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RESEARCH ARTICLE

Variable grain legume yields, responses to phosphorus and rotational effects on maize across soil fertility gradients on African smallholder farms

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Abstract Promiscuous soyabean varieties have potential to contribute significantly to income generation, food security and soil N budgets on smallholder farms. One of the major factors limiting this potential is farmers' preference to allocate nutrient resources to food security cereal crops on the most fertile fields, leaving grain legumes to grow on residual fertility on infertile fields. Two experiments were conducted to: (i) compare the current farmer practice with targeting manure and single super phosphate (SSP) to soyabean in a three-year rotation cycle on two fields with different soil fertility: an infertile sandy soil and a more fertile clay soil; and (ii) assess the effects of variability of soil fertility within and across farms on productivity of soyabean and groundnut. In the first experiment, soyabean (<0.2 t ha^{-1}) and maize yields (<0.7 t ha^{-1}) without fertilizer were poor on a degraded sandy soil. Both crops responded poorly to SSP due to deficiency of other nutrients. Manure application significantly increased soyabean and maize yields, led to yield stabilization over three seasons and also significantly increased the proportion of N_2 fixed by soyabean (measured using ^{15}N natural abundance) from 60% to 83%. On the sandy soil, P was used more efficiently and gross margins were greater when SSP and manure were applied to maize in a maize–soyabean rotation. Soyabean and maize yields without fertilizer inputs were larger on clay soil with moderate fertility (0.4–0.7 t ha^{-1} and 2.0–2.3 t ha^{-1} respectively) and were significantly increased by application of SSP and manure. Within rotations, P recovery was higher when manure and SSP were applied to maize (43 and 25%) than when applied to soyabean (20 and 19%). However, application of manure to soyabean on the clay was more profitable than application to maize for individual crops and within rotations. In the second experiment, soyabean and groundnut yields were largest (~ 1 and ~ 0.8 t ha^{-1} respectively) on plots closest to homesteads on wealthy farms, which were more fertile due to good past management. Yields were poor (< 0.5 t ha^{-1}) on other fields which previously had received little nutrient inputs. Soyabean and groundnut yields correlated well with available P (R^2 = 0.5–0.7) and soil organic C (SOC) contents (R^2 = 0.4–0.6). For smallholder farmers to maximise benefits from legume production they need to focus attention on the more fertile plots, although production should be optimized in relation to maize. Targeting nutrients to maize as currently practiced by farmers was more efficient and economic under poor soil fertility conditions, whilst potential exists to increase income by targeting manure to soyabean on the more fertile soils.

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Introduction

Continuous cultivation of maize (*Zea mays* L.) as a sole crop with little addition of nutrients has contributed to depletion of soil fertility on smallholder farms in sub-Saharan Africa (Sanchez et al. 1997). Legumes have the potential to contribute to the soil N budget through biological N_2-fixation (BNF), and are potentially a cheap alternative to mineral N fertilizers for providing N to crops (Boddey et al. 1997; Giller et al. 1997). Grain legumes are more attractive to most smallholder farmers than other legume-based technologies, such as green manures, which do not contribute directly to income or food security (Giller 2001; Snapp et al. 2002). However, most grain legumes have high N harvest indices and may only have a small or net negative contribution to the soil N budget (Giller and Cadisch 1995). Grain legumes with low N harvest indices, such as, promiscuous varieties of soyabean (*Glycine max* [L.] Merrill), produce good grain yields and leave substantial amounts of N in residues for following crops (Mpepereki et al. 2000; Vanlauwe et al. 2003). Promiscuous soyabean varieties are, therefore, considered suitable for smallholder farmers as they have multiple uses, from selling soyabean as a cash crop for oil processing, to use as nutritious food and improvement of crop yields (Mpepereki et al. 2000).

Groundnut is currently the main grain legume cultivated by smallholder farmers in Zimbabwe, but its production has declined over the years, both in terms of area planted and the yields attained (Waddington and Karigwindi 2001). The thrust to promote production of grain legumes on smallholder farms has recently shifted from groundnut to soyabean, which resulted in rapid adoption of soyabean in some districts of Zimbabwe from 55 farmers in 1996 to 5000 in 1999. Production of soyabean by smallholder farmers also increased from 415 t in 1995 to 12,500 t in 2002 (Agricultural Economics and Marketing Division 2001). Similarly, production of soyabean is also expanding rapidly in the smallholder sector in West Africa (Sanginga et al. 2002a).

Major challenges exist to enhance productivity of soyabean and other grain legumes under smallholder farm conditions (Snapp et al. 2002). Soils cultivated by smallholder farmers are predominantly infertile and sandy, with small contents of soil organic matter, available P and bases, and are also acidic. Under such conditions, productivity of grain legumes and BNF are constrained by poor availability of nutrients, especially P (Giller 2001). Other factors constraining production of grain legumes are directly linked to farmers' preferences, as they favour the main staple crop, maize, over grain legumes, to ensure food security instead of income generation (Giller et al. 1997; Svubure 2000). As farmers lack adequate nutrient resources to fertilize all crops, they prefer to apply fertilizers to maize, the staple food security crop and rarely target fertilizers directly to grain legumes, that are mostly grown on residual fertility. Farmers also reserve the largest areas on the most fertile plots, often closest to homesteads, for maize, and allocate small portions of outfields poor in fertility to production of grain legumes (Waddington and Karigwindi 2001; Zingore et al. 2007). The poor productivity of grain legumes has led to low N_2 fixation (<5 kg N ha^{-1} year^{-1}) on smallholder farms and to small planted areas (often $<10\%$) of the cultivated area (Giller 2001). Chikowo et al. (1999) demonstrated that P fertilizers and manure could be used more efficiently in groundnut–maize rotations when applied to groundnut. Potential also exists to increase yields of grain legumes by growing them on larger areas of more fertile fields on smallholder farms (Okogun et al. 2005).

For effective integration of grain legumes into smallholder farming systems dominated by maize, there is need to focus attention on alternative agronomic practices that could improve yields of not only grain legumes, but more importantly maize, by increasing the overall supply of N and efficiency of resource use. This study was conducted to investigate two key questions related to farmer management practices on productivity of grain legumes and maize: (i) Is the current practice of targeting nutrient resources to maize and growing grain legumes on residual fertility more efficient than targeting nutrients to grain legumes, so that maize grown on residual fertility would capitalize on larger amounts of N_2 fixed?; and (ii) Is there variability in productivity of grain legumes and their response to P along gradients of decreasing soil fertility with distance from the homesteads and does this variability have implications on the impact of grain legume production at the farm level? We conducted two on-farm field experiments in Zimbabwe to assess: (i) the potential to improve nutrient use efficiencies in soyabean–maize rotations by targeting manure and mineral P to soyabean on contrasting soil types; and (ii) the productivity of soyabean and groundnut, and their response to P, across soil fertility gradients on farms owned by farmers with differing resource endowment.

Materials and methods

Study site

The experiments were conducted on smallholder farmers' fields in Murewa district, northeast Zimbabwe (17°49′ S, 31°34′ E). The area receives 750–1000 mm of rainfall annually, distributed in a unimodal pattern between November and April. The total rainfall for the second and third seasons was less than the long-term average for Murewa (830 mm), and all three seasons were characterised by prolonged periods of poor rainfall at different stages of crop development. Total rainfall was least during the third season, in which there was also a prolonged mid-season drought. The dominant soils in the area are sandy soils (Lixisols) derived from granite, which are inherently poor in fertility. Dolerite intrusions into the granite give rise to smaller areas of more fertile red clay soils (Luvisols) in close proximity to the granitic sands.

Field experiments

Experiment 1

The experiments were designed following detailed characterization of soil fertility variability within and across farms and farmers' resource use strategies through different participatory tools including focus group discussions and resource flow mapping (Zingore et al. 2007). One of the key research areas for improving resource use efficiency and farmers' income identified by farmers was targeted application of scarce organic and mineral nutrient resources to the main cereal and grain legume crops. In the first set of experiments, researcher management was required for consistent experimentation across sites and over three seasons in both fertilizer application and yield measurements. This was also necessary to obtain accurate data for calculation of nutrient use efficiencies and nutrient contents of crop residues.

The experiment was conducted on two smallholder farms for three cropping seasons (2002/03–2004/05). One site was located on a degraded sandy soil outfield (3% clay, 5% silt and 92% sand) which had the following chemical properties: 0.3% SOC, 3 mg kg^{-1} available P, pH (water, $CaCl_2$) of 4.5, 3.9 and a cation exchange capacity (CEC) value of 2 cmol$_c$ kg^{-1}. The second site was on a more fertile red clay soil (34% clay, 18% silt and 48% sand) with the following chemical properties: 0.9% SOC, 12 mg kg^{-1} available P, pH (water, $CaCl_2$) of 5.6, 4.9 and a CEC value of 16 cmol$_c$ kg^{-1}.

At both sites soyabean and maize were planted in a two-course rotation for three seasons: soyabean–maize–soyabean for the rotation in which soyabean was grown in the first season, and maize-soyabean–maize where maize was grown in the first season. A promiscuous soyabean variety, Magoye, which nodulates freely with indigenous rhizobia (Musiyiwa et al. 2005) was used as the test cultivar. Continuous sole crops grown without any amendments were included to provide baseline yields of maize and soyabean. Cattle manure and single super phosphate (SSP) were applied to crops in the first and last season. The experiment consisted of the following treatments:

i. Soyabean-soyabean-soyabean (no SSP or manure applied)
ii. Maize-maize-maize (no SSP or manure applied)
iii. Soyabean–maize–soyabean (no SSP or manure applied)
iv. Soyabean–maize–soyabean (SSP applied in the first and third seasons)
v. Soyabean–maize–soyabean (manure applied in the first and third seasons)
vi. Maize–soyabean–maize (no SSP or manure applied)
vii. Maize–soyabean–maize (SSP applied in the first and third seasons)
viii. Maize–soyabean–maize (manure applied in the first and third seasons)

The manure and SSP were applied separately as farmers use manure as a substitute of basal P fertilizers and do not apply these in combination. SSP was applied at the recommended rate for maize in the study area (30 kg P ha^{-1}) and manure also was applied to provide 30 kg P ha^{-1}. Only one rate of P was applied due to the limited field sizes and the high number of treatments per site. The same quality of manure, collected from one farm, was used at the two sites in the first and third seasons. The manure that was used in the 2002/03 season had a P content of 0.22% and that used in the 2004/05 season had a P content of 0.19%; the manures were applied at 13.6 t ha^{-1} and 15.8 t ha^{-1} respectively to supply P at 30 kg ha^{-1}. Although farmers in Murewa have limited amounts of manure, they commonly apply the manure on small cropped areas thereby achieving high application rates of more than 10 t ha^{-1}. Manure contributed other nutrients, besides P. The major nutrients added were: 122 kg N ha^{-1}; 27 kg Ca ha^{-1}; 5 kg Mg ha^{-1} and 54 kg K ha^{-1} in the first season, and 126 kg N ha^{-1}; 28 kg Ca ha^{-1}; 10 kg Mg ha^{-1} and 47 kg K ha^{-1} in the third season. In the first and third seasons, 70 kg N ha^{-1} (ammonium nitrate) was applied to all maize plots, except the continuous maize. The N was split applied (35 kg ha^{-1}) at about three and six weeks after crop emergence.

The soyabean residues were incorporated in the top 20 cm after harvest in the first season. Maize residues, which farmers invariably use to feed cattle, were removed to mimic farmers' management. The residual effects of SSP and manure applied to maize and soyabean in the first season on the subsequent crop in rotation were examined in the second season. All the maize plots following soyabean on the granitic sand were split into sub-plot treatments: (i) 70 kg N ha^{-1} (also applied as ammonium nitrate at about 3 and 6 weeks after emergence); and (ii) no N added. The plots on the red clay soil (6 m × 4.5 m) were smaller than on the sandy soil (6 m × 9 m) due to a smaller area of the field on the clay soil; hence the maize following soyabean on the clay soil was all top-dressed with 70 kg N ha^{-1} in the second season. The experiment at each site was set up in a completely randomised block design with three replicates.

Experiment 2

Farmers of different wealth status manage their plots differently and this leads to differences in soil fertility between fields of wealthy and poor farmers. Different farm and field typologies (FT) were developed (Zingore et al. 2007) to allow assessment of the implications of differences in wealth status and differences in management of plots on productivity of groundnut and soyabean and their response to P fertilizer. Four classes of farm resource groups (RG) were generated using indicators given by farmers during focus group discussions (Table 1). The farmers in the rich categories (RG1 and RG2) owned cattle and used manure to fertilize crops. The RG1 and RG2 farmers also used larger amounts of mineral fertilizers than farms in the RG3 and RG4 categories. FT were developed on farms in the different wealth categories to map variability in soil fertility within farms. Farmers preferably applied nutrient resources to fields closest to homesteads leading to gradients of decreasing soil fertility with increasing distance from homesteads and on this basis fields at different distances from homesteads were grouped into three categories on RG1–RG3 farms: homefield (FT1), mid-distant (FT2) and outfields (FT3). The poorest households (RG4) had small farms, which were only divided into two fields types (FT1 and FT2). For further details of the farm and FT see Zingore et al. (2007).

On the sandy soil, the experiment was established on 33 fields covering a wide range of soil chemical properties: 3 farms × 3 farms types × 3 plot types for RG1–RG3 farms and 3 farms × 2 plot types for RG4 farms. The 33 fields were on 25 different farms, with the experiment established on one field on 17 farms and on two different field types on each of the other 8 farms. On each field, four plots (5 m × 5 m) were marked out with the following treatments: groundnut without inputs; groundnut + 30 kg P ha^{-1} as SSP; soyabean without inputs; and soyabean + 30 kg P ha^{-}1 as SSP. On the clay soil, the plots were selected according to three fertility categories defined by available P status: high (>10 mg kg^{-1}); medium (5–10 mg kg^{-1}); and low (<5 mg kg^{-1}). Three fields were selected in each fertility category, so that nine fields on nine different farms were selected on the clay soil. Fewer fields were selected on the clay soil because few farms were located on it.

Stover and grain determination

At harvest, maize grain and stover yields were determined from net plots (2 m × 2.7 m), with

Table 1 Indicators of the wealth status of the farmers and the characteristics of the different wealth groups at Murewa, Zimbabwe

Indicators of wealth status and other characteristics	Resource group 1 (very rich)	Resource group 2 (rich)	Resource group 3 (poor)	Resource group 4 (very poor)
Farm size	Farm size about 3 ha	Farm size about 3 ha	Farm sizes <3 ha	Farm sizes about 1 ha
Livestock ownership	>10 cattle	<10 cattle	Do not own cattle, but have goats and chickens	Do not own cattle, but have goats and chickens
Farming implements	Scotch cart, plough, cultivator, harrow and wheelbarrow and all small implements	All implements but rarely a scotch cart	Small implements such as hoes, shovels, axes and wheel burrows	Small implements such as hoes, shovels, axes and wheel burrows
Draught power	Oxen for draught power	Oxen for draught power	No draught power	No draught power
Production orientation	Produce grain and vegetables for sale	Produce grain and vegetables for sale	Grain crops grown for subsistence, sell vegetables only at farm gate	Grain crops grown for subsistence, sell vegetables only at farm gate
Hire or sell of labour	Afford hiring labour	Do not regularly hire labour	Cannot afford to hire labour	Sell labour locally
Mineral fertilizer use	>500 kg AN per season	<500 kg AN per season	<500 kg AN per season	Do not regularly use mineral fertilizers

Adapted from Zingore et al. (2007)

soyabean biomass yields determined at flowering from micro-plots outside the net plot and grain yields determined after 4 months, from the net plot. Soyabean and groundnut grain and stover in Experiment 2 were determined from entire 5 m × 5 m plots after four months. Fallen soyabean leaves were picked and weighed together with the stover. Moisture content was determined for grain samples using a moisture meter and grain yields were corrected to 12.5% moisture content. Stover samples were dried in the oven at 70°C for 72 h to determine moisture content.

Plant material analysis and estimation of N_2-fixation

Stover and grain samples for maize and soyabean from Experiment 1 were analysed for total N content using the micro-Kjeldahl method and for total P using the modified Oslen method (Anderson and Ingram 1993). The proportion of N fixed by the soyabean was measured only in the third season using the ^{15}N natural abundance method with maize as the non-N_2-fixing reference. The maize samples used as reference were collected from the continuous maize plots. The $\delta^{15}N$ analysis was performed at the Stable Isotope Facility, UC Davis. The $\delta^{15}N$ in soyabean and maize seed and residues were determined using a continuous flow IRMS (Europa Scientific Hydra 20/20, SerCon, Cheshire, UK). The ^{15}N values ($\delta^{15}N$) are presented as the per mil (‰) deviation of that sample from the isotopic composition of a reference compound:

$$\delta^{15}N(‰) = 1000 \times [(R_{sample}/R_{reference}) - 1]$$

where R is the isotope ratio (^{15}N:^{14}N) and the reference compound is atmospheric N_2 with a ratio of (0.0036765).

The proportion of legume N derived from N_2-fixation was subsequently calculated as:

$$\% N_2\text{ - fixation} = 100 \times \frac{\delta^{15}N\text{ (reference crop)} - \delta^{15}N\text{ (legume N)}}{\delta^{15}N\text{ (reference crop)} - B}$$

where $\delta^{15}N$ (reference crop) is the $\delta^{15}N$ of the reference plant grown in the same soil as the legumes. B is the $\delta^{15}N$ of soyabean when grown with N_2 as the only source of N, a measure of isotopic fractionation during N_2-fixation. The B value of −1.4‰ for soyabean from Boddey et al. (2000) was used.

Calculation of P uptake efficiencies

Apparent P recovery efficiencies (RE_P) were calculated for maize and soyabean in Experiment 1 using the formula:

$$RE_P = \frac{P_{uptake} - P_{uptake(0P)}}{P_{applied}}$$

Where P_{uptake} is the P taken up by the crop from plots amended with SSP and manure, $P_{applied}$ the P applied and $P_{uptake(0P)}$ the P taken up by the crops in rotations without P applied. The residual recovery of P applied in the first season by the crops grown in the second season was expressed as a percentage of P applied in the first season. P recovery efficiency for complete rotations was calculated by adding the efficiencies for the individual seasons (season 1 and 2).

Gross margin analysis

The economic benefits of targeting SSP and manure to the maize and soyabean (Experiment 1) were calculated for individual crops each season by subtracting the field value of the output from the field value of inputs (fertilizers and seed). For each season, the field value of inputs included the cost of fertilizers and seed at the time of planting on the District market where farmers procure inputs and the costs of transporting these inputs to the farms. Also for each season, the field value of the output was taken as the price of soyabean and maize grain at the District market at the time of harvesting, and this did not include the costs of transportation and marketing. The yields from the experiments were reduced by 10% to allow for the lower yields expected if the crops were managed by farmers. There is no market for manure in the study area and farmers consider it a free resource; hence the value of manure used for analysis of gross margins was estimated using two indirect approaches. In the first approach manure was given the same value as that of the amount of fertilizer supplying a similar amount of P. Although manure supplies other nutrients and organic matter, only the value of P was considered since this is the focus nutrient of this study (Moll 2003). Manure use is labour intensive and in the second approach the cost of labour required to dig manure from the kraal, transport and apply it in the fields was added to the value of manure estimated in the first approach. Including labour costs is practical for labour-constrained households where opportunity costs for labour are high. The costs of inputs and outputs used for gross margin analysis for the three seasons are presented in Table 2. For each treatment, the gross margins for the three seasons were obtained by adding the gross margins for the individual seasons. The discount factor $[1/(1 - r)^t]$ was used to adjust gross margins calculated each season to the values for the first season. Where r is the interest in US$, estimated at 5%, and t the number of years.

Soil analysis

Soils were sampled (0–20 cm) in all fields for Experiments 1 and 2 and prepared for analysis by air-drying and sieving (<2 mm). The soils were analysed for soil organic C (SOC) using the Walkley-Black method, available P using the Bray method, CEC using the ammonium acetate method and pH (1:2.5 w/v ratio) was measured in water and 0.01 M $CaCl_2$ (Anderson and Ingram 1993).

Statistical analysis

Plant biomass and grain yields were analysed for each of the three seasons by analysis of variance using GENSTAT Release 7.0. Regression analysis was used to examine relationships between variability in

Table 2 Prices for inputs and outputs used for analysis of gross margin for the three seasons

	Unit	Year 1	Year 2	Year 3
Inputs				
Single super phosphate	US$ kg^{-1} P	2.10	–	2.40
Ammonium nitrate	US$ kg^{-1} N	1.40	–	1.30
Manure	US$ kg^{-1} P	2.10	–	2.40
Manure labour	ha^{-1}	90	–	90
Maize seed	US$ kg^{-1}	0.70	0.70	0.80
Soyabean seed	US$ kg^{-1}	0.90	1.00	1.00
Outputs				
Maize grain	US$ t^{-1}	280	280	340
Soyabean grain	US$ t^{-1}	820	700	740
Labour for manure aplication	US$ ha^{-1}	90		90

soyabean and groundnut productivity and available P and organic C in the soil. The Student's *t*-test was used to evaluate the effects of SSP on soyabean and groundnut grain yields in Experiment 2. The *t*-test was performed for three groups of plots: whole range of plots; plots with available P less than 5 mg kg^{-1} (50% of the plots); and plots with available P of 5 mg kg^{-1} or greater. The Student's *t*-test was also used to compare increases in soyabean yields when P was applied with those for groundnut.

Results

Yields of soyabean and maize in response to P and manure applications on contrasting soils

Soyabean and maize grain yields on plots without nutrient inputs were poor on the depleted sandy soil (Fig. 1a). Direct application of SSP did not significantly increase soyabean yields on the sandy soil, but the yields were significantly increased with manure: from 0.2 t ha^{-1} to 0.6 t ha^{-1} in the first and from 0.1 t ha^{-1} to 0.4 t ha^{-1} in the third season (Fig. 1a). Maize yields on the sandy soil were significantly increased by addition of N without P in the first season, but the effects of N alone were not significant in the third season (Fig. 1b). On the sandy soil, the largest maize yields were on plots where manure and mineral N fertilizer was applied. The maize yields when N was applied with SSP (1.1–1.5 t ha^{-1}) were significantly less than the 2–3 t ha^{-1} achieved with manure. For all seasons, the yields for the treatments without amendments were significantly greater on the more fertile clay soil, and these ranged from 0.5 t ha^{-1} to 0.6 t ha^{-1} for soyabean and from 1.8 t ha^{-1} to 2.3 t ha^{-1} for maize (Fig. 2). On the clay soil, soyabean yields were significantly increased by addition of SSP and manure. Maize grain yields for the fertilized plots decreased in the order: N+manure ~ N+SSP > N alone, in the first season, and N+manure > N+SSP > N alone, in the third season (Fig. 2b).

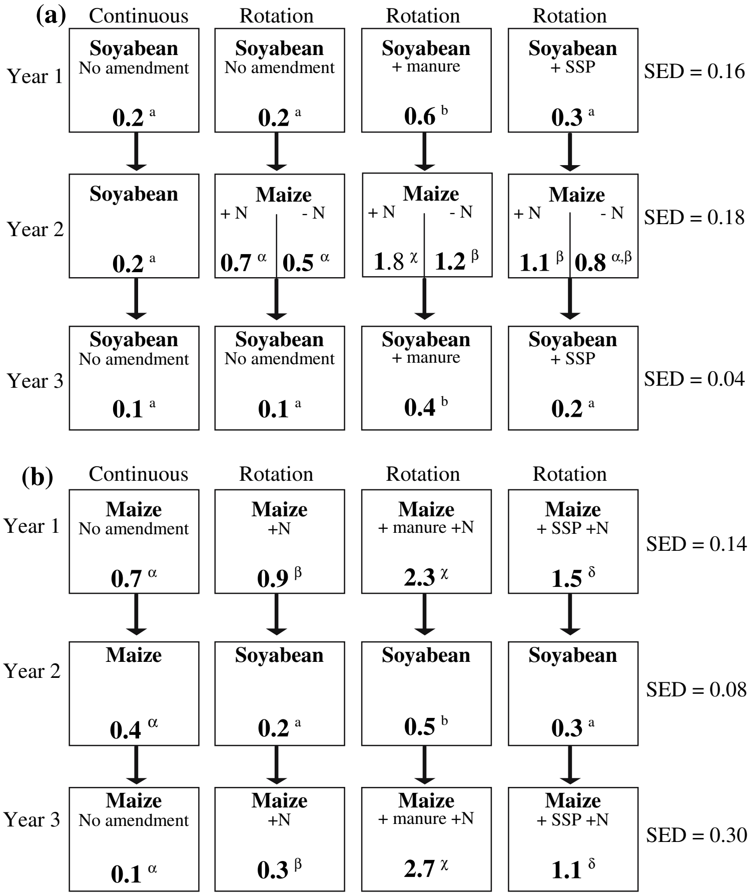

Fig. 1 Grain yields (t ha^{-1}) for maize and soyabean under direct application of SSP or manure, or grown on residual fertility for rotations that started with soyabean (**a**) and maize (**b**) on the granitic sandy soil at Murewa, Zimbabwe. For each year, soyabean yields followed by a different letter and maize yields followed by a different symbol were statistically different ($P < 0.05$). (N.B. soyabean and maize yields cannot be compared with each other)

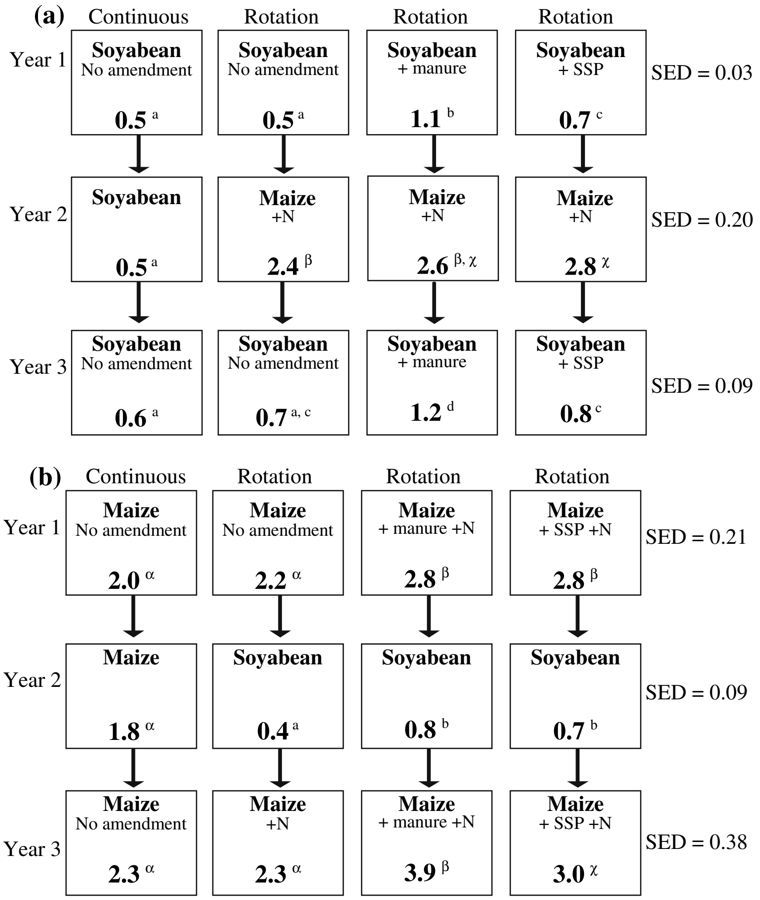

Fig. 2 Grain yields (t ha^{-1}) for maize and soyabean under direct application of SSP or manure, or grown on residual fertility for rotations that started with soyabean (**a**) and maize (**b**) on the red clay soil at Murewa, Zimbabwe. For each season, soyabean yields followed by a different letter and maize yields followed by a different symbol were statistically different ($P < 0.05$). (N.B. soyabean and maize yields cannot be compared with each other)

Effects of soyabean fertilization on grain and stover N contents and N_2-fixation

The total amounts of N accumulated by soyabean grown without fertilizer inputs on the sandy soil were very small (<15 kg N ha^{-1}). On plots where SSP was applied, total N contents in soyabean grain and stover were 25 and 15 kg ha^{-1} for the first and third seasons (Table 3a). Total N in soyabean grain and stover was significantly increased above all other treatments to 44 and 31 kg ha^{-1} when manure was applied in the first and third seasons respectively. In addition, the greatest proportion of N_2 fixed by soyabean on the sandy soil in the third season was on the plots where manure was applied (83%), which was significantly greater than the 61–64% for soyabean without amendments and those amended with SPP (Table 3a). The greater proportion of above ground N in soyabean was in the grain (N harvest indices ranged between 0.52 and 0.62). Soyabean accumulated less N when grown on residual fertility than when manure and SSP were applied directly in the first season (Table 3a).

The amount of N in soyabean biomass was larger on the clay soil than the sandy soil. For the first and third seasons when manure and SPP were directly applied, the largest amounts of N were accumulated on plots with manure (69 and 81 kg N ha^{-1}) followed by plots with SSP (48 and 59 kg N ha^{-1}) and were least on the plots without any amendment (37 and 44 kg N ha^{-1}) (Table 3b). Except for the SSP treatment, the proportion of N derived from N_2-fixation on the clay soil in the third season was >65%.

Residual effects of SSP and manure on maize and soyabean production and rotational effects of soyabean on maize

In the second season, the maize grain yields following soyabean without any amendments on the sandy

Table 3 Amount of N in soyabean grain and residues and proportion of N_2 fixed (2004/05 season) during the the two course rotation: soyabean (2002/03)—maize—soyabean (2004/04) with P directly applied to soyabean; and maize—soyabean (2003/04)—maize with P applied to maize at Murewa, Zimbabwe, (a) granitic sandy soil and (b) red clay soil

	2002/03 (P directly applied)		2003/04 (residual effects)		2004/05 (P directly applied)				
	Grain N (kg ha^{-1})	Stover N (kg ha^{-1})	Grain N (kg ha^{-1})	Stover N (kg ha^{-1})	Grain N (kg ha^{-1})	Stover N (kg ha^{-1})	δ^{15}N (‰)	%N from N_2-fixation	Amount N fixed (kg ha^{-1})
(a)									
Continuous sole soyabean	7.4	5.4	8.2	6.4	3.9	2.8	0.52	61	4.1
Rotation no amendment	9.4	7.1	9.3	7.3	5.3	3.6	0.36	64	5.7
Rotation + manure	24.3	19.5	19.6	12.1	18.5	12.7	−0.55	83	25.9
Rotation + SSP	13.1	12.0	10.6	7.1	8.1	6.4	0.50	61	8.8
SED	3.1	3.3	1.2	1.2	1.7	0.8		5.5	
(b)									
Continuous sole soyabean	21.2	16.1	18.7	14.0	28.2	16.1	0.16	67	29.7
Rotation no amendment	22.7	16.3	16.8	15.7	28.9	17.9	−0.46	80	37.4
Rotation + manure	46.3	22.6	33.7	21.6	55.2	26.1	−0.26	76	61.8
Rotation + SSP	29.6	18.0	26.3	17.9	38.6	19.9	1.43	40	23.4
SED	4.2	3.0	4.0	3.1	4.7	1.4		12	

^{15}N maize reference = 3.50 (sandy soil) and 3.31 (clay soil)

Table 4a Apparent P recovery efficiency (%) with SSP and manure directly applied to maize and soyabean

	Granitic sandy soil				Red clay soil			
	Soyabean		Maize		Soyabean		Maize	
	2002/03	2004/05	2002/03	2004/05	2002/03	2004/05	2002/03	2004/05
Manure	8	7	28	36	10	12	19	34
SSP	3	2	16	12	5	5	21	19

[a] Soyabean

[b] Maize

Table 4b Apparent P recovery efficiency (%) with residual P recovery in the second season after application

	Granitic sandy soil			Red clay soil	
	Soyabean	Maize		Soyabean	Maize
		−N	+N		+N
Manure	6	12	19	9	10
SSP	1	4	10	6	14

[a] Soyabean

[b] Maize

Table 4c Apparent P recovery efficiency (%) with total efficiencies for the two-year rotation at Murewa, Zimbabwe

	Granitic sandy soil			Red clay soil	
	Soyabean		Maize	Soyabean	Maize
Crop sequence	Sb[a]–Mz[b] (0N)	Sb–Mz (+N)	Mz(+N)-Sb	Sb–Mz (+N)	Mz(+N)-Sb
Manure	20	27	34	20	43
SSP	7	13	17	19	25

[a] Soyabean

[b] Maize

soil was not significantly different from those of the continuous maize plots, both with and without N applied (Fig. 1). Maize yields were largest on plots following soyabean produced with manure: 1.2 t ha^{-1} without N and 1.8 t ha^{-1} with N. The residual effects of manure applied to maize in the first season on soyabean grain yield in the second season were also strong and produced significantly greater yields than the other treatments (Fig. 1b).

Maize grain yields on clay soil in the second season were least on the plots where maize was cropped continuously without fertilizer inputs (Fig. 2b). Manure and SSP applied to maize in the first season led to significantly greater soyabean yields in the second season than those for soyabean following maize without amendments (Fig. 2b). However, soyabean was less productive on the clay soil when grown on residual fertility in the second season than with manure in the first season.

P recovery efficiencies by soyabean and maize: Direct application, residual effects and complete rotations

Apparent P recovery efficiencies (RE_P) when manure and SSP were applied directly to maize were greater than when applied to soyabean in the first and third seasons (Table 4a). The RE_P by soyabean were poor on the sandy soil (7–8% for manure and 2–3% for SSP), and less than the RE_P by maize (28–36% with manure and 12–16% with SSP). RE_P by soyabean were also poor on the clay soil and these were less than those for maize (Table 4a). Efficiency of P recovery from manure was greater than from SSP, except for maize on the clay soil for 2002/2003 season, when the RE_P was greater for the SSP treatment.

The residual RE_P for soyabean on the two soils was <10% and addition of N led to a substantial increase in RE_P for maize on the sandy soil (Table 4b). The RE_P of P applied to soyabean in the first season by the maize crop in the second season were less than direct RE_P in the first season on both soils (Table 4b).

For the complete crop rotations in the first two seasons, P was recovered most efficiently when applied to maize with addition of N in the first season than when applied to soyabean. Soyabean (SSP)–maize rotation recovered the least amount of P applied (7%) on the sandy soil, when no N was applied to the maize crop and 13% when N was applied. The greatest RE_P was observed for the maize (manure)—soyabean rotation on the clay soil, where the cumulative RE_P was 43% over the two seasons.

Economics of targeting P in soyabean-maize rotations

In the first season, the financial benefits from maize and soyabean without fertilizer inputs were small on the granitic sandy soil (Table 5a). Greatest benefits for both maize and soyabean were obtained with manure, even with the cost of labour for manure use included. Maize was more profitable than soyabean when manure and SSP were applied, despite the extra cost of mineral N added to maize. In the second season, addition of N alone to maize led to a reduction in gross margins for all treatment without manure (Table 5b). On the clay soil, maize was more profitable than soyabean without P applied or with SSP, but soyabean was more profitable when manure was applied in the first and third seasons (Table 5a, c). Application of N in combination with manure or with SSP was required to substantially increase gross margins, which were reduced with application of mineral N alone in the first and third seasons.

On the sandy soil, gross margins for maize following soyabean in the second season decreased in the order: manure > SSP > no amendment, both with N added and without N added (Table 5b). On the clay soil, greatest gross margins were on maize plots following soyabean amended with manure in the first season.

Overall, gross margins for the three seasons for continuous soyabean and maize plots did not differ substantially with rotations without addition of P, which were also small due to poor yields (Table 5d). On the sandy soil addition of manure to maize led to greater gross margins within rotations than addition to soyabean, whilst the differences for SSP were marginal. The gross margins for three-year rotations with SSP were <40% of similar crop sequences with

Table 5 Gross margins (US\$ ha^{-1}) for the first (a), second (b) and third (c) seasons and cumulative gross margin (d) of maize-soyabean rotations amended with manure or single super phosphate at Murewa, Zimbabwe

	Granitic sandy soil			Red clay soil	
(a)					
First season crop	Soyabean	Maize		Soyabean	Maize
Continuous sole crop	89	139		304	468
Rotation no amendment	119	94		310	416
Rotation + manure (a)	298	394		650	496
Rotation + manure (b)	212	308		564	410
Rotation + SSP	125	183		379	510
(b)					
Second season crop	Maize (0N)	Maize (+N)	Soyabean	Maize	Soyabean
Continuous sole crop	78	-	75	257	228
Rotation no amendment	103	53	92	442	196
Rotation + manure	260	298	229	489	428
Rotation + SSP	174	225	109	468	339
(c)					
Third season crop	Soyabean	Maize		Soyabean	Maize
Continuous sole crop	12	-8		316	359
Rotation no amendment	32	-38		331	279
Rotation + manure (a)	136	332		573	489
Rotation + manure (b)	66	254		495	419
Rotation + SSP	7	17		366	338
(d)					
Crop sequence	Sb[a]-Mz[b]-Sb (0N)	Sb-Mz-Sb (+N)	Mz-Sb-Mz (+N)	Sb-Mz-Sb (+N)	Mz-Sb-Mz (+N)
Rotation no amendment	254	204	148	1083	891
Rotation + manure (a)	694	732	955	1712	1413
Rotation + manure (b)	538	576	791	1548	1257
Rotation + SSP	306	357	309	1213	1187

[a] Sb = soyabean

[b] Mz = maize

Manure (a) = manure value similar to fertilizer supplying 30 kg P ha^{-1}; manure (b) = manure valued as fertilizer supplying 30 kg P ha + cost of labour for using manure to fertilize crops

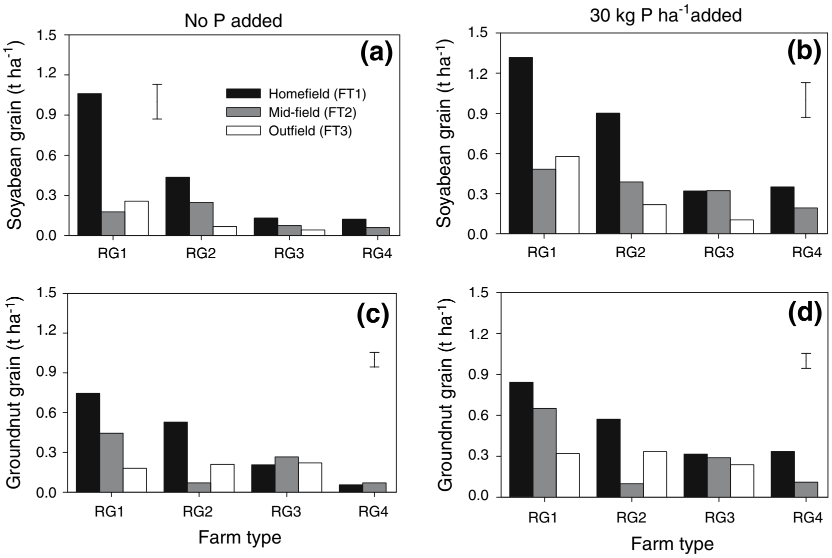

Fig. 3 Grain yields for soyabean and groundnut (±P) across different plots belonging to farmers of different wealth categories on the sandy soil at Murewa (**a**) soyabean −P, (b) soyabean +P, (c) groundnut −P and (d) groundnut +P. Bars represent SEDs

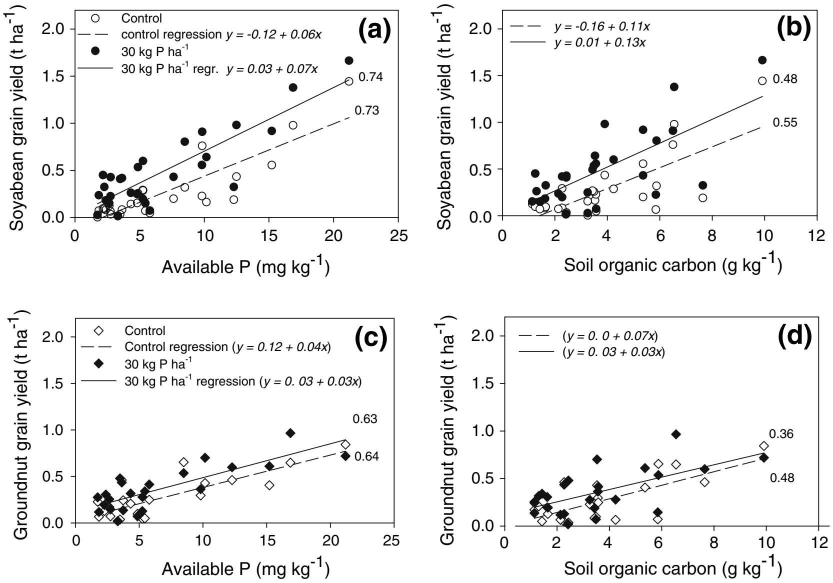

Fig. 4 Relationships between available P and soil organic C (SOC) with soyabean and groundnut yields with and without P fertilizer added at Murewa (**a**) soyabean yields plotted against available P; (**b**) soyabean yields plotted against SOC; (**c**) groundnut yields plotted against available P and; (**d**) groundnut yields plotted against SOC

manure. On the clay soil, gross margins were higher for maize than soyabean when the crops were grown continuously without fertilizer inputs. The profitability of rotations irrespective of crop sequence were in the order: manure > SSP > no P added. The returns from manure application within rotations were still greater than all the other treatments, even after deducting the cost of labour for manure application which amounted to about US$160 for the three seasons. Within rotations, gross margins for the treatment in which manure was applied to soyabean was substantially greater than when applied to maize (Table 5d). Although use of SSP was more economically viable when targeted to maize than soyabean for specific crops, within rotations SSP was used more profitably when applied to soyabean.

Variability of soyabean and groundnut yields on farmers' fields

Soyabean grain yields were largest on the plots closest to homesteads (FT1) on the farms in the wealthiest category (RG1), where more than 1 t ha^{-1} was harvested without P added, compared with less than 0.3 t ha^{-1} on FT2 and FT3 (Fig. 3a). Without P, the yields for soyabean were poor on the RG2, RG3 and RG4 farms and did not significantly differ with farm or field type. The greatest amount of soyabean stover (about 1.5 t ha^{-1}) was produced on FT1 on the RG1 and RG2 farms.

Addition of P increased soyabean yields by 0.2–0.3 t ha^{-1} across the different field types on the RG1 farms, and as a result the gap in yield between the different field types was not reduced by addition of P (Fig. 3b). Soyabean grain yields responded more strongly to SSP on the FT1 of the RG2 farms the FT2 and FT3 and this created a large gradient in yields with SSP between the homefields and the midfields and outfields (Fig. 3b). The yields across all fields on the RG3 and RG4 farms remained poor (<0.4 t ha^{-1}) even when P was added.

The differences in groundnut yields between different fields on the RG1 farms were less than those for soyabean (Fig. 3c). The groundnut yields for control plots on the homefield of the RG2 farms were significantly larger than the midfields and outfields, but the differences in yields between different types of fields on the RG3 and RG4 farms were small. Response of groundnut grain yields to addition of P was not significant on most fields (Fig. 3d). Groundnut stover was over 1 t ha^{-1} on FT1 on RG1, RG2 and RG3 farms, but was <0.8 t ha^{-1} on the rest of the plots. On the clay soil, the soyabean and groundnut yields were in the order: 0.6–0.9 t ha^{-1} and 0.4–0.9 t ha^{-1} respectively on the most fertile fields; 0.2–0.6 t ha^{-1} and 0.2–0.5 t ha^{-1} (medium fertility); 0.2–0.5 t ha^{-1} and 0.3–0.4 t ha^{-1} (poor fertility); (data not shown).

The yields of groundnut and soyabean and their response to P were correlated with available P and SOC (Fig. 4). From the regression analysis, soyabean yields of less than 0.5 t ha^{-1} were found in fields that had <12 mg kg^{-1} available P and about 0.6% SOC without added P. Groundnut was less responsive to available P and SOC and P addition; yields were larger for soyabean than groundnut on the more fertile fields and when P was added (Fig. 4). The proportion of yield variability that was not explained by available P and SOC (Figure 4) can be attributed to differences in management.

Discussion

Effects of SSP and manure application on soyabean and maize yield and soyabean N_2-fixation

Sandy soil

The small soyabean yields and amounts of N_2 fixed without fertilizer inputs on the depleted sandy soil (Fig. 1, Table 3) were due to the poor fertility status of the soil, where available P and exchangeable bases were extremely poor. The soil was also acidic and contained small amounts of organic matter, conditions that are unfavourable for soyabean production (Mpepereki et al. 2000). Degraded sandy soils are widespread in Africa and these soils cannot support soyabean production without fertilizer inputs due to multiple nutrient deficiencies. Yields measured previously on smallholder farms on coarse granitic sands in Zimbabwe were <0.6 t ha^{-1} (Shumba 1983). Carsky (2003) reported similar poor soyabean yields on depleted sandy soils in Benin. Much larger soyabean yields, exceeding 1 t ha^{-1}, have been reported on more fertile soils in Zimbabwe (Kasasa et al. 1999) and Nigeria (Sanginga et al. 2002a). Performance of soyabean, therefore, varies widely depending on site-specific soil and climatic condition.

Deficiency of P is often cited as one of the major constraints to soyabean production on smallholder farms in Africa (Aune and Lal 1997; Giller 2001). Despite the low available P on the degraded sandy soil, soyabean grain yield and N_2-fixation response to SSP directly applied in the first and third seasons was poor (Fig. 1a) due to other limiting factors. The limited productivity of soyabean on the granitic sand without manure could have been due to deficiency of Ca, Mg and other micronutrients such as Mo and Co, which are essential for N_2-fixation (Giller 2001). Zn is also deficient on depleted sandy soils, and severely constrains maize production (Zingore 2006). The substantial increase in yields and proportion of N_2 fixed with direct application of manure was due to its multiple effects such as supply of various nutrients (including P, bases and micronutrients), improving moisture availability and increasing soil pH (De Ridder and Van Keulen 1990). Cattle manure or other organic resources are therefore essential to significantly increase soyabean yields on the depleted fields (Carsky 2003; Zingore 2006).

Net contribution to N balance of the soil by grain legumes is only possible if the amount of N removed in grain is smaller than total amounts of N fixed, provided that all the stover is incorporated. Without considering the N in roots, soyabean added small amounts of N due to the small amounts of N accumulated and marginal differences between the N harvest indices and proportion of N fixed (Table 3a). Even with manure, which generated the largest biomass and fixed the greatest proportion of N, the net contribution of N was <10 kg ha^{-1} in the third season. Although the promiscuous soyabean varieties produced more than 10 t ha^{-1} stover (140 kg N ha^{-1}) when grown on fertile red clay soil on an experimental farm and 2.5–3.9 t ha^{-1} (36–54 kg N ha^{-1}) on more fertile smallholder farmers' fields on the granitic sandy soil (Kasasa et al. 1999), our results indicate that amounts of N accumulated by soyabean can be severely constrained by poor soil fertility on fields cultivated for prolonged periods with little addition of nutrient resources.

Maize yields without fertilizer inputs were also poor on the sandy soil (0.1–0.7 t ha^{-1}), due to the poor soil fertility (Fig. 1b). Application of mineral N alone had little effect on maize yields as P and other nutrients were limiting. Direct addition of SSP and mineral N fertilizer to maize significantly increased yields in the first and the third seasons (Fig. 1a, b). Under such conditions, it may be more beneficial for farmers to apply mineral P on maize rather than soyabean. As with soyabean, application of manure also led to strong effects on maize yields. Beneficial effects of manure were evident for both crops; hence the choice of allocation needs to be assessed in comparative benefits of profitability, rotational effects and nutrient use efficiencies.

Clay soil

Soyabean and maize yields were larger on the more fertile red clay soil (Fig. 2), and the effects of manure were stronger than SSP, although the advantage of manure over SSP was expected to be small on the more fertile clay soil. Residual effects of manure added in the first season could have contributed to the larger yields on plots with manure in the third season. Most of the benefits of manure are due to its multiple effects of correcting deficiencies of base cations and micronutrient and increasing soil organic matter contents. In addition, manure of low quality generally causes immobilization of N in the first season, but can release large amounts of N in subsequent seasons (Nyamangara et al. 1999), which could have also contributed to the greater effects observed with manure in the third season.

The amounts of N accumulated by soyabean in the first and third seasons were larger on the clay soil where up to 62 kg of N was fixed with manure. Such large amount of 'free' N can have strong effects on soil N budgets and food security. The small proportion of N derived from N_2-fixation with SSP on the clay soil were unexpected; it is possible that addition of P on the more fertile soil led to root proliferation, enabling the crop to access more N from the soil. Due to poor N fixation rate, there was a net removal of N from plots amended with SSP (-15 kg N ha^{-1}), as the amount of N removed in grain was greater than that contributed from N_2-fixation (Table 3b).

Residual effects of SSP and manure on maize and soyabean production and rotational effects of soyabean on maize

The effects of targeting SSP and manure to soyabean to enhance its contribution to the N budget of the systems were small on the sandy soil due to the poor productivity and small amounts of N_2 fixed on the two fields. This explains the small yield gains by maize following soyabean fertilized with SSP (Figs. 1, 2). The larger yields of maize following soyabean with manure on the granitic sandy soil could be due to residual effects of manure rather than the effects on N added by the legume. About 20 kg N ha^{-1} was returned in soyabean residues with manure on the sandy soil in the first season (Table 3a). When amounts of potentially mineralized N are considered and losses accounted for, the amount of N from soyabean residues eventually available to maize in the second season was unlikely to have significant effects on maize yields. Mineral N was therefore required to significantly increase yields of maize following soyabean in the second season (Figure 2a). On the clay soil, the larger maize yield following soyabean amended with manure and SSP can be attributed to the combined effects of manure, N returned in soyabean residues and mineral N added. Amounts of N contributed by below-ground material of soyabean are difficult to estimate, due to wide differences in the proportion of soyabean N in roots (11%-50%) measured in different studies (Buresh and De Datta 1991; McNeill et al. 1997).

Our results contrast with results from several studies that have shown striking residual effects of the promiscuous soyabean varieties on subsequent maize crops, attributed solely to increased supply of N through BNF. In a study by Kasasa et al. (1999) in Zimbabwe, Magoye contributed 137–170 kg N ha^{-1} in stover on a red clay soil but only 28–33 kg N ha^{-1} on a granitic sand, which increased maize grain yields by more than 2 and 1 t ha^{-1} respectively. The study by Kasasa et al. (1999) was done in a similar agro-ecological zone, but their sites on the granitic sandy soils were more fertile than the field we used, which could explain the differences observed in amounts of N in stover and effects on maize. In Nigeria, incorporation of promiscuous soyabean residues more than doubled maize yield of the following maize crop without additional mineral N applied (Sanginga et al. 2002b).

P recovery efficiencies by soyabean and maize: Direct application, residual effects and complete rotations

The RE_P values when SSP and manure were applied directly in the first and third seasons were greater for maize than for soyabean (Table 3a), due to larger amounts of P taken up by maize in grain and stover. The RE_P for soyabean was <10% on the granitic sand due to the small biomass and grain yield responses to manure and SSP. The larger RE_P of maize with manure on the granitic sand (28–36%) was due to removal of other limitations, which enhanced uptake of P by maize.

There were small differences in RE_P by soyabean when SSP and manure were applied directly in the first season or when soyabean was grown on residual fertility in the second season on both soils (Table 4a, b). This is despite the larger RE_P by maize in the first season. Maize grown on residual fertility in the second season recovered less P than grown with direct fertilization in the first season. Based on P recovery, it would therefore be more efficient for farmers to target P on maize, which recovered more P under direct fertilization than when P was applied to preceding soyabean crop. RE_P for complete rotations were larger when SSP and manure were applied to maize in the first season.

Economics of targeting P in soyabean-maize rotations

Economic viability is one of the factors that are most likely to drive intensification of soyabean production on smallholder farms (Mpepereki et al. 2000; Mpepereki and Pompi 2003). At the official soyabean:maize price ratio of 2.5–4:1, the economic advantage of soyabean over maize was not apparent on the granitic sand. Based on these prices for maize and soyabean grain, farmers cultivating such soils are unlikely expand the area allocated to soyabean or target nutrient resources to soyabean at the expense of maize. It should be noted, however, that rotating maize with soyabean can also have other indirect economic benefits over maize monoculture through control of weeds, pests and diseases. Currently soyabean is freely marketed in Zimbabwe, and can give much greater financial rewards if sold during periods of low supply and high demand. Prices of maize are regulated by the government and tend to be stagnant throughout the year. In highly inflationary economies, such as currently in Zimbabwe, soyabean:maize price ratios can vary from 2.5:1 (based on official prices) to 10:1. Market information is thus vital for farmers to benefit financially from production of soyabean. Farmers were also growing soyabean and selling seed among themselves, but the local markets for soyabean seed were limited.

For complete rotations, targeting SSP or manure to soyabean was less rewarding in financial terms than targeting to maize. Under these circumstances farmers would benefit more if manure and SSP were targeted to maize rather than soyabean, as commonly practiced. Waddington and Karigwindi (2001) found that groundnut was less profitable than maize (both fertilized and unfertilised) and proposed that this was a major reason why farmers devote only small areas to groundnut production.

On the clay soil, direct application of manure to soyabean in the first and third seasons led to greater returns than direct application to maize, and this led to the higher returns for rotations when manure was applied to soyabean. There are opportunities, therefore, for the farmers on the more fertile soils to increase income by targeting manure to soyabean rather than maize. With SSP, the gross margins for specific crops were greater when applied to maize, but the gross margins for rotations were greater when applied to soyabean. This highlights the need to consider economics for both specific seasons and for complete rotations when designing strategies for allocation of nutrient resources within crop rotations.

The economic benefits derived from manure were greater than those derived from SSP for maize, soyabean and rotations, highlighting the essential role of manure not only in increasing crop production and soil fertility, but also in increased income for farmers. Although manure use is highly demanding in labour, the returns to manure outweigh the additional labour costs. Only P was valued in manure and it is noted that the value could be higher if other nutrients are taken into account as well. For instance, in some smallholder farming systems where manure is scarce and has a market, the value of manure can be five times greater than that of fertilizer with an equivalent amount of nutrients (Moll 2003).

Variability of soyabean and groundnut yields on farmers' fields

The gradients of soil fertility strongly affected soyabean and groundnut yields, and had strong implications on productivity of grain legumes and harnessing N through N_2-fixation. The fields closest to homesteads where productivity of soyabean and groundnut were good (Fig. 3) are the fields that farmers usually reserve for maize production. Most farmers managed the experimental plots as they normally manage their grain legumes, which are given less priority and mostly weeded later than maize. Both initial soil fertility and management are factors that could have strong effects on productivity of grain legumes and their impact on food security and N cycling. Yields of groundnut and soyabean were small on fields further away from homesteads on the rich farms and all fields on poor farms due to poor management histories. Groundnut and soyabean response to P was also restricted on these fields by other factors such as soil acidity and poor availability of bases and micronutrients. Groundnut yields without P were mostly less than soyabean yields on the more fertile fields but were greater on the poor fields where yields were small. Groundnut may therefore be more suitable for depleted fields than soyabean, perhaps because groundnut is thought to be effective at extracting P from soil with small contents of available P (Ae et al. 1996). The plots that were poor in available P were also deficient in Ca, which could have caused the poor response of groundnut to P added in depleted soils. The impact of grain legumes will be limited, unless attention is focused on growing them on the more fertile plots on farms.

Potential of grain legumes to contribute N to the cropping system was also greatest on the homefields of the rich farms, where soyabean and groundnut produced about 2 t ha^{-1} stover, which was more than double the amounts stover produced on the other fields. From the results of the first experiment we can assume differences in proportion of N_2 fixed for the different fields: the larger N_2-fixation rates ($\sim$80%) are expected on the homefields of the wealthy farms and N_2-fixation rates of $\sim$60% are expected on the rest of the fields. The zones of high fertility are often limited to small areas on wealthy farms (Zingore et al. 2007), and therefore, fields where soyabean and groundnut can significantly contribute to N cycling are limited.

Conclusions

Smallholder farmers preferentially apply fertilizers and manure on maize, which is also commonly grown on the most fertile fields. This has contributed to poor performance of grain legumes which are mostly grown on residual fertility on the worst plots. The results from this study showed the farmers' practice of targeting nutrient resources to maize was rational on an infertile sandy soil as this was more profitable than targeting to soyabean. Nutrient resources were also used more efficiently within rotations when directly applied to maize. However, on a more fertile red clay soil, manure was used more profitably when targeted to soyabean rather than maize. On the infertile sandy soil, soyabean yields, N_2 fixed and returns to SSP applied were poor due to multiple nutrient deficiencies. Manure application significantly increased soyabean yields and proportion of N_2 fixed, due to the multiple effects of manure which are key to restoration of soil fertility in depleted fields. Soyabean and groundnut yields varied widely in the farmer-managed trials on fields with different management histories. Yields were largest on the homefields of the wealthy farms where soil fertility was good. Yields were poor (< 0.5 t ha^{-1}) on the mid-fields and outfields of wealthy farms and all the fields of poor farms. Since farmers mainly grow grain legumes on the mid- and outfields, this is one of the reasons for the poor performance of grain legumes on smallholder farms. Response to P was also poor on depleted fields due to other limiting factors. As a results, there are opportunities for farmers to improve productivity of grain legumes by growing them on the more fertile plots on their farms. On the more fertile fields, profitability of maize-soyabean rotations can be substantially increased by targeting nutrient resources to soyabean, rather than maize as commonly practiced by farmers.

This study highlights the profound effects of variability of soil fertility within and across farms on productivity of grain legumes and their contribution to income and N cycling on smallholder farms. Such gradients of soil fertility must be taken into account by researchers and extension workers when making recommendations for application of nutrient resources for individual crops and within crop rotations as opposed to the current blanket fertilizer recommendations. Factors influencing soil fertility such as soil type and historical management can be used to develop farmer-friendly and flexible site- and crop-specific fertilizer recommendations. This will contribute to improved fertilizer use efficiency and returns to investment in fertilizer and labour through: 1. use of appropriate fertilizers for fields with different fertility levels and nutrient deficiencies, which will have wide impact where governments are providing subsided fertilizers; 2. integrated soil fertility management including combined use of mineral and organic nutrients for replenishment of soil fertility in depleted fields where recovery of N and P is low due to poor soil physical structure and multiple nutrient deficiencies; and 3. crop diversification strategies that are more economically viable compared with the current maize-dominated farming systems.

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