (Snapp and Benson, 1995).

Nevertheless, there is a need to move further than just 'recommendations' and 'messages'. However, flexible and targeted they are they provide only part of the information that farmers require. High quality farm management through links between farmers, farmer groups and farm management advisors (provided by input suppliers, government extension services and NGOs) is where to aim (Kumwenda et al., 1997). Active farmer participation is essential. Experience is building in farmer participatory research internationally (Ashby and Sperling, 1994) and in southern Africa (e.g., Scoones et al., 1996; Kanyama-Phiri and Snapp, 1997). However, there remain major issues on how such activity can become organized and be maintained within local communities (without constant attention from 'farmer participatory researchers') and associated difficulties of scaling up to involve many thousands of farmers (Fujisaka, 1993). Often the experience becomes extremely complex, reports are anecdotal, and sustained achievements are difficult to demonstrate. The challenge remains for all the contributors to interact in the most effective and efficient ways, tailored for each situation, to sustain smallholder agriculture in southern Africa.

3. Conclusions

Priorities identified for organic matter technology research in this region include long-term nutrient effects and sustainability of green manure, improved fallow and biomass transfer systems, and how to increase efficiency of N use from organic inputs. Research on legume agronomy, including establishment in degraded soils, and targeted use of fertilizer is required. Combined strategies need to be explored in greater depth. Too often fertility technologies have been viewed as substitutive alternatives rather than investigating additive approaches. Intensification of combined use of small amount of inorganic fertilizers (especially P), animal manures and legumes which provide some grain yield with high quality leaf residues offers enhanced nutrient efficiency with improved food security. Self-nodulating promiscuous types of indeterminate soybean (*Glycine max*), pigeon pea (*Cajanus cajan)*, groundnut (*Arachis hypogaea*), dolichos bean (*Dolichos lablab*), velvet bean (*Mucuna* spp.) and cowpea are among the most promising species for combined strategies in Malawi and Zimbabwe. Technologies exploring composite approaches need to be developed further, with the smallholder farmer as a full partner in such research.

A crucial step will be evaluating, in combination with on-farm biological assessment, farmer-perceived benefits and constraints of these organic matter technologies. One of the most promising technologies which farmers need to be closely involved in evaluating and adopting to fit their circumstances is rotations of maize with legumes. Grain legumes grown on smallholder farms often have low biomass and provide limited benefits. However, combining a short statured grain legume such as groundnut with deep rooted, late maturing pigeon pea is a promising legume/legume intercrop. In rotation with a cereal, this system can provide substantial net N inputs and soil quality benefits, as well as food sufficiency. Also promising technologies are improved fallows where land is available, and biomass transfer systems where labor is sufficient.

Promotion of agronomy of grain and tree legumes with deep root systems, to enhance deep N uptake as well as N inputs from BNF, is one of the most effective ways of improving nutrient cycling on-farm in S. Africa.

References

Ali, M., 1990. Pigeonpea: cropping systems. In: Nene, Y.L., Hall, S.D., Sheila, V.K. (Eds.), The Pigeonpea. CAB International, Wallingford UK and ICRISAT, Hyderabad, India, pp. 279–302.

Araki, S., 1993. The effect of burning, ash fertilization and soil organic matter on productivity of the Chitemene shifting cultivation in northern Zambia. In: Mulongoy, K., Merckz, R. (Eds.), Soil Organic Matter Dynamics and Sustainability of Tropical Agriculture. Leuven, Belgium, Leuven, pp. 367–375.

Ashby, J., Sperling, L., 1994. Institutionalising participatory, client-driven research and technology development in agriculture. Agricultural Administration (Research and Extension) Network Paper 49. ODI: London, UK, 21 pp.

Barrios, E., Buresh, R.J., Sprent, J.I., 1996. Organic matter in soil particle size and density fractions from maize and legume cropping systems. Soil Biol. Biochem. 28, 185–193.

Beri, V., Meelu, O.P., Khind, C.S., 1989. Biomass production, N accumulation, symbiotic effectiveness and mineralization of green manures in relation to yield of wetland rice. Trop. Agric. 66, 11–16.

Biederbeck, V.O., Janzen, H.H., Campbell, C.A., Zentner, R.P., 1994. Labile soil organic matter as influenced by cropping practices in an arid environment. Soil Biol. Biochem. 26, 1647–1656.

Blackshaw, G.N., 1921. Green manuring and soil management. Rhodesia Agric. J. 18, 455–460.

Brown, P., 1962. Provisional fertilizer recommendations. Malawi Ministry of Agriculture, Government Printer, Zomba.

Brown, S., Anderson, J.W., Woomer, P.L., Swift, M.J., Barrios, E., 1994. Soil biological processes in tropical ecosystems. In: Woomer, P.L., Swift, M.J. (Eds.), The Biological Management of Tropical Soil Fertility. Tropical Soil Biology and Fertility Programme Nairobi, Kenya and Wiley-Sayce Publication, UK, pp. 15–46.

Bunderson, W.T., Saka, A.R., Itimu, O.A., Mbekeani, Y., Phombeya, H.S.K., 1991. Management of alley cropping with maize (*Zea mays*) and *Leucaena leucocephala* in Malawi. In: Saka, A.R., Bunderson, W.T., Maghembe, J. (Eds.), Proc. Agroforestry Research and Development in Malawi. Department of Agricultural Research, Lilongwe, Malawi, pp. 171–182.

Costa, F.J.S.A., Bouldin, D.R., Suhet, A.R., 1990. Evaluation of N recovery from mucuna placed on the surface or incorporated in a Brazilian Oxisol. Plant Soil 124, 91–96.

El Awad, H.O., Osman, A.K., Khair, M.A.H., Balala, M.M., 1993. Pigeonpea research for rainfed and irrigated production systems in western and central Sudan. In: Silim, S.N., Tuwafe, S., Singh, L. (Eds.), Improvement of Pigeonpea in eastern and southern Africa. Annual Research Planning Meetings 1993. Bulawayo, Zimbabwe, 25–27 October, ICRISAT, Andhra Pradesh, India. pp. 85–89.

Ehui, S.K., Kang, B.T., Spencer, D.S.C., 1990. Economic analysis of soil erosion effects in alley cropping, no-till and bush fallow systems in southwestern Nigeria. Agricultural Systems 34, 349–368.

Farrell, R.E., Sandercock, P.J., Pennock, D.J., Van Kessel, C., 1996. Landscape-scale variations in leached nitrate: relationship to denitrification and natural N15 abundance. Soil Sci. Soc. Am. J. 60, 1410–1415.

Fujisaka, S., 1993. Learning from six reasons why farmers do not adopt innovations intended to improve sustainability of upland agriculture. Agricultural Systems 46, 409–425.

Giller, K.E., Cadisch, G., 1995. Future benefits from biological nitrogen fixation: An ecological approach to agriculture. Plant Soil 174, 255–277.

Glasner, K.M., Palm, C.A., 1995. Ammonia volatilization from tropical legume mulches and green manures and unlimited and limed soil. Plant Soil 177, 33–41.

Goyal, S., Mishra, M.M., Hooda, I.S., Singh, R., 1992. Organic matter-microbial biomass relationships in field experiments under tropical conditions: effects of inorganic fertilization and organic amendments. Soil Biol. Biochem. 24, 1081–1084.

Grant, P.M., 1967. The fertility of sandveld soil under continuous cultivation. Part I. The effect of manure and nitrogen fertilizers on the nitrogen status of the soil. Rhod. Zamb. Mal. J. Agric. Res. 5, 71–79.

Haque, I., Powell, J.M., Ehui, S.K., 1995. Improved crop-livestock production strategies for sustainable soil management in tropical Africa. In: Lal, R., Stewart, B.A. (Eds.), Soil Management Experimental Basis for Sustainability and Environmental Quality. Adv. Soil Sci. CRC Lewis Publishers Boca Raton, Fl, USA, pp. 293–345.

Hartemink, A.E., Buresh, R.J., Jama, B., Janssen, B.H., 1996. Soil nitrate and water dynamics in Sesbania fallows, weed fallows and maize. Soil Sci. Soc. Am. J. 60, 568–574.

Heisey, P.W., Mwangi, W., 1996. Fertilizer use and maize production in sub-Saharan Africa. CIMMYT Economics Working Paper 96-01. CIMMYT, Mexico, D.F., 35 pp.

Hulugalle, N.R., Lal, R., 1986. Root growth of maize in a compacted gravelly tropical alfisol as affected by rotation with a woody perennial. Field Crops Res. 13, 33–44.

Janssen, B.H., 1993. Integrated nutrient management: the use of organic and mineral fertilizers. In: Van Reuler, H., Prins, W. (Eds.), The Role of Plant Nutrients for Sustainable Food Crop Production in sub-Saharan Africa. Leidschendam: VKP, pp. 89–106.

Jones, R.B., Snapp, S.S., Phombeya, H.S.K., 1996. Management of leguminous leaf residues to improve nutrient efficiency in the sub-humid tropics. In: Cadisch, G., Giller, K.E. (Eds.), Driven by Nature; Plant Litter Quality and Decomposition. CAB International, Wallingford, UK, pp. 239–252.

Kamukondiwa, W., Bergstorm, L., 1994. Leaching and crop recovery of 15N from ammonium sulphate and labelled maize material in lysimeters at a site in Zimbabwe. Plant Soil 162, 193–210.

Kanyama-Phiri, G., Snapp, S.S., 1997. Developing improved organic matter technologies in partnership with smallholder farmers in southern Malawi. Proc., Africa Crop Sci. Conf., 10–15 January, Pretoria, S. Africa.

Kumara Rao, J.V.D.K., Dart, P.J., Matsumato, T., Day, J.M., 1981. Nitrogen fixation by pigeonpea. In: Nene, Y.L. (Ed.), International workshop on Pigeonpeas, vol. 1. ICRISAT Hyderabad, India, pp. 190–199.

Kumwenda, J.D.T., Kabambe, V.H.K., Sakala, W.D.M., 1993. Maize–soybean and maize–bean intercropping experiments. Maize Agronomy Annual Report for 1992/93. Chitedze Agricultural Research Station, Lilongwe, Malawi.

Kumwenda, J.D.T., Waddington, S., Snapp, S.S., Jones, R.B., Blackie, M.J., 1997. Soil fertility management in the smallholder maize-based cropping systems of eastern and southern Africa. In: Eisher, C. (Ed.), The Emerging Maize Revolution. Michigan State University, E. Lansing, MI, USA, pp. 153–172.

Kwesiga, F., Coe, R., 1994. The effect of short rotation *Sesbania sesban* planted fallows on maize yields. For. Ecol. Manage. 64, 199–208.

MacColl, D., 1989. Studies on maize (Zea mays L.) at Bunda, Malawi. II. Yield in short rotation with legumes. Expt. Agric. 25, 367–374.

Mafongoya, P.L., Nair, P.K.R., 1997a. Multipurpose tree prunings as a source of nitrogen to maize under semiarid conditions in Zimbabwe. Nitrogen recovery rates in relation to pruning quality and method of application. Agroforestry Syst., pp. 1–16, in press .

Mafongoya, P.L., Dzowela, B.H., Nair, P.K., 1997b. Effect of multipurpose trees, age of cutting and drying method on pruning quality. In: Cadisch, G., Giller, K.E. (Eds.), Driven by

Nature; Plant Litter Quality and Decomposition. CAB International, Wallingford, UK, pp. 167–174.

Mafongoya, P.L., Nair, P.K.R., 1997c. Multipurpose tree prunings as a source of nitrogen to maize under semiarid conditions in Zimbabwe. Interactions of pruning quality and time and method of application on nitrogen recovery by maize in two soil types. Agroforestry Syst., pp. 1–14, in press.

Mafongoya, P.L., Barak, P., Reed, J.D., 1997d. Carbon, nitrogen and phosphorus mineralization from multipurpose tree leaves and manure from goats fed these leaves. Soil Biol. Biochem., in press.

Mukurumbira, L.M., 1985. Effects of rate of fertilizer nitrogen and previous grain legume crop on maize yields. Zimbabwe Agric. J. 82, 177–179.

Murwira, H.K., Kirchmann, H., 1993. Nitrogen dynamics and maize growth in a Zimbabwean sandy soil under manure fertilization. Commun. Soil Sci. Plant Anal. 24, 2343–2359.

Murwira, H.K., 1995. Ammonia losses from Zimbabwean cattle manure before and after incorporation into soil. Trop. Agric. Trin. 72, 269–276.

Muza, L., 1995. Green manuring through legume relay cropping in maize in communal areas of Zimbabwe. Proc. 2nd South Eastern Africa Soil Fertility Network Workshop, Kadoma, Zimbabwe. Sponsored by CIMMYT and Rockefeller Foundation. CIMMYT, Harare, Zimbabwe.

Nandwa, S.M., 1995. Synchronization of nitrogen mineralization with N uptake through maize stover placements and N fertilization under continuous maize monocropping systems in Kenya. Ph.D. Dissertation. University of Exter, UK, 344 pp.

Natarajan, M., Mafongoya, P.L., 1992. A study on intercropping of pigeonpea (Cajanus cajan L Millsp.) with maize, sunflower and groundnut in Zimbabwe. Zimbabwe J. Agric. Res. 30, 163–171.

Nleya, G.G., Mugwira, L.M., 1991. Integrated plant nutrition in Zimbabwe. FAO Fertilizer Plant Nutrition Bulletin 12, 359–366.

Nyathi, P., Campbell, B.M., 1993. The acquisition and use of miombo litter by small-scale farmers in Masvingo, Zimbabwe. Agroforestry Syst. 22, 43–48.

Ong, C., 1994. Alley cropping – ecological pie in the sky?. Agroforestry Today 6, 8–10.

Palm, C.A., 1995. Contribution of agroforestry trees to nutrient requirements of intercropped plants. Agroforestry Syst. 30, 105–124.

Palm, C., Wangari, N., Gichuru, M., 1996. Selection of organic inputs for soil fertility management. In: Waddington, S.R. (Eds.), Soil Fertility Network for Maize-based Farming Systems in Selected Countries of southern Africa. Research Results and Network Outputs in 1994 and 1995, CIMMYT, Harare, Zimbabwe, pp. 19–24.

Pieri, C., 1995. Long-term soil management experiments in Semiarid Francophone Africa. In: Lal, R., Stewart, B.A. (Eds.), Soil Management Experimental Basis for Sustainability and Environmental Quality. Adv. Soil Sci. CRC Lewis Publishers, Boca Raton, FA, USA, pp. 225–266.

Rattray, A.G.H., Ellis, B.S., 1952. Maize and green manuring in southern Rhodesia. Rhodesia Agric. J. 49, 188–197.

Rodell, M.G.W., Hopley, J.D.H., Boaltwod, J.N., 1980. Effects of applied nitrogen, kraal compact and maize stover on yields of maize growth on a poor granite soil. Zimbabwe Agric. J. 77, 229–232.

Ruhigwa, B.A., Gichuru, M.P., Tariah, N.M., Isirimah, N.O., Douglas, D.C., 1993. Spatial variability in soil chemical properties under *Dactyladenia barteri*, *Alchornea cordifolia*, *Senna siamea* and *Gmelina arborea*. Expt. Agric. 29, 365–372.

Saka, A.R., Phomebya, H.S.K, Itimu, O.A., Jones, R.B., Minae, S., Snapp, S.S., 1995. Agroforestry Commodity Team Annual Report. Dept. Agric. Research, Malawi Ministry of Agriculture, Lilongwe, Malawi, 90 pp.

Sakala, W.D.M., 1994. Crop management interventions in traditional maize pigeonpea intercropping systems in Malawi. M.Sc. Thesis. Crop Science Dept., Bunda College of Agric., University of Malawi, Lilongwe, Malawi.

Scoones, I., Chibudu, C., Chikura, S., Jeranyama, P., Machaka, D., Machanja, W., Mavedzenge, B., Mombeshora, B., Mudhara, M., Mudziwo, C., Murimbarimba, F., Zirereza, B., 1996. Hazards and Opportunities, Farming Livelihoods in Dryland Africa: Lessons from Zimbabwe. Zed Books: London, England and New Jersey, USA, 267 pp.

Scoones, I., Toumin, C., 1998. Soil nutrient balances: what use for policy? Agric. Ecosyst. Environ. 71, 257-269..

Shumba, E.M., Dhliwayo, H.H., Mukoko, O.Z., 1990. The potential of maize-cowpea intercropping in low rainfall areas of Zimbabwe. Zimbabwe J. Agric. Res. 28, 33–38.

Smaling, E., 1993. Soil nutrient depletion in sub-Saharan Africa. In: Van Reuler, H., Prins, W. (Eds.), The Role of Plant Nutrients for Sustainable Food Crop Production in Sub-Saharan Africa. VKP, Leidschendam, pp. 53–68.

Somda, Z.C., Powell, J.M., Fernandez-Rivera, S., Reed, J., 1995. Feed factors affecting nutrient excretion by ruminants and fall of nutrients when applied to soil. In: Powell, J.M., Fernandez-Rivera, S., Williams, T.O., Renard, C. (Eds.), Livestock and sustainable nutrient cycling in mixed farming systems of Sub-Saharan Africa. ILCA, Addis Abbaba, Ethiopia, pp. 227–246.

Snapp, S.S., 1994. Improving fertiliser efficiency with small additions of high quality organic inputs. Proc. 1st South Eastern Africa Soil Fertility Network Workshop, Salima, Malawi. Sponsored by CIMMYT and Rockefeller Foundation, CIMMYT, Harare, Zimbabwe.

Snapp, S.S., Benson, T., 1995. GIS to develop area-specific fertilizer recommendations in Malawi: soil resources, yield potential and decision trees. Agronomy Abstracts. American Society of Agronomy 1995 Annual Meetings, ASA, Madison, WI, USA, 301 pp.

Snapp, S.S., Phombeya, H.S.K., Materechera, S.A., 1996. An agroforestry-based test of light/large fractionation methods in soil organic matter analysis. Proc. 25th annual symposium, Crop Science Society of Zimbabwe. June, 1995, Harare, Zimbabwe, pp. 34–38.

Tanner, P.D., Mugwira, L., 1984. Effectiveness of communal area manures as sources of nutrients for young maize plants. Zimbabwe Agric. J. 81, 31–36.

Thomas, D., Sumberg, J.E., 1995. A review of the evaluation and use of tropical forage legumes in sub-Saharan Africa. Agric. Ecosyst. Environ. 54, 151–163.

Versteeg, M.N., Koudokpon, V., 1993. Participative farmer testing of four low external input technologies, to address soil fertility decline in Mono province (Benin). Agric. Syst. 42, 266–276.

Waddington, S.R., 1994. Overview of the current situation and previous impact of adaptive agricultural research in southern Africa. In: Craswell, E.T., Simpson, J. (Eds.), Soil Fertility and Climatic Constraints in Dryland Agriculture. Proc. ACIAR/ SACCAR Workshop at Harare, Zimbabwe, 30 August–1 September 1993, ACIAR Proceedings No. 54, pp. 7–14.

Waddington, S.R., Heisey, P.W., 1997. Meeting the nitrogen requirements of maize grown by resource-poor farmers in southern Africa by integrating varieties, fertilizer use, crop management and policies. In: Edmeades, G.O., Bänziger, M., Mickelson, H.R., Peña-Valdivia, C.B. (Eds.), Developing Drought and Low N-Tolerant Maize. Proc. Symp., CIMMYT, El Batán, Texcoco, Mexico D.F Mexico, 25–29 March 1996.

Weil, R.R., Mughogho, S.K., 1993. Nutrient cycling by Acacia albida (Syn. Faidherbia albida) in agroforestry systems. Technologies for Sustainable Agriculture in the Tropics. ASA Special Pub. No. 56. American Society of Agronomy, Madison, WI., USA, pp. 97–108.