Progress in lifting soil fertility in Southern Africa[1]

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Abstract

Crop productivity in southern Africa is limited by poor soil nutrient status. Local farmers crop highly depleted old soils with little external support for inputs and markets, and few resources of their own. These circumstances have led to widespread low input and output farming now characterized by nutrient mining, low productivity, food insecurity and non-sustainability. In response, agricultural research and development has increasingly focused on the generation and use of a range of soil fertility technologies to better manage smallholder agricultural resources and provide useful products. Best Bet soil fertility technology options now available include zone and end-use specific mineral fertilizer recommendations, conditional fertilization based on rainfall for maize, lime amendments, improved cattle manure and compost systems, annual grain legumes, green manure rotations and intercrops, improved fallows, beneficial trees in croplands, biomass transfer systems and nutrient use efficient cereals. Specific examples are presented of mucuna green manure in combination with mineral fertilizer, groundnut-maize rotations, and pigeonpea/maize intercrops, which have short-term financial benefits plus important productivity and sustainability benefits over 10+ years. These technologies were extensively tested with smallholder farmers on their spatially and temporally diverse farms, to maximize use and benefits. Information and promotion activities are described that have been moderately successful in encouraging farmer use of the Best Bets. Greater adoption will depend on appropriate input supply policies to support farmer investments in soil fertility and provide markets for products.

Media summary

We now know about many soil fertility technologies that improve soil fertility on smallholder farms in southern Africa. Some useful options are being promoted, with mixed success.

Key words

Sustainability, maize, N fertilizer, mucuna/velvet bean, pigeonpea, groundnut, farm integration, niches

The soil fertility challenge in southern Africa

Research to improve the fertility of southern Africa’s soils has been underway for about 100 years. However, during the 1990s, increased evidence of widespread soil fertility decline, stagnant food production and deepening food insecurity in the smallholder mixed subsistence and cash crop arable systems of eastern and southern Africa led to a well-documented major expansion of research on soil fertility processes, the development and dissemination of integrated soil fertility technologies and advocacy for nutrient replenishment strategies (see Blackie 1994; Kumwenda et al 1996,1997; Sanchez et al 1997). Farmers themselves increasingly perceive poor soil fertility as a major constraint (e.g. Gatsi et al 2000). Ways to reduce and manage soil infertility in sub Saharan Africa have received almost constant attention from agricultural research and development agencies and donors in recent years and a vast amount of information is now available. Sanchez and Jama (2002) have recently updated progress in meeting this challenge.

Mixed maize + legume + livestock systems dominate in the subhumid and some semi-arid zones of southern Africa. Nutrient balance studies conducted from single farm to national scales showed that nutrient depletion rates far exceed replenishment in these systems. Most smallholder farms receive little or no mineral fertilizer, relying instead on small amounts of a range of organic and mineral sources of nutrients found on farms. Yet offtake of nutrients in crops is often high with intensive continuous cropping, and losses from other sources such as leaching can be large. Stoorvogel et al (1993) and Smaling (1998) estimated that the annual net nutrient depletion exceeds 30 kg N and 20 kg K/ha of arable land in Malawi and Zimbabwe, as well as several countries in eastern Africa.

Soil organic matter (SOM), which is central to the sustainability of soil fertility on smallholder farms in the tropics (Woomer et al 1994), has declined to very low levels. Current SOM inputs (from leguminous trees in fallows, tree leaf litter, cereal and legume crop residues, weeds, animal manures, composts) are insufficient to maintain SOM levels in most smallholder soils while in the low-rainfall marginal areas it is not possible to grow enough biomass to maintain SOM. As an example, while composting is a practice increasingly promoted for Malawian farmers, most crop residues are already incorporated into the soil by farmers during annual re-ridging. The composting of remaining modest amounts of low quality plant biomass is unlikely to make a major contribution. When cropped to sole maize, the soils in smallholder systems in Zimbabwe can supply only about 30 kg N/ha per cropping season because of these critically low levels of SOM and N (Mapfumo and Mtambanengwe 1999). Further N mineralization is dependent on annual organic inputs produced in crop residues (e.g. groundnut and maize) and retained on the field or cycled through animals (as cattle manure). In some wetter communal lands of northern Zimbabwe, soils on topland fields (that previously grew annual crops) now hold such low nutrient levels that maize will commonly give near zero grain yield without fertilizer. As well as a direct contributor to reduced productivity, soil infertility is a major source of inefficiency in the returns to other inputs and management committed to smallholder farms, including N fertilizer and labour. For example, Mushayi et al (1999) showed that smallholder farmers in wet and average rainfall seasons in northern Zimbabwe get very low responses to the N fertilizer they apply to otherwise adequately weeded and managed maize crops grown on the extremely common sandy soils derived from granite (Figure 1). Agronomic N use efficiencies (NUEs) of <10 kg grain/kg N applied were common on farmers' crops compared to 23-49 kg grain/kg N applied at a nearby experimental station site with a more fertile soil of similar pedology. On such soils, a complex of low SOM, low amounts of several cations, soil acidity and low P, contribute to the low realized NUEs (Mushayi et al 1999; Mapfumo and Mtambanengwe 1999).

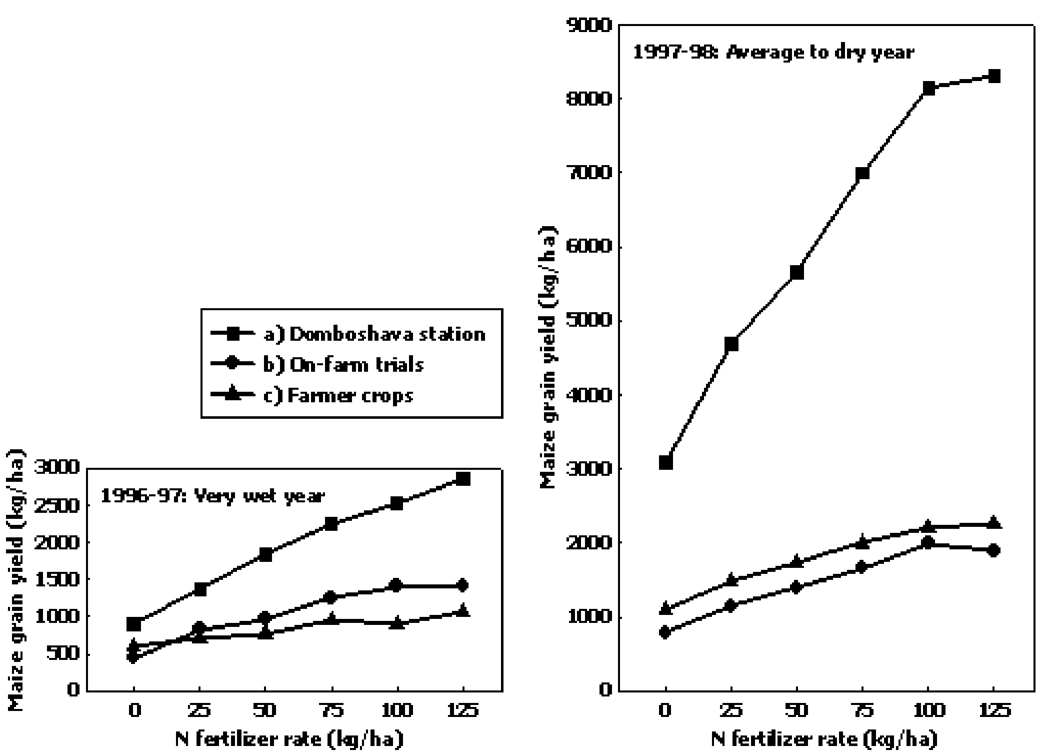

Figure 1. Maize grain yield response to N fertilizer on granitic sandy soils in subhumid zones of northeastern Zimbabwe, 1996-1998: Measured a) at Domboshava research farm, b) in smallholder farm trials and c) on smallholder farmer maize crops. Data from 22 smallholder farms by Mushayi et al (1999).

The challenge remains how to maintain soil fertility and crop productivity under the income and, increasingly, land and labour constraints faced by smallholders. In wetter equatorial zones, rehabilitation or recapitalization strategies for acidic and P fixing soils are required, while the inherently depleted and sandy soils in many parts of southern Africa need good management of frequent moderate amounts of nutrient inputs from a range of sources (e.g. Kumwenda et al 1996, 1997; Sanchez et al 1997). Mineral fertilizers are often costly (with N:maize grain price ratios of about 6 in Zimbabwe and 9 in Malawi) and not available (e.g. Kumwenda et al 1996, 1997; Sanchez et al 1997). There are no single simple technology solutions and many (Kumwenda et al 1996, 1997; Snapp et al 1998; Giller et al 1998; Murwira and Palm 1999) propose that farmers more routinely implement integrated soil fertility management strategies that combine a range of on-farm soil fertility resources with external ones on different parts of their farms to take advantage of local fertility and water conditions. These include modest mineral fertilizer, SOM and NP inputs from animal manures and legumes, plus N-use efficient maize. Timely crop management to achieve good crop responses and policies to support access to soil fertility inputs by resource-poor farmers are vital. For smallholder maize-based farming systems in southern Africa, Kumwenda et al (1996 and 1997), Snapp et al (1998) and Giller et al (1998) present comprehensive reviews of the problem and possible solutions, with their recent update and expansion by Mafongoya et al (2003).

In this paper, we describe progress in developing a wide range of soil fertility technology options for and with smallholder farmers in southern Africa, the benefits they provide for short-term productivity (food security) and longer-term sustainability, and their promotion and integration into actual farming systems.

Helpful Best Bet technology options

A wide range of helpful organic and inorganic (mineral) soil-fertility technology and cropping system options (Table 1) has been developed for smallholders in southern Africa. The technologies resulted from widespread participatory research and testing with the farmers on their farms, particularly in Malawi and Zimbabwe. Criteria used in the selection of these most useful "Best Bet" options have included (Mekuria and Waddington, 2002):

- Longer-term contribution to raising soil fertility.
- Ability to raise crop yields and generate profit in the short term (1-2 years).
- Appropriate for many farmers across important agroecologies.
- Compatibility with other components of the farming system.
- Small additional cash and/or additional labour requirements.
- Only a small reduction in maize yields or substitution by production of other crop.
- Where possible, little competition for arable land.

Because most of these cropping systems are in unimodal rainfall zones with a long dry season, legume green manures and improved fallows can only be grown in the main cropping season and so they replace food crops on the land.

Most of the technologies and cropping systems options provide some short-term soil-fertility and crop-productivity benefit and several end uses, which makes them attractive to farmers. They are compatible with farmer circumstances and effective within farmer resource constraints (cash, labour and land). These soil fertility input and cropping options offer farmers the "Best Bets" for improved productivity, sustainability, useful products and income. Technologies meeting most of these criteria should be adoptable by farmers.

Short-term yield and economic benefits from technologies

Smallholder farmers need to feed themselves as well as the soil. Because they have so few resources, they resort to continuous cropping without inputs that depletes nutrients, leads to soil erosion and soil degradation. They will be principally interested to use soil fertility technologies that raise crop yields and provided more food in the short term – over several months to a year or two after use. Many of the technology options listed in the previous section are of this type; providing good quick improvements in productivity of food crop yields in economic ways. In this section we illustrate the types of benefits available through more detail on two technologies, one involving organic matter and nitrogen inputs from a green manure crop of velvet bean (*Mucuna pruriens*), and another the more efficient use of mineral fertilizer inputs for hybrid maize through soil type and end-use specific fertilizer recommendations.

Table 1. "Best Bet" soil fertility input and cropping system technologies for smallholder maize-based farming systems in Malawi and Zimbabwe.

Technology	Target		Expected ease of adoption by farmers[1]	Adoption potential[2] (number of farmers)
	Agro-ecology	Farm type		
	Malawi			
	Soil-fertility technology			
Area-specific NP fertilizer recommendation for hybrid maize	All areas by soil type and market or home use	Richer and middle income farmers	++	900000
Optimum combinations of organic and mineral fertilizers	Most of Malawi		++	1000000
'Magoye' promiscuous soybean	All mid-elevation areas	Richer cash croppers	++	300000
Tithonia spp. biomass transfer to maize	Zones with *Tithonia* spp.	*Tithonia* spp. growing on or near farm and labour available	+++	40000
	Fertility-enhancing cropping system			
Groundnut in rotation with maize, and pigeonpea intercropped with other grain legumes	All mid elevation areas	Medium to large holdings	+++	400000

Tephrosia undersowing of maize	Mid elevation and lakeshore areas	Medium to large	++	400000
Mucuna + maize rotations	Most of Malawi, poorer soils	Medium to large	+	200000
Faidherbia albida trees in cropland	Adaptation range (500-1000 masl)		++	500000
Sesbania undersowing	Mid elevation areas	Larger holdings	+	100000
Pigeonpea + maize intercropping	South and central Malawi	Smaller holdings	++++	1000000
Off-season “Dimba” maize to exploit fertile wetlands	Dambo (seasonal wetland) areas throughout Malawi	Access to dambo	++	200000
Soil fertility x *Striga* interactions	*Striga* affected areas		+++	150000
		Zimbabwe		
		Soil-fertility technology		
Fertilizer management package for maize (conditional on rainfall) and grain legumes	Subhumid and semiarid areas	All except poorest farms in driest areas	+++	1000000
Liming on acidic sandy soils	Acidic soils in subhumid areas	Higher-input farms	++	300000
Phospho-compost	Subhumid zones	Farmers near Dorowa rock P mine plus cattle kraal	++	50000
Optimum combinations of organic and mineral fertilizers	Subhumid and wetter semi-arid areas		++	600000
Improved cattle manure management, including anaerobic	All, except driest areas where farmers reluctant	Farmers with cattle	+	250000

composting	to use manure			
Fertility-enhancing cropping system				
Pigeonpea rotations and intercropping	Subhumid areas		++	150000
Soybean (inoculated and promiscuous) in rotation with maize	Subhumid areas on better soils	Cash crop farmers	+++	300000
Mucuna + maize rotations	Subhumid areas		+	100000
Other grain-legume rotations	Subhumid and wetter semi-arid		+++	700000
Cowpea/maize intercrop	Subhumid and wetter semi-arid	Most farmers	++++	1200000

[1] + = low ++ = moderate +++ = high ++++ = extremely high
[2] Numbers of farmers that should find a technology beneficial and accessible. From estimates by key informant scientists.

Mucuna green manure in Malawi, Zimbabwe and Zambia

A green manure legume is one that is grown specifically for its biomass to provide organic matter to the soil and N to a subsequent, usually cereal, crop. There has been renewed interest by researchers and some farmers in such systems in recent years because mineral N fertilizer has become more expensive and fields continue to become less fertile. In our search for a green manure, we have found velvet bean (*Mucuna pruriens*) to be the most consistent producer of biomass and provider of N, except on some of the most depleted soils (where its contribution would be most needed). Additionally the grain is used as a food crop of last resort in southern Malawi and parts of northern Mozambique, and its leaves are sometimes used as a fodder for ruminant livestock in Zimbabwe and Zambia, which helps with farmer adoption. Even on depleted sandy soils in Zimbabwe, velvet bean routinely produced over 2 t/ha of above-ground biomass and over 5 t/ha in many cases, performing far better than other green manures such as sunnhemp (*Crotalaria juncea*) and fish bean (*Tephrosia vogelii*) (Table 2) (Hikwa et al 1998). N inputs of 101-348 kg N/ha, leading to maize grain yields of 2.3 t/ha on sandy soils (64% higher than maize following a weedy fallow) have been measured from mucuna green manure in Zimbabwe (Whitbread et al 2004).

Table 2. Biomass production (kg/ha, dry mass) by three green manure legumes with and without P, on exhausted sandy soils in six smallholder communal areas in northern Zimbabwe, 1996/97 season.

Communal Area (Site)	Velvet bean	Sunnhemp	Fish bean

	+ P	- P	+ P	- P	+ P	- P
Gokwe South (1)	2368	1916	1688	858	0	0
Gokwe South (2)	1826	1964	809	1000	0	0
Nyazura (1)	8020	7240	0	0	0	0
Nyazura (2)	6490	6610	0	0	0	0
Chiduku (1)	1757	1865	grazed	grazed	70	34
Chiduku (2)	4538	2703	116	13	64	66
Mangwende (1)	318	317	311	290	145	145
Mangwende (2)	5351	5250	5000	5040	3127	3125
Zvimba (1)	2410	1260	0	0	0	0
Zvimba (2)	850	1620	0	0	0	0
Chihota (1)	10665	5290	8460	2315	0	0
Chihota (2)	4275	3405	505	550	0	0

In Malawi, velvet bean averaged over 7 t/ha of above-ground biomass when grown with P at some relatively depleted sites, and following maize crops it gave up to 3.5 t/ha of grain against around 1 t/ha from continuous unfertilized maize (Sakala et al 2001). Early incorporation of green manure residues at flowering leads to a higher maize grain yield response than late incorporation after seed harvest (Sakala et al 2001). Sakala et al (2003) showed on farmers' fields in central Malawi, that mucuna can almost double the N in the grain of a following maize crop, compared with continuous unfertilized maize (Figure 2).

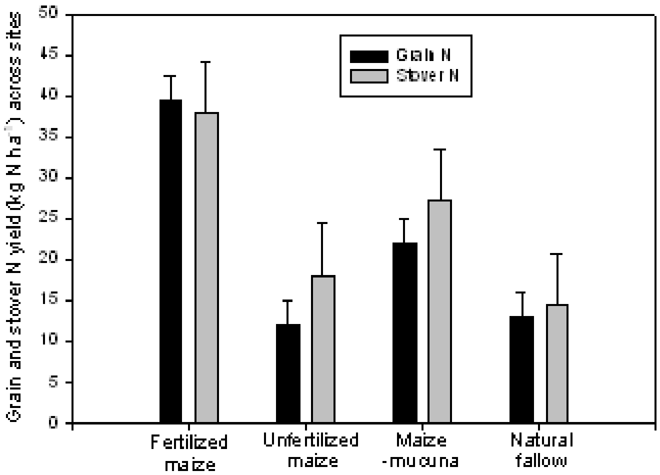

Figure 2. Maize grain and stover nitrogen from a maize-mucuna rotation, continuous maize and a natural fallow on 26 smallholder farms in central Malawi (From Sakala et al 2003).

Mucuna green manure can also raise the use efficiency of expensive mineral fertilizer. A combination of mucuna residues and NP fertilizer increased fertilizer use efficiency for maize grain yield in Malawi (Table 3). Fertilizer use efficiency was higher at the lower rate (35 kg N/ha) for both year one (when the green manures had just been incorporated) and year two, when the fertilizer was added one season after incorporation of the green manure.

Table 3. The effect of three different rates of mineral fertilizer following early or late incorporated legume residues or sole maize on the grain yield (t/ha) of maize across five sites for two seasons (1997-1999) in Malawi. Early = incorporation at maximum flowering or pod initiation, Late = incorporation just after harvest of mature legume grain. Maize residues were incorporated during mid dry season re-ridging.

Treatment	Fertilizer (N:P:K) rate			
Legume incorporation	0	35:10:0+2S	69:21:0+4S	mean
Mucuna early	2.1	2.6	3.5	2.7
Mucuna late	2.2	2.6	3.5	2.8
Crotalaria juncea early	2.2	3.1	3.7	3.0
C. juncea late	1.8	2.9	3.6	2.8
Lablab purpureus early	2.0	2.8	3.4	2.7
L. purpureus late	1.7	2.9	3.4	2.7

Maize (Control)	1.2	2.2	2.7	2.0
mean	1.9	2.7	3.4	2.7
	Legume	Fertilizer	Interaction	
Significance	0.001	0.001	NS	
SED	0.09	0.07	0.02	
CV (%)	6.1	8.7	8.7	

Recently mucuna-maize rotations have been tested and promoted more widely with farmers in central-north Malawi (Sakala et al 2003), especially on otherwise fertile but N deficient sandy soils of the Kasungu Plain where they are expected to offer highest benefits. Across 26 farms, maize following mucuna yielded 1.5 t/ha of grain, double the yield (0.8 t/ha) from plots where unfertilized maize followed unfertilized maize (Table 4) (Sakala et al 2003). At these farms, maize fertilized with the zone specific fertilizer recommendation (35N:10P:0K+2S) yielded 2.6 t/ha grain.

Table 4. Maize grain yield (t/ha) after mucuna green manure at 26 farms in four areas of central and northern Malawi, 2001/2002 (From Sakala et al 2003).

Area	No. of farms	Fertilized maize	Unfertilized maize	Maize after mucuna	Maize after fallow	Mean (t/ha)
Ntcheu	6	3.6	1.1	1.6	1.4	1.9
Kasungu	5	1.7	0.8	1.2	0.9	1.1
Vangalala	6	1.4	0.4	0.7	0.6	0.8
Zombwe	5	3.6	0.9	2.4	1.3	2.0
Mean		2.6	0.8	1.5	1.0	1.5
			SED	Prob.		
Site			0.248	<0.001		
Treatment			0.248	<0.001		

Site x Trt	0.496	NS

A financial analysis developed from on-farm research by Hikwa et al (1998) in northern Zimbabwe, involving mucuna or sunnhemp with combinations of mineral fertilizers in rotation with maize (Table 5), confirmed that the mucuna rotation contributes to increased maize yield and a high benefit:cost ratio of 3.37 at a 30% discount rate and 3.17 at a 50% discount rate. The addition of 45 kg N/ha to maize after mucuna further raised the benefit cost ratio to 4.42 suggesting that combinations of green manure with mineral fertilizer will be a better option for farmers who can afford the fertilizer.

Table 5. Financial analysis of mucuna and sunnhemp green manures in Zimbabwe communal areas, indicating net present values (NPV) in US$ and benefit cost (B/C) ratios.

Treatment	NPV at 30% discount rate	B/C ratio	NPV at 50% discount rate	B/C ratio	rank
Mucuna (incorporated) + $100P_20_5$+45N	517	3.3	333	3	3
Mucuna (incorporated) + $0P_20_5$ +45N	684	4.73	449	4.42	1
Mucuna (incorporated +) $0P_20_5$ +0N	350	3.37	254	3.17	2
Sunnhemp (incorporated) +$100P_20_5$ +45N	277	2.3	188	2.2	5
Sunnhemp (incorporated) +$100P_20_5$ +0N	207	2.07	136	1.94	6
Sunnhemp (biomass removed) + $100P_20_5$ +45N	277	2.56	194	2.47	4

In central Zambia, mucuna and sunnhemp green manures followed by maize are reported to be more profitable than a fertilized maize crop alone (Mwale et al 2003). A broader financial analysis of mucuna and other green manure systems in Zimbabwe and Malawi (Mekuria and Siziba 2003) showed that the discounted incremental costs of including mucuna in one season instead of maize are outweighed by the discounted incremental benefits of increased maize yields in two subsequent seasons. Pay-offs to investing in mucuna as a green manure were positive though modest in magnitude for both land constrained and land adequate smallholder farmers (Table 6). Net Present Values were US$ 152 in Zimbabwe and US$ 19 in Malawi. Returns to mucuna were strongly influenced by the maize yield response and the discounting factor. The Malawi results are affected by the low marginal increase in maize yield over maize after maize. However, farmers also aim to minimize risk and want to maintain household food security. The probabilities of negative returns with mucuna rotations were calculated to be 30% in Zimbabwe and 38% in Malawi. Such a risk is quite substantial for land-constrained farmers who have to forgo one season of maize harvest to grow mucuna (Mekuria and Siziba, 2003).

Table 6. Net present values (NPV, US $) per ha for investing in mucuna as a green manure in Malawi and Zimbabwe (From Mekuria and Siziba 2003).

	Zimbabwe (Discounting at 50%)	**Malawi (Discounting at 34%)**

(In US$)	Land constrained farmers	Land adequate farmers	Land constrained farmers	Land adequate farmers
Total costs	37.1	57.5	56.6	50.8
Total benefits	189.9	189.9	70.1	70.1
NPV (US$)	152.8	132.4	13.5	19.4

Conclusions on mucuna green manures are that resource poor farmers who cannot afford fertilizers would benefit from growing mucuna compared to continuous maize cropping or abandoning the field to a natural fallow. The mucuna needs to be targeted to where it will grow well and give maximum N benefit, such as an otherwise fertile sandy soil, rather than extremely depleted acidic and shallow soils. For a mucuna green manure rotation, farmers need moderately large pieces of land and adequate labour. Where livestock are important in the system, as in much of Zimbabwe, rather than it be grown as a traditional green manure with green residues incorporated into the soil towards the end of the rains, mucuna is often more acceptable as a ley crop grown into the long dry season for ruminant grazing (Maasdorp et al 2004). Remaining residues would be ploughed into the soil during normal land preparation with first rains.

Zone-specific fertilizer recommendations for hybrid maize in Malawi

These have greatly improved the regional efficiency of fertilizer use on maize within Malawi. Until the late 1990s, Malawi had one blanket fertilizer recommendation for maize. Over the last 10 years zone-specific fertilizer recommendations have been developed through a major effort principally by the Maize Commodity Team. The maize grain yield response to N and P fertilizer on-farm was shown to be poor, often well below 20 kg maize grain/kg nutrient applied. This coupled with the high cost of fertilizer in Malawi meant that the blanket fertilizer recommendation of 96 kg N/ha was rarely economic. Missing nutrient trials and widespread chemical analyses of soil showed regional deficiencies of Zn, S, B and K. In deficient regions, average yields improved by 40% over the existing N and P application when the deficiencies were satisfied. New basal fertilizer blends with these nutrients were developed with fertilizer suppliers. Several possible zone-specific fertilizer recommendations were verified at well over 2000 on-farm sites throughout Malawi with the extension service and farmers. Through economic analysis, GIS maps and decision trees, economic zone-specific fertilizer recommendations were developed based on soil texture and farmer production goals (Benson 1998; Kumwenda and Benson 1999). The new recommendations were usually zero on light texture soils and 35 kg N/ha on medium texture soils, if the maize was for market sale. For home consumption (when the cost of buying grain to eat, if not produced on the farm, was included in the financial analysis) values were usually either 69 (light soils) or 92 kg N/ha (medium soils). The high cost of buying food grain from distant markets financially justifies the use of higher amounts of N/ha on maize being grown for home consumption.

Longer-term sustainability benefits

Many of the benefits from soil fertility interventions on soil biophysical properties, efficiencies of input use and crop productivity are manifest over the longer term, but our knowledge of these effects on smallholder farms remains patchy. Ten years ago, Swift et al (1994) described several longer-term arable experiments in Africa that address organic and inorganic soil fertility inputs and crop rotations. However, all were researcher-managed on research stations and reflected very poorly the circumstances facing the African farmer (Swift et al 1994; Scoones 2001). Since then, some work has been conducted on smallholder farms in southern Africa with the inputs and management that farmers use to measure longer-term (over six to ten years, and onward) trends in soil fertility and crop productivity for current and proposed soil fertility practices. Here we describe results from longer-term work with two of the most commonly used soil fertility maintenance cropping systems in the region; groundnut-maize rotations and pigeonpea/maize intercropping.

Groundnut-maize rotations in Zimbabwe

Non-systematic groundnut-maize rotations are widely practiced by smallholders in subhumid northern Zimbabwe (Snapp et al 1998; Waddington and Karigwindi 2001). Large increases in maize yields are common following groundnut on research stations in Zimbabwe (e.g. Mukurumbira 1985; Waddington and Karigwindi 2001) but can be absent or very low on smallholder farms where farmers grow saved seed of groundnut on depleted acidic soils with few fertilizer inputs and inadequate weeding, and commonly allow animals to graze haulms (Waddington and Karigwindi 2001). Groundnut-maize rotation experiments were conducted for nine years on six smallholder farms and under simulated smallholder management on a research station (Domboshava) with granitic sandy soils. In nine years of continuous maize cropping at the six on-farm sites, maize grain yields declined (at a rate of 0.066 t/ha per year) without fertilizer to around 0.5 t/ha. While two cycles of a 3-year rotation of groundnut with unfertilized maize raised maize grain yields by 2.15 t/ha and 1.48 t/ha at the research station (Figure 3), the effects on smallholder farms were much smaller (Figure 4). Existing smallholder practices (few inputs and moderate management) with groundnut produced relatively poor groundnut crops (averaging less than 0.10 t/ha groundnut grain) that raised maize grain yields by just 0.21 t/ha and 0.38 t/ha (48% and 44%) in two cycles of the rotation (Figure 4) (Waddington and Karigwindi 2001). Contributors to low groundnut yields include low achieved plant densities, low soil P and Ca status (Waddington and Karigwindi 2001).

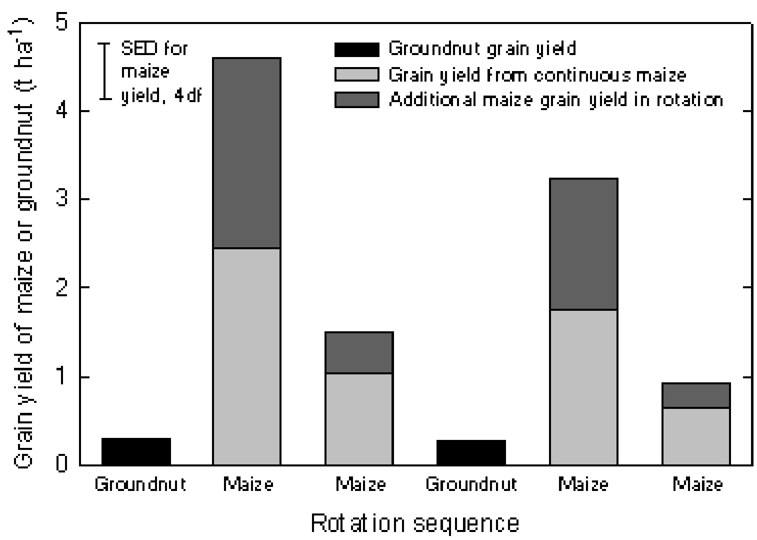

Figure 3. Grain yield of groundnut and maize (t/ha) in two cycles of a groundnut-maize-maize-groundnut rotation without fertilizer at Domboshava station, Harare, Zimbabwe, 1994-2001.

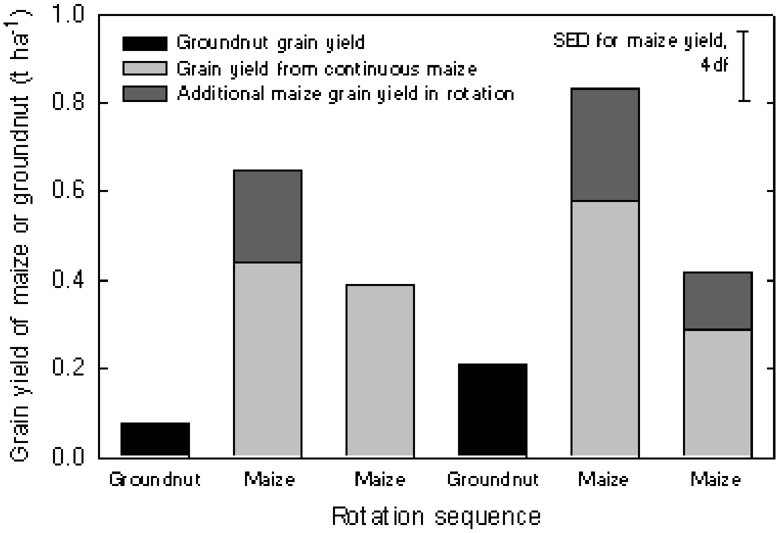

Figure 4. Grain yield of groundnut and maize (t/ha) in two cycles of a groundnut-maize-maize-groundnut rotation without fertilizer, averaged over five smallholder farms in Chinyika and Chiduku, northeast Zimbabwe, 1995-2001.

From this study it is clear that the farmer's current practice with groundnut rotation contributes to the productivity and sustainability of smallholder maize systems in sub-humid Zimbabwe by maintaining modest increases in maize yields, but by far less than can be expected under better conditions. In addition to maize, the groundnut + maize rotation provides some groundnut grain, which has a high value for household food and sale. However, economics and longer-term farm system sustainability are not always compatible. From a short-term financial analysis viewpoint, the economic viability of this practice on farm is doubtful (Waddington and Karigwindi 2001). If labour for the groundnut component of the rotation is costed, it is usually more profitable to grow continuous maize, especially with fertilizer.

Pigeonpea/maize intercrop in Malawi

Pigeonpea/maize intercropping is very common in southern and central Malawi where land and farm animals are scarce but the human population high, primarily to produce more food or cash and only secondarily to maintain soil fertility (Kumwenda et al 1996). The growth and development of intercropped maize and late-maturing pigeonpea complement each other so that the slow early growth of pigeonpea does not reduce maize yields (Kumwenda et al 1996; Giller 2001). The distinct rooting patterns of maize and pigeonpea also allow the two crops to obtain nutrients from different soil layers. Pigeonpea matures on residual moisture well after maize is harvested and the amount of N added by fallen leaves (up to 90 kg N/ha) is similar to sole crop pigeonpea (Kumwenda et al 1996; Sakala et al 2000; Giller 2001). Additionally the grain has a ready market for national and export sale for dhal. Late maturing pigeonpea intercropped with maize can often produce a dry matter yield of 3 t/ha from leaf litter and flowers and, even if the seed is harvested for food, the leaf fall is sufficient for some N accumulation.

Using the CENTURY soil organic C model to simulate long term trends in soil C and grain yields for several continuous maize and maize-pigeonpea systems predicted that continuous low-input sole maize plots with the maize stover removed would give a larger decline in total soil organic C compared with other plots where residues were returned (Figure 5). Under annual cropping, high nutrient depletion is due to high outputs of nutrients in harvested products (Smaling 1998) and for Malawi the situation is aggravated by the removal of crop residues from the field for other uses. Intercropped pigeonpea plots with the residues returned to the soil and the addition of some N fertilizer should raise soil C and maintain crop grain yields better over the 50-year simulation period than with sole maize (even with maize residues returned to the field) (Figure 5). In Malawi, intercropping maize and pigeonpea gave a better predicted long term N balance compared with sole maize at the same level of fertilizer (20 kg N/ha and 80 kg N/ha) (Sakala et al 2000).

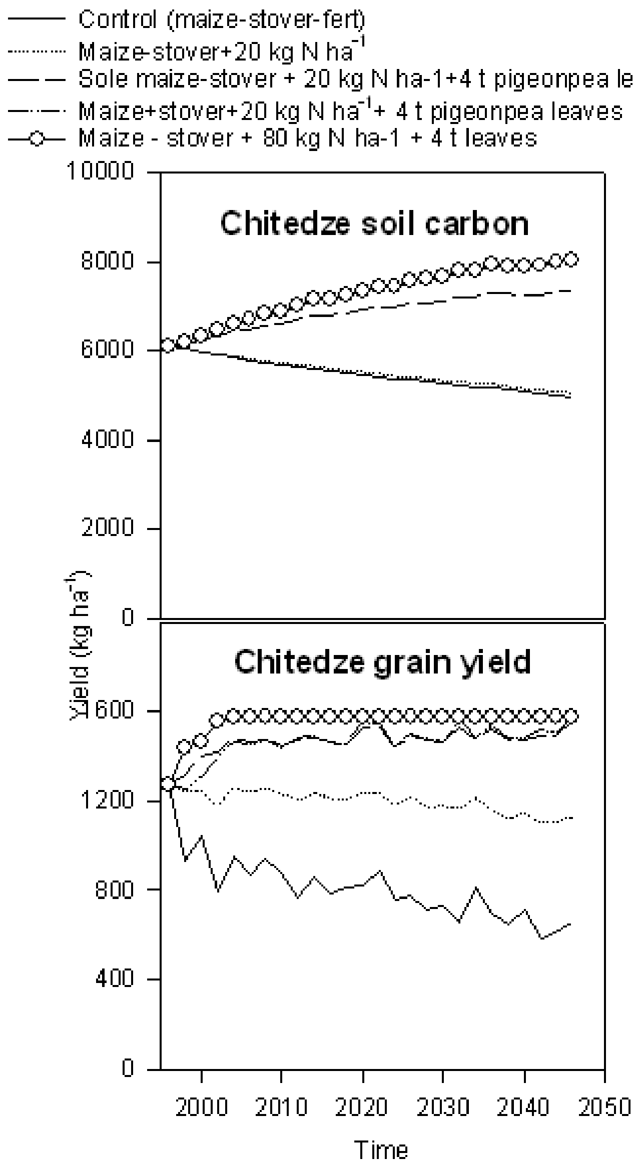

Figure 5. Fifty-year simulations of soil C and grain yield for maize-pigeonpea systems at Chitedze, Malawi, using the CENTURY model.

Integration into real smallholder farms

Southern African smallholder maize-based systems are complex, involving several crops and animals produced to meet several needs. Spatial variability in soil type and water conditions on farm is compounded by farmer decision-making on crop and field management strategies in space and time that reduce risk and improve resilience (e.g. Carter and Murwira 1995; Scoones and Toulmin 1998; Budelman and Defoer 2000; Scoones 2001). Because resources (mineral nutrients, seed, labour) are limited, such practices increase heterogeneity on most farms, as farmers tend to concentrate resources in small areas (parts of fields near homesteads) where soil fertility is maintained while the majority of their (outer) fields are mined of nutrients (e.g. Carter and Murwira 1995; Rowe and Giller 2003). This spatial variability is increasingly recognized to offer opportunities for the more efficient use of soil fertility inputs and crops across the farm (Carter and Murwira 1995; Scoones 2001). Smallholder farmers already manage a set of soil fertility practices and inputs that varies each cropping season by field type, rainfall pattern and the availability of resources such as labour, cattle, cash and market access (e.g. Carter and Murwira 1995; Murwira and Palm 1999). To be accepted, therefore, a new soil fertility technology has to integrate into the existing farming system and offer something new. Farmer participatory research and extension approaches to technology assessment and whole farm management are now widely used for this. Murwira and Palm (1999) and Amede (2003) describe the development and use of decision support guides and trees, that blend farmer knowledge and decision making with crop productivity and residue decomposition data, to select legumes and other organic inputs, and their management for cropping systems, soil types, and environments.

Recent farmer participatory testing of legume-based soil fertility technologies in Malawi and Zimbabwe is leading to insights on where they may best fit on farms (Snapp et al 2002). In subhumid central Malawi, Kamanga (2002) reported that pigeonpea, which is relatively new to farmers in the area, was well liked by most farmers, especially females, and was considered specially suited to wetter sandy soil areas around dambo margins. In semi-arid south-central Zimbabwe, farmers were more interested to grow most legumes (including cowpea and mucuna green manure) on relatively fertile homestead fields rather than shallow toplands or abandoned arable fields (Kamanga et al 2003). Farmers believed that pigeonpea and groundnut could be produced successfully from dry season plantings in the relatively wet dambo/dambo margin areas. Such spatial information about technology performance and farmer interest in niches is now being brought together in whole farm simulation model frameworks (e.g. Rowe and Giller 2003) to better understand interactions and tradeoffs and eventually help farmers optimize their resources. Biophysical soil fertility management initiatives need to be incorporated into farming systems, combined with livelihood strategies and supported by appropriate policies if they are to be effective.

Promotion of Best Bet technology

Different ways have been employed to promote the use of Best Bets in Malawi and Zimbabwe (Mekuria and Waddington 2002). Information brochures were developed on Best Bets and many thousands of copies have been produced and distributed to farmer advisors in extension services, colleges, farmer unions and NGOs. There has been participatory extension and farmer training with the technologies, involving widespread on farm testing, modification and promotion through a range of partnerships with extension services, farmer groups and NGOs. Farmer feedback on the technologies (Snapp et al 2002), their fit into their systems and types of support farmers need have been obtained. Pilot scale activities have been undertaken to multiply and distribute inputs such as seed of Best Bet legumes to farmers, farmer groups, and NGOs. Several technologies were promoted in an extension led initiative over four years with almost 4000 farmers in Chihota Communal Area, Zimbabwe (see Mekuria and Waddington 2002). There, farmer groups conducted 100s of group demonstrations and farmer experiments on several technologies including liming, soybean rotation, groundnut rotation, velvet bean and sunnhemp green manuring. Farmers also got involved in ways to improve the attractiveness of new technologies, particularly soybean, through sharing of cookery recipes and dishes. The project emphasized field days, group learning and farmer-to-farmer sharing of knowledge.

Institutional arrangements such as Commodity Task Forces on maize in Malawi and soybean in Zimbabwe also helped to focus awareness and channel resources into large-scale efforts to disseminate some of the Best Bets. The Maize Task Force in Malawi mounted more than 2000 demonstrations in villages throughout the country on zone specific fertilizer recommendations for maize and this approach helped Malawi's zone-specific fertilizer recommendations to be accepted by the extension service in 1997 and their policy implications to be assessed with Government. These more flexible recommendations are now promoted nationwide. Soil Fert Net members within the Maize Task Force provided the technical input on expected benefits from technology options and helped develop input support strategies for a nationwide initiative to give fertilizer, and maize- and legume-seed starter packs to all 1.8 million smallholder households in Malawi during the 1998/99 and 1999/2000 cropping seasons. Collectively the Government of Malawi, UK Department for International Development, European Union and the World Bank provided over US$23 million for this program in 1998/99. It has had a major impact on human nutrition and household food security in Malawi, and is an excellent example of where technical scientists have influenced Government and donor policy.

The foregoing biophysical and economic assessments show that some Best Bet soil fertility technologies are viable options for southern Africa's smallholders to tackle soil fertility problems and increase maize production and food security. However, the adoption of Best Bet options by local farmers has often been very selective (Mekuria and Waddington 2002), while the number using mineral fertilizers has declined during the last 10 years. Analysis of awareness and adoption patterns in selected sites in Zimbabwe revealed that 86% of farmers use cattle manure, 58% soybean, 35% green manure and only 13% lime (Mano 2003). Institutional factors often constrain adoption. For example, in a recent farmer survey in Mozambique, 12% of farmers had some access to credit and 76% had never seen an extension agent. It is now becoming clear that to enhance the use and adoption of soil fertility Best Bets from promotion initiatives in the region will require policy support to improve access to inputs (particularly seeds and fertilizer) and market linkages for outputs. Adoption of grain legumes will increase when farmers can market their surplus production at favourable prices. For example in Zimbabwe, lack of a cowpea grain market discouraged further adoption of cowpeas by farmers. Details on adoption practices and how they may improve are in *Institutional and policy support is essential to promote the adoption of soil fertility technologies on maize-based smallholder farms in Southern Africa*; a poster paper presented at 4ICSC by Mekuria and Waddington (2004).

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References

Amede T (2003). Pathways for fitting legumes into east African highland farming systems: A dual approach. In 'Grain Legumes and Green Manures for Soil Fertility in Southern Africa: Taking Stock of Progress'. (Ed. SR Waddington). pp. 21-29. (Soil Fert Net-CIMMYT, Harare, Zimbabwe).

Benson TD (1998). Developing flexible fertilizer recommendations for smallholder maize production in Malawi. In 'Soil Fertility Research for Maize-Based Farming Systems in Malawi and Zimbabwe'. (Eds. SR Waddington, HK Murwira, JDT Kumwenda, D Hikwa and F Tagwira). pp. 275-285. (Soil Fert Net and CIMMYT-Zimbabwe, Harare, Zimbabwe).

Blackie MJ (1994). Maize productivity for the 21st century: The African challenge. Outlook on Agriculture 23,189-195.

Budelman A and Defoer T (2000). Not by nutrients alone: a call to broaden the soil fertility initiative. Natural Resources Forum 24,173-184.

Carter S and Murwira HK (1995). Spatial variability in soil fertility management and crop response in Mutoko Communal Area, Zimbabwe. Ambio 24,77-84.

Giller KE, Gilbert R, Mugwira LM, Muza L, Patel BK and Waddington SR (1998). Practical approaches to soil organic matter management for smallholder maize production in southern Africa. In 'Soil Fertility Research for Maize-Based Farming Systems in Malawi and Zimbabwe'. (Eds. SR Waddington, HK Murwira, JDT Kumwenda, D Hikwa, and F Tagwira), pp. 139-153. (Soil Fert Net and CIMMYT-Zimbabwe, Harare, Zimbabwe).

Giller KE (2001). Nitrogen Fixation in Tropical Cropping Systems, 2nd edition. 423 p. (CAB International, Wallingford, UK).

Hikwa D, Murata M, Tagwira F, Chiduza C, Murwira H, Muza L and Waddington SR (1998). In 'Soil Fertility Research for Maize-Based Farming Systems in Malawi and Zimbabwe'. (Eds. SR Waddington, HK Murwira, JDT Kumwenda, D Hikwa, and F Tagwira), pp. 81-84. (Soil Fert Net and CIMMYT-Zimbabwe, Harare, Zimbabwe).

Kamanga BCG (2002). Farmer experimentation to assess the potential of legumes in maize-based cropping systems in Malawi. Risk Management Project Working Paper 02-02. 16p. (CIMMYT, Mexico, DF).

Kamanga BCG, Shamudzarira Z and Vaughan C (2003). On-farm legume experimentation to improve soil fertility in the Zimuto Communal Area, Zimbabwe: Farmer perceptions and feedback. Risk Management Project Working Paper 03-02. 26p. (CIMMYT, Mexico, DF).

Kumwenda JDT, Waddington SR, Snapp SS, Jones RB and Blackie MJ (1996). Soil fertility management research for the maize cropping systems of smallholders in southern Africa: A review. Natural Resources Group Paper 96-02. 35p. (CIMMYT, Mexico, DF).

Kumwenda JDT, Waddington SR, Snapp SS, Jones RB and Blackie MJ (1997). Soil fertility management in southern Africa. In 'Africa's Emerging Maize Revolution' (Eds. D Byerlee and CK Eicher). pp. 157-172. (Lynne Rienner, Boulder, CO, USA).

Kumwenda JDT and Benson TD (1999). Agronomic results of the 1676 on-farm maize fertiliser verification trial sites in Malawi. In 'Maize Production Technology for the Future: Challenges and Opportunities'. Proceedings of the Sixth Eastern and Southern Africa Regional Maize Conference, 21-25 September 1998. pp. 247-249. (CIMMYT and EARO, Addis Ababa, Ethiopia).

Maasdorp BV, Jiri O and Temba E (2004). Contrasting adoption, management, productivity and utilisation of mucuna in two different smallholder farming systems in Zimbabwe. In 'Tropical Legumes for Sustainable Farming Systems in Southern Africa and Australia' (Eds. AM Whitbread and BC Pengelly). pp. 154-163. (ACIAR, Canberra, Australia).

Mafongoya PL, Mugendi DN, Jama B and Waswa BS (2003). Maize based cropping systems in the subhumid zone of east and southern Africa. In 'Soil Fertility Management in Africa: A Regional Perspective' (Eds. MP Gichuru, A Bationo, MA Bekunda, HC Goma, PL Mafongoya, DN Mugendi, HK Murwira, SM Nandwa, P Nyathi and MJ Swift). pp. 73-122. (Academy Science Publishers with TSBF-CIAT, Nairobi, Kenya).

Mapfumo P and Mtambanengwe F (1999). Nutrient mining in maize-based systems of rural Zimbabwe. In 'Maize Production Technology for the Future: Challenges and Opportunities'. Proceedings of the Sixth Eastern and Southern Africa Regional Maize Conference, 21-25 September 1998. pp. 274-277. (CIMMYT and EARO, Addis Ababa, Ethiopia).

Mano R (2003). Economics and institutional challenges affecting technology adoption for sustainable development of African agriculture: A synthesis of experiences from Zimbabwe. Paper presented at the Soil Fertility Mini Symposium, International Conference of Agricultural Economists, 25-31 August, 2003, Durban, South Africa.

Mekuria M and Waddington SR (2002). Initiatives to encourage farmer adoption of soil fertility technologies for maize-based cropping systems in southern Africa. In 'Natural Resources Management in African Agriculture: Understanding and Improving Current Practices'. (Eds. CB Barrett, F Place and AA Aboud). pp. 219-233. (CAB International, Wallingford, UK).

Mekuria M and Siziba S (2003). Financial and risk analysis to assess the potential adoption of green manure technology in Zimbabwe and Malawi. In 'Grain Legumes and Green Manures for Soil Fertility in

Southern Africa: Taking Stock of Progress'. (Ed. SR Waddington). pp. 215-221. (Soil Fert Net-CIMMYT, Harare, Zimbabwe).

Mukurumbira LM (1985). Effects of rate of fertilizer nitrogen and previous grain legume crop on maize yields. Zimbabwe Agricultural Journal 82,177-179.

Murwira HK and Palm CA (1999). Developing multiple fertilizer use strategies for smallholder farmers in southern Africa. In 'Maize Production Technology for the Future: Challenges and Opportunities'. Proceedings of the Sixth Eastern and Southern Africa Regional Maize Conference, 21-25 September 1998. pp. 205-209. (CIMMYT and EARO, Addis Ababa, Ethiopia).

Mushayi PT, Waddington SR and Chiduza C (1999). Low efficiency of nitrogen use by maize on smallholder farms in sub-humid Zimbabwe. In 'Maize Production Technology for the Future: Challenges and Opportunities'. Proceedings of the Sixth Eastern and Southern Africa Regional Maize Conference, 21-25 September 1998. pp. 278-281. (CIMMYT and EARO, Addis Ababa, Ethiopia).

Mwale M, Masi C, Kabongo J and Phiri LK (2003). Soil fertility improvement through the use of green manure in central Zambia. In 'Grain Legumes and Green Manures for Soil Fertility in Southern Africa: Taking Stock of Progress'. (Ed. SR Waddington). pp. 173-177. (Soil Fert Net-CIMMYT, Harare, Zimbabwe).

Rowe E and Giller K (2003). Legumes for soil fertility in southern Africa: Needs, potential and realities. In 'Grain Legumes and Green Manures for Soil Fertility in Southern Africa: Taking Stock of Progress'. (Ed. SR Waddington). pp. 15-19. (Soil Fert Net-CIMMYT, Harare, Zimbabwe).

Sakala W, Cadisch G and Giller KE (2000). Interactions between residues of maize and pigeonpea and mineral N fertilizers during decomposition and N mineralization. Soil Biol. Biochem. 32,679-688.

Sakala WD, Kumwenda JDT, Saka AR and Kabambe VH (2001). The potential of green manures to increase soil fertility and maize yields in Malawi. Soil Fert Net Research Results Working Paper 7. 8 p. (CIMMYT, Harare, Zimbabwe).

Sakala WD, Ligowe I and Kayira D (2003). Mucuna–maize rotations and short fallows to rehabilitate smallholder farms in Malawi. In 'Grain Legumes and Green Manures for Soil Fertility in Southern Africa: Taking Stock of Progress'. (Ed. SR Waddington). pp. 161-163. (Soil Fert Net-CIMMYT, Harare, Zimbabwe).

Sanchez PA, Shepherd KD, Soule MJ, Place FM, Buresh RJ, Izac AMN, Mokwunye AU, Kwesiga FR, Ndiritu CG, and Woomer PL (1997). Soil fertility replenishment in Africa: An investment in natural resource capital. In 'Replenishing Soil Fertility in Africa', SSSA Special Publication 51. (Eds. RJ Buresh, PA Sanchez and F Calhoun). pp 1-46. (Soil Science Society of America, Madison, WI, USA).

Sanchez PA and Jama BA (2002). Soil fertility replenishment takes off in east and southern Africa. In 'Integrated Plant Nutrient Management in Sub-Saharan Africa: From Concept to Practice'. (Eds. B Vanlauwe, J Diels, N Sanginga and R Merckx). pp. 23-45. (CAB International, Wallingford, UK).

Scoones I (2001). (Ed.). Dynamics and Diversity: Soil Fertility and Farming Livelihoods in Africa: Case Studies from Ethiopia, Mali and Zimbabwe. 244 pp. (Earthscan, London, UK).

Scoones I and Toulmin C (1998). Soil nutrient balances, what use for policy? Agriculture, Ecosystems and Environment 71,255-267.

Smaling EMA (1998). Nutrient flows and balances as indicators of productivity and sustainability in sub-Saharan African agroecosystems. Agriculture, Ecosystems and Environment 71,1-346.

Snapp SS, Mafongoya PL and Waddington S (1998). Organic matter technologies for integrated nutrient management in smallholder cropping systems of southern Africa. Agriculture, Ecosystems and Environment 71,185-200.

Snapp S, Kanyama-Phiri G, Kamanga B, Gilbert R and Wellard K (2002). Farmer and researcher partnerships in Malawi: Developing soil fertility technologies for the near-term and far-term. Experimental Agriculture 38,411-431.

Stoorvogel JJ, Smaling EMA and Janssen BH (1993). Calculating soil nutrient balances in Africa at different scales. I. Supranational scale. Fertilizer Research 35,227-235.

Swift MJ, Seward PD, Frost PGH, Qureshi JN and Muchena FN (1994). Long-term experiments in Africa: Developing a database for sustainable land use under global change. In 'Long-term Experiments in Agricultural and Ecological Sciences'. (Eds. RA Leigh and AE Johnston). pp. 229-251. (CAB International, Wallingford, UK).

Waddington SR and Karigwindi J (2001). Productivity and profitability of maize + groundnut rotations compared with continuous maize on smallholder farms in Zimbabwe. Experimental Agriculture 37,83-98.

Whitbread AM, Jiri O, and Maasdorp B (2004). The effect of managing improved fallows of *Mucuna pruriens* on maize production and soil carbon and nitrogen dynamics in sub-humid Zimbabwe. Nutrient Cycling in Agroecosystems 69,59-71.

Woomer PL, Martin A, Albrecht A, Resck DVS and Scharpenseel HW (1994). The importance and management of soil organic matter in the tropics. In 'The Biological Management of Tropical Soil Fertility'. (Eds. PL Woomer and MJ Swift) pp. 47-80. (Wiley-Sayce, Chichester, UK).

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