Exploring diversity within smallholder farming systems in Zimbabwe

Nutrient use efficiencies and resource management strategies for crop production

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Dit onderzoek is uitgevoerd binnen de onderzoekschool: Production Ecology and Resource Conservation.

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Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit,
prof. dr. M.J. Kropff
in het openbaar te verdedigen
op maandag 29 mei 2006
de namiddags te vier uur in de Aula

Shamie Zingore (2006)

Exploring diversity within smallholder farming systems in Zimbabwe: Nutrient use efficiencies and resource management strategies for crop production.

PhD thesis, Wageningen University, Wageningen, The Netherlands.
With summaries in English and Dutch

ISBN: 90-8504-411-1

Abstract

This thesis characterizes the dynamic and spatial variability of soil fertility on smallholder farms in Zimbabwe and its effects on crop production. Appropriateness of resource management strategies for the heterogeneous biophysical and socio-economic conditions on the smallholder farms is also explored.

Assessment of soil organic C (SOC) contents along cultivation chronosequences revealed rapid decline in SOC within the initial 5 years of cultivation when woodland soils were cleared for subsistence maize cultivation without fertilizer inputs. Commercial farming with intensive use of mineral fertilizers and incorporation of maize stover led to more gradual decline of SOC: at equilibrium, contents of SOC in a clay soil were 15 t C ha^{-1} greater than the contents in a similar soils on smallholder farms.

Resource flow mapping was used to characterize differential management of nutrient resources between and within farms for three seasons. Wealthy farmers who owned cattle concentrated large amounts of manure on fields closest to their homesteads (homefields), and applied small amounts to fields further away (outfields) which led to gradients of decreasing soil fertility with increasing distance from the homesteads. Partial nutrient balances were largest on the homefield of the wealthy farms. N and P partial balances differed little across plots on the poor farms (–5 to +5 kg per plot) due to limited nutrients applied and small off-take from small harvests.

In field experiments, maize yields larger on the homefields than outfields on a clay soil and a sandy soil. Maize responded poorly to application of mineral fertilizers or manure on the outfields on the sandy soil. Application of manure at a rate of more than 15 t ha^{-1} yr^{-1} for three seasons was required to significantly restore productivity of the outfields on the sandy soil. In a pot experiment, it was established that the depleted sandy soil was deficient in many nutrients including nitrogen, phosporus, calcium and Zn. Soyabean yields were also poor on the depleted sandy soil (<0.2 t ha^{-1}) and responded little to phosphorus fertilizer due to deficiency of other nutrients. Manure application significantly increased soyabean 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%. Within soyabean-maize rotations, P use efficiency was higher when manure and SSP were applied to maize (43 and 25%) than when applied to soyabean (20 and 19%).

A farm characterization tool linked to optimization and simulation models was used to analyze trade-offs between resource use options on farms in contrasting wealth categories. Crop production was not viable on a poor farm without cattle, which relied on selling labour to meet food security. Although the performance of the poor farm could be improved by expanding the area sown to groundnut, this was not feasible due to large labour requirements. On a wealthy farm, maize was most productive when manure was applied in combination with cattle manure. Groundnut intensification on the wealthy farm would be more economic and labour-effective if a small area is grown with basal fertilizer (7%N, 14%P_2O_5, 8%K), rather than expanding the area sown to groundnut without fertilizer inputs.

A simple dynamic model (FARMSIM) was used to explore long-term effects of resource management strategies on variability of soil fertility and maize yields. Simulations with FARMSIM showed a rapid development of gradients of SOC and maize yields within the farm when different rates of manure were applied. The wide variability of farm and field types was summarized into only three zones of fertility with the aid of the model. Desirable contents of SOC, based on crop productivity, were achieved in the long-term with manure applied at 5 t ha^{-1}. A simple analysis taking into account the amount of labour needed for implementing the different strategies showed that if labour is a major constraint, concentration of resources on the fields closest to the homestead is the best option. The study highlights the need to consider the wide biophysical and socio-economic variability on smallholder farms for designing appropriate strategies for soil fertility management.

Preface

This study was developed within the concepts of the Nutrient Use in Animal and Cropping Systems – Efficiency and Scales (Africa - NUANCES) framework, which is exploring temporal and spatial aspects of nutrient management on smallholder farms in Africa. The initial phase of the study was funded by the International Fund for Agricultural Development (IFAD) and the Department for International Development (DFID) through the Tropical Soil Biology and Fertility institute of CIAT. The final phase of the study in Wageningen was made possible with funds from the Rockefeller Foundation. I am very grateful for the financial support from these institutions.

I acknowledge the support of many people who have been instrumental in allowing this thesis to be completed. My sincere thanks go to my promoter Professor Ken Giller whose insightful advice played a pivotal role in structuring the study, and for the unparalleled attention during the course of the study. I owe much of my career development to him, having studied under his guidance since I was an undergraduate student. I would also want to extend my sincere gratitude to my co-promotor Dr. Rob Delve for facilitating funding for the initial phase of the study. The unwavering support and invaluable guidance he provided throughout the duration of the study was a great motivation. Many thanks to Dr. Herbert Murwira and Dr. Mark van Wijk, my supervisors, for the helpful comments and constructive criticism. The wealth of knowledge they provided was instrumental in sharpening the scope of the study.

I am grateful to Dr. Ernesto Gonzalez and Pablo Tittonell for assisting me in the modelling component of my work. Your great effort and commitment made the many hours behind the computer enjoyable. I want to thank Felix Murimbarimba and Francis Dzvene for assisting me with my field work and taking care of the experiments when I was away. It was a great pleasure to work alongside Bonaventure Kayinamura, Pauline Chivenge, Leonard Rusinamhodzi and Talkmore Mombeyarara who were fellow students and research assistants at TSBF-CIAT in Harare.

I thank all the people at the Plant Production Systems Group, Wageningen University for the support they gave me during my stay in Wageningen. I would particularly like to thank Dr. Nico de Ridder for the helpful comments on my papers and for arranging the trips and dinners for students. I am grateful to Ria van Dijk and Charlotte Schilt the secretaries at the Plant Production Systems Group for assisting with all the administrative matters. The burden of writing this thesis was lessened by the support and company of students in the ‘Attic’; Shibu Ibrahim, Trinh van Mai, Bongani Ncube, John Ojien, Samuel Guto, Jessica Milgroom, AfioZannou and Comfort Kudadjie. Many thanks for the inspiration and peer support.

Lastly, I am indebted to my wife Kumbirai whose support, love and patience enabled me to complete this work.

Dedicated to my mother Rubi, my wife Kumbirai and my daughter Ropafadzo

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CHAPTER 1

General Introduction

1.1. Background

Poor soil fertility is the fundamental constraint to productivity of smallholder farms in sub-Saharan Africa (Sanchez et al., 1997). Most farmers cultivate crops continuously on the same plots with small additions of nutrient resources, which has led to severe depletion of soil fertility. Evidence from nutrient balances for sub-Saharan Africa show large negative values, indicating rapid decline in soil fertility (Stoorvogel et al., 1993; Stoorvogel et al., 1998). In addition to poor management practices, the problem of poor soil fertility has been exacerbated by the marginal sandy soils predominantly cultivated by smallholder farmers in Zimbabwe and much of sub-Sahara Africa. These sandy soils are inherently infertile. They are poorly buffered and contain small amounts of soil organic matter due to a poor capacity to stabilize the soil organic matter physically. Sandy soils under long-term smallholder maize cultivation are acidic and poor in soil organic matter (Grant, 1981; Nyamangara et al., 2000).

Use of mineral fertilizers has significantly increased food production in other parts of the world, but mineral fertilizers are scarce and exorbitantly priced in sub-Saharan Africa. This has led to poor adoption by smallholder farmers (Quiñones et al., 1997). Another important factor discouraging wide adoption of mineral fertilizers by smallholder farmers is the variable responses to fertilizer use due to variable soil fertility conditions (Nandwa et al., 1998) and seasonal variation in rainfall (Piha, 1993). On the other hand, organic nutrient resources such as cattle manure are also available in limited quantities and cannot sustain crop production when used exclusively. Due to scarcity of nutrient resources, integrated use of organic nutrient resources and mineral fertilizers is essential for sustainable soil fertility management on smallholder farms (Vanlauwe, 2004). Mineral and organic nutrient resources have different functions on soil fertility and crop production and their use in combination can have synergic effects, which lead to greater resource use efficiencies than when used separately (Giller, 2002). Cattle manure is a key nutrient resource on smallholder farms as it is in many cases the only organic nutrient resource available in substantial quantities. Manure plays an important role in maintenance of soil fertility, particularly on the sandy soils, due to its multiple benefits that include supply of nutrients, increase soil pH and soil organic matter (Grant, 1981; Bayu et al., 2005).

Symbiotic biological N_2-fixation (BNF) is considered an important option for improving soil N budgets and to reduce the reliance on mineral N fertilizers for crop production on smallholder farms (Giller, 2001). Several technologies based on BNF, including improved fallows, alley cropping, green manures, and rotation or intercropping of cereal crops with grain legumes have been developed to increase 'free' N contributed by legumes in smallholder farming systems.

Grain legumes are more appealing to smallholder farmers as they contribute to income and food security in addition to contributing N to associated cereal crops (Snapp et al., 2002). However, most grain legumes have high N harvest indices and may have a small or a net negative contribution to soil N budget, as much of the N_2 fixed is removed in harvested grain. Grain legumes with low N harvest indices, such as promiscuous soyabean (*Glycine max* [L.] Merrill) varieties, are suitable for fulfilling many roles as they produce good grain yields and leave substantial amounts of N in residues for following cereal crops in rotations (Mpepereki et al., 2000; Vanlauwe et al., 2003). Cultivation of promiscuous soyabean varieties is expanding rapidly in many countries in sub-Saharan Africa because their multiple benefits give them an advantage over other grain legumes (Sanginga et al., 2002).

Concerted research efforts over many years to remedy the problems associated with depletion of soil fertility in sub-Saharan Africa have yielded little practical results, as evidenced by poor adoption of promising technologies by the farmers. Conversely, soil fertility and crop production continue to decline at rapid rates. One of the reasons for the lack of implementation of technologies developed over the years is that most of the studies aimed at addressing problems of poor soil fertility were done at plot scale and targeted at isolated technologies; hence they were unsuitable for the complex socio-economic and biophysical variability that typify smallholder farms (Giller et al., 2006). Improved understanding of the socio-economic and biophysical variability and functioning of smallholder farming systems is an important step towards improved targeting of interventions (Defoer, 2002).

1.2. Heterogeneity in smallholder farming systems

Farming systems in sub-Saharan Africa exhibit a high degree of heterogeneity, determined by a complex set socio-economic and biophysical factors. Access to different resources varies considerably between farmers. Cattle ownership is a major indicator of the wealth status of households, as cattle has many essential roles, which include provision of milk, meat, draught power and manure (Achard et al., 2003; Schlecht et al., 2006). Cattle play an important role in maintenance of soil fertility through recycling nutrients from crop residues and transfer of nutrients from rangelands (Bationo et al., 1991; Williams et al., 1995). Soil fertility also varies considerably within farms (Elias et al., 1998; Shepherd et al., 1998). Smallholder farms consist of multiple plots that differ in soil fertility status due to differences in inherent soil properties and differential allocation of nutrient resources (Smaling et al., 1996; Deckers, 2002; Giller et al., 2006). The variation generated by differential resource management is mostly driven by farmers' preference to apply nutrient resources to fields closest to homesteads, a pattern of resource management that is evident across smallholder farms in sub-Saharan Africa (Prudencio, 1993; Tittonell et al., 2005). Systematic allocation of nutrient resources to fields closest to homesteads is driven by various factors including lack of adequate resources to apply evenly across farms, shortage of labour and concentrating resources on plots that are more secure against grazing by livestock (Carter et al., 1995; Chikuvire, 2000). By concentrating cattle manure to preferred fields, farmers in Zimbabwe may apply as much as 80 t of manure ha^{-1} at one time (Mugwira and Murwira, 1998). In many regions, manure is available in limited quantities as few farmers own cattle. It was estimated that less than 10% of the cropped area in Niger received manure, indicating that zones where high soil fertility is maintained by addition of manure are a small proportion of cultivated areas (Achard et al., 2003; Schlecht et al., 2004).

1.3. Implications of soil fertility gradients on crop production

Crop yields and nutrient use efficiencies inevitably vary between different plots due to heterogeneity in soil fertility. Tittonell et al. (2005) observed that maize yields in farmers' fields decreased with increasing distance from homesteads, in correlation with decreasing soil fertility. However, yield differences in farmers' fields are not only due to differences in soil fertility arising from past management, but also due to current allocation of resources. Farmers apply more nutrients and invest more labour on the most fertile plots to ensure good production by timely planting and weeding (Tittonell et al., 2006). Variability in soil fertility within farms presents a major challenge for efficient allocation of limited nutrient resources, in the short-term and in the long-term.

1.4. Modelling resource allocation on smallholder farms

Several crop-soil models have been successfully developed to simulate effects of resource interaction on crop yields at the field level. Since farm management decisions at the farm level are influenced by a complex set of biophysical and socio-economic factors, models that operate at the field level cannot adequately evaluate the suitability of resource management options for different farms. For improved targeting of interventions suitable for smallholder farms varying in resource endowment, there is a need for tools that incorporate crop-soil-livestock interactions within the socio-economic environment of smallholder farm (Jones et al., 1997; Thornton et al., 2001). There is scope to integrate existing biophysical simulations with optimization models, which allows analysis of biophysical and socio-economic tradeoffs (Castelan-Ortega et al., 2003; Stoorvogel et al., 2004). The paucity of farm characterization data in sub-Saharan Africa has also led to calls for simple decision-guide-based models that consider the main biophysical and socio-economic factors influencing resource use efficiency of resource use on heterogeneous smallholder farms (Shepherd et al., 1998; Rowe et al., 2006; Giller et al., 2006).

1.5. Rationale

Improving efficiency of use of the limited purchased mineral fertilizers and locally available organic resources offers the only realistic opportunity for smallholder farmers to raise crops yields, maintain the soil resource base and improve the household economy. There is increasing realization that a systems approach to studying management of soil fertility encompassing soil-crop-livestock interactions, variability of soil fertility between plots, farmer resource endowment and economics of management options is required to identify relevant opportunities for improving resource use efficiency (Giller et al., 2006). Many studies have been focused at single technologies and done at plot scale where variability biophysical and socio-economic heterogeneity was not considered, which has resulted in poor adoption. This study aims to evaluate spatial and dynamic resource allocation strategies for crop production at the farm level. The farm level is chosen as the main unit of analysis because it is at this level that farmers make decisions on investment and use of resources. Analysis of resource use at the farm level recognizes the diversity in resource endowment and soil fertility within and between farms which enables development of strategies suitable for farms with similar resources and constraints. At this level, farmers are often faced with conflicting options for use of limited resources. For example, farmers have to decide on allocation of fertilizer resources to different fields and crops. On mixed farms, farmers have to decide on use of crop residues for enhancing soil organic mater and ameliorating soil fertility or for feeding livestock.

The complexity and large amount of farm level data that must be taken into account when analysing resource use at farm level necessitates development and application of farm level models (Okoruwa et al., 1996; Shepherd and Soule, 1998; Thornton and Herrero, 2001). The models and decision support tools are useful for integration of farm level soil, crop, livestock and economic data thereby providing a platform for a holistic analysis of trade-offs between resource management options on different farms.

1.6. Objectives of the study

The thrust of this study was to evaluate the effects of resource management strategies on spatial variability of soil fertility and crop yields on smallholder farms in Murewa, Zimbabwe, and to assess appropriateness of soil improving technologies for specific farms and plots. The specific objectives were as follows:

1. to assess the effects of effects of long-term cultivation of maize with little fertilizer inputs on soil organic matter on contrasting soils, and to measure the contribution of maize to soil organic matter following clearance of woodlands for maize cultivation.
2. to assess the influence of resource endowment and resource management patterns on smallholder farms on variability of soil fertility, crop yields and nutrient balances.
3. to assess the interaction between soil type, fertility status, and application of different sources of nutrients on maize production and nutrient use efficiencies.
4. to determine the investment in nutrient resources required on the depleted outfields to reduce gradients of soil fertility and improve their productivity relative to the homefields.
5. to compare the benefits of targeting mineral P or cattle manure on the legume or the cereal crop in soyabean-maize rotations, in terms of productivity, profitability and nutrient use efficiencies for individual crops and complete rotations.
6. to apply an integrated modelling approach that combines a farm database with simulation and optimization models to analyse trade-offs between resource use alternatives in terms of food security, cash balance, nutrient balances and labour requirement on contrasting smallholder farms.
7. to explore the impact of long-term and short-term nutrient allocation strategies on spatial variability of soil fertility, crop yields and resource use efficiencies on smallholder farms using a simple but dynamic farm-scale model.

1.7. Outline of the thesis

Chapter 2 details the long-term dynamics of soil organic matter in fields exposed to long-term cultivation of maize with little fertilizer inputs and stover removal on contrasting soil types. The contribution of maize to soil organic matter in fields cultivated for different ages is quantified using the ^{13}C natural abundance technique.

In Chapter 3, I describe crop and nutrient management strategies by farmers differing in resource endowment and their influence on variability in soil fertility, crop yields and nutrient balances. Chapter 4 presents the variability in maize yields and nutrient use efficiencies across soil fertility gradients created by differential resource management on contrasting soils. This chapter also explores the possibility to replenish soil fertility in degraded outfields by repeated application of nutrients. Chapter 5 builds on findings in Chapter 4, to establish the deficiencies of nutrients limiting crop production in poorly managed fields. Changes in soil properties on homefields and outfields after three years of adding mineral fertilizers and manure are also reported in Chapter 5.

The variability of soyabean and groundnut yields across soil fertility gradients is investigated in Chapter 6. Chapter 6 also assesses the potential to improve P use efficiency within maize-soyabean rotations by targeting manure or mineral P fertilizer to soyabean to improve its contribution of N to the subsequent maize crop.

Chapter 7 describes an integrated modeling approach that combines a farm-level characterization tool, an optimization model and simulation models. The integrated modeling approach is applied to analyse trade-offs of resource use options and evaluate optimization of resource use on farms in contrasting wealth categories.

Chapter 8 synthesizes results of the different chapters using a relatively simple simulation model (FARMSIM) and evokes the long-term implications of resource management options on soil fertility and maize production. The model results are interpreted within the condition on smallholder farms to indicate maize production potential of different nutrient resource management options across soil fertility gradients on farms with different access to resources. Lastly, concluding remarks are given to highlight the major conclusions drawn from the study and recommendations for future research. A detailed description of FARMSIM given in a paper included as Appendix 1.

CHAPTER 2

Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe

This chapter has been published as:

Zingore, S., Manyame, C., Nyamugafata, P., Giller, K.E., 2005. Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe. *European Journal of Soil Science* 57, 727-736.

Abstract

Subsistence farmers in Africa depend largely on the soil organic matter to sustain crop productivity. Long-term changes in soil organic carbon and nitrogen were measured after woodland clearance for smallholder subsistence farming or for commercial farming. The contents of organic carbon and nitrogen in soil under reference woodlands were largest (53.3 t C ha^{-1}, 4.88 t N ha^{-1}) in a red clay soil (~50% clay+silt), followed by a granitic sand (~12% clay+silt; 22.8 t C ha^{-1}, 1.47 t N ha^{-1}) and least (19.5 t C ha^{-1}, 0.88 t N ha^{-1}) in a Kalahari sand (~5% clay+silt). Organic carbon declined rapidly under cultivation to attain new equilibria within 10 years on all smallholdings. Greatest losses occurred in soils that initially contained most carbon and nitrogen in the order: red clay (22.4 t C ha^{-1} and 1.0 t N ha^{-1}) > granitic sand (13.2 t C ha^{-1} and 0.8 t N ha^{-1}) > Kalahari sand (10.6 t C $ha^{-1}$and 0.5 t N ha^{-1}). On the clay soil, commercial farming with intensive use of mineral fertilizers and incorporation of maize stover led to more gradual decline: at equilibrium contents of carbon and nitrogen were 15 t C ha^{-1} and 1.7 t N ha^{-1} greater than on smallholdings with similar soil and climate.

In the Kalahari sand the $\delta^{13}C$ of organic C remained constant after woodland clearance and maize contributed less than 10% of the total C even after 55 years. The $\delta^{13}C$ signature increased slightly with increasing duration of cultivation by smallholders in the granitic sands and red clay soil where maize contributed 29% and 35% of the C at equilibrium. Under more productive commercial farming, the carbon derived from maize accounted for 50% of the total after 10 years of cultivation and 67% at equilibrium. The persistence of woodland carbon in the sandy soil is attributed to chemical stabilization resulting from large concentrations of lignin and polyphenols in the tree litter, or as charcoal.

2.1. Introduction

Soil organic matter is crucial to the sustainability of crop productivity on small subsistence farms in Africa, as subsistence farmers use little fertilizer and thus depend heavily on nutrients mineralized from the organic matter. Much soil organic matter is stored in the soil under natural vegetation, but it declines rapidly when the soil is cultivated until a new equilibrium is reached. The decline in organic matter under cultivation has been attributed to various factors, which include reduced organic material returned to the soil, exposure of aggregate-protected soil organic matter and accelerated erosion.

The stocks of organic matter in any soil are governed by the interaction of the quality and quantity of organic matter inputs, the type of soil and climate. Soil texture has a strong influence and several studies have shown a direct relationship between % clay+silt and organic matter (Feller and Beare, 1997; Hassink, 1996). Clay and silt help to protect organic matter from microbial attack through direct interaction (termed textural stabilization) and through formation of aggregates which sequester organic matter within them (Six *et al*., 2000; Six *et al*., 2002). Most smallholders in Zimbabwe farm on sandy soils which contain little organic matter, even under native woodland, owing to the restricted capacity of such soils to protect the soil organic matter physically. Under natural vegetation the small amounts of organic matter contained in the sandy soils are predominately in the labile particulate fraction and are highly susceptible to loss when the soil is cultivated.

Where woodland dominated by C3 plants is cleared for maize production, the differences in depletion of the ^{13}C isotope between C3 plants and the C4 maize crop provide a means for determining the fate of the original soil organic matter, which is derived mainly from C3 plants, as well as revealing the subsequent contribution to organic matter by the replacement maize crop (Boutton *et al*., 1998). Plants with a C3 photosynthetic pathway (most herbs and trees) discriminate more strongly against $^{13}CO_2$, and their $\delta^{13}C$ values range from -22 to -32 ‰, whereas C4 plants (tropical grasses and cereals) are less depleted and have $\delta^{13}C$ values ranging between -9 to -17 ‰ (Farquhar *et al*., 1989). In maize-based farming, the fraction of soil organic carbon derived from maize varies widely from 10% to 50% depending on the soil type, the amount of maize residues added and the period under cultivation (Ludwig *et al*., 2003; Flessa *et al*., 2000; Collins *et al*., 1999).

Long-term experiments under the conditions of smallholding are essential for our understanding of the impact of continuous cultivation with little fertilizer on the dynamics of organic matter in the soil. There have been few such experiments in Africa, despite the importance of organic matter in sustainable production. We studied the impact of the change from natural woodland to intensive smallholder agriculture for up to 70 years on the amounts of organic matter in the major soil types in Zimbabwe. We did so at three sites, and at each we also chose an uncultivated area of similar soil and climate to represent the initial state of the soil organic matter. We also studied the effect of commercial farming with large amounts of fertilizer at one of the three sites. Finally, we explored the contributions of the vegetation, originally in the woodland and later maize, to organic matter over various durations of cultivation, using natural labelling with ^{13}C as tracer.

2.2. Materials and methods

2.2.1. Site selection

At each site, the organic matter status of the soil cultivated for varying durations was compared with that of an adjacent reference woodland under similar soil and climate. We assumed that initially the organic matter contents of all the soils were similar in the fields to those of woodland. We chose three different areas on smallholdings on the major soil types under smallholder farmer cultivation in Mafungautsi, Masvingo/Chivi, and Chikwaka to provide sites with large differences in clay+silt contents (Tables 1 and 2). For all areas, the history of land clearance was initially mapped from aerial photographs taken in 1974, 1984 and 1996 and SPOT images in 1992. We established the exact dates of clearance by asking the farmers, which was particularly important for establishing the dates when fields were cleared before 1974. We also recorded the farmers' management practices, and we surveyed each area to verify the information from remotely sensed data and check for soil uniformity at the identified sites. Soil samples were taken from 'outfields', at least 50 m from homesteads, which comprise the majority of land on smallholdings.

Table 1. Percentage of smallholders practising various soil fertility strategies and yields estimates for the sites.

Management		Mafungautsi	Masvingo	Chikwaka (Smallholder)
Practice fallowing (%)		47	12	0
Used mineral fertilizers (%)		14	31	80
Used cattle manure (%)		14	50	37
Other soil amendments[a] (%)		0	50	37
Crop rotations (%)		29	37	50
Maize yields	<1 t ha^{-1}	63	56	13
	1-2 t ha^{-1}	28	44	38
	2-3 t ha^{-1}	8	0	50
Stover management	Cattle feeding (%)	92	81	88
	Burning (%)	3	0	0
	Incorporation (%)	5	19	12

[a]Other soil amendments include leaf litter and soil from termite mounds.

2.2.2 Woodland and smallholder farms

The natural vegetation at Chikwaka and Chivi/Masvingo is dry miombo woodland dominated by the caesalpinioid legume trees *Brachystegia spiciformis* and *Julbernardia globiflora* (Table 2). *Baikiaea plurijuga* (Zimbabwe Teak) is naturally the dominant tree on the Kalahari sands at Mafungautsi, although mature trees are no longer common in the remaining woodland as they

Table 2. Climate, soil and vegetation of the sites, including some chemical analyses from the woodland reference soils.

Site and location	Climate	Soil characteristics	Vegetation
Mafungautsi 28°54' S 18°24' E	Annual rainfall between 650 and 800 mm. Mean annual temperature 25°C.	The soils at the top of the catena where we sampled are deep, well drained aeolian sands containing very little clay (3%) and silt (2%). Clay minerals dominated by kaolinite. $pH_{(water)}$ 5.1, CEC 1.6 $cmol_c$ kg^{-1}, available P 11 mg kg^{-1}. Luvic Arenosols (FAO).	Dry deciduous woodland originally dominated by *Baikiaea plurijuga* and *Brachystegia spiciformis* trees. Dense tree canopy with sparse grass understorey dominated by *Hyparrhenia* spp.
Masvingo 20°30' S 30°30' E Chivi 20°12' S 30°48' E	Annual rainfall between 400 and 750 mm. Mean annual temperature 24°C.	Well drained granitic sandy soils containing little clay (9-10%) and silt (2%). Middle catena soils are deep and well drained. The dominant clay type is kaolinite. $pH_{(water)}$ 4.9-5.1, CEC 1.6-2.0 $cmol_c$ kg^{-1}, available P 2-6 mg kg^{-1}. Haplic Lixisols (FAO).	Miombo woodland, dense tree canopy and sparse grass understorey. *Brachystegia spiciformis* and *Julbernardia globiflora* are the dominant trees. Understorey dominated by *Hyparrhenia* spp.
Chikwaka Commercial sites 17-18° S 30-31° E Smallholder site 17°42' S 31°24'	Annual rainfall between 800 and 1000 mm. Mean annual temperature 24°C.	Dolerite derived red clay soils, Chromic Luvisols (FAO). These soils are deep and drain freely. Clay (32-35%) dominated by kaolinite, silt (15-16%). $pH_{(water)}$ 5.5-5.6, CEC 6.6-7.9 $cmol_c$ kg^{-1}, available P 20-23 mg kg^{-1}.	Miombo woodland, dense tree canopy and and sparse grass understorey. *Brachystegia spiciformis* and *Julbernardia globiflora* are the dominant trees. Understorey dominated by *Hyparrhenia* spp.

have been cut for timber. This type of woodland, in which *Brachystegia spiciformis* is also abundant, is described by White (1983) as 'Zambezian dry deciduous forest'. In all three sites the understorey vegetation in the woodland is dominated by grasses of the genus *Hyparrhenia*. *Andropogon, Digitaria, Loudetia* and *Eragrostis* spp. are also common. Dry miombo woodland has an annual net biomass production between 1.2 and 2.0 t ha^{-1} (Frost, 1996). Almost all rain falls in the summer between November and April and the winter is dry. Temperatures are warmest in October before the rainy season starts and ground frosts may occur in June/July.

Woodland was cleared at all sites by stumping and removal of logs, except at Mafungautsi where the trees were burnt in the fields. Management was similar on all of the smallholdings: maize year after year with little or no fertilizer inputs (Table 1). Yields of maize achieved by smallholders were generally less than 2 t ha^{-1}, except on the heavier clay soil at Chikwaka. Maize stover was either removed and used as fodder or grazed *in situ*. The soil was tilled conventionally to a depth of 15-20 cm annually by using ox-drawn ploughs. Soil samples from the smallholder sites were collected only from fields where maize had been cultivated continually, without fertilizer.

2.2.3. Commercial farms

Commercial farms were managed very differently. Their soils were tilled to about 20 cm by tractor-drawn plough. Large fertilizer dressings of between 160 and 200 kg N ha^{-1} and 30-35 kg P ha^{-1} were applied annually. Unless drought limited growth, maize grain yields were 7-8 t ha^{-1}, with a concomitant 10-12 t ha^{-1} stover. Farmers estimated that between 80 and 100% of the stover was returned to the soil and incorporated during land preparation for the succeeding crop. Maize was rotated with irrigated winter wheat on six of the 19 fields sampled.

Table 2 lists, and Figure 1 shows the distribution and extent of the major soil types in Zimbabwe. The data for Masvingo and Chivi, both in Masvingo province, were combined and considered as a single 'site' on the basis of similar soil and climate.

2.2.4. Soil and leaf material sampling and preparation

We selected three 20 m x 20 m plots as replicates at random in the reference woodland areas, avoiding unrepresentative areas such as termite mounds. Ten pits were dug in each plot and samples were collected from the top 20 cm at depths corresponding to the recognizable horizons. For each plot, the ten samples from each depth (each about 100 g) were then bulked together to form a composite sample. The sampling depths in the top 20 cm were as follows. At Mafungautsi 0-8 cm (A1 horizon) and 8-20 (A2 horizon), and at Masvingo and Chivi 0-10 cm (A1 horizon) and 10-20 cm (A2 horizon). In the Chikwaka red clay the A1 horizon was shallow and there were no clear horizon boundaries so we collected samples from the 0-10 cm and 10-20 cm depths.

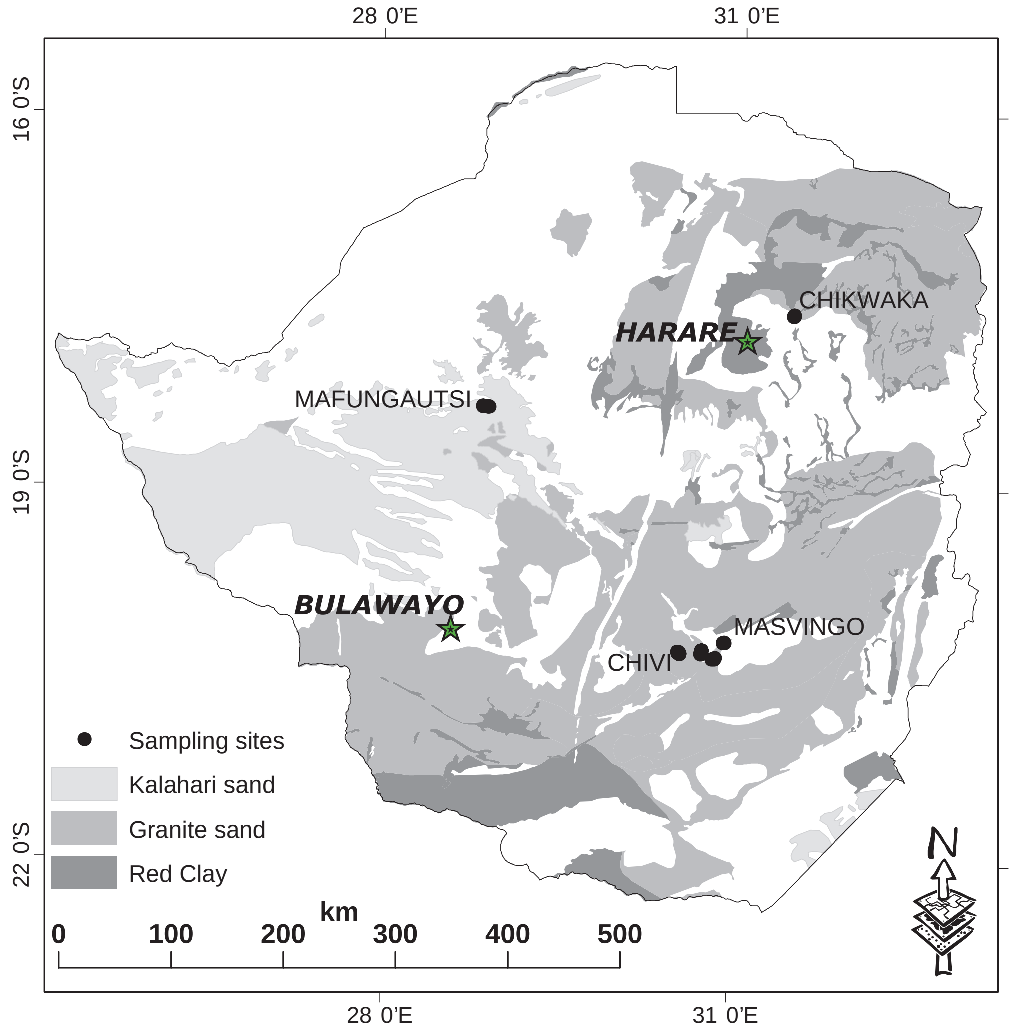


Figure 1. Map of Zimbabwe showing the distribution of the major soil types studied and the location of the sites.

In the arable fields at Mafungautsi and Masvingo, samples were collected from the AP1 and AP2 horizons, but in Chikwaka the samples were collected from depths corresponding to those used for sampling in the woodland. Three 20 m x 20 m plots acting as replicates were also selected in each field; within each plot three samples were collected per depth and bulked together to form a composite sample. Undisturbed cores of soil (4 cm diameter and 5 cm deep) were collected from the designated horizons in each field and woodland reference and used to determine bulk density.

The soil samples were air-dried in wooden trays and sieved to pass 2-mm. Larger pieces of organic material and stones were thereby eliminated. A sub-sample for chemical analysis was obtained by spreading the sample thinly on a plastic sheet and quartering. Most of the soil samples from Mafungautsi were contaminated with charcoal that could easily be distinguished as small, black particles under the microscope. We removed large charcoal particles from the soil by hand. After removing the charcoal, we crushed the samples to pass through a 0.5-mm sieve and stored them for chemical analysis. Large particles of charcoal were not observed in the soil from the other sites.

Leaf material for ^{13}C signature analysis was collected from the dominant C3 and C4 plants in the woodland, from the floor, and from the maize. The leaf material was oven-dried at 70 ºC and ground to 0.5 mm.

2.2.5. Laboratory methods

All the soil samples were analysed for C, N, particle size and bulk density; the samples from the woodland sites were also analysed for available P, CEC, Ca, Mg and K. Total soil N was determined by semi-micro Kjeldahl digestion (Anderson and Ingram, 1993). The C content and ^{13}C signatures of the soil organic matter and vegetation were determined on a PDZ Europa Roboprep biological sample converter coupled to a PDZ Europa 20-20 stable isotope mass spectrometer. Weighted means were then used to calculate the contents of organic C and N in the top 20 cm of soil. We converted the concentrations of organic C and N for each sampling depth to contents per unit area (ha) using the corresponding values for bulk density and depth.

The isotope ratios were expressed as $\delta^{13}C$ using the formula:

$$\delta^{13}C = \{(^{13}C/^{12}C \text{ sample})/(^{13C}/^{12}C \text{ reference})-1\} \times 1000 ‰$$

The proportion of soil organic matter derived from the maize was determined as (Jolivet *et al.*, 2003)

$$f_{\text{maize},t} = (\delta_{\text{soil},t} - \delta_{\text{ref}})/(\delta_{\text{maize}} - \delta_{\text{ref}})$$

where $f_{\text{maize},t}$ is the fraction of organic C derived from maize, $\delta_{\text{soil},t}$ is the measured $\delta^{13}C$ value of the organic C at time *t*, δ_{ref} is the $\delta^{13}C$ of the organic C in the woodland soil and δ_{maize} is the $\delta^{13}C$ of the maize crop. This equation is ideal for partitioning organic carbon according to its origin when an abrupt transition from pure C3 to pure C4 occurs, but such transitions are rare. In applying this equation to our woodland sites where there is a small contribution from C4 plants, we assume that organic C derived from C4 and C3 plants has similar dynamics. We also assumed that the only C input to cultivated fields was from maize, and the input of C4 and C3 weeds was negligible. Fields on commercial farms where winter wheat had been grown under irrigation were excluded from this analysis.

2.2.6. Statistical analysis

The dynamics of organic C and N in bulk soils, and the kinetics of organic C from woodland and maize plants were described by the single exponential function:

$$Y_t = Y_e + (Y_0 - Y_e)\exp(-kt)$$

where Y_t is the amount of organic C or N at a particular time, t, of cultivation in years, Y_e is the amount of C or N at equilibrium under cultivation, Y_0 is the amount of C or N under woodland and k is a rate constant (year^{-1}). For Masvingo and the commercial fields at Chikwaka where we had more than one reference site, the values of Y_0 were taken as the mean of our measurements. We assumed that the overall decomposition process can be described well by using first-order rate kinetics, taking soil organic matter as a homogeneous pool (Lobe *et al*., 2001). At all of the sites we took initial contents of C and N, Y_0, as the measured values. A similar function was fitted to the estimates of accumulation of maize-derived C:

$$Y_t = Y_e + (Y_0 - Y_e)\exp(-kt),$$

where Y_0 was fixed at zero.

2.3. Results and discussion

2.3.1. Initial soil organic carbon and nitrogen under native woodland

The initial contents of C and N were largest under woodland at all sites, and these were related to the content of clay+silt in the order Mafungautsi < Masvingo < Chikwaka smallholder < Chikwaka commercial (Figure 2, Table 3). The Chikwaka clay soil contained at least twice as much organic carbon (53.3 t C ha^{-1}) and organic nitrogen (4.88 t N ha^{-1}) as the Masvingo granitic sand (22.8 t C ha^{-1}, 1.47 t N ha^{-1}) and the Mafungautsi Kalahari sand (19.5 t C ha^{-1}, 0.88 t N ha^{-1}). The large difference in the contents of C and N between the reference site for Chikwaka smallholder and the commercial sites (Figure 2e and f) arises because the smallholdings were

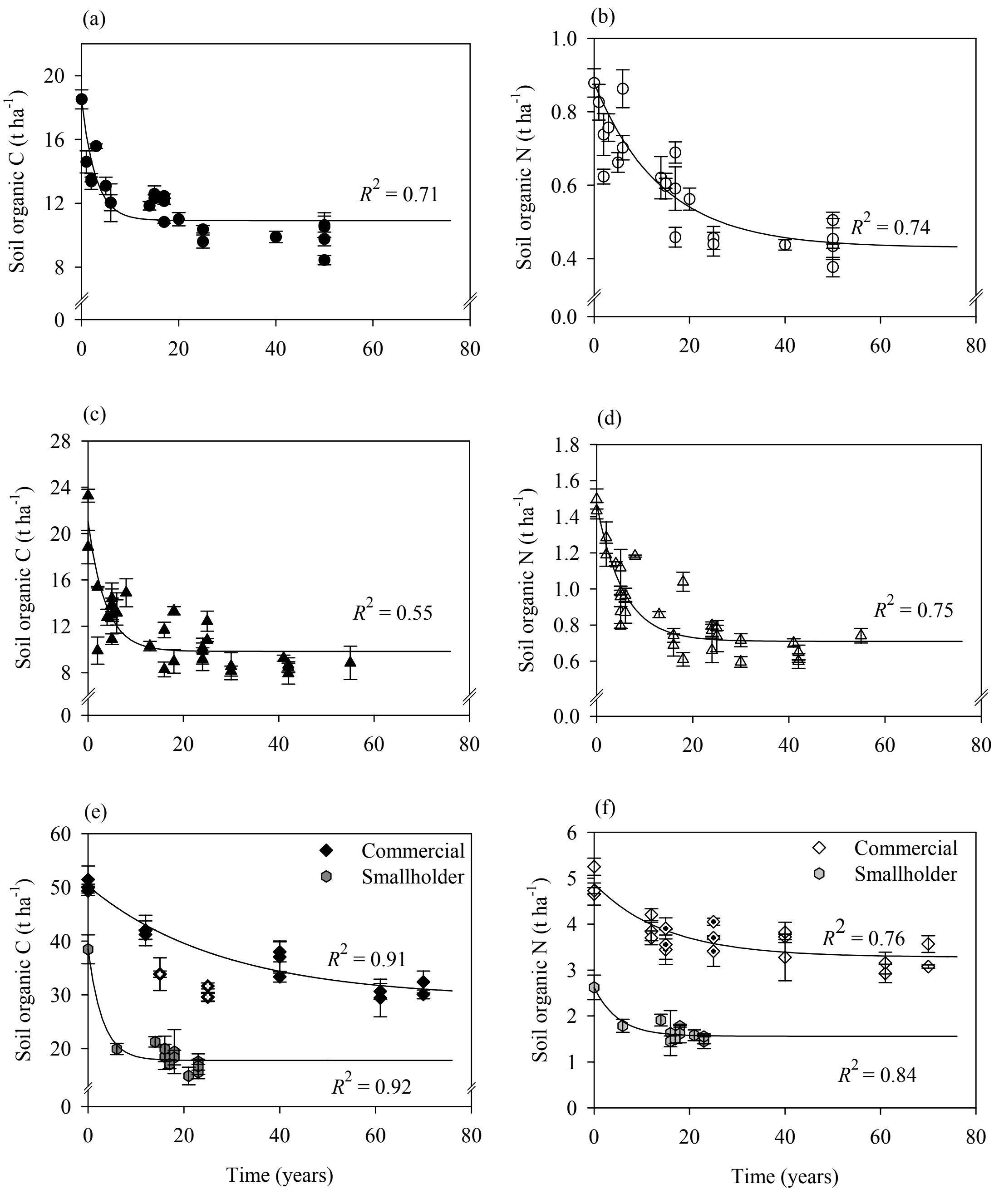


Figure 2. Changes in organic C and N in the soil with period of cultivation in the Mafungautsi (a, b), Masvingo (c, d), Chikwaka smallholder and Chikwaka commercial farming sites (e, f). Sampling depth 20 cm; lines represent fitted exponential functions. The dotted symbols represent commercial fields from the Chikwaka site where irrigated wheat had been grown during the winter seasons.

established in secondary woodland which had previously been under commercial maize production. We confirmed this by examining the aerial photographs and asking the farmers. The woodland used as reference for the smallholdings at Chikwaka was re-established 20 years previously, and so we can deduce that a much longer fallow is required to restore organic matter to the original content under the conditions prevailing there.

The major factors expected to influence the stocks of C under woodland were (i) the amount and quality of organic material added annually, (ii) the decomposition rates of both added and native organic matter and (iii) the capacity of the soils to protect organic matter physically. Feller and Beare (1997) suggest that soils containing less than 20% clay+silt do not stabilize organic matter significantly, which explains the small amounts of organic C and N and in the woodland soils at Mafungautsi and Masvingo. Hassink (1996) suggested that a particular soil can hold a certain amount of organic matter only up to a saturation point, which is determined by the clay+silt content (see Six *et al*., 2002). Beyond that point, excess organic matter added to the soil is rapidly decomposed. The marginally greater organic matter contents in the soil at Masvingo than at Mafungautsi are probably due to the larger contents of clay+silt.

The larger contents of C and N in the clay soil under woodland at Chikwaka are presumably due to the greater capacity of the soil to store organic matter because the soil sequesters and protects organic matter in aggregates. The primary production in woodland at Chikwaka is also expected to be greater than at Mafungautsi and Masvingo because the Chikwaka region receives more rain (Table 2). In consequence more litter and dead roots are added to the soil there. The influence of larger inputs might, however, be partly offset by faster decomposition of organic matter because the soil remains moist for longer.

2.3.2. Dynamics of soil organic carbon and nitrogen under cropping

Rapid decline of organic C and N was evident in the initial years of cultivation on smallholdings at all sites (Figure 2). There were no significant differences in rate constants, k, for the decline of organic C and N across the smallholder sites, except at Mafungautsi where k for organic N was smaller than those for Masvingo and Chikwaka (Table 3). The magnitude of decline, which is the balance between losses by decomposition and erosion and gains from addition of organic material, was greatest in the Chikwaka clay soil, where 22 t organic C ha^{-1} and 1 t N ha^{-1} were lost within the first 10 years of cultivation. These losses are 53% of the initial organic C and 41% of the initial organic N. The smallest decreases on smallholdings were at the Mafungautsi site on

Kalahari sand (Figure 2). The poor productivity of crops on smallholdings, coupled with return of little of the crop residues to the soil resulted in the rapid losses of organic matter across all sites. The slower decline for organic nitrogen at Mafungautsi is probably due to the small initial contents.

Table 3. The initial (Y_0), equilibrium (Y_e) and change constants (k) for organic C and N in the soil derived from fitted exponential functions.

	Organic C			Organic N		
	Y_0 (t ha^{-1})	Y_e (t ha^{-1})	k (year^{-1})	Y_0 (t ha^{-1})	Y_e (t ha^{-1})	k (year^{-1})
Mafungautsi	19.5 (1.1) [a]	8.9 (0.3)	0.31 (0.06)	0.88 (0.04)	0.43 (0.05)	0.07 (0.02)
Masvingo	22.8 (1.6)	9.6 (0.6)	0.26 (0.06)	1.47 (0.05)	0.72 (0.01)	0.21 (0.02)
Chikwaka (Smallholder)	41.9 (1.9)	19.5 (0.6)	0.29 (0.09)	2.62 (0.14)	1.56 (0.07)	0.20 (0.09)
Chikwaka (Commercial)	53.3 (2.0)	34.3 (1.5)	0.09 (0.02)	4.88 (0.30)	3.28 (0.16)	0.06 (0.03)

[a]Standard errors in parentheses.

In addition, woodland clearance might accelerate losses of soil by erosion, and hence of C and N in the topsoil by erosion. Soil erosion rates of up to 12 t ha^{-1} year^{-1} have been measured on the granitic sandy soil under conventional tillage in several parts of Zimbabwe (Elwell and Stocking, 1988; Vogel, 1992). Such losses are likely to have a strong impact on losses of organic matter. According to the Universal Soil Loss Equation (USLE), erodibility is proportional to the ratio (silt+very fine sand)/(1-clay) (Wischmeier and Smith, 1978), so the Mafungautsi Kalahari sand is more susceptible to erosion than the granitic sands or the Chikwaka clay soil because it contains so much fine sand (30%). The Chikwaka clay, which has a larger proportion of fine particles than the granitic sands, is more resistant to erosion because it is better aggregated.

Our results show rapid losses of soil organic matter in sandy soils, although not as fast as those from other tropical agro-ecosystems. Feller and Beare (1997), for example, found that equilibrium under cultivation in a sandy soil was attained in about 3 years compared with 10 years in the similar Masvingo soil. Lobe *et al.* (2001) reported even greater losses of organic C and N in coarse-textured soils in South Africa, though there equilibrium was not reached in 34 years as a result of continued loss of organic matter by wind erosion.

The rapid decline in organic C in the Chikwaka clay on smallholdings can be attributed to the originally large amounts of 'active' organic matter in the clay soil under woodland. In uncultivated soils, particulate organic matter fraction is protected in macroaggregates, but is rapidly lost when macroaggregates are disturbed by tillage (Six *et al.*, 2000). Despite the greater losses of organic C and N at Chikwaka, equilibrium was attained at substantially larger contents than those for Mafungautsi and Masvingo (Table 3).

Losses under commercial farming at Chikwaka were relatively small, with a 36% decline in organic C and a 32% decline in organic N to the calculated cultivation equilibrium (Figure 2e and f). At equilibrium the organic C and N under commercial management exceeded those on smallholdings by 15 t C ha^{-1} and 1.7 t N ha^{-1}. Whereas smallholders apply little fertilizer, commercial farmers applied large amounts of mineral fertilizers with annual applications of N ranging between 160 and 200 kg ha^{-1}. Large yields were achieved under commercial management and large amounts of stover were returned to the soil after harvesting, thereby maintaining at larger concentrations of organic matter in the soil.

2.3.3. Changes in $^{12}C/^{13}C$ isotopic ratios and long-term change in organic matter from woodland plants and maize

The C3 tree litter from all woodland sites was more depleted in ^{13}C ($\delta^{13}C$ values between -26‰ and -27‰: mean=26.4; s.e.=0.3; *n*=12) than was the C4 grass (mean=13.9; s.e.=0.2; *n*=12) or maize litter (mean=14.1; s.e.=0.3; *n*=12) with $\delta^{13}C$ values ranging from -13.8‰ to -14.2‰. Litter collected from the woodland floors, which was a mixture of C3 and C4 litter, had $\delta^{13}C$ of about -22‰. The $\delta^{13}C$ values of the woodland soils, ranging from -21.3‰ to -22.8‰, reflected a mixed input of both C3 and C4 organic matter, but with the C3 trees contributing most to organic C (Figure 3). Carbon isotope ratios of organic matter in soil are directly related to those of the vegetation from which it is derived, in situations where the composition of the vegetation is stable (Boutton, 1996). The measured ^{13}C signatures and the relative contributions to organic C by C3 and C4 plants are typical of miombo woodlands composed of trees (mostly C3) and sparse grasses in the understorey vegetation (mostly C4). The organic matter in the secondary woodland soil used as reference for the Chikwaka smallholdings had a larger $\delta^{13}C$ value (Figure 3). The most likely explanation is that part of the soil organic matter was derived from the maize grown at the site before cultivation was abandoned and the site allowed to revert to woodland.

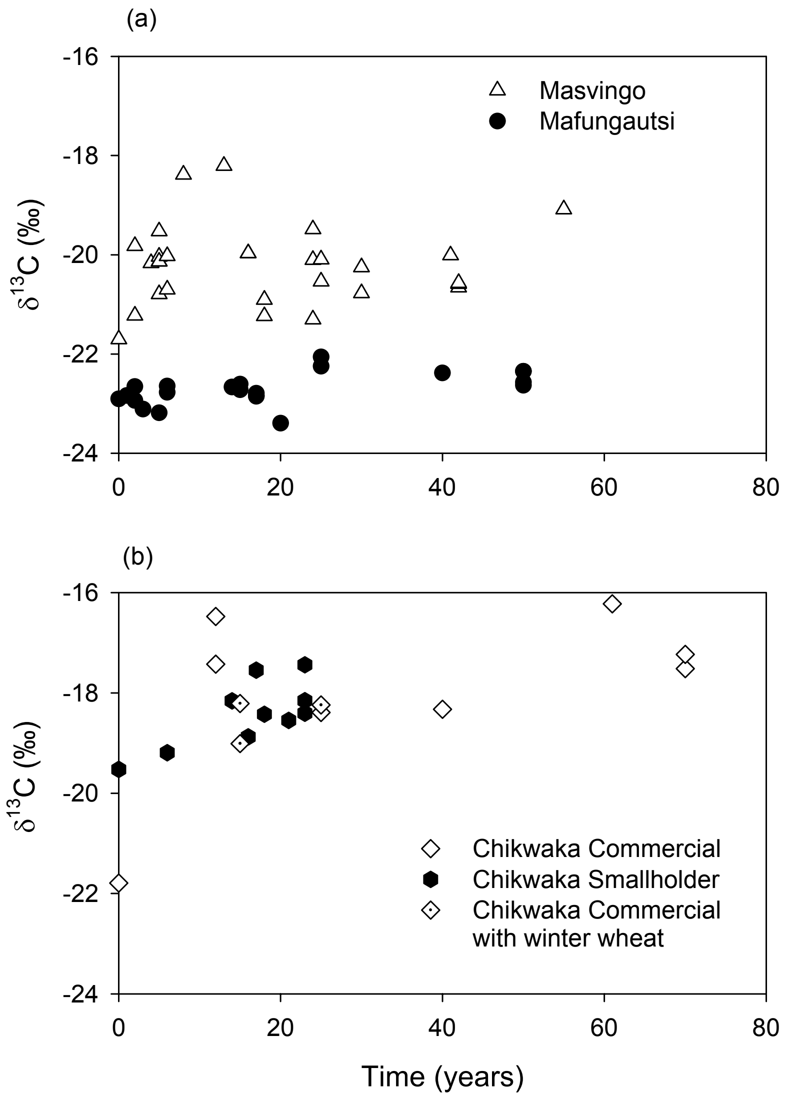


Figure 3. ^{13}C signatures of organic C in fields cultivated for different periods along the Mafungautsi, Masvingo, Chikwaka smallholder and Chikwaka commercial farming sites.

Interpretation of changes in ^{13}C signatures is subject to error caused by further fractionation during decomposition. Lignin is more depleted in ^{13}C by 2-6‰ in a wide range of plant species, and there may be decline in the δ^{13}C signatures during decomposition as recalcitrant lignin accumulates relative to other forms of organic matter (Benner *et al.,* 1987). The isotopic differences due to photosynthetic discrimination between C3 and C4 plants (average 14‰) are, however, between 5-15 times greater than $\delta^{13}C$ changes resulting from environmental and biological effects (Boutton, 1996).

We expected the change in vegetation at the time of clearance from predominantly C3 to C4 maize to induce increases in the $\delta^{13}C$ signatures of the organic matter, but did not observe this at Mafungautsi (Figure 3). Measured $\delta^{13}C$ values remained remarkably constant over the 55 years of cultivation, and there was no significant contribution to organic C by the maize crop (Table 4; Figure 4a). The small contribution of maize to organic matter in the soil at Mafungautsi can be attributed to the small crops produced and the small inputs of organic matter on smallholdings and the lack of physical protection in the sandy soils. Maize contains little lignin or polyphenols (Palm *et al.,* 2001) and its residues therefore decompose rapidly. McDonagh *et al*. (2001) obtained similar results in long-term studies on smallholdings in Tanzania. Jolivet *et al*. (1997; 2003) and Ludwig *et al*. (2003) have similarly found little accumulation of maize organic matter in sandy soils or in coarse fractions of clay soils in various temperate soils. The proportion of maize carbon we found in Mafungautsi is, nevertheless, much less than that observed in other studies.

Table 4. The initial (Y_0) and equilibrium (Y_e) contents of organic C in the soil and the change constants (k) for the original woodland organic C and the C derived from the subsequent maize as produced by the fitted exponential functions.

	Woodland organic C			Organic C from maize		
	Y_0 (t ha^{-1})	Y_e (t ha^{-1})	k (year^{-1})	Y_0 (t ha^{-1})	Y_e (t ha^{-1})	k (year^{-1})
Mafungautsi	19.5 (1.2) [a]	8.6 (0.39)	0.29 (0.06)	0 (0.19)	0.8 (0.4)	0.05 (0.05)
Masvingo	22.8 (1.4)	8.0 (0.48)	0.43 (0.08)	0 (2.1)	3.2 (0.9)	0.17 (0.13)
Chikwaka (Smallholder)	41.9 (2.1)	14.3 (1.0)	0.20 (0.05)	0 (2.1)	7.7 (3.9)	0.03 (0.17)
Chikwaka (Commercial)	53.3 (5.2)	15.1 (2.0)	0.29 (0.09)	0 (7.6)	28.7 (2.9)	0.14 (0.08)

[a]Standard errors in parentheses.

According to the model we fitted, 90% of the organic C present in the Mafungautsi Kalahari sand at equilibrium under cultivation can be traced back to that originally present under woodland, and less than 10% was contributed by maize (Table 4). The woodland C at equilibrium is equivalent to 44% of the original woodland C. Persistence of such a large proportion of the initial C in a soil

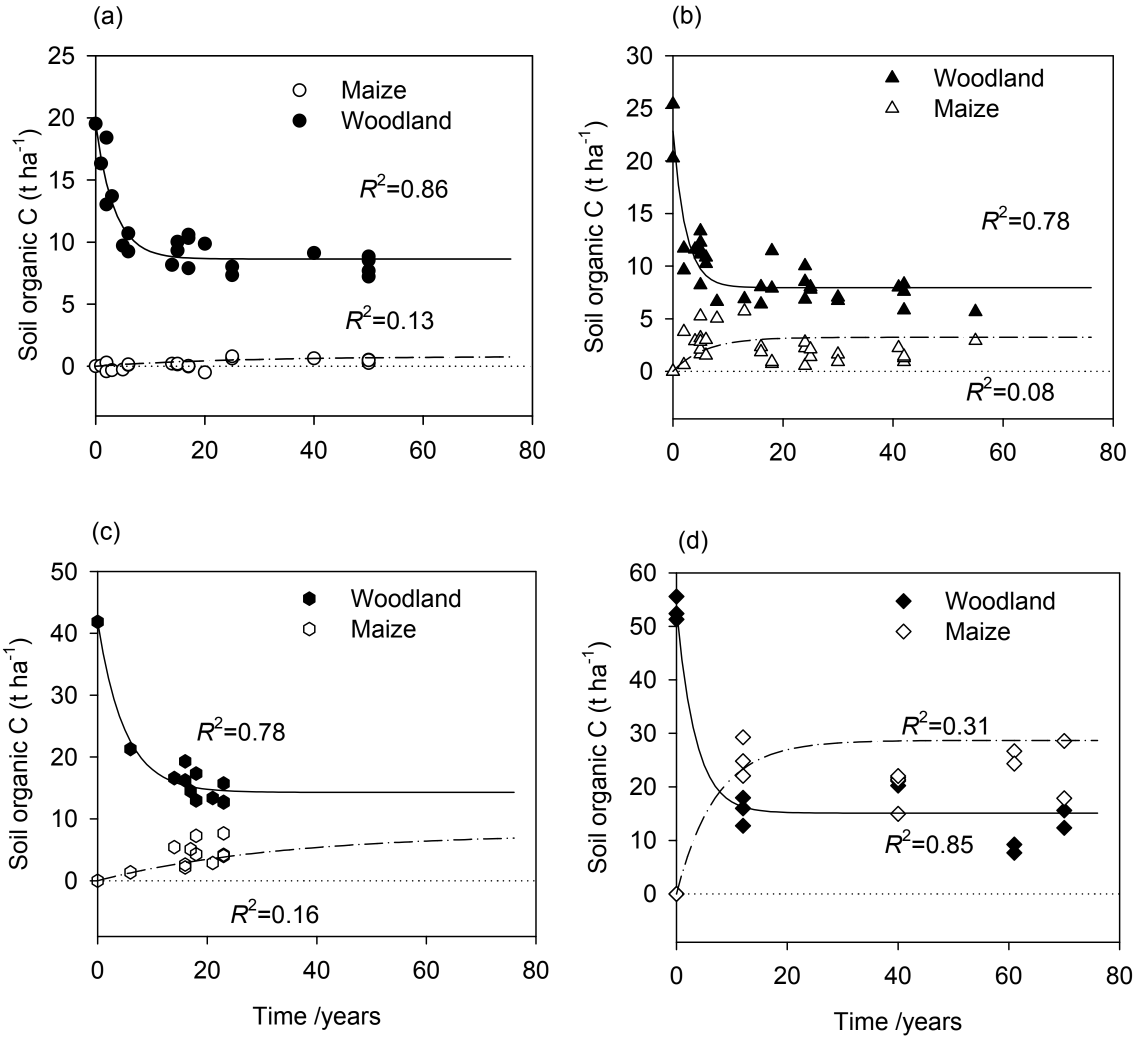


Figure 4. Changes with period of cultivation in organic C derived from woodland vegetation and from maize based on the ^{13}C analysis in the (a) Mafungautsi, (b) Masvingo, (c) Chikwaka smallholder and (d) Chikwaka commercial farming sites (fields where irrigated wheat had been grown during the winter seasons were excluded from this analysis). Sampling depth 20 cm; lines represent fitted functions for woodland organic C (continuous) and maize organic C (broken).

where little physical stabilization can be expected suggests that this fraction was chemically stabilized. The litter in the miombo woodlands dominated by *Brachystegia spiciformis* is characterized by large lignin and polyphenol concentrations (Nyathi and Campbell, 1994; Mtambanengwe and Kirchmann, 1995). Lignin is structurally recalcitrant and is highly resistant to decomposition. Polyphenols react with proteins to form stable polyphenol–protein complexes that resist decomposition (Handayanto *et al.*, 1997). Another possible explanation for the persistence of organic matter from the original woodland in the Mafungautsi Kalahari sand was charcoal in all the fields sampled. Charcoal is chemically stabilized and almost inert with a turnover time of thousands of years (Skjemstad *et al.*, 1996). Buschbacher *et al.* (1988) also found little change in $\delta^{13}C$ of the soil organic matter when a woodland (predominantly of C3 plants) was cleared for pasture (C4 grass). This they attributed to a large proportion of passive, physically-stabilized organic matter masking the changes in the active fraction, where the more recent organic matter was concentrated. In the sandy soils at Mafungautsi physical stabilization is unlikely.

In the soil at Masvingo, $\delta^{13}C$ of the organic C increased rapidly in the first few years of cultivation by 1.6‰ (Figure 3). This increase was not sustained because of the small returns of maize residues and the small capacity of the soil to stabilize organic matter. Maize carbon, however, constituted a significant proportion of total organic C at equilibrium (29%), presumably because of the somewhat larger clay+silt content. Despite the larger $\delta^{13}C$ values, the contribution of maize to organic C in the Chikwaka smallholdings site was not substantially more (35%) than that in the soil at Masvingo (Figure 4c). The small contribution from maize to organic C on smallholdings at Chikwaka can be explained by the small additions of maize stover, despite the greater capacity of the red clay soil to protect organic matter physically.

Changes in $\delta^{13}C$ values of the organic C were largest under commercial farming at Chikwaka (Figure 4). In sharp contrast to all of the smallholdings, under long-term commercial maize production organic C derived from maize amounted to 29 t ha^{-1}, representing almost 70% of the total organic C at equilibrium (Table 4; Figure 4d). Organic C from the woodland at Chikwaka showed similar decline constants and equilibrium values on both smallholdings and commercial farms (Table 4). This suggests that the dynamics of the original woodland C were independent any ‘priming’ effects caused by addition of fertilizers or large amounts of maize stover.

The annual inputs of maize C to the C in the soil at equilibrium (A) can be calculated from the fitted regressions for soil C derived from maize (Table 4 and Figure 4) as:

$$A = kY_e$$

Further we assume that approximately 25% of the maize C is converted to humus C after 1 year of decomposition under tropical conditions (Ayanaba and Jenkinson, 1990) and that 25% of the C was added as roots. Such calculations indicate an input of only 0.3 t ha^{-1} of maize stover in the Mafungautsi soil, which is not unrealistic given that grain yields recorded in the area were small (often <1 t ha^{-1}) and much of the stover was eaten by cattle (Table 1). However, estimates from similar calculations of inputs to the soil of 4.2 t ha^{-1} of maize stover (which would suggest grain yields exceeding 3 t ha^{-1}) on the Masvingo smallholdings, and of 40.2 t ha^{-1} under commercial agriculture in the Chikwaka site are excessive. By contrast, farmers estimated that 10-12 t ha^{-1} of maize stover was returned to the soil under commercial management in Chikwaka (see above). The large variation in $\delta^{13}C$ of the soils from commercial farms in Chikwaka indicates considerable uncertainty in the estimates of both the equilibrium (Y_e) and the rate constant (k) which probably explains these overestimates of maize C inputs.

2.4. Conclusions

Sandy soils (< 11% clay) contained little organic C and N under native woodland. The sandy soils have a small capacity to store organic matter and the woodlands in Zimbabwe are fairly light and slow growing, producing small litter inputs. The small reserves of organic matter present in natural vegetation were rapidly depleted within a few years of cultivation on smallholdings. We attribute this to the small quantities of biomass produced and the consumption or removal of stover. Maize contributed little to organic matter in the sandy soils because of this and the small capacity of the soils to protect organic matter physically. The soil organic matter derived from C3 plants that persisted was probably chemically stabilized. The Chikwaka clay soil contained the largest quantities of organic matter under woodland, but lost the most under smallholder management. In commercial farming on clay soil, equilibrium was reached at organic C and N contents double those on nearby smallholdings with similar soil. In commercial cropping system much larger amounts of organic matter were returned to the soil from maize. This highlights the essential role of mineral fertilizers in producing large crops which in turn replenish and sustain organic matter in the soil.

Our results have clear implications for land use in southern Africa. If Zimbabwe, or other countries in southern Africa were able to return agricultural land to woodland and thereby increase carbon storage in the soil, the gains would be much greater in soils that are rich in clay. However, such soils are also the most agriculturally productive, cover a relatively small area and are unlikely to be taken out of production. By using mineral fertilizers and returning crop residues to the soil, much more C can be stored as organic matter than under subsistence agriculture. Improving agriculture on smallholdings could enhance food security and the life of the rural poor, as well as sequestering more carbon in the soil.

CHAPTER 3

Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe

This chapter is in press as:

Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E., 2006. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agriculture Ecosystems and Environment*.

Abstract

An improved understanding of soil fertility variability and farmers' resource use strategies is required for targeting soil fertility improving technologies to different niches within farms. We measured the variability of soil fertility with distance from homesteads on smallholder farms of different socio-economic groups on two soil types, a granite sand and a red clay, in Murewa, northeast Zimbabwe. Soil organic matter, available P and CEC decreased with distance from homestead on most farms. Soil available P was particularly responsive to management, irrespective of soil type, as it was more concentrated on the plots closest to homesteads on wealthy farms (8 to 13 mg kg^{-1}), compared with plots further from homesteads and all plots on poor farms (2-6 mg kg^{-1}). There was a large gap in amounts of mineral fertilizers used by the wealthiest farmers (>100 kg N and >15 kg P per farm; 39 kg N ha^{-1} and 7 kg P ha^{-1}) and the poorest farmers (<20 kg N and <10 kg P per farm; 19 kg N ha^{-1} and 4 kg P ha^{-1}). The wealthy farmers who owned cattle also used large amounts of manure, which provided at least 90 kg N and 25 kg P per farm per year (36 kg N ha^{-1} and 10 kg P ha^{-1}). The poor farmers used little or no organic sources of nutrients. The wealthiest farmers distributed mineral fertilizers evenly across their farms, but preferentially targeted manure to the plots closest to the homesteads, which received about 70 kg N and 18 kg P per plot (76 kg N ha^{-1} and 21 kg P ha^{-1}) from manure compared with 23 kg N and 9 kg P per plot on the mid-fields (26 kg N ha^{-1} and 10 kg P ha^{-1}), and 10 kg N and 1 kg P per plot (and ha^{-1}) on the outfields. Crop allocation on the homefields was most diversified on the wealthiest farms where maize was allocated 41% of the area followed by grain legumes (24%) and paprika (21%). Maize was grown on at least 83% of the homefields on farms with less access to resources. All the farmers invariably applied nutrients to maize but little to groundnut. Maize grain yields were largest on the homefields on the wealthy farms (2.7 to 5.0 t ha^{-1}), but poor across all fields on the poor farms (0.3 to 1.9 t ha^{-1}). Groundnut grain yields showed little difference between farms and plots. N and P partial balances were largest on the wealthy farms, although these fluctuated from season to season (–20 to +80 kg N per farm and 15 to 30 kg P per farm; average 21 kg N ha^{-1} and 8 kg P ha^{-1}). The partial balances on the wealthy farms were largest on the homefield (20 to 30 kg N and 13 kg P per plot; >26 kg N ha^{-1} and >13 kg P ha^{-1}), but decreased to 10 to 20 N and 6 to 9 kg P per plot (<20 kg N ha^{-1} and 13 kg P ha^{-1}) in mid-fields and –7 to +10 kg N and –1 to +1 kg P per plot (<10 kg N ha^{-1} and <2 kg P ha^{-1}) in the outfields. N and P balances differed little across plots on the poor farms (–2 to +4 kg per plot; -5 to +4 kg ha^{-1}) due to limited nutrients applied and small off-take from small harvests. This study highlights the need to consider soil fertility gradients and the crop and nutrient management patterns creating them when designing options to improve resource use efficiency on smallholder farms.

3.1. Introduction

Aggregated nutrient balance estimates at national and regional levels for sub-Saharan Africa have shown overall large negative balances (Stoorvogel et al., 1993; Van den Bosch et al., 1998). At such scales variability is driven by soil forming factors, such as, underlying geology and position on the landscape, jointly termed the 'soilscape' (Deckers, 2002). In contrast, variation in soil fertility associated with resource management at the farm level has generally been overlooked, despite evidence that such affects nutrient use efficiencies and productivity of both crops and livestock (Smaling and Braun, 1996; Giller et al., 2006). In addition, there are strong indications that nutrient balances differ widely between farms in different wealth categories and between plots at different distances from homesteads (Baijukya and de Steenhuijsen Piters, 1998; Elias et al., 1998; Shepherd and Soule, 1998).

Differences in the wealth status of the farmers contribute significantly to the variability of fertilizer use, as the richer farmers purchase and use larger amounts of mineral fertilizers (Tittonell et al., 2005). In addition, the richer farms own more cattle and thus, through manure, import significant quantities of nutrients to their farms during the dry season from grazing of crop residues on communal grazing areas and other farmers' fields (Swift et al., 1989; Achard and Banoin, 2003). Consequently, nutrients accumulate on wealthier farms, often at the expense of the poorer farms.

Within farms, soil fertility status of different plots on smallholder farms in sub-Saharan Africa may vary considerably due to both inherent factors and different resource management strategies (Defoer et al., 2000; Rowe et al., 2005; Tittonell et al., 2005). Smallholder farms consist of multiple plots managed differently in terms of allocation of crops, fertilizers and labour resources; making within-farm soil fertility gradients caused by management strategies a common feature (Scoones and Toulmin, 1999; Tittonell et al., 2005). In most cases, both organic and mineral fertilizer resources are preferentially allocated to the part of the farm used for growing the main food security crop, often close to the homestead, whilst plots further away are neglected. Such management decisions culminate in creation of gradients of decreasing soil fertility with distance from the homestead (Elias et al., 1998; Vanlauwe et al., 2002; Briggs and Twomlow, 2000). Even where small quantities of manure and mineral fertilizers are available, farmers still apply these at high rates by concentrating them on small areas. For instance, farmers in Zimbabwe apply cattle manure at amounts as high as 80 t ha^{-1} yr^{-1} by concentrating cattle manure on preferred plots (Mugwira and Murwira, 1998). The underlying reasons for targeting of nutrient resources to few fields are not fully understood, but important factors include farm size, distance of different plots from the homestead, restricted availability of fertilizers and manures, availability and efficiency of labour use, risk of theft and the need to reduce risk associated with erratic rainfall (Carter and Murwira, 1995; Chikuvire, 2000; Nkonya et al., 2005).

Availability of organic and mineral nutrient resources, their management under spatially variable soil fertility conditions has consequences on the soil resource base, cropping patterns and crop yields on smallholder farms. Understanding the spatial and dynamic resource use strategies is necessary as a foundation for designing relevant and sustainable interventions to improve resource use efficiency at the farm level. Heterogeneity in soil fertility within and between small farm units (0.9-3 ha), mostly consisting of contiguous plots, has largely been ignored by studies discussing technology interventions, although this may be essential for understanding their success. Few studies have also been undertaken to assess the effects of resource endowment on farmers' decisions in terms of allocation of different cropping activities to different plots. This study thus sought to assess variability in soil fertility, management of nutrient resources and crop allocation patterns between and within farms in different wealth groups and the impact of this variability on production. An initial survey of 50 farms was conducted to identify different types of farmers varying in resource endowment and production objectives. Eight case-study farms were then selected on which the flow of resources was monitored over three years (seasons) to establish both spatial and temporal resource allocation patterns giving rise to soil fertility gradients, and their impact on crop production and nutrient balances.

3.2. Materials and methods

3.2.1. The study site

The study was conducted in the Murewa smallholder farming area (population density 104 people km^{-2}) which is located about 80 km east of Harare and lies between 17° and 18° S and 31° and 32° E. The area has a sub-tropical climate and is characterized in Zimbabwe as having a high potential for crop production. It is in an agroecological zone (Natural Region II), which receives 750-1000 mm rainfall annually, distributed in a unimodal pattern (December-April). The soils in the area are predominantly granitic sandy soils (Lixisols) with low inherent fertility. A smaller proportion of the area has more fertile dolerite-derived clay soils (Luvisols) that are considered the best agricultural soils in Zimbabwe (Nyamapfene, 1991).

Farmers practice a mixed crop-livestock system with maize (*Zea mays* L.) as the dominant staple crop. Other crops commonly cultivated in Murewa include groundnut (*Arachis hypogaea* L.), sweet potatoes (*Ipomoea batatas* L.), sunflower (*Helianthus annuus* L.) and assorted vegetables.

Cattle are the main livestock and are grazed in a communal system where cattle graze freely in rangeland during the day and are tethered in kraals close to homesteads at night. Close interaction between crop and cattle production occurs through crop residues that are used to feed cattle and the reciprocal use of manure to fertilize crops.

3.2.2. Development of farm typology and selection of case study farms

Focus group discussions were conducted with the community members in Chiwara village (31°49'E, 17°51'S; 120 households) to identify farmer criteria, to be used as a basis for grouping themselves into different wealth classes. Farmer-identified indicators of wealth status were ranked, and based on these criteria all the farmers in the village were allocated to one of four different wealth groups. A farmer survey was conducted using a sample of 50 households randomly selected out of the 120 households in the village to characterize the households and classify then into different groups. Having confirmed the resource endowments of the farms through the surveys and farm walks, eight case-study farms were selected for detailed resource flow mapping. There were two from each of the four wealth categories (referred to as Resource groups 1-4) that were identified by the farmers. In addition, farms were selected to ensure that two farmers in each of the four categories were located on the two major soil types, the granitic sandy soils and the red clays. This was not possible for the richest category on the clay soil as no farmer in this category wished to participate in the resource flow mapping exercise because of the time it would cost. Therefore the farm that was selected had granitic sands closest to the homestead and red clay soil on the outfield.

3.2.3. Development of plot typologies

The farms in Murewa mostly consist of one large field demarcated into smaller plots that are at different distances from the homestead. Few farmers have detached plots far from homesteads, except small gardens, which are used for growing various vegetables. The gardens are located in the low lying vleis, close to rivers where clay contents are higher and accumulation of nutrients occurs due to sedimentation of eroding soil down the slope. Detailed analysis of management of these gardens was excluded from this study, as our aim was to explore management of plots used for producing main crops. Of the eight farms selected, six had contiguous plots, whilst the other two had plots detached from the ones closest to the homestead. The slope of the main fields is generally gentle and hence influence of topography on variability of soil fertility within farms is restricted. Fields were demarcated into different plot types (PTs) in accordance to what farmers considered their best, average and worst plots on the farms. Farmers classified the different plots within their fields in terms of (i) distance from the homestead, (ii) perception of soil fertility status and yield potential and (iii) resource allocation trends. These criteria generated different

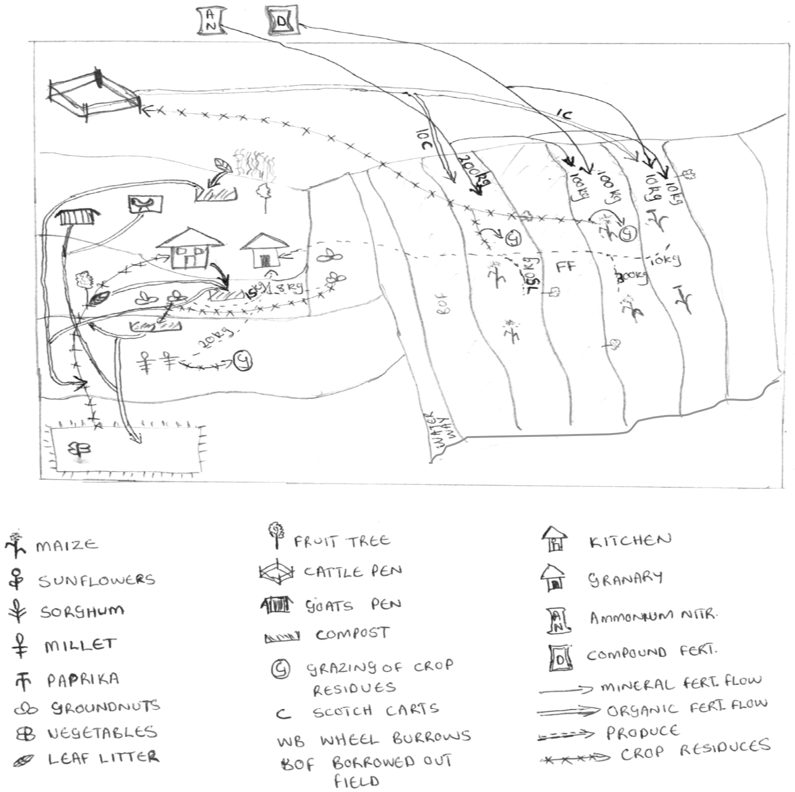
PTs that were categorized as best (PT1), average (PT2) and worst (PT3). On farms with more than three plots, the plots with similar characteristics were combined into one PT (Figure 1). Farmers in the poorest resource group (RG 4) owned small farms and only divided their farms into good (PT1) and poor (PT2) plots (due to small farm sizes).

3.2.4. Resource flow mapping at household level

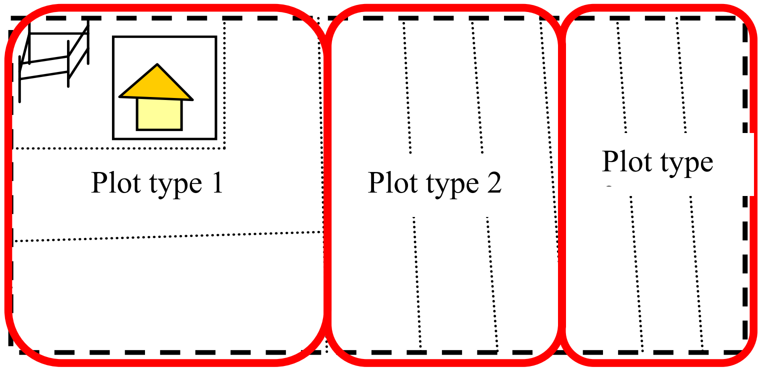
Resource flow mapping at household level was done using the procedure of Defoer et al., (2000), taking the farm as a system consisting of different subsystems linked together by movement of resources (Swift et al., 1989). In brief, the eight selected farms were visited during the middle of the cropping season and during a farm tour, taken together with the farmers, nutrient management strategies were discussed and obvious nutrient deficiencies were noted. Following the tour, farmers drew maps of their farms outlining the crop and livestock components and indicated how the household, cropping and animal components were linked together by movement of nutrients between the subsystems. For the cropping system, different plots were identified and management details, including type of crop grown and inputs on each plot type, were recorded. The farms were revisited at the end of the cropping season when grain and stover yields were measured and how they were used (within farms or sold) was noted. Quantities of locally available organic resources and crop yields were given in local units and these were converted to standard weights after estimating conversion factors. Cattle manure is a bulky resource which was transported to the fields using carts. We estimated the amounts of manure used by measuring the amount of manure that a fully loaded cart (400-600 kg) on the different farms carries and we multiplied that with the number of cart loads of manure applied. During the second and third seasons, crop biomass and grain yields were estimated by destructive sampling from micro-plots demarcated in farmers' plots. The actual sizes of the plots drawn by the farmers were measured using a Garmin (GPSII) Global Positioning System (GPS) unit with a position error of between 3 and 10 m. Resource use on the case study farms was mapped for three cropping seasons starting with the 2001/2002 to the 2003/2004 seasons to capture details of year-to-year management of resources by the farmers.

3.2.5. Calculation of nutrient balances

The information from the resource flow maps was used to calculate partial and full N and P balances at farm and plot scales for the case-study farms for the three seasons. Nutrient balances were also calculated for maize and groundnut, which were the main crops. Calculations were limited to N and P, which are the most limiting nutrients on these soils (Grant, 1981). The partial nutrient balances at the plot level (kg plot^{-1}) were calculated by subtracting total nutrients



AMMONIUM NITR = Ammonium nitrate
COMPOUND FERT = Basal fertilizer



Field type	Plot type 1		Plot type 2		Plot type 3		
Area (ha)	0.4	0.4	0.3	0.5	0.3	0.3	0.3
Crop	Groundnut	Millet	Lent out	Maize	Fallow	Maize	Paprika
Amm. nitrate (kg)	-	-	-	200	-	100	100
Compound fert. (kg)	-	-	-	-	-	100	10
Cattle manure (kg)	-	-	-	5000	-	-	500
Leaf litter (kg)	-	100	-	-	-	-	-
Yield (kg plot^{-1})	25	20	-	750	-	1900	15
Yield (kg ha^{-1})	60	50	-	1500	-	3170	60

Figure 1. An example of a resource flow map drawn by a farmer at Murewa (a), and a translation (not to scale) depicting demarcation of the farm into different field types and conversion of input and output quantities from local to standard units (b).

removed from plots in harvested products, including grain and stover, from the respective total nutrients added as inputs (manure, mineral fertilizer and crop residues, compost and leaf litter). The partial farm level balances (kg $farm^{-1}$) were obtained from the difference between total nutrient inputs and total outputs from all plots on a farm. At the farm level, direct movements of nutrients between plots were considered as internal flows and these were not included in the calculations of nutrient balances. Nutrients removed from the cropping system but recycled within the farm, e.g. stover removed and fed to livestock or composted, were considered as output in the current season, and if applied in the subsequent season these were then taken as inputs. The balances for maize and groundnut were presented per unit area (kg ha^{-1}) by subtracting total N and P removed in grain and stover from total N and P added in inputs to the respective crop and dividing by the area occupied by each crop. The nutrient contents of manure were calculated after analysis of samples taken from households with cattle. Crop grain and stover nutrient contents were estimated from the Organic Resource Database (Palm et al., 2001). It was assumed that 70% of the grain legume N was derived from biological N_2-fixation (Giller, 2001). NUTMON transfer functions were used to calculate full N and P balances to assess the potential effects of resource management on soil nutrient stocks (Van den Bosch et al., 1998). The inputs from natural processes were as follows: wet and dry atmospheric inputs and non-symbiotic N_2-fixation. The processes considered in calculations of outflows were: soil erosion, leaching and denitrification. Due to the uncertainties of the transfer functions (Faerge and Magid, 2004), we also calculated N and P losses using estimations from field measurements in Zimbabwe (Elwell and Stocking, 1988; Chikowo et al., 2004). The rate of soil erosion used was 20 t ha^{-1} yr^{-1} (Elwell and Stocking, 1988). The full balances calculated by transfer functions and estimation from fields measurement from previous studies were used to indicate the range in full balances that can be expected on different plots and fields.

3.2.6. Soil sampling and analysis

Soils (0-20 cm) were sampled in the plots identified in resource flow mapping at different distances from the homesteads. For the RG1 farm on clay, an alternative farm was selected for soil sampling since the one used for resource flow mapping had sandy soil on plots closest to the homestead. Three samples were collected randomly in each plot, air-dried and sieved (<2 mm). The three samples from each of the plots sampled were analysed separately to give indication of within-field variability of soil properties. Areas of discontinuity such as termite mounds and areas under trees, which constitute small areas under cultivation (Chikuvire, 2000) were avoided. Samples were air dried and passed through a 2 mm sieve and analysed for particle size distribution (hydrometer method), organic C (SOC) (Walkley-Black), total N (micro-Kjeldahl), available P (Olsen), cation exchange capacity (in ammonium acetate) (Anderson and Ingram, 1993).

3.2.7. Statistical analysis

Analysis of variance for soil fertility parameters in different plot types and N and P inputs, outputs, and balances at the plot and farm levels were conducted using Genstat 6. Inspection of the data showed no consistent relationship between soil type and inputs, outputs and nutrient balance at the farm and plot level. We consequently pooled together data for different soil types and analysed it using the models 'Farm type x Season' for the farm level, 'Farm type x Plot type x Season' for the plot level and 'Farm x Crop' for N and P balances for maize and groundnut. Standard errors of soil chemical properties were calculated for each plot using the three samples collected, to assess the variability of soil properties within plots.

3.3. Results and discussion

3.3.1. Wealth classes and characterization of households

The farmers in Murewa, like farmers elsewhere in sub-Saharan Africa (Elias et al., 1998; Shepherd and Soule, 1998; Achard and Banoin, 2003) considered cattle to be the most important indicator of wealth status (Table 1). This is due to the multiple functions that cattle have in the economy of smallholder farms e.g. cattle are a major capital investment and also contribute to food security through provision of milk and meat. Other benefits of cattle are indirect and include synergies within the mixed farms leading to improved crop productivity as cattle permit timely ploughing of fields, and provide nutrients through manure (Murwira et al., 1995). The other criteria were ranked in the order: draught power > farm size > farming implements > production orientation (commercial of subsistence) > hire or sell of labour > use of mineral fertilizers.

Using the indicators of wealth status, farmers generated four different resource groups (RGs), broadly divided into rich and poor on the basis of cattle ownership (Table 1). Depending on the number of cattle owned, farmers in the rich category were further divided into a very rich resource group (RG1) and the rich resource group (RG2). The poor group was also sub-divided into poor (RG3) and very poor (RG4) resource groups: distinguished by smaller landholdings and sale of labour by farmers in the RG4. The eight case study farms, two in each of the four wealth categories were representative of the characteristics of the respective RGs in the village (Table 2).

Table 1. Indicators of the wealth status of the farmers and the characteristics of the different 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 less than 3 ha	Farm sizes about 1ha
Livestock ownership	Own more than 10 cattle	Own less than 10 cattle	Do not own cattle, but have goats and chickens	Do not own cattle, but have goats and chickens
Farming implements	Own scotch cart, plough, cultivator, harrow and wheel-barrow and all small implements	Own all implements but rarely a scotch cart	Own only small implements such as hoes, shovels, axes and wheel-barrows	Own only small implements such as hoes, shovels, axes and wheel-barrows
Draught power	Own oxen for draught power	Own 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 to hire	Do not regularly hire labour	Cannot afford to hire labour	Sell labour locally
Mineral fertilizer use	Use large amount of mineral fertilizers (about 10 bags AN)	Mineral fertilizers used (< 10 bags AN)	Mineral fertilizers (< 10 bags AN)	Do not regularly use mineral fertilizers

Table 2. Average resource endowment on the farms in the village (n=50) and in the selected case study farms (n=8) in the different farmer resource groups in Murewa.

Level	Farm type	No of farms	Household size	Farm size (ha)	Cattle	Oxen	Goats	Chickens	Scotch carts
Village	RG1	8	7 (5-11)[a]	3.1 (2.5-4.1)	12 (10-16)	2 (1-3)	2 (0-7)	8 (2-20)	1 (1-2)
	RG2	14	5 (3-11)	2.5 (2.0-4.2)	7 (2-9)	1 (0-2)	3 (0-5)	5 (0-9)	0.4 (0-1)
	RG3	12	6 (4-9)	2.2 (1.4-2.8)	0	0	2 (0-4)	6 (1-13)	0
	RG4	16	4 (2-7)	1.0 (0.5-1.3)	0	0	0	3 (0-6)	0
Case study farms	RG1	2	6	2.8	14	3	3	5	1
	RG2	2	5	2.4	6	1	3	6	0.5
	RG3	2	6	2.2	0	0	1	5	0
	RG4	2	3	0.8	0	0	0	2	0

[a] The range of values are presented in parenthesis

The largest proportion of the farmers was in the RG4 category, whilst the smallest proportion was in the RG1 category. Despite an average cattle ownership of three per household within the village, less than half of the farmers owned cattle. Ownership of other resources was also strongly skewed towards the farms in the richer RGs, as farmers in these groups also owned larger farms and possessed greater quantities of other assets. Household size was notably smaller in the RG4 category; whose household heads were mostly widows. The wide variability of resource endowment observed indicates strong variability between farms in access to resources and constraints to production. The poorest farmers are faced with multiple constraints, which include small farm size, poor and competing demands for labour, lack of draught power and manure and lack of cash to buy fertilizers.

Characteristics of households across villages in Murewa collated from surveys conducted between 1988 and 1998 showed mean arable landholding of three ha, average household size of six people, cattle ownership of 71%, goat ownership of 42% and scotch cart ownership of 48% (Chuma et al., 2000). The average farm size from this collated information between 1988-1998 is larger than that observed in our study (1.9 ha) in 2003-5, whilst other assets, except goats, were distributed more evenly across farms than we observed (Table 2).

3.3.2. Variability of soil chemical properties as influenced by soil, farm and plot types

As expected SOC contents were larger on farms located on the red clay soil compared with those on the granitic sand (Figure 2a). The strong influence of texture on SOC can be explained by the capacity of clay soils to protect SOC through textural and structural effects (Six et al., 2002). The only exception was observed on the PT1 of farms in RG2, which had similar SOC contents despite the different soil types. For farms on the same soil type, SOC concentrations in plots closest to the homesteads were significantly largest on farms in the rich categories, these were in the order: RG1 >RG2 = RG3 = RG4 for sites on the clay soil and RG1 = RG2 > RG3 = RG4 for the sandy soil sites (Figure 2a). The larger SOC contents on PT1 on RG1 and RG2 farms were due to preferential application of cattle manure on these fields. The similar SOC on PT1 of the RG2 with those of RG3 and RG4 farms on the clay soil could not be explained by resource availability, although it is possible that the rates of manure applied by the RG2 farmers were insufficient to maintain large SOC contents. SOC contents decreased with distance from homesteads across all the farms. The steepest decline was observed on RG2 farm on the sandy soil that had a PT3 furthest from the homestead. The plots furthest from the homesteads on the RG1 and RG2 farms received less cattle manure, and consequently the SOC contents in these plots were not significantly different from SOC contents in corresponding plots on RG3 and RG4 farms.

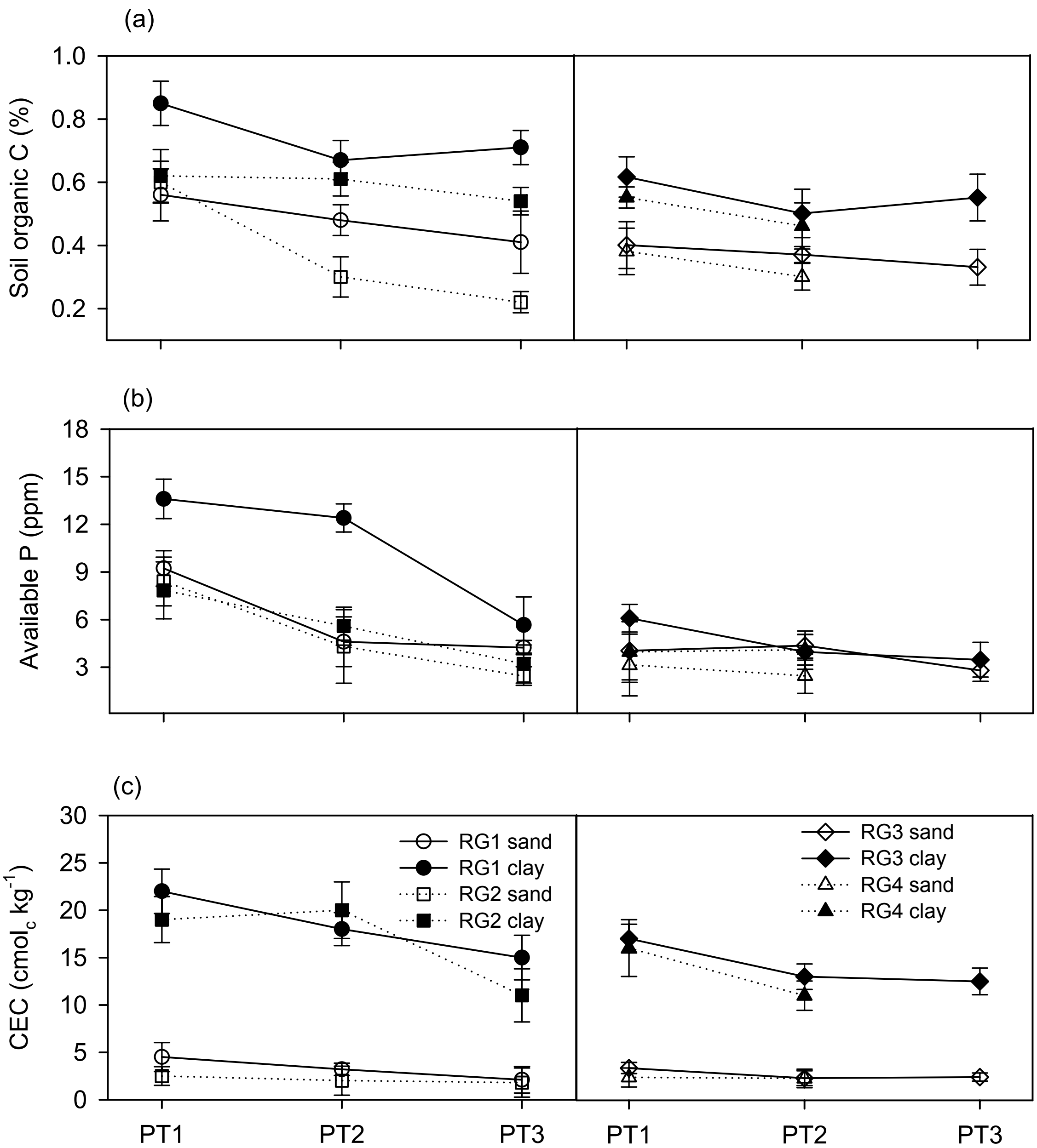


Figure 2. Variability of soil organic carbon (a), available P (b) and cation exchange capacity (c) with plot type on farms in different socio-economic groups situated on contrasting soil types at Murewa. Bars show standard deviation values.

A previous study that measured contents of SOC in outfields cultivated for different numbers of years after miombo woodland clearance revealed that there is a rapid loss in SOC in the initial 5-10 years of cultivation to reach equilibrium at about 0.6% C on the red clay soil and about 0.3% C on the granitic sand (Zingore et al., 2005). The SOC contents measured on the PT1 of the RG1 farm on clay (about 0.8%), PT1 of RG1 and RG2 farms on sand (about 0.6%) were larger than the equilibrium values measured by Zingore et al. (2005), suggesting that better management of homefields results in higher SOC compared with the poorly managed outfields. The SOC contents on the outfields of most of the farms were similar to equilibrium SOC contents on similar soil types in the earlier study.

Available P was most concentrated on PT1 on the rich farms (Figure 2b). There was a steep decline of available P with distance from the homestead on the rich farms such that available P on PT3 was similar across the different farm categories. The available P contents were small in all plots on farms in the RG3 and RG4 categories and did not show a strong relationship with soil texture, in contrast with the trends observed for SOC. Available P was the soil chemical factor most responsive to management, consistent with results obtained elsewhere in sub-Saharan Africa (Vanlauwe et al., 2002; Esilaba et al., 2005; Tittonell et al., 2005). This is because P is strongly bound in soil, and differences are largely dependent on amounts of P added. Despite the larger concentration of available P on the PT1 plots of the RG1 and RG2 farms, these values were still below the critical value commonly quoted in Zimbabwe as 15 mg kg^{-1} for good crop growth. Problems of P deficiency can thus be still expected on these “hot spots” of nutrient accumulation, although they should be less severe than on the plots further away from homesteads and the plots on the RG3 and RG4 farms.

CEC was also strongly influenced by soil type, and also by plot type on the farms on the clay soil. CEC was significantly greater on the PT1 across all farm categories on the clay soil, and on the PT2 of the RG1 and RG2 farms on the clay soil (Figure 2c). Despite the decline in CEC with distance from the homesteads, the CEC on the clay soil was significantly greater than on the sandy soil, across all farm and plot types. The small CEC values on all the plots on the sandy soil can be explained by the small clay contents and concomitant small SOM concentrations. The larger CEC values on PT1 of all the farms and PT2 of the RG1 and RG2 farms result from to the larger concentrations of SOM, whereas the plots further away from the homesteads had smaller CEC due the small SOM concentrations.

Within farms, gradation of chemical properties was not due to texture, as the texture was not significantly different across plots on individual farms (Table 3). The different plots on the case study farms were contiguous, except PT3 on the RG2 and RG3 farms on the sandy soil, and the slope of plots was also gentle (< 3%), which reduced the variability in soil fertility due to position within the soil-scape.

Table 3. Area of different plot types (PT) and their location in relation to the homestead for the four different farmer resource groups in the Murewa smallholder-farming site.

	Plot type	Distance from homestead (km)	Area (ha)	Clay+silt contents (%)	
				Granitic sand	Red clay
Resource Group 1	PT 1	0.03	0.9	12	55
	PT 2	0.07	0.9	14	50
	PT 3	0.15	1.0	15	53
Resource Group 2	PT 1	0.02	1.0	9	51
	PT 2	0.05	0.5	11	60
	PT 3	0.8	0.9	8	61
Resource Group 3	PT 1	0.02	0.5	13	49
	PT 2	0.04	0.8	15	51
	PT 3	0.07	0.9	15	51
Resource Group 4	PT 1	0.02	0.4	12	52
	PT 2	0.3	0.4	14	53

3.3.3. N and P inputs, crop production, N and P outputs and partial balances

Fertilizer use varied drastically between the rich and poor farms. The amounts of mineral N fertilizer used (>100 kg N per farm) were significantly largest on the RG1 farms in each of the three seasons, followed by RG2 farms (Figure 3a). The farmers in the RG3 and RG4 categories used little mineral N fertilizer in the first season, but the RG3 farmers increased use of mineral N fertilizers in the second and third seasons such that they matched mineral N use by the RG2 farmers. The 2002/2003 and 2003/2004 seasons were unusual in that the Zimbabwe Government offered free bags of ammonium nitrate as relief following the drought in the 2001/2002 season, which explains the increased use of mineral N by the RG3 and RG4 farmers in the last two seasons. There were no significant differences in the amounts of mineral P used by the RG1 and RG2 farmers across the three seasons, although these fluctuated from season to season (Figure 3b). In contrast to the consistent use of mineral P fertilizers by farmers in RG1 and RG2 categories, farmers in the RG3 and RG4 categories used mineral P fertilizers in two of the three seasons and the amounts they used were small (< 10 kg P per farm) (Figure 3b).

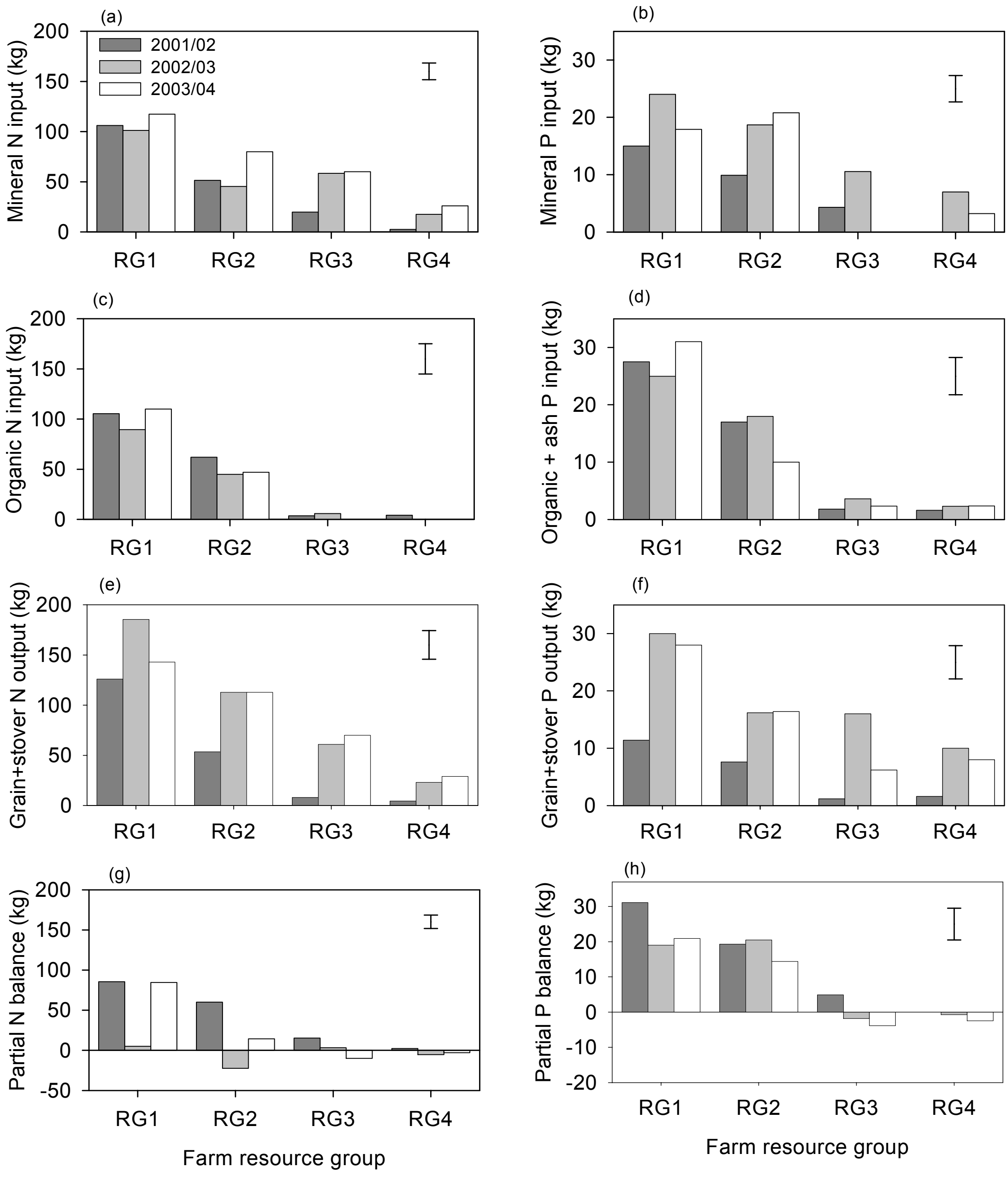


Figure 3. Mineral N and P inputs (a and b), organic N and P inputs (c and d), N and P removed in grain and stover (e and f) and partial N and P balances (kg $farm^{-1}$) combined for all plots on farms (averaged for the two farms in each category) in different resource groups at Murewa for the three seasons. RG1 – resource group 1; RG2 – resource group 2; RG3 – resource group 3; RG4 – resource group 4. Bars show SEDs.

The rich farmers are commercially orientated, growing maize and paprika as cash crops, and thus they were able to invest in mineral fertilizer to achieve high yields. Much more fertilizer was used in Murewa in the early 1990s, when farmers often applied the recommended rates 350 kg ha^{-1} compound D (8%N, 6%P, 6%K) and 250 kg ha^{-1} ammonium nitrate, which altogether amount to 116 kg N ha^{-1} (Chuma et al., 2000). The amounts used decreased by about 50% during the later years following the removal of subsidies on fertilizers and a subsequent increase in fertilizer prices. Our results showed that the decline has continued in recent years as even the richest farmers used much less fertilizer. Though many farmers in the study area use some fertilizer, the rates applied were far below recommended rates.

Both amounts of N and P in organic resources used on the farms were strikingly related to farm resource group in the order: RG1 > RG2 > RG3 ~ RG4 (Figure 3c and 3d). The major form of organic N and P was cattle manure, which explains the large differences in the organic N and P used by farms owning cattle (RG1 and RG2) and the poor farmers without cattle (RG3 and RG4). Cattle play a major role in recycling of nutrients in the smallholder farming systems, particularly in the free grazing systems such as that of Murewa (Swift et al., 1989; Murwira et al., 1995). Cattle also freely graze stover left in the fields following harvest; through this flow there may be net transfer of nutrients from the poor farms without cattle to the rich farms. The amounts of usable manure produced annually, calculated from amounts applied to plots, were 20 t and 8 t per farm on the RG1 and RG2 farms respectively. The organic sources of nutrients that the poor households used included compost and leaf litter collected from miombo woodland. Ash was also used. The total amounts of compost and leaf litter used per farm per season were less than 300 kg, which equated to less than 5 kg N and P (Figure 3c and 3d). These sources of nutrients can only provide small amounts of nutrients due to the limited quantities available and the high labour demands associated with their collection and application.

Resource availability, and consequently resource use at the farm level, was much greater for the rich households. The picture that emerged from the plot level also showed an unbalanced distribution of nutrients and this depended on farm type and source of nutrients. There was no significant difference in mineral N added to the different PTs on the RG1 farms, where the largest amounts were used, and also on the RG4 farms where the least was used (Figure 4a).

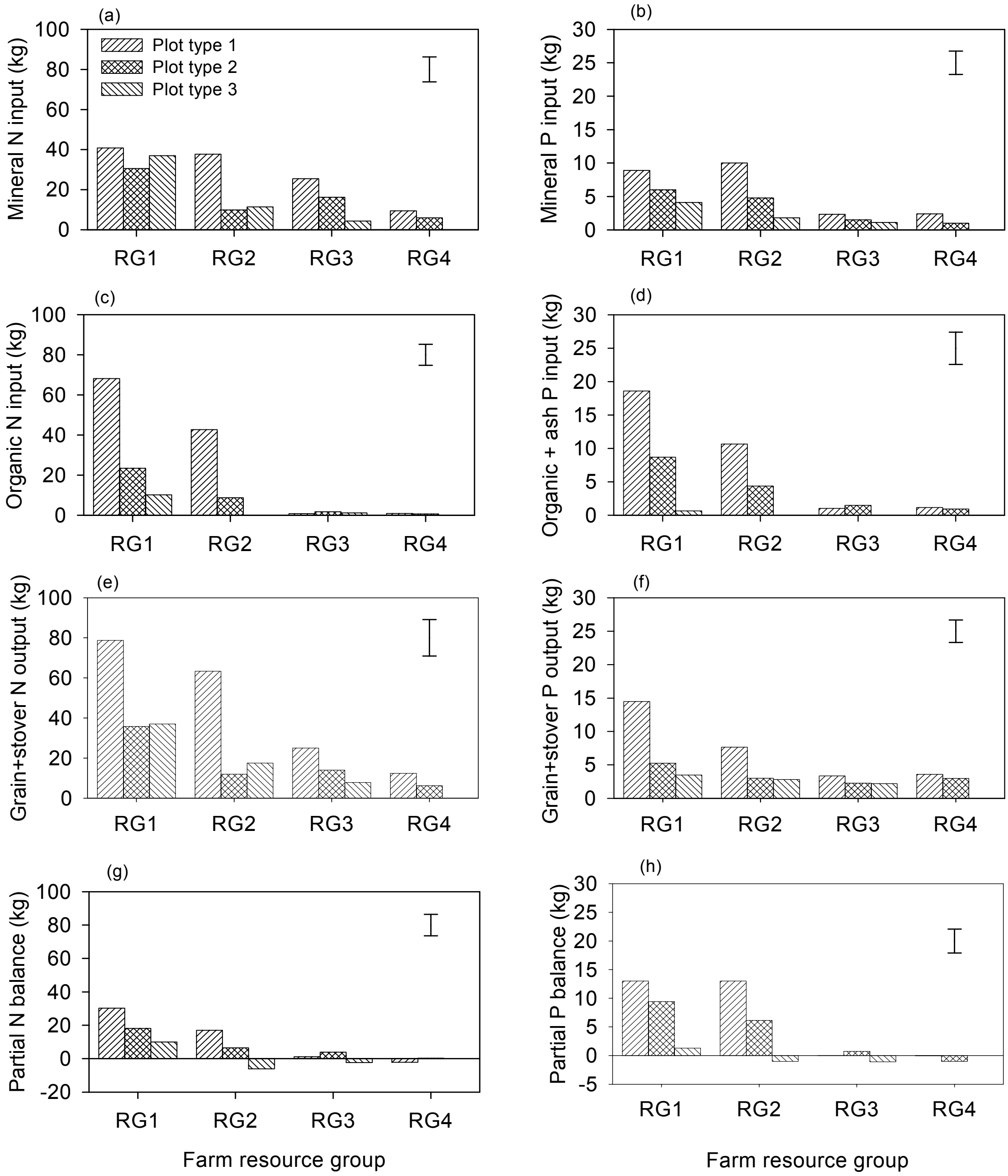


Figure 4. Annual (kg plot^{-1} yr^{-1}) mineral N and P inputs (a and b), organic N and P inputs (c and d), N and P removed in grain and stover (e and f) and partial N and P balances for the different plot types on farms in different resource groups at Murewa. Data show means for the three seasons. RG1 – resource group 1; RG2 – resource group 2; RG3 – resource group 3; RG4 – resource group 4. Bars show SEDs.

The lack of discrimination in allocation of fertilizer resources by the poor RG4 farmers can be attributed to the small amounts of fertilizers available coupled with the smaller farm sizes. At the other extreme, the richest households (RG1) also distributed mineral N fertilizers evenly across all plots at moderate rates. The distribution of mineral N on the RG2 and RG3 farms significantly decreased with distance from the homesteads (Figure 4a). The decrease in the amount of mineral N applied with distance from the homestead on the RG2 and RG3 farms was due to the limited amounts available and farmers' preference to fertilize the plots closest to the homestead. The amount of mineral P targeted to the different plots also decreased with distance from the homesteads for all farm types, although the differences were in most cases not significant. Generally, the amounts of mineral P applied were small, not exceeding 10 kg per plot, even on the PT1 (Figure 4b).

The PT1 on the RG1 and RG2 farms received significantly larger amounts of organic N and P compared with PT2 and PT3 on the respective farms (Figure 4c and 4d). For security of livestock, cattle pens where livestock are tethered at night are stationed close to the homesteads. Cattle manure collected from these pens is thus preferentially applied to PT1, which is closest to the homestead. Unlike mineral fertilizer, cattle manure is bulky and demands labour for transporting to plots further away from the homestead. This discourages farmers from applying large amounts of manure to the outfields. Within farms, cattle may also act as conveyers of nutrients from PT2 and PT3 to PT1. The amount of organic N and P used across the plots on the RG3 and RG4 farms were small, and showed no trend with plot type (Figure 4a and 4b).

On a ha basis, the RG1 farmers applied the largest amount of mineral N and organic N (Table 4), despite the larger farm sizes. At the plot level, there were small differences in application rate of mineral N and P between the RG1, RG2 and RG3 farms on the PT1. This is because the larger amounts of mineral N and P applied on the PT1 of RG1 were spread over a wider area. The amount of N applied per ha was similar across all plots on the RG1 farms, but decreased substantially from PT1 to PT2 on the RG2 and RG3 farms (Table 4).

3.3.4. Crop production and nutrient outputs

Maize was the dominant crop grown by the farmers and it was allocated the largest proportion of the area across all plots and also received the largest proportion of both organic and mineral N and P (Figure 5 and 6). This is because maize doubles as a food security crop and a cash crop. Maize yield was greatest on PT1 of the RG1 farm (4.2 t ha^{-1}) and least on the PT3 of the RG3 farm and PT2 of the RG4 farm (0.5 t ha^{-1}) (Table 5). The maize yields decreased according to the

Table 4. Annual (kg ha^{-1} yr^{-1}) mineral N and P inputs, organic N and P inputs, N and P removed in grain and stover and partial N and P balances for the different plot types and all plots combined (field) on farms in different resource groups at Murewa.

Farm	Plot/ Field level	Mineral inputs (kg ha^{-1} yr^{-1})		Organic/ash inputs (kg ha^{-1} yr^{-1})		Outputs (kg ha^{-1} yr^{-1})		Partial Nutrient Balance (kg ha^{-1} yr^{-1})	
		N	P	N	P	N	P	N	P
[a]RG1	PT1	45	10	76	21	87	16	34	15
	PT2	34	7	26	10	40	6	20	11
	PT3	37	4	10	1	37	3	10	2
	Farm	39	7	36	10	54	8	21	8
RG2	PT1	38	10	43	11	63	8	18	13
	PT2	20	10	17	9	24	6	13	13
	PT3	13	2	0	0	19	3	-6	-1
	Farm	25	7	21	6	39	6	7	8
RG3	PT1	51	5	1	2	50	7	2	0
	PT2	20	2	2	2	18	3	4	1
	PT3	5	1	1	0	9	2	-3	-1
	Farm	21	2	1	1	21	4	1	0
RG4	PT1	24	6	2	3	31	9	-5	0
	PT2	15	3	2	2	16	7	2	-2
	Farm	19	4	2	3	24	8	-3	-1

[a]RG1 – resource group 1; RG2 – resource group 2; RG3 – resource group 3; RG4 – resource group 4

trend: PT1 > PT2 > PT3 for all farms, except on the RG3 farm where the yield from PT1 was less than that from PT2. The gradients of maize productivity were caused by combined effects of past management (giving rise to soil fertility gradients) and present nutrient management (nutrients concentrated on more fertile plots).

Grain legumes (predominantly groundnut, but also some cowpea (*Vigna unguiculata* L.), common bean (*Phaseolus vulgaris* L.), Bambara groundnut (*Vigna subterranea* L.) and soyabean (*Glycine max* [L.] Merril.) were mainly grown on PT1 of the RG1 farms (Figure 5). The RG1 farms thus benefited most from biological N_2-fixation due to the larger grain legume production

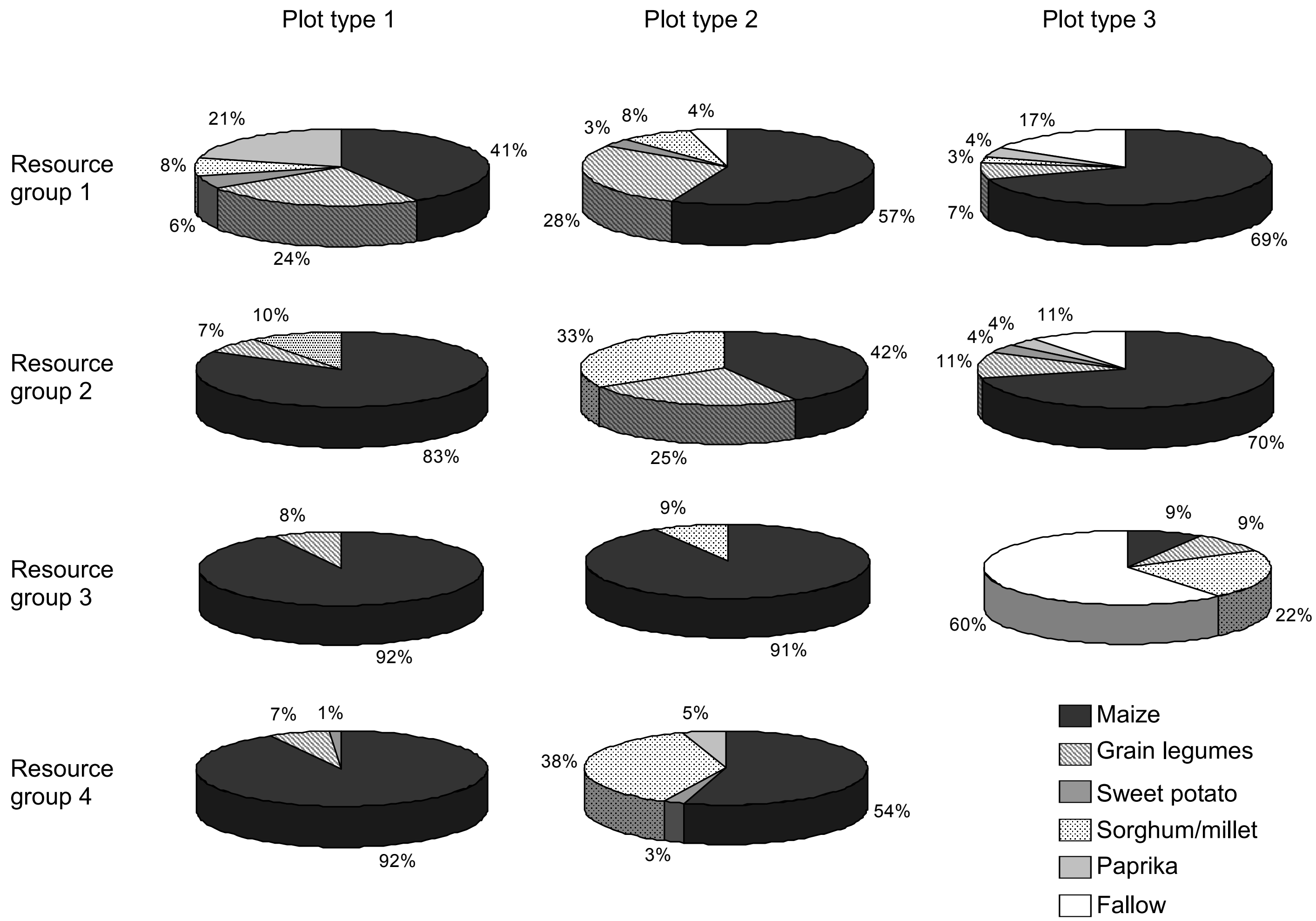


Figure 5. Proportion of the area of the different plot types on farms in different resource groups allocated to the different crop types over three cropping seasons (2001/2002, 2002/2003 and 2003/2004) at Murewa.

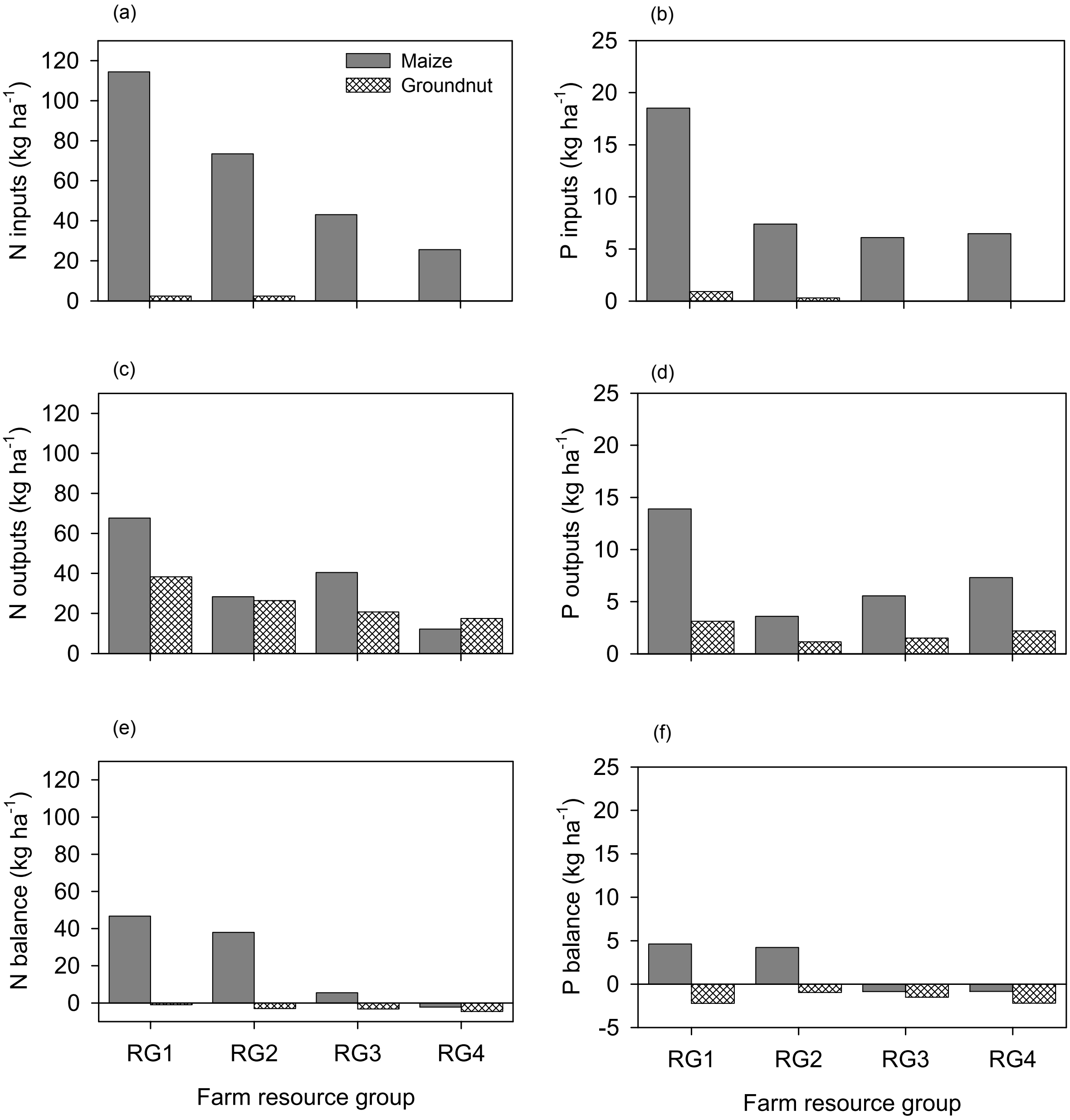


Figure 6. Average annual nutrient inputs for maize and groundnut (a) N and (b) P, nutrient outputs (c) N and (d) P, and partial nutrient balances (e) N and (f) P, as influenced by farm resource endowment at Murewa.

Table 5. Crop yields (t ha^{-1}) averaged for the 2001/02, 2002/03 and 2003/04 seasons across farm resource groups and different plot types on the case-study farms in Murewa

Crop	Resource Group 1			Resource Group 2			Resource Group 3			Resource Group 4	
	PT1	PT2	PT3	PT1	PT2	PT3	PT1	PT2	PT3	PT1	PT2
Maize	4.4 (2.7-5.0)[a]	3.6 (1.5-4.8)	2.9 (0.7-4.1)	2.7 (1.3-5.0)	0.8 (0.6-1.0)	1.1 (0.5-1.4)	1.2 (0.5-1.4)	1.5 (0.8-1.9)	0.5 (0.2-0.7)	0.8 (0.3-1.7)	0.5 (0.3-1.4)
Groundnut	0.7 (0.6-0.7)	0.8 (0.6-0.9)	0.5 (0.4-0.6)	0.6 (0.4-0.8)	0.6 -	0.3 (0-0.5)	0.8	-	0.2	0.5 (0.4-0.5)	-
Bambara groundnut	-	-	-	-	0.2 -	0.4 -	0.2	-	-	0.3 (0.2-0.5)	-
Common bean	-	-	0.1 (0-0.2)	-	-	-	-	-	-	-	-
Soyabean		0.5								0.3	
Sorghum/ millet	0.1 -	1.0 -	1.3 -	0.9 (0.8-1.0)	0.8 -	0.6 (0.1-1.0)	-	0.1 -	0.7 -	-	0.3 (0.1-0.5)
Sweet potato	3.2 -	1.5 -	-	-	-	1.3	-	-	-	1.2	1.8
Paprika	2.1 (1.9-2.3)	0.1 -	-	-	-	0.8 -	-	-	-	0.0	-

[a] Ranges of yields are shown in parenthesis.

on the more productive PT1, although the total amounts of N_2 fixed per farm were less than 15 kg ha^{-1}. The poorer households were mainly concerned about food security and allocated a large proportion of PT1 to maize. The yields of groundnut were poor and showed little difference with farm and plot types, although the yields were least on PT3 on the RG1, RG2 and RG3 farms (Table 5). The poor groundnut yields were partly due to the small amounts of fertilizers and manure applied (Figure 6). The small areas and poor yields of groundnut and other grain legumes are common on smallholder farms, and these were within the range found at other sites in Zimbabwe (Svubure, 2000).

About a third of the PT1 of the RG1 farms was allocated to paprika (*Capsicum annuum* L.), a cash crop, but paprika was not grown by the RG3 farmers in any of the plots and only allocated a small area in the PT3 of the RG2 farms and the PT2 of the RG4 farms (Figure 5). Paprika has recently been introduced into the area as a cash crop and the RG1 farmers integrated it into their cropping system by growing it on a significant part of their PT1. Gross margins from maize have decreased due to unattractive grain prices (Chuma et al., 2000) and the rich farmers adopted paprika as an alternative cash crop to maize.

Sorghum (*Sorghum bicolor* [L.] Moench.) and finger millet (*Eleusine coracana* [L.] Gaertn.) on the RG2, RG3 and RG4 farms were mainly allocated to PT2 and PT3. The poor rains during the 2001/2002 season caused the small yields for sorghum/millet on PT1 on the RG1 farm and PT2 of the RG3 farm, rather than the fertility status of plots or management. The farmers fallowed part of PT3 and the proportion fallowed was largest on the RG3 farm (Figure 5). Fertilizer use has decreased in Murewa over the past years (Chuma et al., 2000), and farmers have focused crop production on the more productive plots close to the homestead. The RG4 farmers did not fallow any of their plots due to the small farm sizes.

The relationship of N and P removed in cropped products at farm and plot scales were consistent with the trends for N and P inputs as they significantly decreased with resource endowment of the farms (Figure 3e and 3f) and plot type (Figure 4e and 4f). Nutrient outflows from the arable plots reflected the productivity of the farms as larger crop yields result in removal of larger amounts of nutrients in grain and stover. The largest amounts of N and P were removed from PT1 on the RG1 and RG2 farms as these were most productive due to use of large amounts of mineral and organic resources and higher soil fertility status of the plots.

The wealthy farms removed most of the stover after harvest and used it as supplemental feed for cattle during the dry season when the availability of grass in the rangeland is poor. Information given by the farmers suggests that 90% of the stover is removed and a similar proportion grazed from the plots on poor farms. Most farmers appreciated the value of groundnut residues as a rich source of N to subsequent crops and also cattle. The groundnut residues were either composted or directly incorporated on the poor farms, but mostly fed to cattle on the rich farms. The N and P outputs for the first season were less than the subsequent two seasons for all farm types as a result of the drought, which drastically reduced crop yields.

3.3.5. Farm and plot scale nutrient balances

The partial N and P balances at the farm scale were positive for the RG1 farms, although the N balance for the second season was significantly less than those of the first and third seasons (Figure 3g and 3h). The P balance on the RG2 farms was also positive in all seasons, closely matching those of the RG1 farms in the second and third seasons, but the N balance on the RG2 farms was significantly less than that for the RG1 farms and was negative for the third season. N and P balances were mostly negative on the RG3 and RG3 farms. In the seasons in which the balances were positive on RG3 and RG4 farms, the values were very small and were less than 15 kg N per farm and 5 kg P per farm (Figure 3g and 3h).

The PT1 and PT2 of the RG1 and RG2 farm, which received large amounts of manure, had significantly the largest partial N and P balances and contributed most to the large balances on these farms (Figure 4g and 4h). The N and P partial balances on all plot types on the RG3 and RG4 farm were either close to zero or negative (Figure 4f). On some plots, large additions of N and P did not translate into larger nutrient balances, as these were counter balanced by higher productivity and concomitant large export of nutrients. This is clearly shown in PT1 on the RG3 farm that had a smaller N balance compared with PT2 that received less N inputs.

Nutrient balances are determined by a complex set of both biophysical and socio-economic factors (Esilaba et al., 2005; Nkonya et al., 2005). The partial balances at the farm level on the case study farms in Murewa seem to be strongly driven by livestock ownership (and thus availability and use of manure) and use of mineral fertilizers. The large positive balance on the RG1 farms was due to large amounts of manure mainly applied to PT1 and mineral fertilizers distributed evenly across the farms. Such large amounts of nutrient inputs were able to counteract the concomitantly larger amounts of nutrients harvested in grain and stover. The most negative N balance that occurred on the RG2 farms in the second season was due to a high output in a year where few nutrients were added. Such negative balances can be expected on farms where large soil nutrient stocks are available as crops draw on nutrient reserves from the soil. It is also possible that nutrients taken up by the crops came from the residual benefits of nutrients applied in the previous season, which was a drought year. The restricted crop production on the RG3 and RG4 farms due to small inputs and the small nutrient stocks in the soils meant that nutrient balances on these farms were close to zero. The results highlight the need to assess the balances over several seasons so as to capture the influence of dynamics of soil fertility management and seasonal variability of rainfall (Haileslassie et al., 2005). Despite the positive partial nutrient balances, estimated full N and P balances from both transfer functions and field measurements were mostly negative for all plots and farms, indicating that soil nutrient stocks were declining even on the fields which received large amounts of nutrients. Full N balances ranged from -25 to -51 kg ha^{-1}, mainly due to large losses estimated for erosion. The full P balances were also negative for all farms and plots (-2 to -15 kg ha^{-1}), except for PT1 of the RG1 farm and 0 and 2 kg ha^{-1} PT1 and PT2 of the RG2 (0 to 2 kg ha^{-1}). Full nutrient balances are calculated from transfer functions and previous measurements, and may be inaccurate due to high uncertainties in the transfer functions used to calculate nutrient inflows and outflows from natural processes (Faerge and Magid, 2004).

3.3.6. Farmers' perception of soil fertility gradients and their management

Farmers were aware of the existence of soil fertility gradients on their farms and readily distinguished more productive plots from the less productive ones. They recalled that all the plots were highly productive in the initial years of cultivation, and in subsequent years they sustained crop production by application of mineral fertilizers, which were then affordable and readily available. According to the farmers, the depletion of plots furthest from the homesteads only began over the last 15 years when the prices of fertilizers increased sharply. As a result, the farmers could not afford fertilizers to apply across their farms. From this historical perspective, the farmers perceived the soil fertility gradients induced by management as temporary features of their farms, which they can easily reduce if fertilizers 'become readily available at affordable prices'. The farmers valued the role of manure as a source of nutrients, but saw little opportunity in increasing manure production by increasing the herd size. Farmers also acknowledged that their current management trends are influenced by recurrent droughts, and they concentrate the resources on plots close to homesteads, which they cultivate and plant early.

3.3.7. Inferences from the spatial and dynamic resource use patterns

Zones of nutrient accumulation were limited to the plots closest to the homesteads on the rich farms that owned cattle and used large amounts of cattle manure and fertilizers. The soil fertility status of the homefields was maintained by preferential application of organic and mineral nutrient resources on these plots. The zones of nutrient accumulations were much smaller than depleted areas as they are limited to plots close to homesteads on the rich farms. Management of plots seemed to be mainly driven by crop choice as farmers preferably applied nutrients to maize, which was also allocated the largest area on the most fertile plots as it is the food security crop.

From our discussion with farmers and analysis of spatial and dynamic resource management trends, the following are some of the topical issues that warrant further investigation to assess and improve resource use efficiencies on the farm:

- There is need to evaluate the efficiencies with which different types of mineral fertilizers and manure are used across the soil fertility gradients and assess if the current strategies are the most suitable in terms of resource use efficiency, productivity and profitability.
- To assess of the potential to extend the zones of high soil fertility and the required investments in terms of nutrients, labour and cash to reclaim the degraded zones.
- Except on the richest farms, grain legumes are mostly targeted to the less fertile plots with few nutrient inputs. The grain legumes only benefit from residual benefits of fertilizers directly applied to the maize crop in the preceding season. There is thus a need to assess if the benefits of biological N_2-fixation, and productivity on the whole farms could be improved by increasing the area under grain legumes on the more fertile plots.
- The current resource use patterns should be weighed against optional scenarios within the constraints faced by the farmers and their multiple objectives. Comparison of resource use options must also account for trade-offs in terms of productivity, economics, labour demand and maintenance of soil fertility (Giller et al., 2006).

3.4. Conclusions

Large differences in nutrient management between farms were observed and these were linked to resource endowment. These differences explained variability in soil fertility, and led to differences in productivity and nutrients balances between fields on different farms and between fields within farms. Cattle were the main cause of concentration of nutrients, which led to accumulation of manure and application of large amounts of nutrients on plots closest to the homesteads on rich farms. Plots further away from households, and all plots on the poor farms were less fertile, especially with regard to availability of P. Partial N and P balances were mostly positive on the rich farms due to the large amounts of manure and mineral fertilizers used. N and P balances were also largest on the plots closest to the homesteads on the rich farms, but differed little across plots on the poor farms where soil fertility differences were small and differences in the amounts of fertilizers used were also small. At the crop level, inflows of both mineral and organic fertilizers were higher for maize compared with groundnut, as farmers invariably targeted the fertilizers to the maize crops and little or nothing to the groundnut. As a consequence, N and P balances were mostly positive for maize and negative for groundnuts. Full N balances were negative for all farms and plots, due to large losses estimated for soil erosion, leaching and denitrification.

CHAPTER 4

Soil type, historical management and current resource allocation: three dimensions regulating variability of maize yields and nutrient use efficiencies on African smallholder farms

This chapter has been submitted for publication as:

Zingore, S., Murwira, H.K., Delve, R.J. and Giller, K.E., 2006. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agriculture Ecosystems and Environment*.

Abstract

Soil fertility varies strongly between different fields within and between farms as a consequence of inherent factors and differential management and this has implications for crop production and nutrient use efficiencies on smallholder farms. Fields closest to homesteads (homefields) typically receive most nutrients and as a result are more fertile than fields further away (outfields). We conducted experiments for three years (seasons) that assessed maize yields following application of 100 kg N ha^{-1} with different rates of P (0, 30, 50 kg ha^{-1}) from two sources (single super phosphate and cattle manure) on homefields and outfields of smallholder farms on a granitic sandy soil and a red clay soil. Soil organic matter, available P, and exchangeable bases were greater on the homefields than outfields, due to farmers' preferential allocation of nutrient resources on fields closest to homesteads. For three seasons, maize yields on control plots were larger on the homefields than outfields for both soil types in the order: homefield clay (1.5-2.1 t ha^{-1}) > homefield sand (0.8-1.0 t ha^{-1}) ~ outfield clay (0.6-0.8 t ha^{-1}) > outfield sand (0.1-0.3 t ha^{-1}). The differences in yields between homefields and outfields are attributed to differences in fertility status due to a combination of soil type and past management. Application of mineral N at 100 kg ha^{-1} significantly increased maize yields on homefields in the first season: from 2.1 to 3.0 t ha^{-1} on the clay soil and from 1.0 to 1.5 t ha^{-1} on the sandy soil. Effects of N alone were not significant on the outfields due to other limiting factors. Greatest yields of about 6 t ha^{-1} were achieved on the homefield on clay soil with 100 kg N ha^{-1} and 30 P kg ha^{-1} (SSP). Manure gave larger yields (3-4 t ha^{-1}) than SSP (2-3 t ha^{-1}) on the homefield on sandy soil and outfield on clay soil. Maize did not respond significantly to N, dolomitic lime and P (both from manure and SSP) on the depleted outfield on sandy soil in the first and second seasons. Only in the third season of application of manure (at least 30 P kg ha^{-1} yr^{-1}, about 17 t ha^{-1} yr^{-1}) was a significant response in grain yields observed. Large amounts of manure are therefore required for several seasons to restore the fertility of depleted outfields on the sandy soils. In the first season, apparent P recovery efficiencies were greatest (55 - 65%) when P was applied at 10 kg ha^{-1} on the homefield on clay soil (manure), outfield clay soil (manure and SSP) and the homefield on sandy soil (manure). Apparent P recovery was less than 40% when P was applied at 30 kg ha^{-1}. Apparent recovery efficiency increased when P was repeatedly applied in the second and third season due to residual effects of P. On the outfield on sandy soil apparent P recovery efficiency was initially poor (<20%), irrespective of source or rate of P applied, but increased to 60%, 40% and 25% in the third season following application of manure at 10 kg P ha^{-1}, 30 kg P ha^{-1}, 50 kg P ha^{-1} respectively for three seasons. In a second experiment, measurement of grain yields at different rates of N application revealed that about 6 t ha^{-1} can be achieved at high N application rates (up to 120 kg N ha^{-1}) on the homefield on clay soil, with P

applied. Attainable yields were smaller (2-3 t ha^{-1}) on the homefield on sandy soil and outfield on clay soil and less than 60 kg N ha^{-1} was required to attain at least 90% of the maximum yields on these fields. Except on the outfield on sandy soil, apparent N recovery efficiency by maize was greatest at low N application rates with P applied. Maize responses to N, SSP, manure and dolomitic lime and attainable yields varied strongly on different fields. A three dimensional perspective to soil fertility management encompassing (i) soil type, (ii) past management of fields and (iii) targeted application of mineral fertilizers and manure is imperative for improving nutrient use efficiencies on smallholder farms.

4.1. Introduction

Nutrient use efficiencies by crops and attainable yields vary strongly between different fields on smallholder farms in sub-Saharan Africa due to wide differences in soil fertility (Giller et al., 2006). The variability of soil fertility on smallholder farms is two-fold; it can be inherent, arising from a combination of differences in parent material and position on the catena referred to as the 'soilscape effect' (Deckers, 2002). The second source of variation is brought about by resource management strategies by farmers, who concentrate mineral and organic nutrient resources on fields closest to homesteads and add little to fields further away. This has led to the commonly observed gradients of decreasing soil fertility with increasing distance from homesteads (Prudencio, 1993; Tittonell et al., 2005; Zingore et al., 2006a). The gradients of soil fertility have a strong bearing on crop production and efficiency of resource use at the farm level and should be considered when designing strategies for use of nutrient resources.

Sandy soils derived from granite are the soils predominantly cultivated by smallholder farmers in Zimbabwe. These sands are inherently poor in fertility, and contain small amounts of soil organic matter, even under natural woodland vegetation, due to a poor capacity to store soil organic matter. Sandy soils exposed to long-term cultivation under smallholder management with little fertilizer inputs are acidic, and poor in nutrients. The most common deficiencies are N and P, but deficiencies of Ca, Mg and micronutrients also occur on the most depleted fields (Grant, 1981). Smaller areas cultivated by smallholder farmers fall under red clays derived from dolerite, which are considered the most important soils for agriculture in Zimbabwe due to their rich inherent fertility (Nyamapfene, 1991). The red soils are also well-structured, giving them good drainage and aeration properties.

Superimposed on the inherent variability in soil fertility is the heterogeneity caused by differential resource management by farmers. Homefields that recurrently receive large amounts of nutrients from both mineral fertilizers and manure are characterised by high concentrations of available P and soil organic matter, and a pH conducive for crop growth (Tittonell et al., 2005; Zingore et al., 2006a). Moisture availability may also be better on these homefields than on outfields, due to better infiltration rates and water holding capacity facilitated by the high soil organic matter contents. On the contrary, outfields which receive little resources are depleted in most nutrients and are poor in soil organic matter. The yields on outfields are worsened by high incidence of weeds due to infrequent weeding. Nutrient use efficiencies inevitably vary between the homefields and outfields due to interactions between availability of soil nutrients, soil physical properties and other management related constraints, such as weed infestation (Vanlauwe et al., 2006).

Current fertilizer recommendations for maize (*Zea mays* L.) in Zimbabwe are based on potential yields, and do not make provision for differences in attainable yields due to variations in soil fertility within and between farms, or access to resources for improving soil fertility. Recommended nutrient application rates for maize production in areas with annual rainfall of ~800 mm are about 120 kg N ha^{-1}, 30 kg P ha^{-1} and 25 kg K ha^{-1}. These 'blanket' fertilizer recommendations are inappropriate for the spatially variable soil fertility conditions on smallholder farms.

There is a need to refocus recommendations for mineral fertilizer and manure use so that they can be matched to the gradients of soil fertility on smallholder farms. Since both organic and mineral nutrient resources are available to farmers in limited quantities, efficient use of nutrients resources through strategic allocation in time and space offers the only realistic opportunity for sustainable soil fertility management. The objectives of this study were to assess (i) the interaction between soil type, fertility status, and application of different sources of nutrients on maize production and nutrient use efficiencies, (ii) the potential to improve resource use efficiency by strategic application of nutrient resources at different rates across soil fertility gradients (iii) the 'resilience' of the large nutrient stocks on the homefield in relation to how long the farmers can achieve reasonable yields without applying N and/or P, and (iv) the investment in nutrients and the time-frame required to replenish the fertility of depleted outfields and improve their productivity relative to the homefields.

4.2. Materials and Methods

4.2.1. The study site

The study was conducted at the Murewa smallholder farming area (population density 104 km^{-2}) which is located about 80 km east of Harare (17°49'S, 31°34'E). The area has a sub-tropical climate and is characterized in Zimbabwe as a high potential crop production agroecological zone (Natural Region II), which receives 750-1000 mm rainfall annually, distributed in a unimodal pattern (December-April). Rainfall for the seasons (2002/3-2004/5) the experiments were conducted is presented in Figure 1. The soils in the area are predominantly granitic sandy soils (Lixisols) with low inherent fertility. The site was ideal for contrasting different soil types because dolerite intrusions give rise to smaller areas with more fertile clay soils (Luvisols) in close proximity to the sandy soils (Nyamapfene, 1991). Gradients of decreasing soil fertility from homesteads are characteristic of the farms in Murewa. Available P and soil organic carbon decrease significantly with distance from homesteads, particularly on farms with cattle due to preferential application of manure and mineral fertilizers on fields closest to the homesteads (Zingore et al., 2006a).

4.2.2. Selection and characteristics of experimental sites

Selection of sites was based on initial work of Zingore et al. (2006a) that established the existence of large variability of soil fertility between different fields on the same farm, and on different farms. The main experiment (Experiment 1) was established on two farms in the medium wealth category: one was on the sandy soil and the other on the red clay soil. On each of these two farms, a field closest to the homestead (< 50 m) and another at some distance (100–500 m) were selected to provide fields representative of typical homefields and outfields in the area. The four fields were therefore; well-managed and fertile homefields on the clay and sandy soils, and poorly managed and infertile outfield on the clay and sandy soils (Table 1a). The homefields were about a third of the farm area on the two farms, whilst the outfields were larger (about half the area on the sandy soil and slightly more than a third on the clay soil).

4.2.3 Field Experiments

Experiment 1

Maize response to mineral N was determined on the four different zones of soil fertility, as described above, at different rates and sources of P supplied as mineral fertilizer and an organic source (manure). Mineral N (ammonium nitrate; 100 kg N ha^{-1}) was split applied in equal amounts at about 3 and 6 weeks after plant emergence in all plots, except the control.

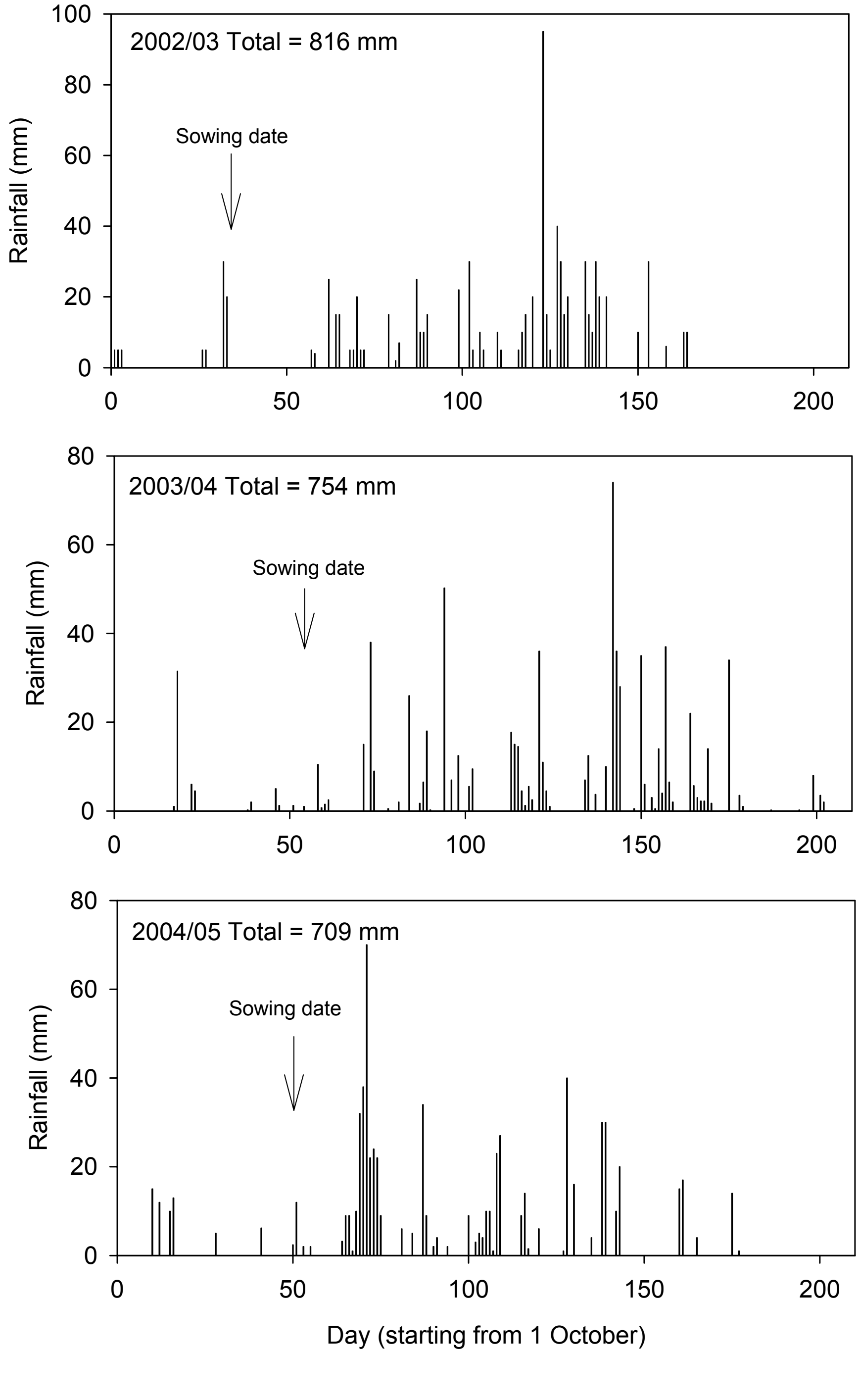


Figure 1. Total rainfall and its distribution at Murewa for the three seasons the experiments were conducted (2002/3-2004/5).

Table 1a. Selected soil properties for the fields used in experiment 1, at Murewa.

	Sand (%)	Silt (%)	Clay (%)	C (%)	N (%)	pH (water, $CaCl_2$)	Avail. P (mg kg^{-1})	CEC ($cmol_c$ kg^{-1})
Sandy Homefield	85	2	13	0.5	0.04	5.1, 4.9	7.2	2.2
Sandy Outfield	88	4	8	0.3	0.03	4.9, 4.5	2.4	1.6
Clayey Homefield	46	15	39	1.4	0.08	5.6, 5.3	12.1	24.2
Clayey Outfield	42	14	44	0.7	0.05	5.4, 5.0	3.9	22.0

Table 1b. Selected soil properties for the fields used in experiment 2, at Murewa.

	Sand (%)	Silt (%)	Clay (%)	C (%)	N (%)	pH (water, $CaCl_2$)	Avail. P (mg kg^{-1})	CEC ($cmol_c$ kg^{-1})
Sandy Homefield	84	6	10	0.8	0.09	5.2, 5.0	12.5	3.1
Sandy Outfield	86	3	11	0.2	0.01	4.6, 4.2	1.5	2.2
Clayey Homefield	49	16	35	1.5	0.10	5.8, 5.4	10.0	27.2
Clayey Outfield	46	16	38	0.8	0.06	5.1, 4.8	5.6	23.3

Different rates of P from cattle manure and mineral P (single super phosphate - SSP) were applied at planting and incorporated in the top 20 cm of the soil using hoes. Manure P contents were 0.16% (first season), 0.20% (second season) and 0.19% (third season), and these were used to calculate the amounts of manure required for different rates of P in each season. These were: 6 t ha^{-1} (10 kg P ha^{-1}) and 19 t ha^{-1} (30 kg P ha^{-1}) in the first season; 5 t ha^{-1} (10 kg ha^{-1}), 15 t ha^{-1} (30 kg P ha^{-1}) and 25 t ha^{-1} (50 kg P ha^{-1}) in the second season; and 5 t ha^{-1} (10 kg ha^{-1}), 16 t ha^{-1} (30 kg P ha^{-1}) and 26 t ha^{-1} (50 kg P ha^{-1}) in the third season. The average concentration of other major nutrients in manure were: 0.9% N; 0.2% Ca; 0.05% Mg and 0.4% K. Treatments with dolomitic lime ($CaCO_3$ and $MgCO_3$) applied at a rate of 500 kg ha^{-1} were included in the first season to assess the effects of liming and supply of both Ca and Mg on maize yields and N uptake on the different zones of soil fertility. The rate of dolomitic lime applied was calculated to increase pH on the sandy soil by about 1 unit. The red clay soil has a larger buffer capacity against pH changes, and the dolomitic lime applied at 500 kg ha^{-1} was expected to increase the pH on that soil by less than 1 unit. Dolomitic lime contains 18% Ca and 11% Mg so that 500 kg ha^{-1} supplied 90 kg Ca ha^{-1} and 55 kg Mg ha^{-1}. The treatments in the first season on each of the four fields were:

i. Control
ii. 100 kg N ha^{-1}
iii. Manure equivalent of 10 kg P ha^{-1}, 100 kg N ha^{-1}
iv. Manure equivalent of 30 kg P ha^{-1}, 100 kg N ha^{-1}
v. Manure equivalent of 30 kg P ha^{-1}, 100 kg N ha^{-1}, dolomitic lime (500 kg ha^{-1})
vi. 10 kg P ha^{-1} (SSP), 100 kg N ha^{-1}
vii. 30 kg P ha^{-1} (SSP), 100 kg N ha^{-1}
viii. 30 kg P ha^{-1} (SSP), 100 kg N ha^{-1}, dolomitic lime (500 kg ha^{-1})
ix. 100 kg N ha^{-1}, dolomitic lime (500 kg ha^{-1})

Plots of 6 m x 4.5 m were used and the experiment was laid out in a completely randomized block design with three replicates at each site. The experiment was run for three consecutive seasons, starting with the 2002/03 season. SSP, manure and ammonium nitrate were applied in each of the three seasons, with modifications to some of the treatments in the second and third seasons. Maize responses to P in the first season indicated that more than 30 kg P ha^{-1} was needed on some of the fields to reach maximum yields. Therefore, plots that had received dolomitic lime and P in the first season (30 kg P ha^{-1} manure and dolomitic lime; treatment 5) and (30 kg P ha^{-1} SSP and dolomitic lime; treatment 8) were used to test larger applications of P (50 kg ha^{-1}) from manure and SSP respectively, in the second and third seasons, without further application of dolomitic lime. As dolomitic lime had small effects on maize on most fields in the first season it was considered unlikely that this would interfere with interpretation of maize response in the subsequent seasons.

Experiment 2

Experiment 2 was used to measure N use efficiencies at different rates of N application, with and without P, and was also established on four fields representative of the different field types described above (Table 1b). The experiment was located on four fields on four different farms. Experiment 2 was conducted only for two seasons, 2003/2004 and 2004/2005. The experiment was laid out in a split-plot design with three blocks at each site. Plots of 12 m x 4.5 m were used with N as the main plot treatment, applied at 0, 30, 60, 90, and 120 kg ha^{-1} and split-plot treatments of 0 and 30 kg P ha^{-1}.

4.2.4. Field measurements

For both experiments maize grain and stover yields were determined after four months at the end of the season from net plots measuring 2 m x 2.7 m. Moisture contents determined for grain samples were used to corrected grain yields to 12.5% moisture content. Stover samples were dried in the oven at 70 ºC for 72 hours to determine moisture contents, which were used to correct stover yields measured in the field to dry matter produced.

4.2.5. Laboratory measurements

All maize stover and grain samples were ground to less than 0.5 mm and analysed for total N content using the micro-Kjeldahl method and for total P using the modified Olsen method (Anderson et al., 1993). Soils were sampled before the start of the experiments in the first season to characterize the four fields. Three blocks were marked in each of the fields and three soil samples were randomly collected from each block from the 0-20 cm depth. The three samples from each block were then bulked together to form a composite sample, so that three samples were collected for analysis from each field. The samples were then analysed for particle size distribution, soil organic carbon, total nitrogen, available P (Olsen), cation exchange capacity, exchangeable Ca, Mg and K, and pH using standard methods (Anderson et al., 1993). Manures used in Experiment 1 were analysed for total N and P using the micro-Kjeldahl method and the modified Olsen methods respectively. Ca, Mg and K contents of manure were determined by atomic absorption spectroscopy, after extraction from ashed samples.

4.2.5. Calculations and Statistical Analysis

Two indices used for nutrient use efficiency: apparent recovery efficiency (*RE*) and agronomic efficiency (*AE*) were calculated for P applied in Experiments 1 and for N applied in Experiment 2. Apparent recovery efficiency (RE_X) was calculated as net P or N uptake per amounts supplied (i). Agronomic N or P use efficiency (AE_X) was calculated as kg grain produced per kg N or P applied (ii).

$$RE_X = \frac{U_X - U_0}{F_X} \quad \text{(i)}$$

$$AE_X = \frac{Y_X - Y_0}{F_X} \quad \text{(ii)}$$

Where X is N or P, U_X is total N or P taken up by the crop, U_0 is the crop N or P uptake in plots without N or P, F_X is the amount of N or P applied in fertilizer for N and in manure or fertilizer for P, Y_X is the yield at a particular rate of N or P and Y_0 is the yield for the plots without N or P.

Since P was applied in each of the three seasons, P uptake in the second and third seasons was influenced by residual effects of P applied in the preceding seasons. A simple formula developed by Janssen and Wolf (1988) was used to estimate residual effects of P as follows:

$$Rt = (0.8 - 1.25R1)^{t-1} \times R1$$

Where $R1$ and Rt are the recovery fractions in the first year of application and subsequent season(s) t. The formula was developed with the assumption that if the fraction of P applied is known, the residual uptake by subsequent crops can be calculated; on the basis that (i) P pools are in a steady state i.e. the pool sizes for the plots without P remain constant, and (ii) the labile pool of the fertilized soil decreases in the years after application due to transfer of P into the stable pool and crop uptake (Janssen and Wolf, 1988). The formula could have limitations when P is applied every year and on the homefields where the larger labile P pools may not remain constant on plots where no P was applied.

Grain yields for both experiments were analysed for variance using GENSTAT version 6. Regression analysis was used to describe grain yield responses to P in experiment 1 and to N in experiment 2 using the exponential model:

$$Y_x = Y_0 + \Delta Y_{max}(1 - \exp(-kx))$$

Where Y_x is the grain yield (kg ha^{-1}) at particular rate (x) of N or P (kg ha^{-1}), Y_0 is the yield at zero N or P (kg ha^{-1}), ΔY_{max} is the maximum yield increase from the initial (kg ha^{-1}), and k is the rate constant (kg^{-1}). In some instances, the relationships followed a linear pattern and could not be described using an exponential model. Such trends were analysed using a linear regression function:

$$Y_x = Y_0 + bx$$

Where *b* is a constant and other parameters are as described for the exponential model.

4.3. Results

4.3.1. Maize yields and nutrient uptake efficiencies at different rates and sources of P on fields with different initial fertility

Maize yields for control and sole N treatments plots for three seasons and effects of dolomitic lime in the first season

There was wide variability in maize yields between the soil types and fields located at different distances from the homestead in Experiment 1. Maize grain yields for control plots were significantly larger on the homefields than outfields, on both the red clay soil and the granitic sand for all three seasons (Figure 2a). The homefield on the red clay soil produced the significantly largest maize yield (about 2.1 t ha^{-1}) in the first season without any nutrient inputs. The control yields for the homefield on the clay soil were smaller (about 1.5 t ha^{-1}) in the second and third seasons. This was the largest yield decrease over time recorded for the control plots on all fields. The yields for the control treatment on the outfield on the clay soil (0.6-0.8 t ha^{-1}) were half those on the homefield (1.5-2.1 t ha^{-1}) (Figure 2a). On the sandy soil, the control yields on the homefield were about 1 t ha^{-1} in the first season, less than half the corresponding yields on the homefield on clay soil, and did not change significantly in the second and third seasons. The smallest yields on control plots for the three seasons were produced on the outfield on the sandy soil (< 0.3 t ha^{-1}).

Addition of 100 kg N ha^{-1} alone significantly increased maize yield on the two homefields in the first season: to 1.5 t ha^{-1} on the sandy soil and 2.9 t ha^{-1} on the clay soil (Figure 2b). The maize yields with 100 kg N ha^{-1} (Y_0) declined with season of application from about 1.5 and 2.9 t ha^{-1} (in the first season), to 1.1 and 2.2 t ha^{-1} (in the second season), and 1.0 and 1.9 t ha^{-1} (in the third season) on the homefields on the sandy soil and red clay soil respectively. There was no significant response to 100 kg N ha^{-1} alone on the outfields (Figure 2b). There were no significant effects of dolomitic lime on most fields. The only exception was the homefield on sandy soil where dolomitic lime with 100 kg N ha^{-1} resulted in about 3.0 t ha^{-1} maize grain compared with about 1.6 t ha^{-1} produced with 100 kg N ha^{-1} and no dolomitic lime (Figure 3).

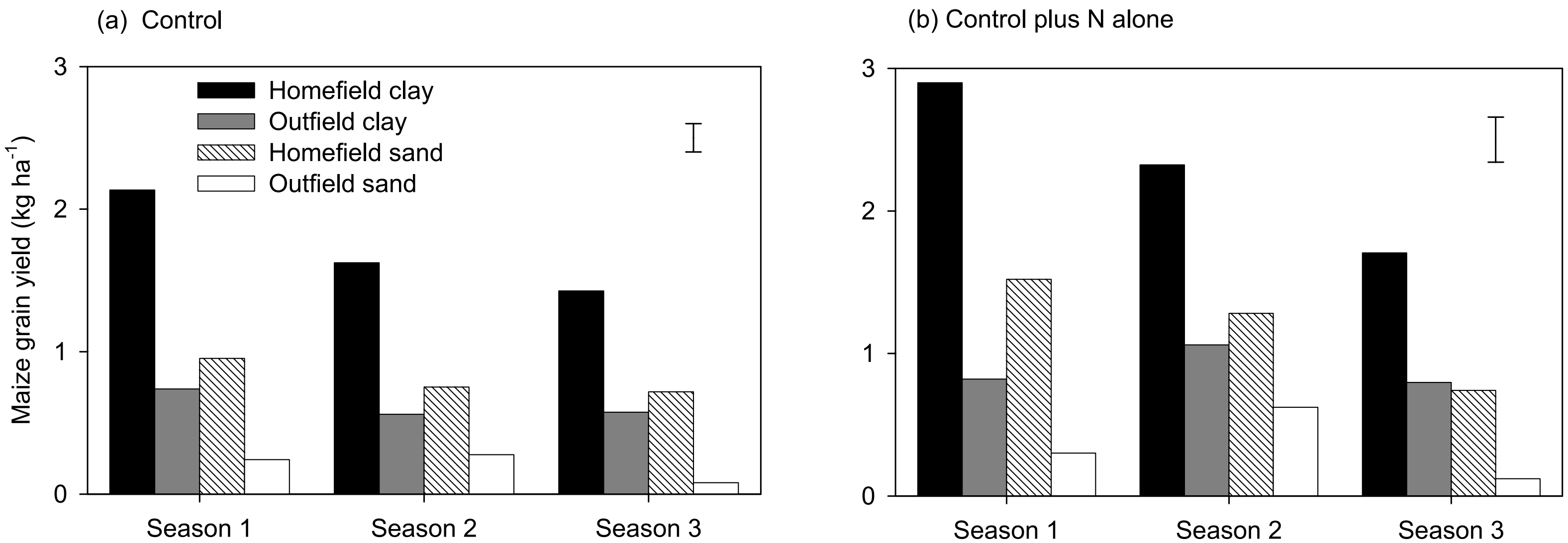


Figure 2. Yield from control plots (a) and effects of adding N alone (b) on the homefields and outfields fields on the granitic sand and the red clay soil at Murewa for three seasons. Bars show SEDs.

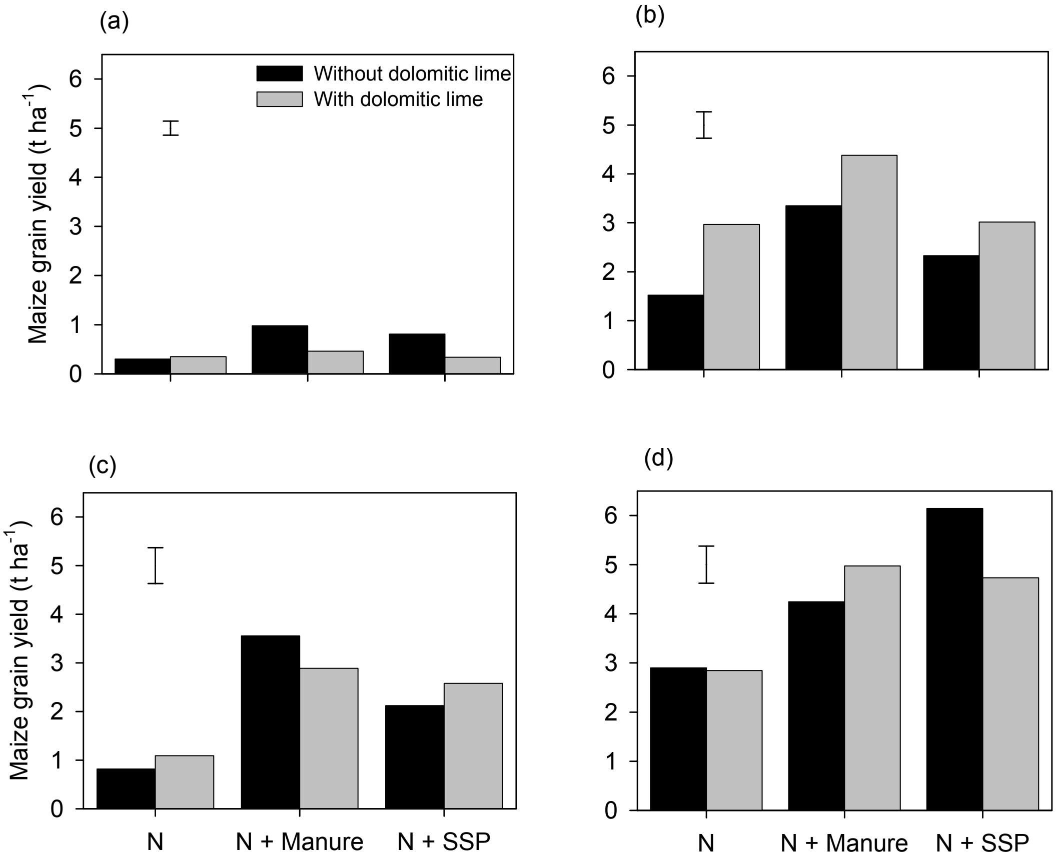


Figure 3. Effects of dolomitic lime with 100 kg N ha^{-1} and 30 kg P ha^{-1} on maize yields on fields with different initial fertility in the first season: (a) sand outfield; (b) sand homefield; (c) clay outfield; and (d) clay homefield. Bars show SEDs.

Effects of N at different rates and sources of P on maize productivity

Application of SSP or manure with 100 kg N ha^{-1} on the homefield on the sandy soil increased maize yields in the first season, but optimum responses were attained at low P application rates of 10 kg ha^{-1} (Figure 4a). Increasing the rate of P application to 30 kg ha^{-1} led to small returns. Manure produced larger yields than SSP on the homefield on the sandy soil, at all rates of P, except in the second season. Application of 5-6 t manure ha^{-1} on a yearly basis with mineral N was thus required to sustain maize yields on the sandy soil with a long-term history of manure application.

The response of maize to N at the different rates of P in the first season was very poor on the outfield on the sandy soil, irrespective of the source of P. The maximum yields attained ($Y_0 + \Delta Y_{max}$) were less than 1 t ha^{-1} with application of 100 kg N ha^{-1} and 30 kg P ha^{-1} (Figure 4a). The outfields on the sandy soil showed signs of improved maize yields in the second season of manure application, although the increases were not significant (Figure 4c). Only in the third season (Figure 4e) did manure significantly increase yields on the outfield on sandy soil, against decreases in yields for the sole N treatment. The yields remained markedly small on the outfield on the sandy soil with all SSP treatments (Figure 4c and 4e).

The maximum yields attained were significantly larger on the homefield on the red clay than the homefield on the sandy soil (Figure 4). Maize yields on the homefield on the clay soil increased linearly to about 6 t ha^{-1} in the first season when SSP was applied at 10 and 30 kg P ha^{-1}. The ($Y_0 + \Delta Y_{max}$) yield attained with 30 kg P ha^{-1} from manure was about 4 t ha^{-1}, 2 t ha^{-1} less than that with SSP. The linear increases in yield up to 30 kg P ha^{-1} on the homefield on clay soil suggested increases in grain yields were possible at higher P application rates, and therefore an extra treatment with 50 kg P ha^{-1} was included in the second and third seasons. Maize yields with 10 kg ha^{-1} SSP on the homefield on the clay soil were unchanged in the second season, but the yield at 30 kg P ha^{-1} decreased by about 1 t ha^{-1} compared with the first season and no further increases were observed when 50 kg P ha^{-1} was applied ($Y_0 + \Delta Y_{max} = 5.6$ t ha^{-1}). Yields from the treatments combining mineral N with 10 kg and 30 kg P ha^{-1} from manure were larger in the second season than the first. Consequently, the responses to P from SSP and manure were similar in the second season (Figure 4d). The yields with SSP continued to decrease in the third season, where the maximum yield were less than 5 t ha^{-1}, about 1.5 t ha^{-1} less than the maximum yield for the first season obtained with 30 kg P ha^{-1}. Although maize yields with manure were also less in the third season (due to the poor rain distribution) the decreases were less than those for SSP and yields attained with manure were larger than yields with SSP (Figure 4f).

Maize yields at the different rates of P from manure were consistently greater than those from SSP on the outfield on clay soil (Figure 4b, d, f). Manure significantly increased maize yields on the outfield on clay soil such that there were no significant differences in maximum yields ($Y_0 + \Delta Y_{max}$) between the outfield manure treatment and the homefield SSP treatment in the third season. SSP gave poor yield responses on the outfield on the clay soil in all seasons. Such small responses to P were not expected on the outfield on clay soil given the poor available P status of the field and the fact that the soil had greater CEC (Table 1) and exchangeable bases (data not shown).

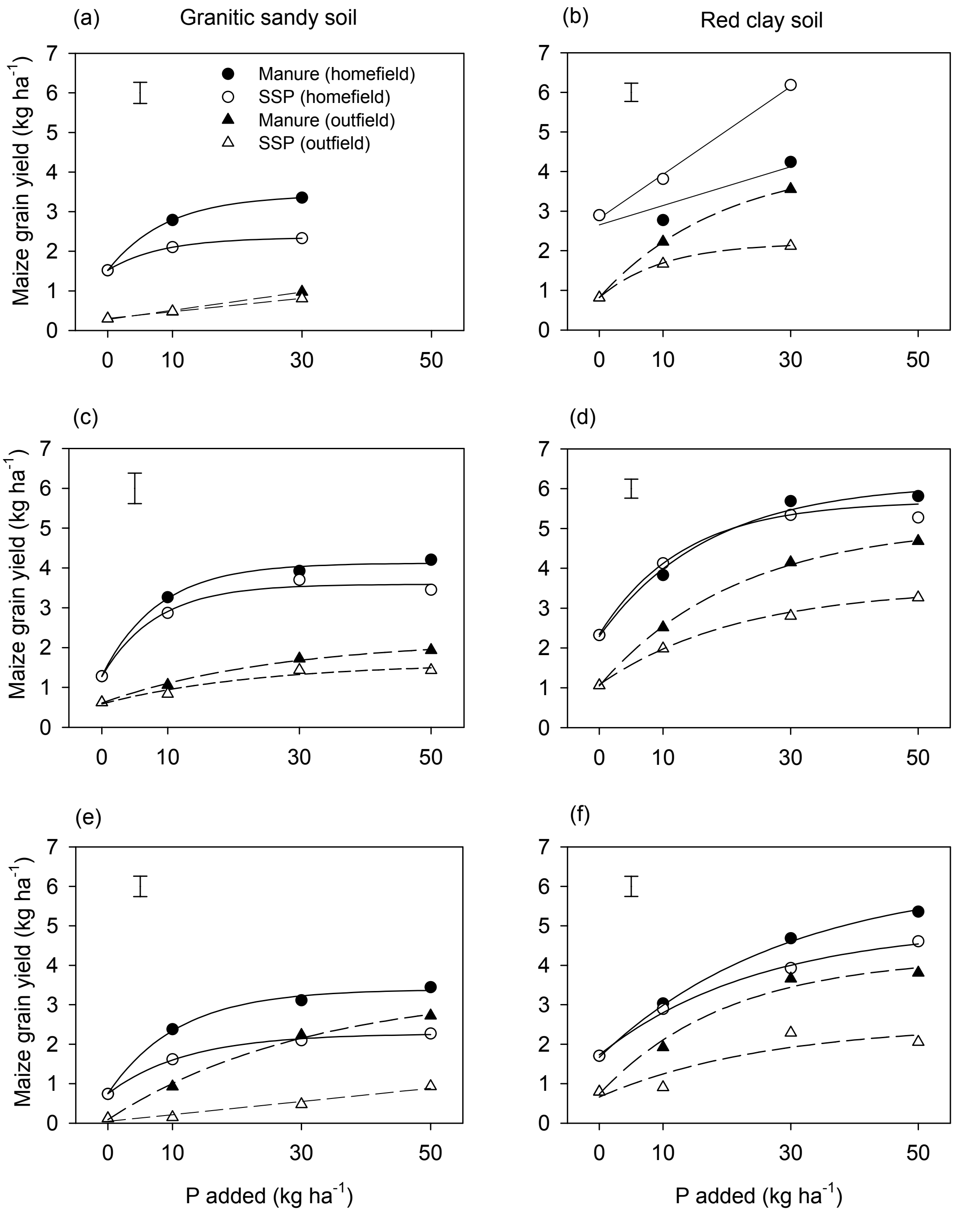


Figure 4. Maize grain yields from the homefield and outfield of the farm on the sandy soil (a) and the clay soil (b) amended with different rates of organic (manure) and mineral (SSP) sources of P and N as ammonium nitrate at a fixed rate of 100 kg N ha^{-1} in the first season. The cumulative effects of repeated additions of the fertilizers in the second and third season are shown in (c) and (e) for the sandy soil and (d) and (f) for the clay soil. Bars show SEDs.

P use efficiencies at different rates and sources of P

Apparent P recovery efficiencies (RE_P) for the three seasons for Experiment 1 varied with soil and field type, the source of P and rate of application (Figure 5). RE_P was greatest when P was applied at 10 kg ha^{-1}, and decreased or remained constant when the rate of P application was increased, except with manure on the homefield on clay soil in the first season. In the first season, RE_P was largest for the outfield (manure) on the clay soil, which was about 60% when manure was applied at 10 kg P ha^{-1} (Figure 5b). This was greater than the RE_P with manure at a similar rate of P for the fields on the sandy soil: about 50% on the homefield and 20% on the outfield. RE_P for treatments with manure applied at 10 kg ha^{-1} was smallest on the homefield on the clay soil (Figure 5b).

In the second and third seasons, the RE_P was least on the outfield on the sandy soil when P was added as SSP (Figure 5c, e). The RE_P on the outfields on sandy soil increased to 46% and 59% when manure was applied at 10 kg P ha^{-1} in the second and third seasons respectively (Figure 5c, e). Repeated application of manure also led to increased RE_P on the homefield on sandy soil in the second and third seasons. On the clay soil, there were small differences in RE_P between the homefield and outfields when manure was applied in the second season and third seasons, but RE_P on the homefield was consistently greater than on the outfield when SSP was applied (Figure 5d).

The increase in RE_P in the second season and third season is not attributable to P applied in the particular seasons only, but also to residual effects of manure and SSP in the preceding season. Estimation of residual P effects of SSP and manure indicated that P applied in the first season contributed 1-13% of P recovered by maize in the second season, whilst P applied in the first and second seasons contributed 2-18% of the P recovered in the third season (Table 2). The trends of agronomic P use efficiency (AE_P) values were similar to trends for RE_P and ranged from 26 to 190 kg grain kg^{-1} P applied on the homefield on sandy soil; 2 to 118 on the outfield; 51 to 180 kg grain kg^{-1} P applied on the homefield on clay soil; 11 to 145 kg grain kg^{-1} P applied on the outfield.

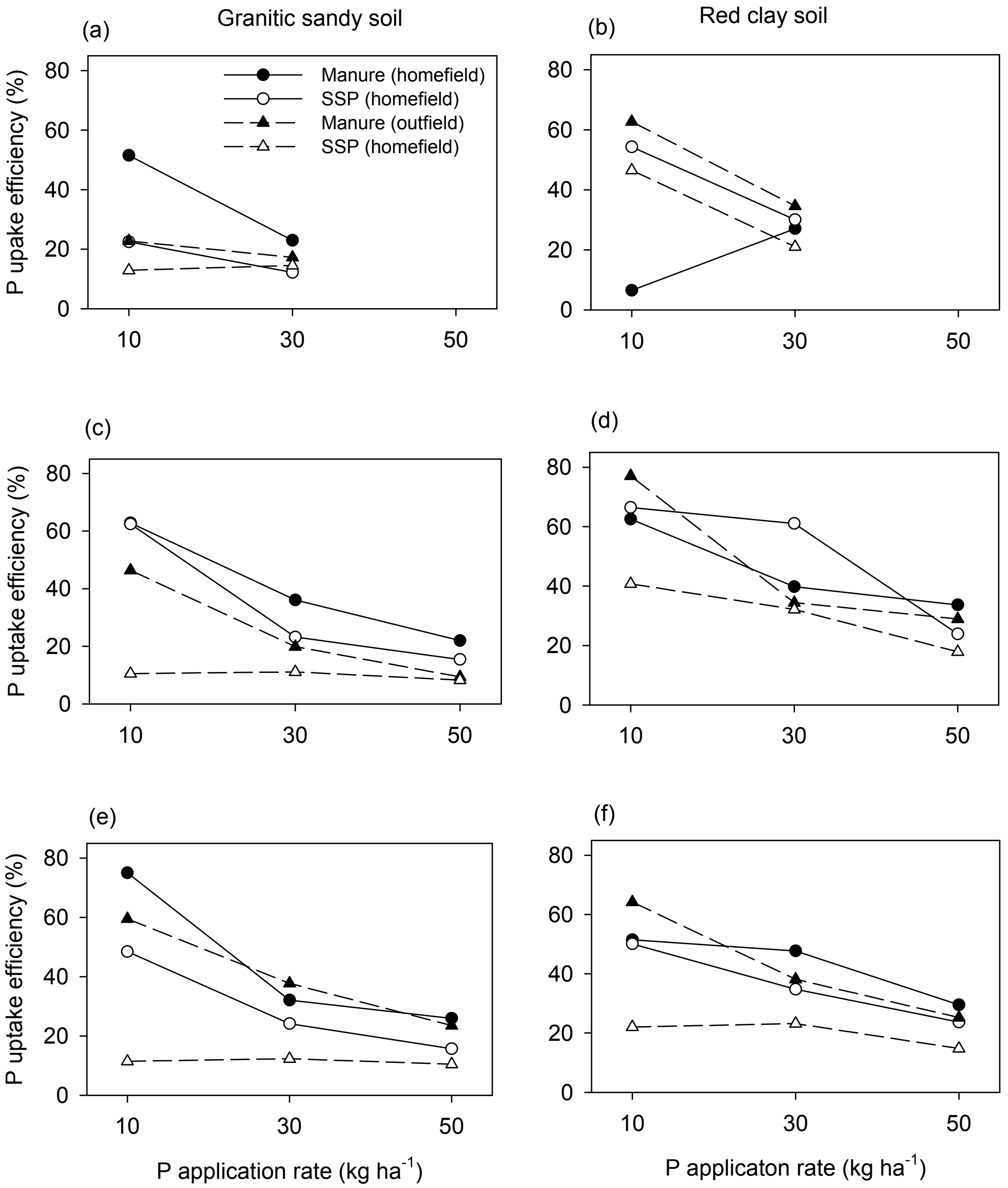


Figure 5. Apparent P recovery efficiencies (RE_P) for three seasons at 100 kg N ha^{-1} as affected by P rate on fields with different initial fertility: (a) sandy soil first season; (b) clay soil first season; (c) sandy soil second season; (d) clay soil second season; (e) sandy soil third season; and (e) clay soil third season.

Table 2. Estimated P uptake efficiencies (%) attributable to residual P applied in the first season (Season 2) and P applied in the first and second seasons (Season 3) in Experiment 1 at Murewa.

Site	P source	P rate (kg ha^{-1})	Season 2	Season 3
Sand homefield	Manure	10	9	11
		30	12	15
		50 [a]	8	11
	SSP	10	11	18
		30	7	12
		50 [a]	9	10
Sand outfield	Manure	10	12	19
		30	10	12
		50	9	5
	SSP	10	6	6
		30	8	6
		50	8	5
Clay homefield	Manure	10	1	6
		30	12	18
		50	13	16
	SSP	10	4	2
		30	9	8
		50	9	11
Clay outfield	Manure	10	4	4
		30	13	17
		50	12	14
	SSP	10	11	16
		30	8	16
		50	10	17

[a] 30 kg ha^{-1} was applied in the first season with N and dolomitic lime to these plots.

4.3.2. Maize yields and N use efficiencies at different rates of N on fields with different initial fertility

Maize yields at different rates of N

Maize grain yields at different rates of N in Experiment 2 were strongly affected by soil type, field type and also by P addition (Figure 6). The effects of P without N on maize grain yields were not significant across all field types. Maximum yields at the highest rate of N (120 kg ha^{-1}) with P were obtained on the homefield on clay soil for both seasons: 6.1 t ha^{-1} in the second season and 4.5 t ha^{-1} in the third season (Figure 6b and 6d). With P applied, yields progressively increased up to 120 kg N ha^{-1}. When N was supplied without P, optimum yields responses were only attained up to 30 kg N ha^{-1}.We can therefore deduce that both P and N were limiting on the homefield on clay soil. N was initially the most limiting, but beyond 30 kg N ha^{-1}, additional P was required to support larger yields.

Similarly, on the homefield on sandy soil, N and P were required to raise maize yields. Strong interactions between N and P were observed on the outfield on the clay soil in the first season where N response up to 30 kg ha^{-1} was strong with P added, but poor without P (Figure 6b). On the outfield on sandy soil, there was no significant effect of N and P on maize yields in the third season, even at high rates of 120 kg N ha^{-1} with 30 kg P ha^{-1} (Figure 6c).

N use efficiencies as affected by P application and rate of N application

The N use efficiencies calculated for Experiment 2 were averaged for the two seasons (Figure 7). Apparent N recovery efficiency (RE_N) were greatest when N was applied at 30 kg ha^{-1} with P on the homefield on clay soil (about 70%), and was about 10% less on the homefield on sandy soil and on the outfield on clay soil (Figure 7a, b). P application led to improved N recovery efficiencies as shown by the greater RE_N with P than without. Except on the outfield on sandy soil, the RE_N decreased with application rate of N and was least when N was applied at 120 kg ha^{-1}. RE_N was poor on the outfield on sandy soil (<15%), irrespective of the application rate of N or P addition.

Agronomic N use efficiencies (AE_N) were greatest on the homefields at the lowest rate of N (30 kg ha^{-1}) with P applied (Figure 7c and 7d). The AE_N was greatest on the homefield on sandy soil with about 50 kg grain kg^{-1} N applied at 30 kg N and P ha^{-1}. This decreased sharply to about 35 kg grain kg^{-1} N at 60 kg N ha^{-1} with 30 kg P ha^{-1} (Figure 7c). P application increased AE_N on all fields except the outfield on sandy soil, where AE_N was less than 10 kg grain kg^{-1} N applied.

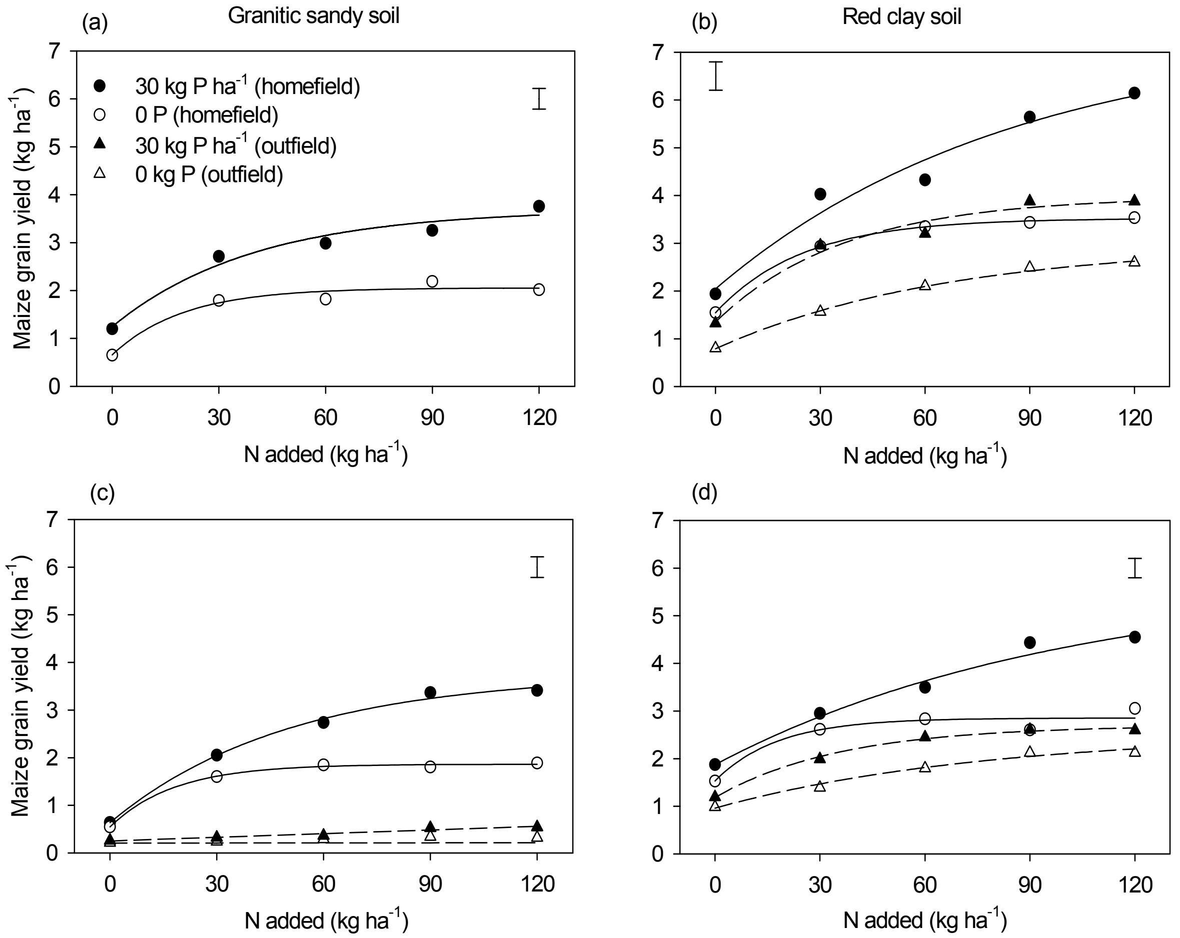


Figure 6. Maize response to different rates of N with and without P for the different fields on the sandy soil in the second (a) and third (c) seasons, and on the clay soil in the second (b) and third (d) seasons. First season data for the outfield on the sandy soil is not available as cattle grazed the field. Bars show SEDs.

4.4. Discussion

4.4.1. Maize yields for control and sole N treatments plots for three seasons and effects of dolomitic lime in the first season

The yields for the control plot in Experiment 1 and 2 (Figure 2a, 6) were strongly related to the fertility status of the fields, particularly available P, which decreased in the order: clay homefield > sand homefield > clay outfield > sand outfield (Table 1a, b). Available P is one of the soil chemical factors most responsive to management and tends be high on fields receiving cattle manure and mineral fertilizers (Vanlauwe et al., 2002; Zingore et al., 2006a). The homefields were more fertile due to farmers' practice of applying manure and mineral fertilizers to fields closest to the homesteads. Reasons for farmers' preference to target fertilizers to homefields in Murewa have been discussed in detail by Zingore et al. (2006a). In Experiment 1 the large difference in yields for control plots between the homefields and outfields were still evident after three years, indicating that the residual soil fertility was effective for several seasons (Figure 2a). In Murewa, farmers who owned cattle applied > 40 kg N ha^{-1} and 10 kg P ha^{-1} every year from manure on the homefields (Zingore et al., 2006a). Such application rates over time lead to a build up of nutrients, which are available to plants for several seasons, as manure has strong residual effects on crop yields (Mugwira et al., 2002).

The larger yields on the red clay soil than the granitic sand for similar field types can be explained by the larger soil organic matter contents, pH and CEC due to the greater clay contents (Grant, 1981). The red clay soil also has a higher water holding capacity, and more water is available to maize than on the sandy soil. Even though the control yields on the homefield on sandy soil were rather poor, these were greater than yields widely measured on the poorly managed fields on the granitic sand, which are in the region of 0.5 t ha^{-1} (Waddington et al., 2001). According to Liebscher's law of the optimum, a production factor that is in minimum supply contributes more to production the closer other production factors are to their optimum (de Wit, 1992). Significant responses to N alone on the homefields suggest that N was the most limiting nutrient, and other nutrients were available in sufficient quantities for maize (Figure 2b, 6). The decline in responses to N in the second and third seasons (Experiment 1) is presumably due to the soil being unable to satisfy the increased demand for other nutrients. The common notion that N is the most limiting nutrient on soils in Zimbabwe held for the well managed fields, but not for the poorly managed outfields where maize did not significantly respond to N. This is due to limitations imposed by other nutrients (e.g. there was little available P) or poor soil physical structure.

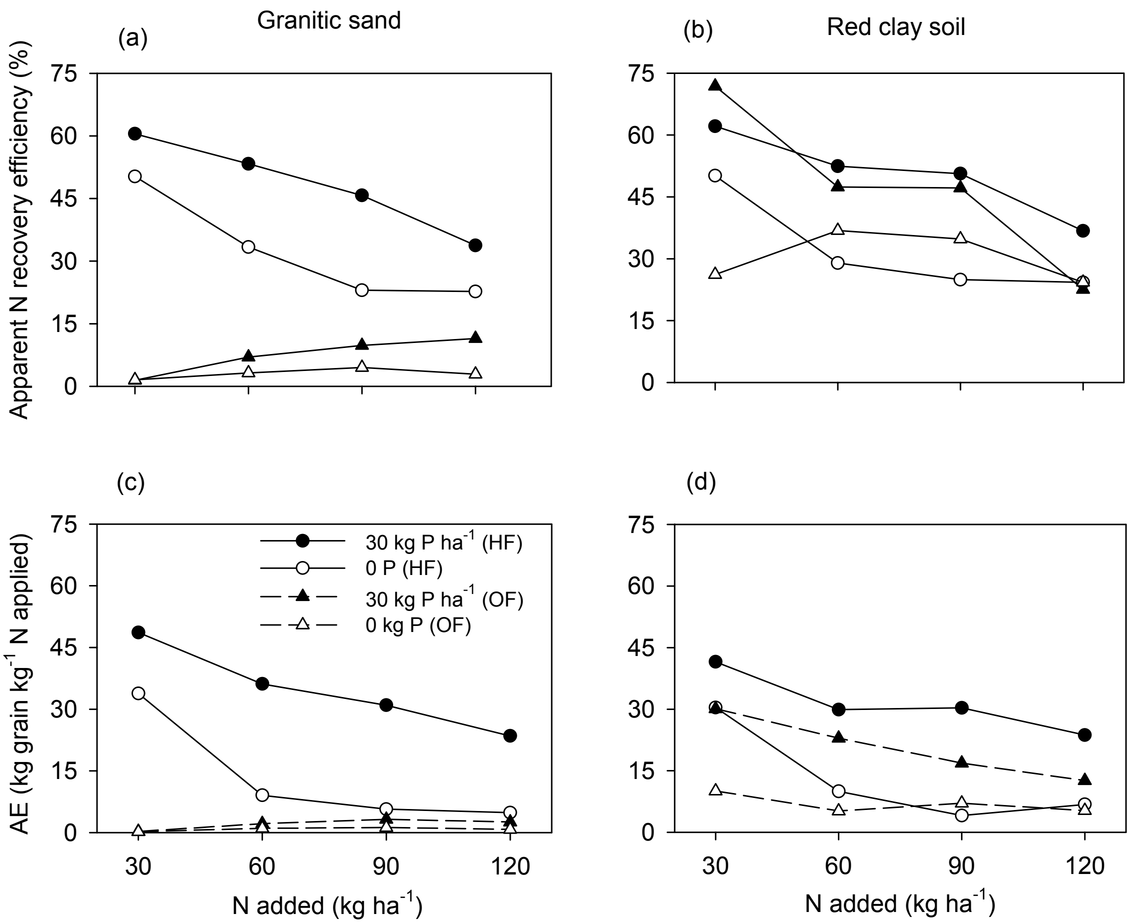


Figure 7. Average N use efficiencies for the 2003/4 and 2004/5 seasons for N applied at differences rates with and without P on homefields (HF) and outfields (OF) on contrasting soils. Apparent N recovery efficiencies for fields on the granitic sandy soil (a); and the red clay soil (b), and agronomic N use efficiencies (AE_N) for the fields on the granitic sandy soil (c); and the red clay soil (d).

The lack of response to application of dolomitic lime can be expected on the red clay soil (Figure 2), which already has a pH suitable for maize growth, and a high CEC and exchangeable Ca and Mg. However, the lack of effects observed on the outfield on the granitic sand, which was acidic and low in CEC and exchangeable Ca and Mg, were unexpected. This may indicate that the outfield was deficient in other nutrients besides N, P, Ca, and Mg, which were overriding. For example, Zn deficiencies have been reported on the granitic sand (Rodel et al., 1973; Grant, 1981) and it is possible that application of dolomitic lime may reduce the availability of micronutrients leading to a small decrease in yields. The strong response to dolomitic lime on the homefield on the sandy soil was probably more due to effects of alleviating Ca and Mg deficiencies than due to increases in pH.

4.4.2. Influence of addition of N, P, manure on maize grain yields on fields with different initial fertility

On the homefield on sandy soil, manure led to greater yields than SPP in two of the three seasons, which indicated that frequent additions of manure are required to sustain maize production on the sandy soil (Figure 4a, c, e). This is consistent with the conclusions of Grant (1981), who recommended annual application of 10 t manure ha^{-1} and 120 kg N ha^{-1}, although our results suggest that much less N is required (Figure 6). The sandy soils have weak capacity to store soil organic matter and nutrients, and application of manure and mineral N fertilizers is required on a yearly basis to maintain good productivity. Organic resources are considered crucial in sustainable crop production on smallholder farms and positively interact with mineral N fertilizers to give good yields due to (i) addition of multiple nutrients including P, base cations and micronutrients; (ii) improvement of the physical properties of the soil; and (iii) improvement of synchrony between availability of N and demand by crops. Mineral N is prone to leaching on the coarse textured soil due to rapid infiltration rates (Piha, 1993) and therefore combinations of manure and mineral N may have led to improved N recovery efficiencies through improved synchrony of N availability and crop demand (Nyamangara et al., 2003).

The reasons for the poor response to N and P on the outfields on the sandy soil in Experiment 1 and 2, seems to be related to multiple nutrient deficiencies and poor water availability. These limitations were gradually corrected by application of mineral N together with manure, but a huge investment of at least 17 t ha^{-1} of manure (30 kg P ha^{-1}) each year for three seasons was needed to significantly improve maize yields (Figure 4a, c, e). Manure is key to replenishment of degraded fields as it supplies multiple nutrients, raises soil pH and improves soil organic matter, which in turn improves the soil physical properties (Grant, 1981; Gandah et al., 2003). Nyamangara et al. (2003) found that manure had no effect on N supply to maize in the season of application due to N immobilization; net N mineralization only occurred in the subsequent seasons. The delayed response to manure on the outfield on sandy soil was not associated with N supply, as mineral N was supplied in large amounts. It is possible that some other nutrients need to be raised above critical levels for maize to respond to the N and P supplied (Giller et al., 2006).

Large yields were obtained on the homefields on clay soil and responses to N and P were good (Figure 4, 6). This is because other nutrients, besides N and P, were available in large quantities due to the high fertility of the soil resulting from both inherent fertility and good past management (Table 1a). The smaller response to manure than SSP in the first season in Experiment 1 is probably due to slow release of P from manure through decomposition. The multiple benefits of manure were important on the outfield on clay soil, and unlike on the outfield on sandy soil, the benefits were immediate. The possible reasons for this include provision of micronutrients, and improvement of soil organic matter content and its subsequent effects on improving soil structure and moisture availability (Bayu et al., 2005).

4.4.3. Nutrient use efficiencies on fields with different initial fertility

In Experiment 1, apparent P recovery efficiency (RE_P) was least on the outfield on the sandy soil as response of maize to mineral N and P was poor due to other nutrient deficiencies (Figure 5c). On the rest of the fields, P uptake was most efficient at the lowest application rate, but decreased with rate of application (Figure 5c, d) due to the decreasing yield response with increasing P application (Figure 4). Low P use efficiencies do not usually translate into large losses, as P accumulates in the soil. With careful management, the P can be utilised by crops in subsequent seasons, particularly on the sandy soils with low P fixing capacity (Piha, 1993).

In Experiment 2, application of N at high rates without P was inefficient, as in most cases more than 50% of the N applied was not recovered by the crop across all fields and, therefore, potentially lost. The poor N use efficiencies may lead to large losses of N as much of the N not taken up by the crop may be lost, mainly through leaching (Chikowo et al., 2004). At most, 5% of the fertilizer N is recovered by crops grown in subsequent seasons (Krupnik et al., 2004). The RE_N with 30 kg N ha^{-1} were greater than values than average values of 23 (range 5 - 41) calculated for African smallholder farms (Krupnik et al., 2004). These average values were calculated with an average N application rate of 68 kg N ha^{-1} on smallholder farms. Except on the outfield on sandy soil, application of P improved N capture. This was due to the removal of P limitation, and the synergistic interaction between N and P on improving root growth could have also amplified N recovery. The poor RE_N with SSP on the outfields was probably due to the interaction of several factors, which include; (i) deficiency of other nutrients besides N and P; (ii) soil acidity; and (iii) poor water availability due to small soil organic matter contents (Giller et al., 2006). The decrease of RE_N with increasing rate of N application is due to the smaller amounts of N captured resulting from diminishing responses. Increasing application rate of N also increases the likelihood of N losses. Agronomic N use efficiencies were largest at low N application rates, and these were comparable to those observed under optimally managed on-station experiments (>50 kg grain kg^{-1} N) (Mushayi et al., 1999). The poor agronomic N use efficiencies on the outfield on granitic sand were typical of poorly managed depleted fields on sandy soils (Mushayi et al., 1999; Wopereis et al., 2006).

Despite the larger yields for similar treatments on the homefield on the clay soil than the outfield, there were little differences overall in RE_P with manure (Experiment 1) and RE_N with P (Experiment 2) (Figure 5, 7). This was due to the similar response to P or N, as the nutrient uptake for the reference plots (U_0) were smaller on the outfield on clay soil. Strategies for improving resource use on smallholder farmers should therefore not only consider attainable yields, but also differences in efficiencies of nutrient use influenced by soil nutrient stocks.

4.4.4. Heterogeneity of soil fertility on smallholder farms: implications for management

The large gaps in yields and nutrient use efficiencies between different fields revealed the need to strategically allocate resources, depending on soil type and historical management: a three dimensional approach to resource use on smallholder farms. The strategies for allocation of fertilizers must be based on attainable yields, nutrient use efficiencies and the effects of organic and mineral fertilizers on fields with different initial fertility. The homefields were more responsive to application of nutrients than outfields; hence farmers need to preferentially apply nutrients on homefields for efficient production (Wopereis et al., 2006). It is therefore currently rational for farmers to concentrate resources on homefields. Target yields for maize on the homefields were 5 to 6 t ha^{-1} on the clay soil and 2 to 3 t ha^{-1} on the sandy with mineral fertilizers or 3 t ha^{-1} with combined application of manure and mineral N fertilizers. Current blanket fertilizer recommendations are inappropriate for the variable soil fertility conditions as application of the recommended 120 kg N ha^{-1} and 30 kg P ha^{-1} leads to oversupply of N and P on the homefield on sandy soil. Our results suggest that returns diminish rapidly on most soils at applications rates higher than 60 kg N ha^{-1} and 10 kg P ha^{-1}.

Application of manure is required to improve maize yields and nutrient use efficiencies on the outfields as maize responded poorly to mineral N and P fertilizers on these fields, which suffer multiple deficiencies. Manure led to improved maize yields in the first season of application on the outfield on clay soil and over three seasons P use efficiencies were similar to those for treatment with manure on the homefield. Opportunities therefore exist for farmers on the clay soil to improve resource use efficiencies in the short-term by applying mineral N and P on the homefields and manure and mineral N on the outfields. Large investment in manure and mineral N was required over three seasons to significantly increase maize yields on the outfield on sandy soil. There are important short-term and long-term trade-offs between optimising nutrient use efficiencies and rehabilitating degraded fields on the poorly buffered sandy soils. The possibility of farmers to invest in large amounts of manure over several seasons where no immediate returns to their investment are found is doubtful, especially given that quantities of manure are limited and the task of transporting manure to outfields is laborious. Average cattle ownership in the area is less than 5 heads per farm (Zingore et al., 2006a). Assuming that a livestock unit produces about 1.5 t yr^{-1} usable manure (Swift et al., 1989), on average less than 10 t ha^{-1} of manure can be produced annually per farm. This is just sufficient to maintain maize production on the homefields (0.5 - 1 ha). It could be rational to suggest that spreading nutrient resources across farms is more efficient than concentrating on the homefields, assuming nutrients are used more efficiently at low application rates (Rowe et al., 2006). Nevertheless, when soil organic matter and other nutrients are critically low on the outfields, it is a better option to concentrate both organic and mineral nutrient resources on the more fertile fields. Farmers are familiar with different zones of fertility on their farms, so that recommendations for nutrient additions can, therefore, be tailored to zones readily identifiable by farmers.

4.5. Conclusions

Fields on smallholder farms are characterized by differences in soil fertility and this led to large differences in maize yields and nutrient use efficiencies. For fields on similar soil type, maize yields were larger and nutrient use efficiencies higher on the homefields than the outfields. This is attributed to the high soil fertility status of the homefields following many years of addition of large amounts of manure and mineral fertilizers. Yields were also larger on a corresponding field type on the red clay soil compared with granitic sands. Factors that contributed to larger yields on the clay soil included greater soil organic matter contents, CEC and exchangeable bases and better water holding capacity. On the clay soils resources would be used more efficiently in the short term if mineral fertilizers are targeted to the homefield and mineral N and manure on the outfield. Manure and mineral N fertilizers were required every season to sustain production on the homefield on sandy soil, whilst large amounts of manure (about 17 t ha^{-1}), applied over three seasons, were required to significantly improve maize yields on the depleted outfield on sandy soil. Manure and other organic nutrient resources are essential for sustainable maize production on the sandy soils and for rehabilitation of degraded fields.

CHAPTER 5

Multiple benefits of manure: a key to maintenance of soil fertility and restoration of depleted sandy soils on African smallholder farms

This chapter has been submitted for publication as:

Zingore, S., Delve, R.J., Nyamangara, J. and Giller, K.E., 2006. Multiple benefits of manure: a key to maintenance of soil fertility and restoration of depleted sandy soils on African smallholder farms. *Plant and Soil*.

Abstract

Manure is a key nutrient resource on smallholder farms in the tropics, especially on poorly buffered sandy soils, due to its multiple benefits for soil fertility. Smallholder farmers in Africa consist of multiple plots that are managed differently, which has led to steep gradients of soil fertility within farms. Farmers preferentially apply manure to fields closest to homesteads (homefields), which are often more fertile than fields further away from homesteads (outfields). Soil chemical parameters on fields representative of homefields and outfields on a sandy soil and a clay soil were measured to assess the long-term effects of manure use. Changes in soil properties in these fields were assessed following three years of mineral N fertilizer application, with manure or mineral P. Limiting nutrients and the capacity of manure to supply N, P, bases and micronutrients were also tested in greenhouse pot experiments using maize. The sandy and clayey homefields were initially more fertile than the outfield on a similar soil type. Addition of about 17 t ha^{-1} manure in combination with ammonium nitrate (100 kg N ha^{-1}) for three successive seasons significantly increased SOC by up to 63%, pH by 0.2 units, available P by 8 mg kg^{-1} and base saturation by 20% on the sandy outfield. Sole N as ammonium nitrate (100 kg N ha^{-1}) or in combination with SSP led to acidification of the sandy soils, with a decrease of up 0.8 pH units after three seasons. In the greenhouse experiment, N and Ca were identified as deficient on the sandy homefield, while N, P, Ca and Zn were deficient or low on the sandy outfield. On the sandy outfield, addition of manure significantly increased the maize shoot biomass and the concentrations of Ca and Zn, but depressed the concentration of N. No nutrient deficiencies were detected on the clayey homefield, whilst P was deficient on the clayey outfield. This study highlights the essential role of manure in sustaining and replenishing soil fertility on smallholder farms through its multiple effects. Manure may not supply sufficient amounts of N required by crops, whilst mineral N and P fertilizers alone do not supply other essential nutrients and may lead to soil acidification. Integrated use of mineral N and P fertilizers and manure is therefore required for sustainable crop production and soil fertility management on smallholder farms in sub-Saharan Africa.

5.1. Introduction

Fragile sandy soils with low inherent fertility are the predominant soils cultivated by smallholder farmers in Zimbabwe and large areas in sub-Saharan Africa. Vast areas of these sands have critically low concentrations of soil organic carbon (SOC) and nutrients, and are also acidic, due to long-term cultivation with little fertilizer inputs (Grant, 1981; Nyamangara et al., 2000). The coarse textured soils are highly susceptible to erosion under cultivation due to poor aggregation and vegetation cover (Burt et al., 2001). Depletion of soil fertility caused by cultivation of crops year-after-year with little fertilizer input and soil erosion has led to very low crop yields. Poor soil fertility and the restoration of depleted fields are recognized as challenges facing farmers throughout sub-Saharan Africa (Sanchez et al., 1997). Cattle manure is a key resource in this regard, due to its multiple effects on soil fertility (Bayu et al., 2005; Murwira et al., 1995). These benefits include supply of N, P, bases, trace elements and increased soil pH. Manure also contributes to maintenance of soil organic matter, which provides cation exchange capacity and improves physical parameters, such as soil structure.

Smallholder farmers in sub-Saharan Africa typically concentrate organic and mineral nutrient resources on fields closest to the homesteads (homefields) and apply little to fields further way (outfields) (Tittonell et al., 2005; Mtambanengwe and Mapfumo, 2005; Zingore et al., 2006a). Consequently, these gradients of resource allocation result in soils on fields closest to homesteads being most fertile, with soil fertility decreasing with distance from the homestead. This management is mainly driven by lack of adequate resources and, when combined with inherent differences in soil quality, results in complex differences in soil fertility between fields on the same farm or between farms located on different soils (Carter and Murwira, 1995; Giller et al., 2006). Zones of nutrient accumulation are often limited to small portions of the cropping area which receive substantial amounts of manure and/or fertilizers.

In on-farm experiments in Zimbabwe, maize (*Zea mays* L.) grown on depleted sandy outfields did not significantly respond to large additions of mineral N and P over three seasons. Responses to combined applications of manure and mineral N were also poor in the first two seasons, but significantly improved in the third season (Zingore et al., 2006b). The poor responses of maize growth to N and P were corrected over time only with repeated applications of large amounts of manure and mineral N fertilizer. This indicated that the initial poor response was due to deficiency of other nutrients besides N and P or other nutrients mediated by organic matter such as water holding capacity. Previous research indicated Zn and B to be limiting on granitic sands in Zimbabwe (Rodel and Hopley, 1973). Assessment of maize on several outfields in the study area (Zingore et al. 2006b) showed consistent nutrient deficient symptoms: stunted growth of maize and leaves characterized by interveinal chlorosis and dead tips, indicating that Zn deficiency was acute on the sandy soil. Maize yield responded strongly to mineral N and P on homefields that had previously received large amounts of manure. The variable responses to N and P were thus strongly influenced by the historical management of the fields, with the stronger responses on the homefields attributable to the larger contents of soil organic matter and other nutrients besides N and P resulting from large amounts of manure in the past.

These multiple effects of manure on soil fertility are not clearly understood. Research on cattle manure has focused on its role to supply N required by crops (Delve et al., 2002 Murwira et al., 1995; Nyamangara et al., 2003), with little attention given to its multiple functions in balancing availability of other nutrients in soils. The wide differences in responses to N and P observed between fields that had received large amounts of inputs in the past, and those that received little, necessitated a detailed study to elucidate the multiple benefits of manure on soil fertility and maize yields. There is also a need to assess the capacity of manure to replenish nutrients in degraded fields, where crops experience multiple nutrient deficiencies. Therefore, the aim of this study was to investigate the effects of manure on soil chemical properties and its capacity to restore depleted soils. Variability of soil chemical properties was assessed on fields with different histories of manure application on a granitic sand and a red clay soil. Changes in SOC, N, available P, pH and exchangeable bases were then measured on experimental plots in the different fields after three seasons of application of mineral N fertilizer with different rates of manure or mineral P fertilizer. In addition, greenhouse experiments were conducted to assess (i) macro and micronutrients deficiencies on sandy and clayey homefields and outfields (ii) the potential of manure to supply N, P, bases and micronutrients in the short term.

5.2. Materials and Methods

5.2.1. Study site, site selection and field experiments

Soil properties and their changes over time were measured on farmers fields during experiments conducted in Murewa (2002-5), in north-east Zimbabwe (17°49'S, 31°34'E). The experiments assessed the efficiencies of nutrient use by maize across soil fertility gradients on smallholder farms and have been previously reported (Zingore et al., 2006b). Experimental sites were selected following detailed characterization of resource use strategies across farms in different wealth categories and their influence on variability of soil fertility within and across farms (Zingore et al 2006a). The most fertile fields were found closest to homesteads on farms of wealthy farmers, who owned cattle and had access to manure. This was because the farmers concentrated the manure on fields closest to the homesteads. Fields further away from the homesteads on the wealthy farms and all fields on poor farms without access to manure were less fertile, as they received little fertilizer input. The experiments were established on four fields (sandy homefield; sandy outfield; clayey homefield and clayey outfield) representative of typical homefields and outfields on the sandy (Lixisol) and clayey (Luvisol) soils on smallholder farms that own cattle. The fields were selected on the basis of distance from homesteads, historical management and soil chemical properties. The four fields had been mostly under maize cultivation for more than three decades. The homefields received large amounts of manure and mineral fertilizer, whilst the outfields received little mineral fertilizers and had no history of manure application. On the four fields, N was applied as ammonium nitrate (100 kg N ha^{-1}), with different rates of P (0, 10 and 30 kg ha^{-1}), from either SSP or cattle manure (Table 1). Manure was applied at 6 and 17 t ha^{-1} yr^{-1}, to supply 10 and 30 kg P ha^{-1} yr^{-1} respectively. In each field, plots (6 m x 4.5 m) were arranged in a randomised complete block design with three replicates. All treatments were applied each season. A control plot, on which no nutrients were applied for the three seasons, was also included. Maize residues were removed after harvesting to mimic management by farmers, who remove the residues to feed cattle.

Table 1. Treatments for the three-year experiment established on fields with different initial fertility to assess variability of efficiencies of nutrient use on farms in Murewa, north-east Zimbabwe.

Treatment and N applied each season	Source and rate of P applied		
	Year 1	Year 2	Year 3
1 (0, control)	None	None	None
2 (100 kg N ha^{-1})	None	None	None
3 (100 kg N ha^{-1})	10 kg P ha^{-1} (manure)	10 kg P ha^{-1} (manure)	10 kg P ha^{-1} (manure)
4 (100 kg N ha^{-1})	30 kg P ha^{-1} (manure)	30 kg P ha^{-1} (manure)	30 kg P ha^{-1} (manure)
5 (100 kg N ha^{-1})	10 kg P ha^{-1} (SSP) [1]	10 kg P ha^{-1} (SSP)	10 kg P ha^{-1} (SSP)
6 (100 kg N ha^{-1})	30 kg P ha^{-1} (SSP)	30 kg P ha^{-1} (SSP)	30 kg P ha^{-1} (SSP)

[1]Single super phosphate.

5.2.2. Soil sampling and analysis

In each field, three soil samples (0-20 cm) were randomly collected from each block before the start of the experiment and bulked to form a composite sample. After three years of treatment application, soils were re-sampled from all plots. Three samples were collected from each plot and bulked together. Samples were air dried and passed through a 2 mm sieve and analysed for particle size distribution, SOC (Walkley-Black), total N (micro-Kjeldahl), available P (Olsen), pH(water) and pH(0.01M $CaCl_2$), cation exchange capacity (in ammonium acetate) and exchangeable bases (Ca, Mg and K) (Anderson and Ingram, 1993).

5.2.3. Greenhouse pot experiments

A greenhouse pot experiment was conducted to determine limiting nutrients on the different fields under controlled moisture conditions. Soils (0-20 cm) were collected from the four different fields described above: homefield and outfield on the sandy and clay soils. The soils were air-dried and sieved through 2 mm, before weighing into pots of 2000 cm^3. The bulk density of the sandy soil was 1.5 g cm^{-3} and that of the clay soil 1.2 g cm^{-3} of which 3 kg and 2.4 kg were filled in pots respectively. The treatments for the pot experiment and amounts of nutrients applied are presented in Tables 2 and 3. Potassium and S were applied to all plots, as K_2SO_4, as K deficiencies are not common in the studied soils and maize grain yield response to S (added in SSP) in the field experiments was not evident. A treatment with dolomitic lime was included to test the effects of increasing pH on maize shoot biomass and nutrient composition. This was important on the sandy soils, where maize growth may be inhibited by soil acidity. The manure used in the greenhouse experiment (macronutrient contents: 1.1% N, 0.18% P, 0.20% Ca, 0.08% Mg and 0.64% K; micronutrients contents: 800 mg kg^{-1} Fe, 22 mg kg^{-1} Cu, 280 mg kg^{-1} Mn, 112 mg kg^{-1} Zn) was collected from a kraal on a smallholder farm in Murewa, and prepared by air drying and grinding to < 0.5 mm.

Nutrient solutions were prepared separately for each soil type, due to differences in field capacity, with sufficient distilled water to attain field capacity on each soil. Manure and dolomitic lime were added directly to pots before application of nutrient solutions and thoroughly mixed with the soils for uniform distribution. The pots were arranged in a randomized complete block design with three replicates. For ease of management, the experiment was done in two phases: pots with sandy soil, both homefield and outfield, were set up first and the pots with the red clay soil were set up in the second phase of the experiment. The greenhouse temperature was not controlled, so the first phase of the experiment was conducted under higher temperatures than the second phase of the experiments. The objective of the experiment was not to compare maize biomass on the different soils, but to assess nutrient deficiencies on each the soils.

Five maize seeds were planted in each pot, to ensure germination, and were thinned to leave one plant after germination. Moisture loss was estimated by weighing the pots every second day and the pots watered to maintain moisture at 70% field capacity. Plants shoots were harvested by cutting at the soil surface five weeks after germination, dried at 70°C for 24 hours and weighed.

Table 2. Treatments (with and without cattle manure) used to assess limiting nutrients on a homefield and outfields on a sandy and red clay soil from Murewa, north-east Zimbabwe.

Treatment	Nutrients (no manure)	Manure
1.	Control	Manure
2.	N	Manure + N
3.	N + P	Manure + N + P
4.	N + P + Ca	Manure + N + P + Ca
5.	N + P + Ca + Mg	Manure + N + P + Ca + Mg
6.	N + P + Ca + Mg + [1]micro-nutrients	Manure + N + P + Ca + Mg + micro-nutrients
7.	N + P + micro-nutrients + dolomitic lime	Manure + N + P + micro-nutrients + dolomitic lime

[1]Micro-nutrients applied are presented in Table 3. Application is based on micronutrients potentially limiting in Zimbabwean soils.

Table 3. Rates of nutrients applied and their form. Calculation of nutrients applied to the plots was done on a volume basis, assuming a depth of 20 cm in the field.

Nutrient/amendment	Form (Compound)	Amounts applied per pot (g)
N	NH_3NO_3	0.40
P	KH_2PO_4	0.13
K	K_2SO_4	0.19
Ca	$CaSO_4$	0.31
Mg	$MgSO_4$	0.15
Zn	$ZnSO_4$	0.03
Cu	$CuSO_4$	0.03
Mn	$MnSO_4$	0.04
B	$Na_2B_4O_7$	0.02
Mo	Na_2MoO_4	0.002
Co	$CoCl_2$	0.005
Manure	Cattle manure	10
Dolomitic Lime	($CaCO_3$, $MgCO_3$)	1.5

Based on field observations that indicated Zn deficiency, a second experiment was conducted to examine if Zn was deficient on the sandy outfield. The treatments were: (i) control; (ii) N + P + Ca; (iii) N + P + Zn; (iv) N + P + Ca + Zn; and (v) N + P + Ca + all micronutrients. We also tested for Zn and Ca deficiency on the soil from the sandy outfield that had received about 17 t of manure ha^{-1} yr^{-1} for three seasons to assess the capacity of manure to alleviate deficiencies of Ca and Zn.

Dried manure and maize shoots samples were ground (<0.5 mm) for analysis of nutrient composition. Total N was determined using the micro-Kjeldahl method and total P using the modified Olsen method (Anderson and Ingram, 1993). The contents of Ca, Mg, K, Zn, Fe, Mn, and Cu were determined by atomic absorption spectrometry (Page et al., 1982). Nutrient concentrations in maize shoots were interpreted as deficient, low, or adequate using values suggested by Marschner (1995), and Mengel and Kirby (2001) (Table 4).

Table 4. Value used to interpret adequacy of nutrients in different fields at Murewa, north-east Zimbabwe using nutrient concentration values of in maize shoots

	N	P	Ca	Mg	Zn	Fe	Mn	Cu
	(%)				(mg kg^{-1})			
Deficient[a]	-	<0.1	<0.2	<0.1	<5	<10	<10	-
Low[a]	-	0.1-0.2	0.2-0.3	0.1-0.2	15-20	10	10-20	-
Adequate[a]	-	0.2-0.5	0.4-1.0	0.2-1.0	20-70	10-300	20-200	-
High[a]	-	0.5-0.8	>1.0	>1.0	70-150	300-550	200-250	-
Critical concentrations[b]	3.0	0.25	0.4	0.15	20	25	15	5

[a] Mengel and Kirby, 2001; [b]Marschner 1995

5.2.4. Statistical Analysis

Analysis of variance (ANOVA) was used to test the significance of differences between means of soil properties after three seasons of N, SSP and manure application, maize grain yields and of maize shoot biomass and nutrient composition in the greenhouse experiments. The statistical analysis was performed using the GENSTAT 7.1 statistical package.

5.3. Results

5.3.1. Initial soil chemical properties of fields with different management histories

On the sandy soil, the homefield had larger contents of SOC, total N and available P compared with the outfield (Table 5a and 5b). The pH of the two fields on the sandy soil was low. The sandy homefield had significantly higher CEC, exchangeable bases and base saturation compared with the sandy outfield. The fields on the clay soil had a larger capacity to store soil organic matter and nutrients and were more fertile than corresponding fields on the sandy soil (Table 6a and 6b). Differential management by the farmer on the clay soil also led to steep differences in soil fertility between the homefield and the outfield; SOC, total N, pH and available P were all initially greater on the homefield than the outfield (Table 6a and 6b).

5.3.2. Changes in soil chemical properties of homefields and outfields after three seasons of N, P and manure application

On the sandy soil, SOC and total N did not change significantly on the homefield after three seasons across all treatments, although manure applications marginally increased SOC and total N (Table 5a). Soil pH (H_2O) increased significantly at the highest rate of manure application (17 t ha^{-1} yr^{-1}), whereas application of sole N fertilizer or N + SSP led to a significant decrease in pH by up to 0.8 units. Compared to the outfields, available P was significantly increased in the two treatments in which SSP or the high rate of manure were applied, but was significantly decreased in the sole N fertilizer treatment on the homefields.

On the sandy outfield, addition of N fertilizer together with manure equivalent to 10 and 30 kg P ha^{-1} increased SOC contents from 0.31% to 0.41% and 0.49% respectively after three seasons (Table 5b). The larger manure application rate (17 t ha^{-1} yr^{-1}) also led to increases in pH, available P, CEC, exchangeable bases (Ca, Mg and K) and base saturation. Similar to the observation on the homefield, N fertilizer alone or combined with SSP caused a significant decline in pH on the outfield. SSP treatments on the sandy outfield also significantly increased available P.

Compared with the initial values, most soil properties remained unchanged on the clayey homefield, except for the significant decline in available P for the control, sole N and the N + SSP (10 kg ha^{-1}) treatments (Table 6a). There were significant differences, however, in SOC contents between treatments. Manure applied at 17 t ha^{-1} yr^{-1} resulted in larger SOC contents than the control and sole N treatments. Manure (17 t ha^{-1} yr^{-1}) led to significant increases in SOC

Table 5. Initial and changes in soil chemical properties after three seasons of application of N at difference rates and sources on fields with different initial fertility at Murewa, north-east Zimbabwe. (a) sandy homefield, (b) sandy outfield.

(a)

Treatment	Organic C (%)	Total N (%)	pH (H_2O, $CaCl_2$)	Available P (mg kg^{-1})	CEC ($cmol_c$ kg^{-1})	Exchangeable bases ($cmol_c$ kg^{-1})			Base saturation (%)
						Ca	Mg	K	
Initial	0.50	0.04	5.1, 4.9	7.2	2.2	0.91	0.32	0.21	73
Control	0.48	0.03	4.9, 4.5	6.6	2.1	0.75	0.24	0.29	65
100 N	0.48	0.04	4.6, 4.1	2.3	2.1	0.62	0.26	0.32	61
100 N + 10 kg P (manure)	0.52	0.04	5.0, 4.8	5.6	2.4	1.13	0.36	0.35	79
100 N + 30 kg P (manure)	0.58	0.05	5.6, 5.2	12.5	2.6	1.19	0.44	0.50	89
100 N + 10 kg P (SSP)	0.49	0.03	4.5, 4.1	9.3	1.9	0.62	0.22	0.29	63
100 N + 30 kg P (SSP)	0.51	0.04	4.5, 4.2	16.5	2.2	0.76	0.13	0.27	56
SED	0.09	0.01	0.2, 0.3	1.7	0.3	0.24	0.19	0.13	12

(b)

Treatment	Organic C (%)	Total N (%)	pH (H_2O, $CaCl_2$)	Available P (mg kg^{-1})	CEC ($cmol_c$ kg^{-1})	Exchangeable bases ($cmol_c$ kg^{-1})			Base saturation (%)
						Ca	Mg	K	
Initial	0.31	0.03	4.9, 4.5	2.4	1.6	0.26	0.19	0.11	37
Control	0.32	0.02	4.9, 4.4	2.5	1.8	0.23	0.21	0.12	33
100 N	0.29	0.03	4.1, 3.5	1.5	1.7	0.15	0.18	0.14	28
100 N + 10 kg P (manure)	0.41	0.03	5.0, 4.7	3.4	1.9	0.31	0.32	0.13	40
100 N + 30 kg P (manure)	0.49	0.04	5.2, 4.9	10.9	2.1	0.53	0.44	0.23	57
100 N + 10 kg P (SSP)	0.29	0.02	4.7, 4.2	4.6	1.6	0.17	0.20	0.12	24
100 N + 30 kg P (SSP)	0.30	0.03	4.6, 4.0	11.5	1.7	0.21	0.27	0.12	29
SED	0.05	0.01	0.12, 0.13	1.6	0.4	0.23	0.16	0.11	8

Table 6. Initial and changes in soil chemical properties after three seasons of application of N at difference rates and sources on fields with different initial fertility at Murewa, north-east Zimbabwe. (a) clayey homefield, (b) clayey outfield.

(a)

Treatment	Organic C (%)	Total N (%)	pH (H_2O, $CaCl_2$)	Available P (mg kg^{-1})	CEC ($cmol_c$ kg^{-1})	Exchangeable bases ($cmol_c$ kg^{-1})			Base saturation (%)
						Ca	Mg	K	
Initial	1.43	0.08	5.6, 5.3	12.1	24.2	11.5	6.2	0.8	78
Control	1.21	0.07	5.6, 5.2	8.3	23.0	11.8	5.9	0.5	80
100 N	1.26	0.08	5.5, 5.3	7.9	23.1	11.9	5.9	0.6	84
100 N + 10 kg P (manure)	1.45	0.07	5.5, 5.3	9.5	24.0	11.5	6.1	0.9	78
100 N + 30 kg P (manure)	1.64	0.09	5.5, 5.3	10.3	24.8	12.4	6.0	0.7	78
100 N + 10 kg P (SSP)	1.45	0.08	5.6,5.4	7.3	23.0	11.5	6.0	0.7	88
100 N + 30 kg P (SSP)	1.40	0.08	5.6, 5.2	13.6	23.2	12.1	5.8	0.7	84
SED	0.15	0.02	0.2, 0.2	2.6	1.6	0.62	0.44	0.21	12

(b)

Treatment	Organic C (%)	Total N (%)	pH (H_2O, $CaCl_2$)	Available P (mg kg^{-1})	CEC ($cmol_c$ kg^{-1})	Exchangeable bases ($cmol_c$ kg^{-1})			Base saturation (%)
						Ca	Mg	K	
Initial	0.75	0.05	5.4, 5.1	3.9	22.0	8.4	6.3	0.3	68.6
Control	0.72	0.04	5.5, 5.2	3.7	23.4	8.9	6.5	0.3	67.5
100 N	0.79	0.05	5.3, 5.0	3.1	23.9	10.4	5.6	0.3	68.6
100 N + 10 kg P (manure)	0.89	0.07	5.5, 5.3	4.1	22.0	9.6	5.5	0.4	70.9
100 N + 30 kg P (manure)	0.91	0.07	5.6, 5.3	4.9	23.4	9.6	5.7	0.4	67.5
100 N + 10 kg P (SSP)	0.72	0.06	5.3, 5.1	4.2	23.2	8.4	5.4	0.3	61.2
100 N + 30 kg P (SSP)	0.75	0.05	5.4, 5.1	6.7	22.9	9.3	5.6	0.3	66.8
SED	0.08	0.02	0.3, 0.2	1.5	1.1	1.3	0.9	0.1	8

Table 7. Maize grain yields (t ha^{-1}) on sandy and clayey homefields and outfields at Murewa, north-east Zimbabwe, subjected to application of mineral N with different rates of manure or single super phosphate.

N and P applied (ha^{-1})	Sandy homefield		Sandy outfield		Clayey homefield		Clayey outfield	
	Season 1	Season 3	Season 1	Season 3	Season 1	Season 3	Season 1	Season 3
Control	1.0	0.7	0.2	0.1	2.1	1.4	0.7	0.6
100 kg N	1.5	0.7	0.3	0.1	2.9	1.7	0.8	0.8
100 kg N + 10 kg P (manure)	2.8	2.4	0.5	0.9	2.8	3.0	2.2	1.9
100 kg N + 30 kg P (manure)	3.4	3.1	1.0	2.2	4.2	4.7	3.6	3.7
100 kg N + 10 kg P (SSP)	2.1	1.6	0.5	0.2	3.8	2.9	1.7	0.9
100 kg N + 30 kg P (SSP)	2.3	2.1	0.8	0.5	6.2	3.9	2.1	2.3
SED	0.16		0.11		0.35		0.21	

content on the clayey outfield. Available P on the clayey outfield was only significantly increased by SSP applied at 30 kg P ha^{-1} yr^{-1}.

5.3.3. Maize grain yields on the sandy and clayey homefields and outfields
Maize grain yields for the control treatment decreased in the order: clay homefield > sandy homefield ~ clayey homefield > sandy outfield, both in the first and third seasons (Table 7). On the clayey homefield, the maize grain yield for the control treatment in the third season was significantly lower than that in the first season by 0.7 t ha^{-1}. Addition of N alone at 100 kg ha^{-1} significantly increased maize grain yields on the sandy and clayey homefields in the first season, but had no significant effect on maize grain yields in the third season. There was no significant maize grain yield response to N alone on the outfields (Table 7).

Maize grain yields were mostly significantly increased when N was applied in combination with SSP or manure on all field except the sandy outfield (Table 7). Application of manure led to higher maize grain yields than SSP on the sandy homefield and clayey outfield in both the first and the third seasons. On the clayey homefield, the maize grain yields with SSP were higher than with manure in the first season, but repeated application of manure for three seasons led to higher yields than SSP. On the sandy outfield, maize grain yield response to N and P was poor, irrespective of the source of P (Table 7). Repeated application of manure (30 kg P ha^{-1}) for three seasons led to a significant increase in maize yields from 1.0 t ha^{-1} in the first season to 2.2 t ha^{-1} in the third season.

5.3.4. Maize shoot biomass and nutrient composition on the sandy homefield and outfield
Maize growth was significantly increased by addition of N alone on the sandy homefield (Figure 1a). Maize growth was also significantly increased above the N and N+P treatments by addition of Ca. Phosphorus+N increased biomass production above the N treatment on the sandy outfield where manure had been applied (Figure 1b), whereas addition of Ca without manure significantly increased biomass in all fields. Addition of Mg alone and dolomitic (which adds both Ca and Mg) lime had marginally depressed maize biomass on the sandy homefield (Figure 1a). Maize biomass was increased with micronutrients on the sandy outfield (Figure 1b).

Manure alone (control) had no effects on maize biomass on the sandy soil (Figure 1a, b), but significantly amplified the response to N and P. On the homefield, maize biomass production was 12 g pot^{-1} when N was added in combination with manure compared with 3 g $plot^{-1}$ when manure alone was applied. There were no significant responses to other nutrients besides N (Figure 1a). On the outfield, manure alone led to only minor increases in maize biomass, but to significant

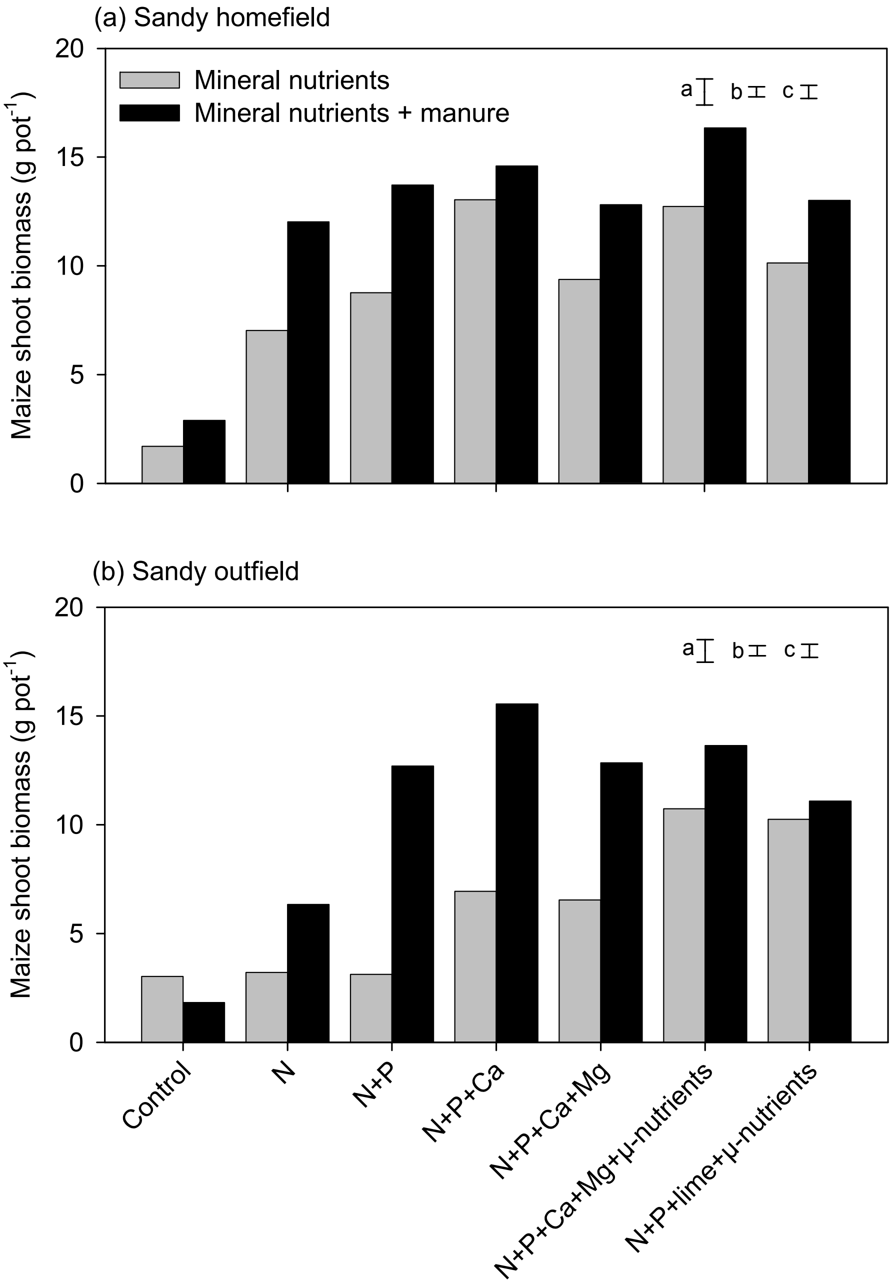


Figure 1. Effects of different nutrients on maize biomass production on sandy soils from Murewa, north-east Zimbabwe, in the greenhouse pot experiment (a) homefield; (b) outfield. Bars show SEDs for different factors: (a) treatments; (b) field type; (c) soil type. All pots were amended with K and S.

Table 8. Nutrient concentrations of maize plants on the sandy soils from Murewa, north-east Zimbabwe, supplied with different combinations of macro- and micronutrients and manure in the greenhouse pot experiment. (a) sandy homefield soil; (b) sandy outfield soil.

(a)

[1]Treat-ment	N (%)		P (%)		Ca (%)		Mg (%)		Zn (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Cu (mg kg^{-1})	
	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M
1	1.6	1.1	0.26	0.33	0.33	0.44	0.22	0.31	36	41	319	288	127	131	9.6	10.4
2	3.2	2.4	0.25	0.27	0.28	0.41	0.30	0.29	31	37	290	280	120	130	10.2	11.4
3	3.4	2.2	0.37	0.33	0.26	0.39	0.30	0.33	29	31	275	302	122	119	11.1	9.9
4	3.0	2.5	0.31	0.31	0.44	0.53	0.26	0.34	32	45	275	296	132	132	10.6	10.9
5	3.1	3.1	0.34	0.28	0.39	0.44	0.31	0.30	33	44	262	305	121	126	11.0	10.3
6	3.1	2.4	0.30	0.32	0.46	0.55	0.29	0.36	48	44	289	300	139	144	11.5	11.5
7	3.3	2.8	0.29	0.31	0.45	0.53	0.31	0.35	40	43	291	292	143	143	10.2	11.5
SED	0.3		0.07		0.06		0.03		4.2		20		13		1.2	

(b)

Treat-ment	N (%)		P (%)		Ca (%)		Mg (%)		Zn (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Cu (mg kg^{-1})	
	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M
1	1.4	1.4	0.15	0.18	0.28	0.43	0.25	0.24	21	29	250	287	136	136	10.1	10.4
2	3.3	2.1	0.19	0.22	0.21	0.32	0.23	0.28	19	28	274	255	124	116	10.8	10.2
3	3.5	2.7	0.30	0.33	0.25	0.41	0.23	0.25	18	21	278	297	125	106	11.3	10.4
4	3.4	3.0	0.32	0.32	0.36	0.38	0.26	0.26	19	29	265	281	111	124	9.8	10.0
5	3.2	2.8	0.31	0.31	0.40	0.49	0.31	0.33	22	33	276	271	136	121	11.6	10.9
6	3.3	2.5	0.32	0.32	0.42	0.41	0.32	0.33	31	29	280	265	142	139	11.9	11.4
7	3.5	3.1	0.32	0.32	0.51	0.44	0.36	0.35	36	38	282	278	148	157	12.8	11.9
SED	0.4		0.04		0.04		0.05		4.6		29		11		1.0	

[1]Treatmets: 1 = control; 2 = N; 3 = N+P; 4 = N+P+Ca; 5 = N+P+Ca+Mg; 6 = N+P+Ca+Mg+micronutrients; 7 = N+P+lime+micronutrients

responses to N and P (Figures 1b). This sharply contrasted with the lack of response to N and P observed without manure (Figure 1b), and indicated that manure supplied substantial amounts of Ca and micronutrients. With manure added, there was no significant additional growth response to Ca and micronutrients. Overall, application of manure gave an increased maize shoot biomass on the sandy outfield compared with most of the nutrient solution treatments.

On the sandy homefield and outfield, the concentration of N in the maize shoots in the control treatment was below critical values given for maize, both with and without manure (Table 8a, b). The concentration of N in the shoots was significantly increased with addition of N, but was significantly reduced with manure in some treatments. On the sandy homefield, the concentrations of all nutrients, except N and Ca, were within the adequate range for maize. On the sandy outfield, the concentrations of P, Ca, and Zn in maize shoots were below the adequate range (low or deficient) in the treatments without the respective nutrients. The concentrations of Mg, Fe, Mn, Cu were in the adequate range and were mainly independent of nutrient addition (Table 8b). On the sandy outfield, the concentrations of Ca and Zn were significantly increased with manure application, except in treatments in which these nutrients were added.

5.3.5. Maize shoot biomass and nutrient composition on the clayey homefield and outfields

The maximum maize biomass obtained for both fields on the clay soil was less than that on the sandy soil, as the treatments with the clay soil were established later in the year when temperatures were lower. None of the major or micronutrients had an effect on maize biomass on the clayey homefield (Figure 2a). On the clayey outfield, there was no response to sole N fertilizer, but there was significant maize growth increase in the N+P treatment, which indicated that either P alone or both P and N were strongly limiting. None of the other nutrient treatments had significant effects on maize biomass (Figure 2b). Dolomitic lime significantly depressed maize biomass on the clayey outfield (Figure 2b).

Manure addition resulted in a small, but rather consistent increase of ~1 g pot^{-1} in maize biomass on the clayey homefield, both alone and combined with other nutrients (Figure 2a). On the clayey outfield, different combinations of nutrients with manure resulted in maize biomass that was not significantly different from that produced by manure alone or by nutrients without manure (Figure 2b).

On the clayey homefield, the concentrations of all nutrients in maize shoots were in the adequate range, although manure significantly reduced N concentration (Table 9a). On the clayey outfield,

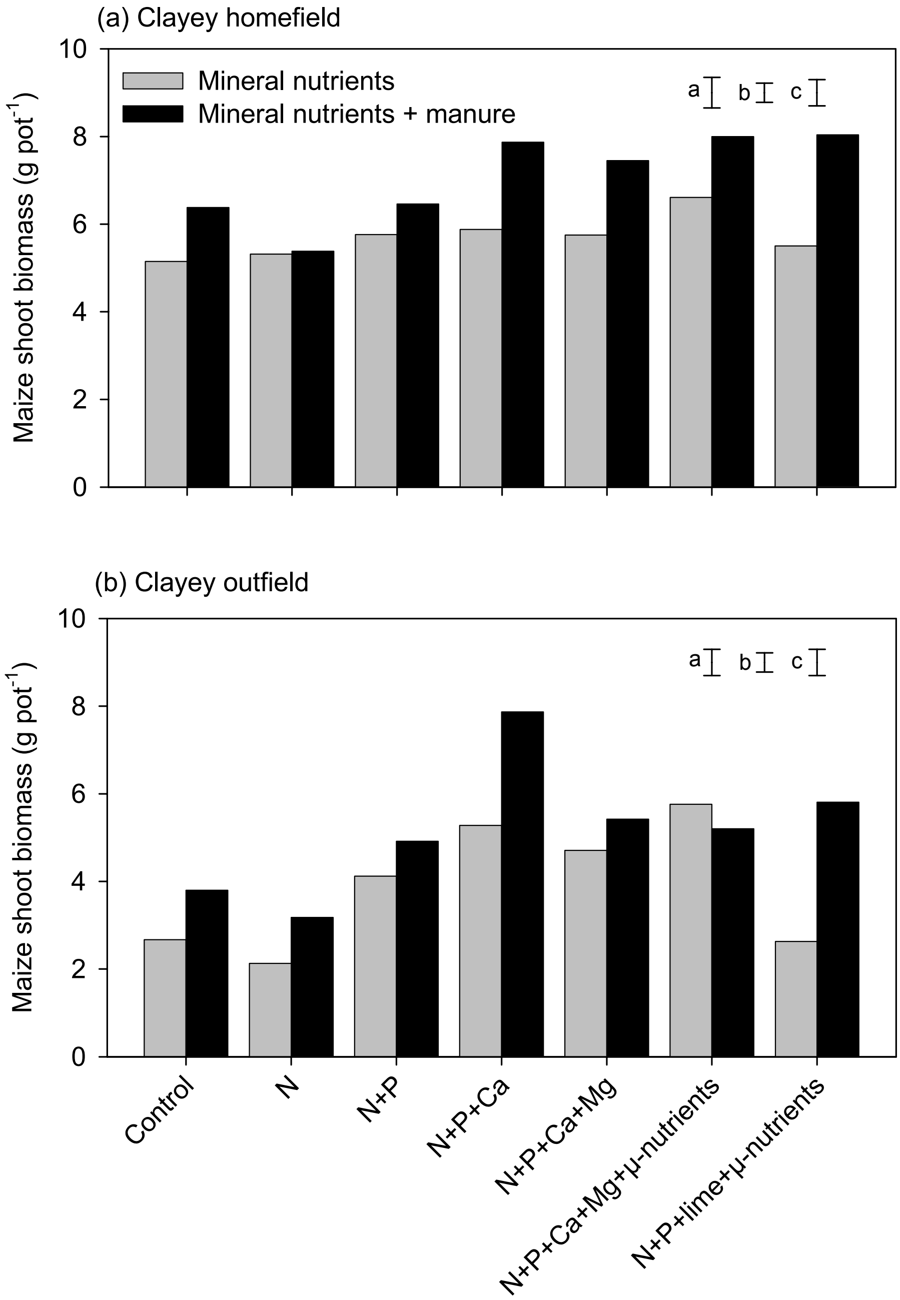


Figure 2. Effects of different nutrients on maize biomass production on clayey soils from Murewa, north-east Zimbabwe, in the greenhouse pot experiment (a) homefield; (b) outfield. Bars show SEDs for different factors: (a) treatments; (b) field type; (c) soil type. All pots were amended with K and S.

Table 9. Nutrient concentrations of maize plants on the clay soils from Murewa, north-east Zimbabwe, supplied with different combinations of macro- and micronutrients and manure in the greenhouse pot experiment. (a) clayey homefield; (b) clayey outfield.

(a)

Treat-ment[1]	N (%)		P (%)		Ca (%)		Mg (%)		Zn (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Cu (mg kg^{-1})	
	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M
1	3.2	2.9	0.31	0.28	0.53	0.55	0.37	0.36	51	42	315	325	127	129	10.3	9.9
2	3.5	3.1	0.30	0.32	0.51	0.57	0.41	0.41	40	42	325	377	130	136	9.5	13.5
3	3.6	3.3	0.34	0.33	0.58	0.63	0.40	0.47	38	43	311	332	131	122	9.1	8.5
4	3.6	3.3	0.34	0.35	0.62	0.65	0.38	0.45	42	41	332	329	125	125	10.9	10.4
5	3.7	2.9	0.32	0.35	0.59	0.61	0.41	0.51	47	49	310	326	126	125	8.7	9.8
6	3.3	3.3	0.34	0.32	0.54	0.69	0.45	0.46	49	51	329	352	134	150	11.5	12.3
7	3.5	3.0	0.36	0.38	0.57	0.55	0.42	0.46	55	53	334	336	123	139	12.1	12.8
SED	0.4		0.02		0.06		0.06		3.3		33		15		2.2	

(b)

Treat-ment	N (%)		P (%)		Ca (%)		Mg (%)		Zn (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Cu (mg kg^{-1})	
	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M	-M	+M
1	2.2	2.6	0.16	0.22	0.43	0.40	0.43	0.43	50	48	350	375	132	129	10.1	11.8
2	3.2	2.9	0.17	0.19	0.45	0.54	0.39	0.42	45	53	375	347	123	123	13.1	11.2
3	3.4	2.9	0.31	0.33	0.43	0.47	0.43	0.44	51	50	352	388	134	125	10.3	10.4
4	3.5	3.3	0.28	0.31	0.49	0.48	0.41	0.40	50	52	320	375	125	140	11.8	10.9
5	3.4	3.2	0.30	0.28	0.56	0.41	0.46	0.42	42	51	323	390	123	129	10.0	10.4
6	2.9	3.1	0.29	0.29	0.48	0.49	0.43	0.36	52	52	401	350	132	141	11.3	13.7
7	3.1	3.2	0.32	0.28	0.53	0.49	0.42	0.40	53	50	350	336	135	145	11.5	12.9
SED	0.2		0.05		0.04		0.03		0.51		44		16		2.4	

[1]Treatmets: 1 = control; 2 = N; 3 = N+P; 4 = N+P+Ca; 5 = N+P+Ca+Mg; 6 = N+P+Ca+Mg+micronutrients; 7 = N+P+lime+micronutrients

the concentration of N maize shoot was low in the control treatment, while the concentration of P was low in the control and the N treatments (Table 9b).

5.3.6. Further experiments to examine Zn deficiency and the capacity of manure to replenish Ca and Zn on the degraded soil

In the second pot experiment, maize biomass for the N+P+Ca treatment was significantly greater than that for the N+P+Zn, suggesting that Ca was deficient on the sandy outfield. (Figure 3). In treatments without Ca, the concentration of Ca in maize shoots (<0.3%) indicated that Ca was deficient (Table 4). The concentration of Zn was in the low or deficient range (14-19 g kg^{-1}). The maize shoot biomass response to micronutrients in this experiment was smaller than in the first pot experiment. No additional maize shoot biomass increase was observed in the N+P+Ca+micronutrients treatment above the N+P+Ca+Zn treatment. The maize shoot biomass for the treatments with N and P, but without Ca or Zn were greater on the sandy outfield manured for three seasons than on the unamended sandy outfield, suggesting that the manure applications had alleviated deficiencies of Ca and Zn (Figure 3). In the manured sandy outfield, the concentration of Ca in maize shoots was significantly increased by an average of 0.05%, although it was still not adequate for maize growth (0.32-0.36%) without addition of Ca. The concentration of Zn in maize shoots on the manured sandy outfield was adequate for normal maize growth in all treatments (27-39 g kg^{-1}).

5.4. Discussion

5.4.1. Differences in soil chemical properties of fields with different management histories

The larger contents of SOC, total N and exchangeable bases observed on the homefields (Table 5, 6) can be linked to larger amounts of manure applied over many years (Prudencio, 1993; Tittonell et al., 2005). Manure has multiple effects on soil chemical properties and in the Sahelian zone, manure applied at 20 t manure ha^{-1} in one season led to substantial increase in SOC (from 0.29% to 0.58%), total N, available P and soil pH (Bationo and Mokwunye, 1991). Smallholder farmers typically remove stover for use as fodder and manure is the only major source of organic matter returned to agricultural fields. It is difficult to build up of organic matter on the sandy soil as shown by the smaller soil organic matter contents, even on the homefield, relative to the clay soil. On the clay soil, the difference in soil organic matter between the homefield and the outfield was approximately 100%, due to larger applications of organic matter over time and the stronger capacity of the clay soil to protect soil organic matter physically, which facilitated larger storage of organic matter from manure on the homefield (Feller and Beare, 1997; Zingore et al., 2005).

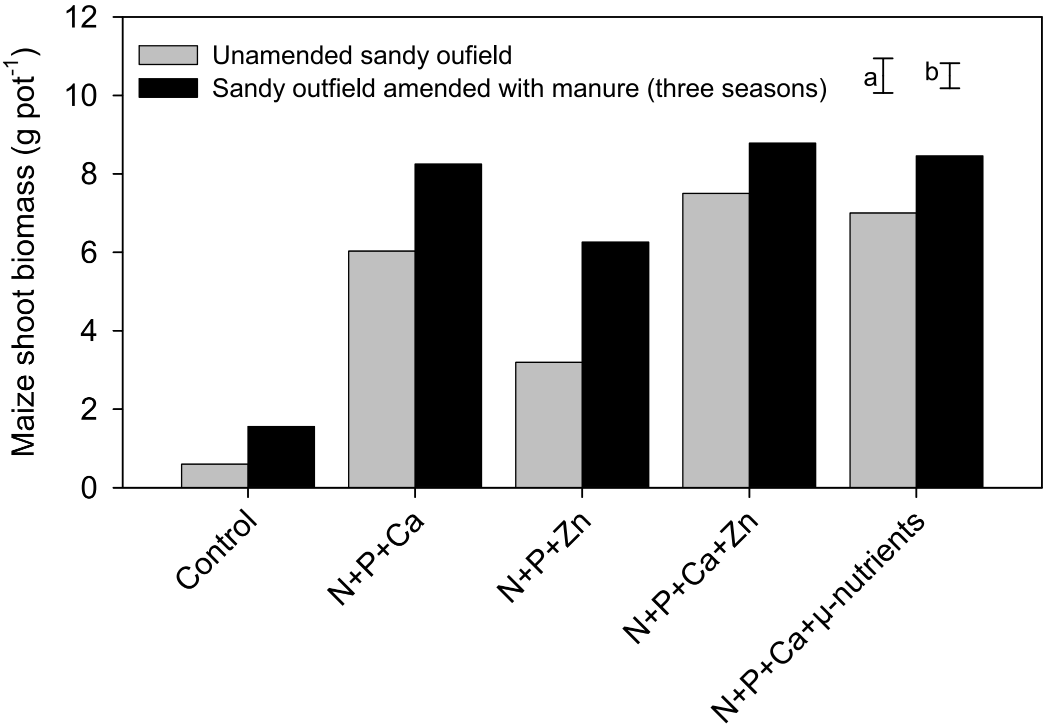


Figure 3. Effects of Ca and Zn on maize biomass on the sandy outfield soil from Murewa, in north-east Zimbabwe in the greenhouse pot experiment. Bars show SEDs: (a) treatments; (b) effect of manure applied in the field experiment. All pots were amended with K and S.

The CEC was low on the sandy soil due to the small clay contents (Table 5a, b). Under such conditions, soil organic matter may contribute the bulk of CEC and buffering capacity (Mapfumo and Giller, 2001; Bationo and Mokwunye, 1991). The higher CEC on the homefield than the sandy outfield was due to the larger SOC content. Assuming that at pH 5-7 the CEC of the kaolinitic clay minerals is 5-10 $cmol_c$ kg^{-1} and that of organic matter about 150-300 $cmol_c$ kg^{-1} (Asadu et al., 1997; White, 1997), clay minerals (about 10% clay) contributed only 0.5-1 $cmol_c$ kg^{-1} and soil organic matter 0.8-1.5 $cmol_c$ kg^{-1} on the homefield and 0.5-0.9 $cmol_c$ kg^{-1} on the outfield. Clay dominated the CEC on the red clay soil and as result the CEC values for homefield and the outfield were similar. The most notable effects of manure on the sandy soil were on exchangeable bases. Manure contains significant amounts of bases, which led to the greater contents of exchangeable bases on the homefield that received manure compared with the outfield. Strong effects of manure on supply of bases were also reported by Lupwayi et al. (2000). The higher pH on the homefields than outfield is due to the release of OH^- ions during decomposition of manure and the buffering from organic compounds released from manure applied in the past (Haynes and Mokolobate, 2001; Whalen et al., 2000). The higher available P values on the homefields may not be attributable solely to manure, as the farmers also used basal fertilizer (7%N, 9%P, 8%K) on these fields in the past. On the clayey outfield, bases and pH were maintained at high values due to the high buffering capacity of the soil (Table 6b). The effects of manure on improving various soil properties have been observed on the granitic sandy soil previously where available P, pH and exchangeable K were greater in plots where farmers applied manure than in plots that received no manure (Carter and Murwira, 1995).

5.4.2. Changes in soil chemical properties of homefields and outfields after three seasons of N, P and manure application

Application of mineral N alone as ammonium nitrate led to acidification on the sandy soils (Table 5a, b) presumably due to: (i) release of H^+ ions during microbial nitrification of ammonium; (ii) accelerated leaching of bases with nitrates; and (iii) uptake of ammonium leading to excretion of H^+ and net acidification of the rhizosphere. These acidifying effects of ammonium nitrate were less profound on the clay soil, due the stronger buffering capacity of the clay. The other major effect of the sole N treatment was significant depletion of available P on the homefields, due to increased removal of P. On the clay soil available P could have also declined due to P fixation without further P addition. Although N is regarded as the most limiting nutrient in Zimbabwe, balanced nutrient application is required, as application of N alone induces depletion of other nutrients (Nyamangara et al., 2000).

The largest increases in soil organic matter were observed on the outfields which initially contained small amounts of organic matter. The manure applied over the three seasons had an average C content of 26%; therefore about 4.4 t C ha^{-1} and 1.5 t C ha^{-1} was added each year for three years in the treatments with 17 t manure ha^{-1} and 6 t manure ha^{-1} respectively. Given that the bulk density of the sandy soil was 1500 kg m^{-3} and that of the clay soil 1200 kg m^{-3}, the increase in SOC contents with 17 and 6 t manure ha^{-1} in the outfields were: 5 t C ha^{-1} and 3 t C ha^{-1} on the sandy soil, and 4 t C ha^{-1} and 3 t yr^{-1} C ha^{-1} on the clay soil. The estimated humification of C added in manure in the sandy outfield, calculated on the basis of amounts of manure C added and that remaining in the soil, were thus 40% and 64% of the C added in manure applied at 17 t ha^{-1} and 6 t ha^{-1} and on the clayey outfield, 20% and 71% respectively. The humification of C from manure will in reality be less than the calculated values as maize will also have contributed to SOC through additional root growth. On the sandy outfield, the highest maize grain yield was 2.2 t ha^{-1} with a stover yield of 3 t ha^{-1} (data not shown). Assuming that roots constitute less than 20% of the aboveground biomass (Balesdent and Balabane, 1992), annual maize roots inputs were less than 1 t ha^{-1} (~ 0.4 t C ha^{-1}). The contribution of roots to soil organic matter was, therefore, not expected to be substantial.

Significant increases in SOC following manure applied at rates between 5 and 20 t ha^{-1} in one season has been observed in other studies in sub-Saharan Africa (Haynes and Naidu, 1998; Bationo and Mokwunye, 1991). The small increases on the homefields are due to the larger initial soil organic matter contents in these soils. After three seasons of manure application at 17 t ha^{-1} yr^{-1} on the outfield, the SOC was similar to that of the homefield, indicating that large additions of manure are necessary to reduce the gradients of SOC on the sandy soil. Such application rates were insufficient to raise the SOC of the clayey outfield to contents initially on the homefield, suggesting that even larger amounts or a longer time-frame of manure application may be required to do that on the clay soil.

Besides SOC and total N, manure had strong effects on available P, exchangeable Ca, Mg and K and pH (Table 5, 6). Field studies in Tanzania showed that manure applied at 20 t ha^{-1} significantly increased available P across depleted farmers' fields (Kaihura et al., 1999). On sandy soils with small total P contents, the effects of manure on P availability are directly related to the release of available phosphate during decomposition (Kaihura et al., 1999). On the clay soil with high P sorption capacity, in addition to direct P supply, organic anions released during decomposition of manure can compete with P sorption sites and increase availability of P (Reddy et al., 1999).

The increase in exchangeable bases is related to their significant concentrations in manures used. Cattle manure generally contains significant amount of Ca, Mg and K (De Ridder and Van Keulen, 1990). Grant (1967) found similar effects of manure on increasing supply of bases for maize on granitic sands in Zimbabwe. Application of N and P fertilizers may have an indirect effect on SOC, through production of larger crops and availing larger amounts of crop residues to replenish soil organic matter. This may not be practical on smallholder farms in Zimbabwe, as stover is mostly removed to feed livestock.

5.4.3. Maize grain yield

For fields on similar soil type, the higher maize yields on the homefields than the outfields (Table 7) are due to the higher soil fertility status of the homefields following many years of addition of large amounts of manure and mineral fertilizers (Table 5, 6). Many studies in sub-Saharan Africa have reported on the beneficial effects of manure on crop yields, both in the short- and the long-term (Bationo et al. 1995; Murwira et al. 1995; Mugwira 1984). Manure improves crop yields through supply of nutrients, reduction of Al saturation in acidic soils as well as improving the soil structure (Bayu et al., 2005; Bationo et al., 2004). The large differences in yields for control plots between the homefields and outfields were still evident after three years, indicating that the residual soil fertility was effective for several seasons. The larger yields on the red clay soil than the granitic sand for similar field types can be explained by the larger soil organic matter contents, pH and CEC due to the greater clay contents. The red clay soil also has a higher water holding capacity, and more water is available to maize than on the sandy soil.

The higher grain yield responses to N alone on the homefields than the outfields in the first season were due to higher availability of other nutrients besides N (Table 7). Repeated application of N alone on the homefields led to a decline in availability of other nutrients and soil acidification on the sandy soil, which explains the lower grain yield responses to N in the third season. On the outfields, maize did not significantly respond to N due to low availability of other nutrients or poor soil physical structure.

On the sandy homefield, addition of manure led to greater yields than SPP in the first and thirds seasons, which indicated that frequent additions of manure are required to sustain maize production on the sandy soil (Figure 4a, c, e). The sandy soils have a weak capacity to store soil organic matter and nutrients, and application of manure and mineral N fertilizers is required on a yearly basis to maintain good productivity (Grant 1981). Organic resources are considered crucial in sustainable crop production on smallholder farms and positively interact with mineral N fertilizers to give good yields due to; (i) addition of multiple nutrients including P, base cations and micronutrients; (ii) improvement of the physical properties of the soil; and (iii) improvement of synchrony between availability of N and demand by crops (Giller, 2002).

The reasons for the poor response to N and P on the sandy outfield could have been multiple nutrient deficiencies and poor water availability. The low Ca/Mg ratios (~1) on the sandy outfield can also inhibit maize growth as it can potentially induce K deficiencies and also degrade soil structure. Large amounts of manure (17 t ha^{-1}) applied each year for three seasons were needed to significantly improve maize yields (Table 7). Manure is key to restore productivity degraded fields as it supplies multiple nutrients, raises soil pH and improves soil organic matter, which in turn improves the soil physical properties (Grant, 1981; Gandah et al., 2003).

5.4.4. Limiting nutrients on homefields and outfields

To elucidate whether poor yields in sandy outfields were principally due to nutrient problems or water availability, pot experiments were conducted under conditions in which water was not a limiting factor. Manure on smallholder farms is generally poor in N, and this, together with high losses of N from manures applied on fields may explain the low availability of N on the homefield on sandy soil (Murwira et al., 1995). The sandy outfield, with no history of manure application, suffered multiple nutrient deficiencies, as evidenced by the low concentrations N, P, Ca and Zn in maize shoots (Table 8b). Zinc deficiencies are associated with extremely low soil fertility conditions (Grant, 1981) and have been reported from sandy soil in Zimbabwe and in other parts in Africa (Rodel and Hopley 1973; Van Asten, 2003). On the sandy homefield, addition of micronutrients had no significant effect on maize biomass and the concentrations of all micronutrients considered were in the adequate range for maize. This is most likely due to the supply of micronutrients in manure. Due to its Zn concentration (Lupwayi et al., 2000) manure been shown to supply significant amounts of Zn to crops (Prasad and Sinha, 1982), which explains the significant increase in maize shoot Zn concentration on the sandy outfield manured for three consecutive seasons. Maize shoot biomass response to Zn could have been reduced by the lower temperatures under which the second pot experiment was conducted. Basal fertilizer containing Zn (compound Z: 8%N; 6%P; 6%K; 6.5%S; 0.8% Zn) was previously produced in Zimbabwe to redress the problems of Zn deficiency, but has not been widely used by smallholder farmers as it has been hardly recommended and was not widely avaialable. Production of Compound Z has recently ceased, and fertilizers available to farmers only contain the major nutrients (N, P, K and S).

Despite the significant effects on maize biomass, manure suppressed the N concentration in maize shoots due its low N concentration (Figure 1a, b). Nitrogen immobilization in the short term was likely, due to the low N content of the manure used (Nyamangara et al., 1999). Manure alleviated deficiencies of P, Ca and Zn in the short-term and our results support the observations of Grant (1981) that the effects manure on supply of nutrients other than N may be responsible for the immediate improvements of maize yields. No nutrient deficiencies were observed on the clayey homefield due to the larger soil organic matter contents and fertility status. The deficiency of P on the clayey outfield could have been due to the removal of P by crops over many years and the high P fixing capacity of the soil.

5.5. Conclusions

This study illustrated that manure is essential for sustainable soil fertility management on smallholder farms, particularly on poorly-buffered, sandy soils. Manure use led to higher soil organic matter, available P, bases, pH and micronutrients on farmers' fields that frequently received large amounts of manure. Production of maize without fertilizer inputs over many years on the sandy outfield led to multiple deficiencies or low availability of nutrients, notably of N, P, Ca and Zn, on the sandy soil. Mineral N and P fertilizers commonly available to smallholder farmers are inadequate to reverse the poor soil fertility status, as they are unable to correct the deficiency of other nutrients (especially bases and micronutrients). Instead, ammonium nitrate lead to acidification of the soils. Also, on the depleted sandy soils maize response to N and P may be poor, as deficiency of other nutrients may override. Manure showed potential to restore soil fertility of the depleted sandy soils as application of manure for three seasons increased soil organic matter, available P, pH, bases and improved Ca and Zn concentrations in maize shoots in the greenhouse. Manure alone, however, may be insufficient to meet the N requirement of the crops. Integrated use of manure and mineral fertilizers is therefore required for sustainable soil fertility management on smallholder farms on sandy soils. The results observed on fields with different histories of manure application and in pot experiments reinforce the essential role of manure in supplying multiple nutrients including P, bases and micronutrients both in the short term and in the long-term, which explains the wide differences in maize response to mineral N and P on the smallhlders' homefields and outfields.

Chapter 6

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

This chapter has been submitted for publication as:

Zingore, S., Murwira, H.K., Delve, R.J., and Giller, K.E., 2006. Variable grain legume yields, responses to phosphorus and rotational effects on maize production across soil fertility gradients on African smallholder farms. *Nutrient Cycling in Agroecosystems*.

Abstract

Promiscuous soyabean varieties have a great potential to contribute significantly to income generation, food security and soil N budgets on smallholder farms. Successful integration of soyabean into cropping systems dominated by maize depends largely on its comparative benefits over the existing maize grain legume rotation. We conducted experiments to compare (i) yields, nutrient use efficiencies and economics for soyabean-maize rotations when manure or mineral single super phosphate (SSP) (30 P kg ha^{-1}) was applied to either soyabean or maize on fields with different soil fertility and (ii) the productivity of soyabean and groundnut and their response to P across soil fertility gradients on farms in different wealth categories. 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%. The effects of applying SSP and manure to soyabean to enhance its contribution to soil N budget were small due to the poor productivity and small amounts of N_2 fixed: the maximum amount of N incorporated in soyabean stover was 20 kg ha^{-1} for the manure treatment. On the sandy soil, P was used most efficiently in maize-soyabean rotations, when SSP was applied to maize. Gross margins were also greater for all treatments when SSP and manure were applied to maize. 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. On the clay soil soyabean fixed more than 67% of its N, except with SSP (40%). Within rotations, P use efficiency was higher when manure and SSP were applied to maize (43 and 25%) than when applied to soyabean (20 and 19%). Application of manure to soyabean was more profitable than targeting to maize, for individual crops and for rotations, whilst SSP applied to maize resulted in greater gross margins. In Experiment 2, which was managed by farmers, soyabean and groundnut grain and stover yields varied widely across different plots on farms in different wealth categories. Yields were largest (~1 t ha^{-1} for soyabean and ~0.8 t ha^{-1} for groundnut) on homefields of wealthy farms which were more fertile due to good past management. Yields were poor (< 0.5 t ha^{-1}) on the mid-fields and outfields on the wealthy farms and all fields on poor farms. Soyabean was more responsive to P addition than groundnut. Soyabean and groundnut yields correlated well with available P (R2 = 0.5-0.7) and soil organic C contents (R2 = 0.4-0.6), but yields also varied widely for fields with similar fertility due to differences in management by farmers. 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 as farmers prefer to grow maize in the fertile plots.

6.1. 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 rather than other legume-based technologies, such as, green manures, which do not contribute directly to income or food security (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, as much of the N is removed in grain (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.

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 from 55 farmers in 1996 to 5000 in 1999. Production of soyabean by smallholder farmers also increased from 415 t in 1995 to 12500 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). The interest in soyabean production has been due to its multiple roles, for cash, food, fodder and soil fertility (Mpepereki et al. 2000).

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 above income generation (Giller et al. 1997; Svubure 2000). Farmers lack adequate nutrient resources to fertilize all their fields and crops and prefer to apply fertilizers to maize, the staple and food security crop, but rarely target fertilizers directly to grain legumes, that are mostly grown on residual fertility. The farmers also reserve the largest areas on the most fertile plots to maize, and allocate small portions of outfields poor in fertility to production of grain legumes (Waddington and Karigwindi 2001; Zingore et al. 2006b). The poor productivity of grain legumes has led to low N_2 fixation (< 5 kg N ha^{-1} yr^{-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. We conducted two on-farm field experiments in Zimbabwe that assessed: (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.

6.2. Materials and Methods

6.2.1. 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 gives rise to smaller areas of more fertile red clay soils (Luvisols) in close proximity to the granitic sands.

6.2.2. Field Experiments

Experiment 1

A promiscuous soyabean variety, Magoye, which nodulates freely with indigenous rhizobia (Musiyiwa et al. 2005) was used as the test cultivar. 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. 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 seasons to give the following treatments:

i. Soyabean-soyabean-soyabean
ii. Maize-maize-maize
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)

SSP was applied at a rate of 30 kg P ha^{-1} and manure was applied to provide 30 kg P ha^{-1}. 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}. Other nutrients besides P were also applied in the manure (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, maize plots, except the continuous maize, received 70 kg N ha^{-1} as ammonium nitrate split applied at about three and six weeks after crop emergence (35 kg ha^{-1}).

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 were not split due to the small area of the field; 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

Experiment 2 assessed the variability in productivity of groundnut and soyabean and their response to P fertilizer on plots at different distances from homesteads (closest (PT1), mid-distant (PT2) and furthest (PT3)) located on farms in different wealth categories (very rich (RG1), rich (RG2), poor (RG3) and very poor (RG4)). 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. The criteria used to develop the different farm and plot typologies is described in detail elsewhere (Zingore et al. 2006b). The RG4 households had small fields, which were only divided into two plot types (PT1 and PT2). The experiment consisted of four plots (5 m x 5 m): groundnut without inputs; groundnut + 30 kg P ha^{-1} as SSP; soyabean without inputs; and soyabean + 30 kg P ha^{-1} as SSP. The experiment was established on three similar plots for farms in each group, and was thus established on a total of 33 plots covering a wide range of soil chemical properties on both soil types. The plots on the clay soil were chosen 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}).

6.2.3. Stover and grain determination

At harvest, maize grain and stover yields were determined from net plots (2 m x 2.7 m), with soyabean biomass yields determined at flowering from micro-plots outside the net plot and grain yields determined after four months, from all of the net plot. Soyabean and groundnut grain and stover in experiment 2 were determined from entire 5 m x 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 ºC for 72 hours to determine moisture content.

6.2.4. 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:

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

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:

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

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.

6.2.5. Calculation of P uptake efficiencies and basic economics of targeting P in maize-soyabean rotations

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).

The economic benefits of targeting SSP and manure to the maize and soyabean (experiment 1) were calculated for individual crops and for complete rotations (first and second seasons) by subtracting the value of the crop from the cost of the fertilizers. No price was attached to manure, as farmers considered it a free resource. The cost of labour for transport and application of manure was also not included in the calculations, as manure is applied in the dry season when opportunity costs are very low.

6.2.6. Soil analysis

Soils were sampled (0-20 cm) in all fields for experiment 1 and 2 and prepared for analysis by air-drying and sieving (2 mm). The soils were analysed for soil organic C 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).

6.2.7. 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 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.

6.3 Results

6.3.1. 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 (Figure 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 to 0.6 t ha^{-1} in the first and from 0.1 to 0.4 t ha^{-1} in the third season (Figure 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 (Figure 1b). The largest maize yields on the sandy soil were on plots where manure and mineral N fertilizer was applied but 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 (Figure 1b).

For all seasons, the yields for the treatments without amendments were significantly larger on the more fertile clay soil, and these ranged from 0.5 to 0.6 t ha^{-1} for soyabean and from 1.8 to 2.3 t ha^{-1} for maize (Figure 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 (Figure 2b).

6.3.2. 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 1a). 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 compared with 61%-64% for soyabean without amendments and those amended with SPP (Table 1a). 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 1a).

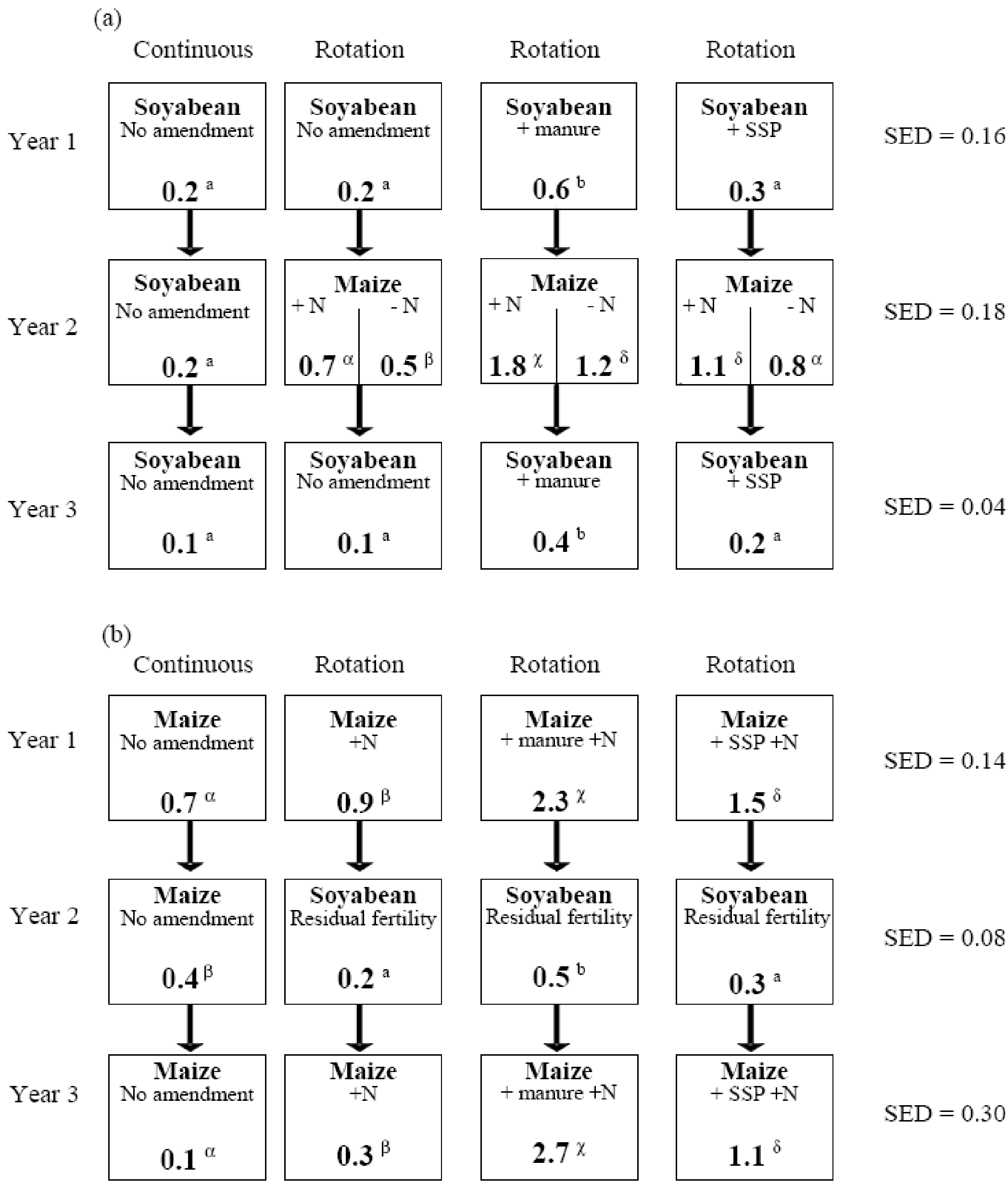


Figure 1. Grain yields (t ha^{-1}) for maize and soyabean under direct application of SSP or manure, or grown on residual fertility for rotations that started with soyabean (a) and maize (b) on the granitic sandy soil at Murewa, Zimbabwe. For each year, soyabean yields followed by a different letter 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).

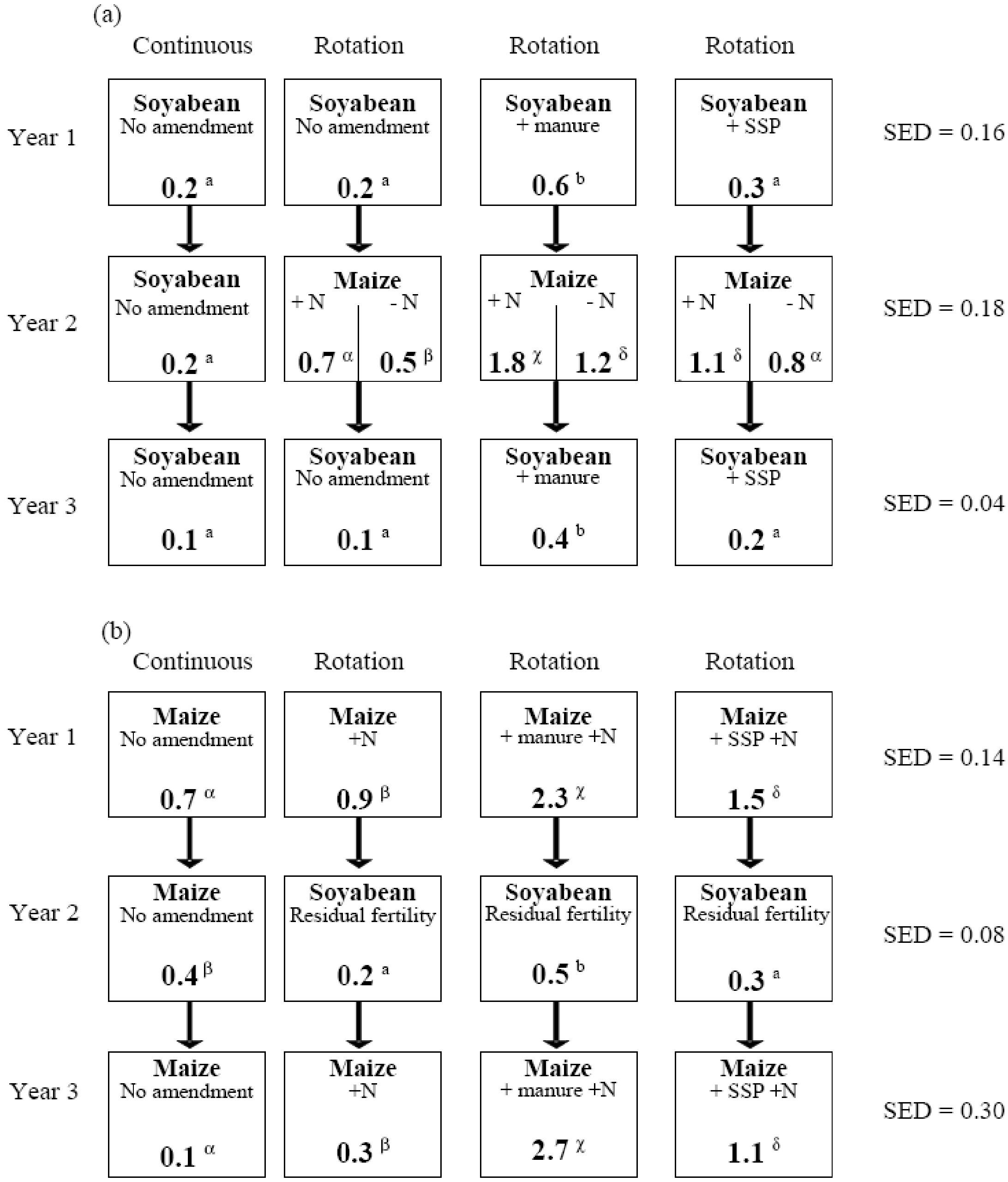


Figure 2. Grain yields (t ha-1) for maize and soyabean under direct application of SSP or manure, or grown on residual fertility for rotations that started with soyabean (a) and maize (b) on the red clay soil at Murewa, Zimbabwe. For each season, soyabean yields followed by a different letter and maize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

Table 1. 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.

(a)

	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})
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
ED	3.1	3.3	1.2	1.2	1.7	0.8		5.5	

(b)

	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})
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	

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

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 1b). The N harvest indices for soyabean on the clay soil were between 0.52 and 0.67. Except for the SSP treatment, the proportion of N derived from N_2-fixation on the clay soil in the third season was greater than 65%.

6.3.3. 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 yield following soyabean without any amendments on the sandy soil was not significantly different from those of the continuous maize plots, both with and without N applied (Figure 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 (0.5 t ha^{-1}) than the other treatments (<0.3 t ha^{-1}) (Figure 1b).

Maize grain yields on clay soil in the second season were least (1.8 t ha^{-1}) on the plots where maize was cropped continuously without fertilizer inputs (Figure 2b). Manure and SSP applied to maize in the first season led to soyabean yields significantly greater (>0.7 t ha^{-1}) than those for soyabean following maize without amendment (0.4 t ha^{-1}) (Figure 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.

6.3.4. 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 2a). The apparent P recovery efficiencies 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). P recovery efficiencies by soyabean were also poor on the clay soil (5% for SSP and 10-12% for manure) and these were less than those for maize (19-34% for manure and 19-21% for SSP) (Table 2a). 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 (Table 2a).

The residual RE_P for soyabean on the two soils were less than 10% and addition of N led to a substantial increase in *REp* for maize on the sandy soil (Table 2b). The recovery efficiencies 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 2b).

For the complete crop rotations in the first two seasons, P recovery was most efficient 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 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.

6.3.5. Economics of targeting P in soyabean-maize rotations

In the first season, the financial benefits of maize and soyabean without fertilizer inputs were small on the granitic sandy soil (Table 3a). Addition of N alone to maize reduced gross margins calculated per ha basis, due to poor N response . Greatest benefits for both maize and soyabean were obtained when manure was applied. Maize was more profitable than soyabean when manure and SSP were applied. This was after accounting for the costs of mineral N added to maize. Application of SSP to soyabean on the sandy soil did not lead to increased gross margins, however, application of SSP to maize led to greater gross margins. On the clay soil,

Table 2. Apparent P recovery efficiency (%) with (a) SSP and manure directly applied to maize and soyabean; (b) residual P recovery in the second season after application and; (c) total efficiencies for the two-year rotation at Murewa, Zimbabwe.

(a)

	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

(b)

	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

(c)

	Granitic sandy soil			Red clay soil	
Crop sequence	Sb[1]-Mz[2] (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

[1]Soyabean; [2]Maize

maize was more profitable than soyabean for all treatments, except with manure (Table 3a). Application of N alone to maize reduced returns by US$49 ha^{-1}. Greater benefits were obtained from maize when mineral N was applied in combination with manure and with SSP. The gross margins on the clay soil were greatest when manure was applied to soyabean.

The gross margins for the second season were calculated considering the costs of mineral N applied to maize only. 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 3b). On the clay soil, greatest gross margins were on maize plots following soyabean amended with SSP in the first season.

Over the first two years, the gross margins 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 3c). When manure was applied, gross margins for the maize (manure + N)-soyabean rotation exceeded those for soyabean (manure)-maize rotation. SSP applied to maize led to greater gross margins than when applied to soyabean. The gross margins for two-year rotations with SSP were about 50% less than those for similar crop sequences with manure. On the clay soil, maize was more profitable 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 rotation without P inputs was more profitable when soyabean was grown in the first season. Also, when manure was applied, the rotation that started with soyabean was more profitable than the rotation that started with maize (Table 3c). There were no marked differences in gross margins for complete rotations when SSP was applied either to maize or soyabean in the first season (Table 3c).

6.3.6. Variability of soyabean and groundnut yields on farmers' fields

Soyabean grain yields were significantly larger on the plots closest to homesteads (PT1) 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 PT2 and PT3 (Figure 3a). Without P, the yields for soyabean were poor on the RG2, RG3 and RG4 farms and did not significantly differ with farm or plot type. The greatest amount of soyabean stover (about 1.5 t ha^{-1}) was produced on PT1 on the RG1 and RG2 farms.

Table 3. Gross margins (US$ ha^{-1}) for two season rotations after application of single super phosphate and manure on maize or soyabean in the first season at Murewa, Zimbabwe.

(a)

	Granitic sandy soil		Red clay soil	
First season crop	Soyabean	Maize	Soyabean	Maize
Continuous sole crop	141	194	371	605
Rotation no amendment	187	163	377	566
Rotation + manure	429	613	803	741
Rotation + SSP	181	274	456	684

(b)

	Granitic sandy soil			Red clay soil	
Second season crop	Maize (0N)	Maize (+N)	Soyabean	Maize	Soyabean
Continuous sole crop	133	-	155	563	359
Rotation no amendment	157	115	180	626	317
Rotation + manure	362	437	360	688	621
Rotation + SSP	249	225	203	736	504

(c)

	Granitic sandy soil			Red clay soil	
Crop sequence	Sb-Mz (0N)	Sb-Mz (+N)	Mz(+N)-Sb	Sb-Mz (+N)	Mz(+N)-Sb
Rotation no amendment	344	302	343	1003	883
Rotation + manure	791 (447)[1]	866 (564)	973 (630)	1491 (488)	1362 (479)
Rotation + SSP	430 (86)	406 (104)	477 (134)	1192 (189)	1188 (305)

[1]Differences in gross margins between the rotation with no amendments and the rotations with manure and SSP are given in parenthesis.

Soyabean yields were increased on most fields by addition of P (Figure 3b). The yields on the different fields on the wealthy farms increased by a similar amount (0.2-0.3 t ha^{-1}), so the gap in yield between the homefield and the mid-fields and outfields was not reduced by addition of P. Application of P on the homefields of the RG2 farms led to grain yield increases that were larger than those for the mid-fields and outfield and this created a large gradient in yields between the homefields and the midfields and outfields (Figure 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 (Figure 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 (Figure 3d). Groundnut stover was over 1 t ha^{-1} on PT1 on RG1, RG2 and RG3 farms, but was less than 0.8 t ha^{-1} on the other plots. The soyabean and groundnut yields on the fields on clay soil were in the order: 0.6-0.9 t ha^{-1} and 0.4-0.9 t ha^{-1} respectively on fields with high fertility ; 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). The yields of groundnut and soyabean and their response to P were correlated with available P and soil organic C (Figure 4). From the regression analysis, soyabean yields of less than 0.5 t ha^{-1} were found in fields that had less than 12 mg kg^{-1} available P and about 0.6% soil organic C without added P. Groundnut was less responsive to available P and soil organic C and P addition; yields were larger for soyabean than groundnut on the more fertile fields and when P was added (Figure 4).

The proportion of yield variability that was not explained by available P and soil organic C (Figure 4) can be attributed to differences in management. Most farmers managed the experimental plots as they normally manage their grain legumes, which are given less priority than maize 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.

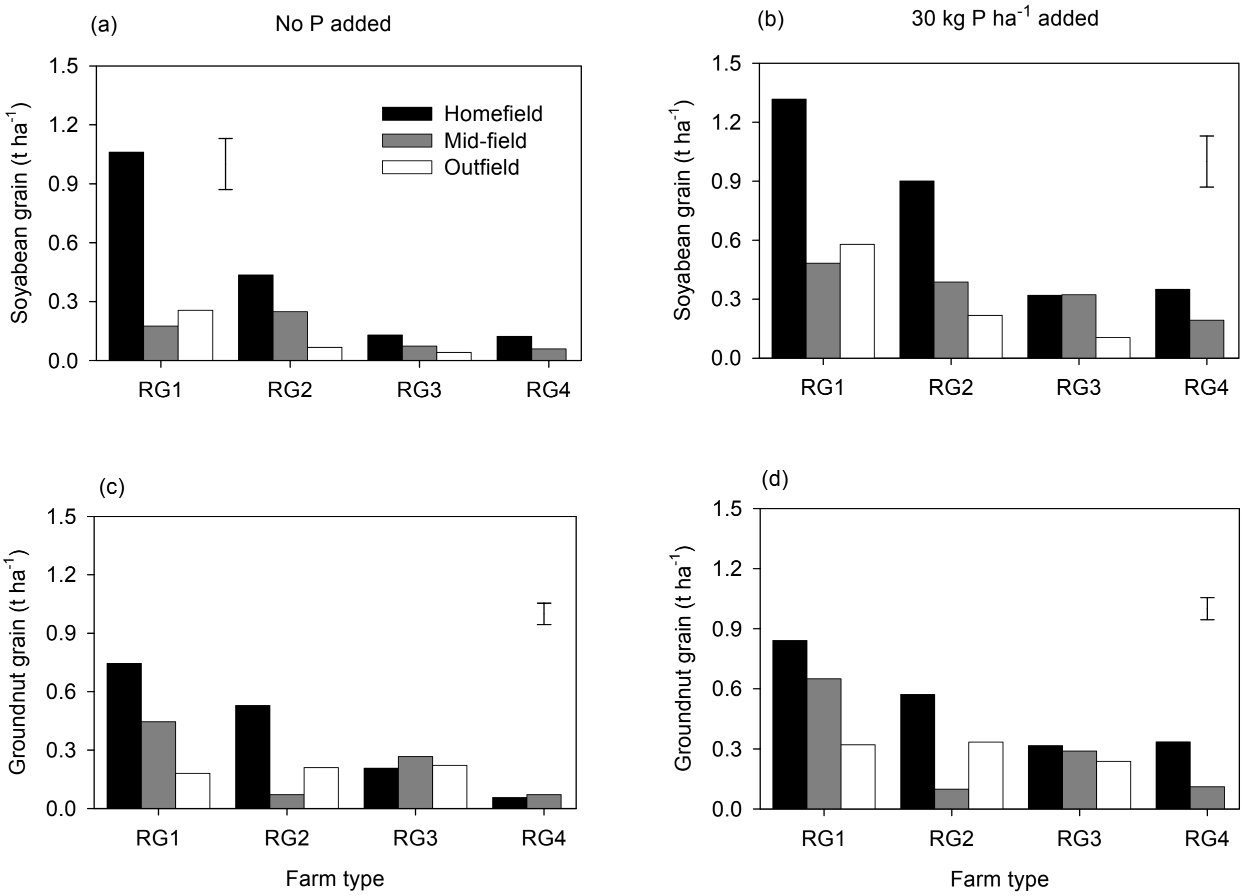


Figure 3. Grain yields for soyabean and groundnut (+/- P) across different plots belonging to farmers of different wealth categories on the sandy soil at Murewa (a) soyabean –P, (b) soyabean +P, (c) groundnut -P and (d) groundnut +P. Bars represent SEDs.

6.4. Discussion

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

Sandy soil

The poor soyabean yields and amounts of N_2 fixed without fertilizer inputs on the depleted sandy soil (Figure 1, Table 1) 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

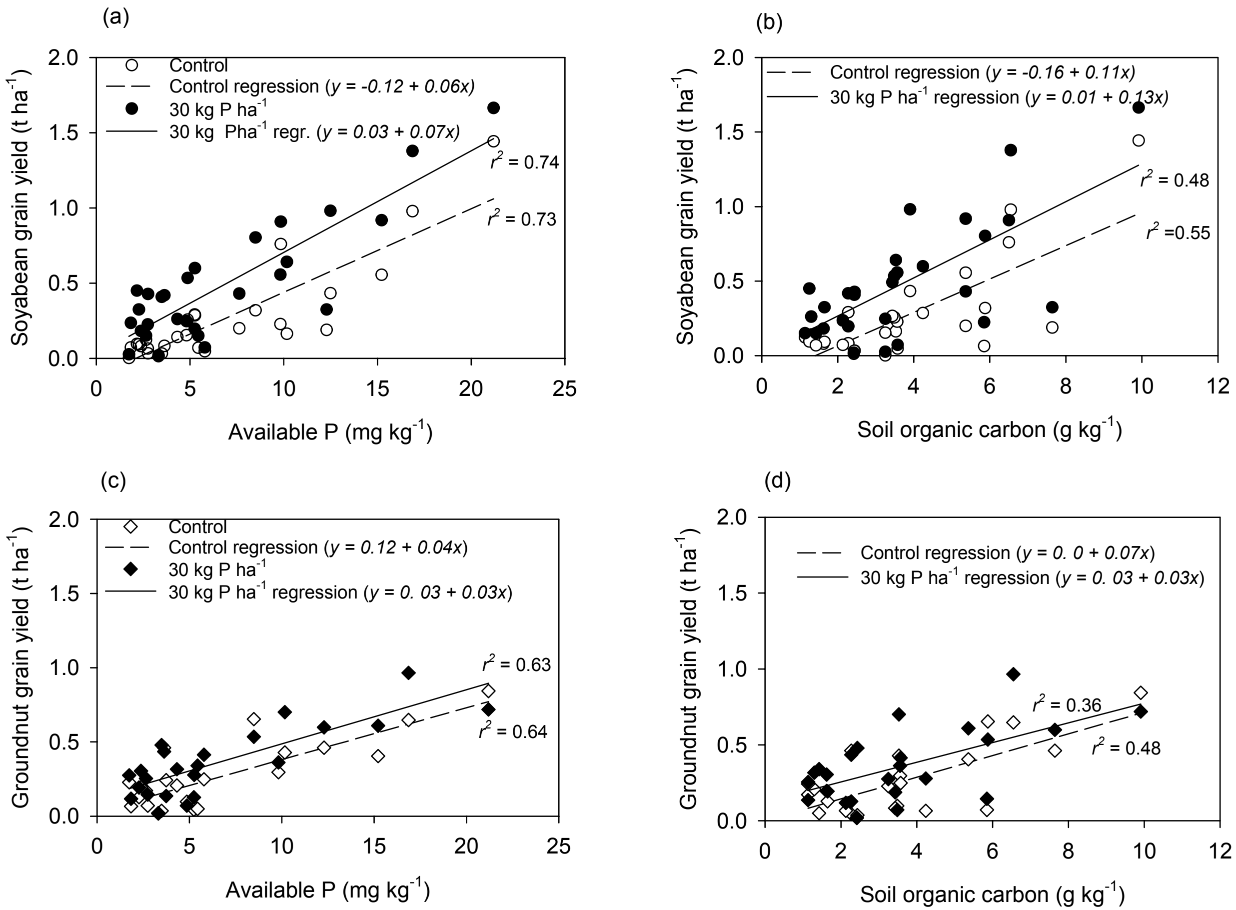


Figure 4. Relationships between available P and SOC with soyabean and groundnut yields with and without P fertilizer added at Murewa (a) soyabean yields plotted against available P; (b) soyabean yields plotted against SOC; (c) groundnut yields plotted against available P and; (d) groundnut yields plotted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

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 less than 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. 2006) and Nigeria (Sanginga et al. 2002a). Performance of soyabean, therefore, varies widely depending on site-specific soil and climatic condition.

P deficiency 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 poor amounts of 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 (Figure 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 et al. 2006b). 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 is therefore essential to significantly increase soyabean yields on the depleted fields, where crop growth response to mineral P fertilizer may be constrained by other factors (Carsky 2003; Zingore et al. 2006c).

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 1a). Even with manure, which generated the largest biomass and fixed the greatest proportion of N, the net contribution of N was less than 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 poorly managed farmers' fields.

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 (Figure 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 (Figure 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 (Figure 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 its multiple effects of correcting Ca and micronutrient deficiencies 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 yields and amounts of N accumulated by soyabean in the first and third seasons were larger on the clay soil, although these were still small in comparison with amount of N that Magoye can potentially accrue in above ground plant parts (Kasasa et al. 2006). The small amounts of N 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 1b).

6.4.2. 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 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 (Figures 1 and 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. Without considering amounts of N_2 fixed, the largest amounts of N returned in soyabean stover in the first season were found with manure on the clay soil (23 kg N ha^{-1}) (Table 1a). When amounts of potentially mineralized N are considered and losses accounted for, the amount of N from soyabean residues 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). It can be further argued that on the clay soil the effects of N added in soyabean stover were obscured by the 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 to increased supply of N through biological N_2-fixation. In a study by Kasasa et al. (2006)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 t ha^{-1} and 1 t ha^{-1} respectively. The study by Kasasa et al. (2006) was done in a similar agro-ecological zone, but the 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). The residual effects of manure applied to maize in the first season on the soyabean crop in the second season were significant on both soils, indicating that both maize and soyabean can benefit from residual effects of manure. SSP did not have significant residual effects on the soyabean on the granitic sandy soil due to other constraints.

6.4.3. 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 2a), due to larger amounts of P taken up by maize in grain and stover. The RE_P for soyabean was less than 10% on the granitic sand due to the small yield responses to manure and SSP. The large 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 2a, 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.

6.4.4. 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 2.5:1, the economic advantage of soyabean over maize were not apparent, especially on the granitic sand. 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 led to greater returns than direct application to maize, but the advantage within the complete rotation was marginal. Use of SSP was more economically viable when targeted to maize than soyabean, both for specific crops and for complete rotations. Based on official prices of maize and soyabean grain, farmers 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.

6.4.5. Variability of soyabean and groundnut yields on farmers' fields

The gradients of soil fertility strongly affected soyabean and groundnut yields, and have 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 (Figure 3) are the fields that farmers usually reserve for maize production. 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 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 (~80%) are expected on the homefields of the wealthy farms and N_2-fixation rates of ~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. 2006a), and therefore, fields where soyabean and groundnut can significantly contribute to N cycling are limited.

6.5. Conclusions

Soyabean yields, N_2 fixed and returns to SSP applied were poor on a depleted sandy soil due to multiple nutrient deficiencies. Manure application significantly increased soyabean yields and proportion of N_2 fixed, due to the multiple effects of manure. Maize was more profitable than soyabean, and fertilizer resources were used more efficiently within rotations when targeted to maize. On the clay soil manure was used more economically when targeted to soyabean rather than maize. 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. Response to P was poor on depleted fields due to other limiting factors. Soyabean and groundnut yields correlated well with available P and soil organic C contents, but also varied widely for fields with similar fertility due to differences in management by farmers (e.g. timing and frequency of weeding). The contribution of grain legumes to income, food security and N cycling on smallholder farms was therefore significantly influenced by soil fertility variability within and across farms and farmer management practices.

CHAPTER 7

Evaluation of resource management options for African smallholder farms using an integrated modelling approach

This chapter has been submitted for publication as:

Zingore, S., Gonzalez-Estrada, E., Delve, R.J., Herrero, M., Dimes, J.P. and Giller, K.E., 2006. Evaluation of resource management options for African smallholder farms using an integrated modelling approach. *Agricultural Systems*.

Abstract

Farm-level analysis of trade-offs between soil fertility management alternatives is required to improve understanding of complex biophysical and socio-economic factors influencing decision making in smallholder farming systems and to identify opportunities for improving resource use efficiency. A farm characterization tool (IMPACT) linked to a generic optimization model (Household) was used to evaluate resource use on farms in contrasting wealth categories. The Household model optimized the net cash income for the farms (accounting for all on-farm and off-farm income, costs of production and expenditure for the households). Alternatives for management of nutrient resource were simulated using other models; APSIM for the crop production and RUMINANT for the livestock component. The output from the simulation models was fed into the Household model and evaluated within the biophysical and socio-economic boundaries of the farms. Analysis of the performance of a poor farmer by IMPACT indicated a yearly net cash balance of US$ -7 per annum (after all needs had been taken care of), mainly due to negative returns from the cropping system. The farmer relied on donated food and fertilizers. The cash balance was negative, even though she also worked for other farmers (i.e. sold labour, about 10 days a month during six months of the crop growing season) to generate income. The net income of the poor farm would be increased to US$81 per annum and the N balance from 7 kg ha^{-1} yr^{-1} to 10 kg ha^{-1} yr^{-1} by expanding the area allocated to groundnut from the current 5% to 31%. This would, however, generate a huge demand in labour in the current year (extra 46-man days) and reduce the P balance from 0 to -1 kg ha^{-1} yr^{-1}. Maize could be managed more efficiently on the poor farm by cultivating a smaller, well-managed area. A wealthy farm household with a maize-dominated cropping system had a net cash balance of US$210 per annum, mainly from sale of crop products. Under current resource management, the net cash balance could be increased to US$290 per annum by optimization of household energy and protein consumption. The net cash balance for the wealthy farm would be further increased to US$448 per annum, and nutrient balances to 271 kg N ha^{-1} and 30 kg P ha^{-1} by expanding the management strategy where maize was grown with a combination of cattle manure and ammonium nitrate fertilizer. To do this, the farmer would need to source more manure (or improve capture and the efficiency with which nutrients are cycled through manure) and invest in 110 man-days extra labour. Expansion of the area grown to groundnut without fertilizer inputs to a third of the farm would reduce net cash balance by US$11 compared with the current crop allocation due to poor groundnut yield. This would also increase labour demand by 155 man-days. Groundnut intensification on the wealthy farm would be more economic and labour-effective if a small area was grown with basal fertilizer (7%N, 6%P, 8%K). Despite reducing

nutrient balances for the arable plots, feeding groundnut residues to lactating cows increased net cash balance by 12-18% for the current year through increased milk production. The integrated modelling approach was useful for linking biophysical and socio-economic factors influencing decision making on smallholder farms and evaluating trade-offs for resource use in terms of nutrient balances, labour use, food sufficiency and cash balance.

7.1. Introduction and modelling approach

7.1.1. Introduction

Smallholder mixed farming systems in sub-Saharan Africa are highly complex due to intricate interactions between the soil, crops and livestock (Thornton and Herrero, 2001). Productivity of crops and livestock is among many factors limited by poor availability of nutrient resources. Improved efficiency with which nutrients are used and cycled between the soil, crops and livestock components is therefore imperative for increasing overall farm production (Giller et al., 2006; Rufino et al., 2006). Crop-livestock interactions are mediated by the use of crop residues to feed livestock, and the reciprocal use of manure to fertilize crops (Powell et al., 2004). Manure is an integral source of nutrients for crops in many smallholder farming systems where small amounts of external fertilizer inputs are used (Murwira et al., 1995). Most farmers concentrate fertilizer and labour resources on plots closest to the homesteads, with little additions to their outfields. This differential management of plots has created gradients of decreasing soil fertility with distance away from homesteads, along which crop production and nutrient uptake efficiencies vary strongly (Prudencio, 1993; Tittonell et al., 2005; Zingore et al., 2006a).

Smallholder farmers face complex decisions on the allocation of scarce resources between different components of their farms due to conflicting demands for their use. Key questions arise at the farm level on resource use such as: How should the limited fertilizer resources available be targeted to different crops and to plots differing in initial fertility? Should all crop residues be used for animal feed, or allocated also for maintenance of soil fertility? Decisions taken by farmers on use of nutrient resources and allocation to crops and different fields are influenced by underlying socio-economic factors, which vary with the wealth status of the farms. Cattle ownership is one of the major indicators of wealth status due to the important role of cattle in the smallholder farming systems (Achard and Banoin, 2003) and cattle owners have an advantage over those without cattle, as they have access to manure and draught power. Farmers who own cattle are also cushioned in seasons of crop failure as they can sell cattle to raise cash to buy food and meet other expenses. Labour availability and ability to hire labour are major factors that determine choices of crops and methods of production by farmers. Choice of crops, their allocation to different fields and crop management is also driven by the need to achieve food security, which is threatened by poor soil fertility, poor access to fertilizers and recurrent droughts (McIntyre et al., 2001). Therefore, technologies attractive to farmers must be within their capacity to provide labour and nutrients, to achieve food security and they should also be economically viable.

For improved understanding of the multiple constraints that farmers face and the factors driving their decision making processes, there is a need for tools that holistically assess current and potential resource management strategies and that provide comparative analysis of food sufficiency, economic viability and maintenance of soil fertility at the farm level (Jones et al., 1997; Thornton and Herrero, 2001). Development of such tools necessitates synergy of optimization models with output from soil-crop and livestock simulation models under realistic biophysical and socio-economic conditions on these farms (Thornton and Herrero, 2001; Castelan-Ortega et al., 2003). Most current crop-soil models have been successfully developed for point-simulation of crop responses and soil nutrient dynamics. Up-scaling their application is required so as to interpret their output at the farm level by taking into account the variable nature of soil fertility within farms, sizes of different plots on the farms and fertilizer resources available to farmers (Patanothai, 1997).

7.1.2. The modelling framework

A combination of farm characterization, optimization and simulation modelling tools was used to analyse and compare the impact of different resource management options at the farm level. The integrated modelling framework used is shown in Figure 1. The Integrated Modelling Platform for Mixed Animal-Crop Systems (IMPACT), a comprehensive farm level database, captures data for crop, soil and livestock management on a monthly basis (Herrero et al., 2006a). The information is organised in seven groups: i. climate; ii. household structure; ii. land use and management; iv. livestock management; v. labour allocation; vi. household dietary pattern; vii. farm sales and expenses. In addition, IMPACT processes these data to provide a base-line analysis of the performance of the farm. This base-line analysis includes monthly financial balance, family's monthly nutritional status and annual partial balances for soil nitrogen (N), phosphorus (P), potassium (K) and carbon (C). In this paper we only assessed the N and P balances, as these are the most limiting nutrients in the sandy soils that predominate in the study area (Grant, 1981).

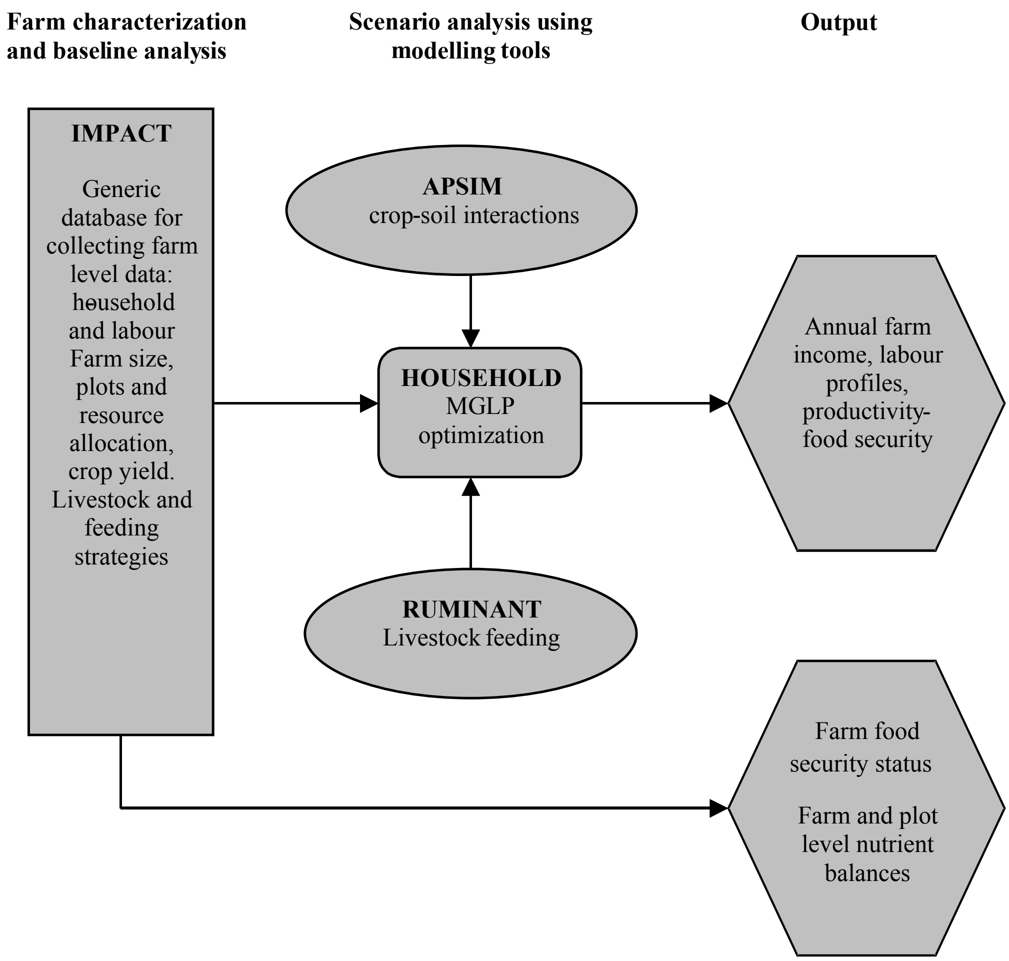


Figure 1. Schematic framework of the integrated modelling approach used to explore options of resource use on smallholder farms at Murewa, Zimbabwe. IMPACT and the models Household, APSIM and RUMINANT are described in the text.

IMPACT was linked to the Household model, a generic multiple-goal model, for analysis of optimization of resource use and trade-offs under a set of constraints at household level. The Household model assesses the impact of management interventions on the performance of farming systems and the livelihoods of the households (Herrero et al., 2006b). The model explicitly incorporates IMPACT data related to on- and off-farm nutrient resources, as well as, their monthly and seasonal management. It also includes information on food security-related factors, off-farm income generation, and labour constraints. Thus, the Household model determines the best combination of farm resources that satisfy a set of objectives according to a series of both management and economic interventions. These objectives can be directed towards maximising net cash balance, minimizing nutrient losses, or minimising risk, amongst others. The important constraints within the Household model include: 1. Farm size and arable plot sizes; 2. Energy and protein sufficiency that can be set at different levels in relation to World Health Organization (WHO) recommended values; 3. Lower limits set on consumption of commodities depending on their cultural importance to the diet; 4. Productivity of a particular plot under specific management and the potential productivity of similar management on other plots. The Household model also incorporates restrictions on labour, cash, livestock numbers, productivity of livestock and milk production.

The Household model can test the effects of alternative nutrient management within the farm by including simulated outputs from other models. The Agricultural Production Systems Simulation Model (APSIM) (Keating et al., 2003) was used to simulate crop-soil management options for targeting different types of fertilizers to fields with different soil fertility levels. APSIM has been widely tested and validated across different farming systems and environments, including those in Zimbabwe, and was on this basis selected to simulate effects of fertilizer and manure application strategies on crop production (Delve and Probert, 2004). The RUMINANT model (Herrero, 1997) was used to simulate production of milk by cows under different crop residue feeding regimes.

The analysis in this paper is based on data collected from smallholder farms in Zimbabwe during the 2003/04 cropping season. We collected data from eight farms in four wealth categories (very rich, rich, poor and very poor). Farms were placed into different wealth categories mainly on the basis of cattle ownership, farm size and use of mineral fertilizers (Zingore et al., 2006a). The scenario analysis, however, is only reported for two farms with contrasting attributes; one male-headed farm household in the very rich category (referred to as wealthy hereafter) and the second a female-headed household in the poor category (referred to as poor hereafter). We limited the number of case study farms as the objectives and constraints faced by farmers were broadly similar for farms in the two rich categories, as well as, those in the two poor categories.

The aims of this study were to:

(i) Evaluate current resource management in terms of food security, cash balance, nutrient balances and labour requirement on two contrasting smallholder farms.

(ii) Analyse optimal land use and crop allocation strategies by linking the IMPACT database to the Household multiple-goal optimization model.

(iii) Assess the effects of potential strategies for use of nutrient resources on the economic performance of farms using a combination of optimization and simulation models.

7.2. Methodology

7.2.1. The study farms

Resource flow mapping was used to collect basic farm data and map use of resources on farms in different socio-economic groups (Zingore et al., 2006a). In addition, data on family structure, livestock management, labour allocation, dietary pattern, sales and expenses, and cost of inputs and outputs for each farm activity was also collected. The current management of plots in terms of crop allocation and fertilizer use on the two study farms is summarized in Table 1. Maize was the dominant crop and fertilizers were used on the maize crop, with little used on groundnut, the major grain legume grown on both farms. Both farms were located on granitic sandy soils (Lixisols) with low inherent fertility. The poor farm, whose household head was a widow, had an area of 1.2 ha of which 0.91 ha was arable. Only the farmer was available to work full-time, chickens were the only livestock owned and a large proportion (60%) of the fertilizers used was donated by the government. The wealthy farm was larger in size (2.9 ha; 2.5 ha arable) with five household members and two hired people working full-time. The wealthy farmer also hired labour during periods of peak demand. The wealthy farm was also well endowed with cattle (10), goats (4) and chickens. The plots on the wealthy farms were demarcated into different zones according to soil fertility status. Plots closest to the homesteads (homefields) were more fertile than mid-fields, which were also more fertile than plots furthest from the homestead (outfields). The plots on the poor farm were demarcated only into homefield and outfields due to the small size of the farm.

7.2.2. Baseline analysis of net revenue, food security and nutrient balances

Food security status, household economics, and farm scale N and P balances for current resource use were assessed using the analysis tool in IMPACT. Food security was evaluated in IMPACT by calculating the household's annual intake of energy and protein based on information collected on dietary patterns. The total annual energy and protein required by each family was computed by adding consumption required by each household member, which differed according to age and sex as per standard guidelines (WHO, 1999). Household economics were assessed by accounting for farm expenses and income. Net revenue was calculated in three categories: crops, livestock and other (non-agricultural activities and off-farm earnings). Calculations of partial N and P balances for the cropping system considered the N and P content of the fertilizer inputs

Table 1. Sizes of different plots[1] and crop and fertilizer allocation patterns on the farms in different wealth categories in Murewa. Application rates for nutrient resources (kg ha^{-1}) are shown in parenthesis.

Wealthy farmer					Poor farmer				
Plot no.	Plot type	Plot size (ha)	Crop	Nutrient resource	Plot no.	Plot type	Plot size (ha)	Crop	Nutrient resource
1	home field	0.40	Maize	AN[2] (150), Manure (16000)	1	home field	0.25	Maize	Urea (15), CPD (40)
2	home field	0.40	Maize	AN (110)	2	home field	0.16	Maize	Urea (20)
3	mid-field	0.05	Sweet potato	Ash (15), manure (1000), CPD (20)	3	mid-field	0.05	Groundnut/beans	
4	mid-field	0.20	Groundnut		4	mid-field	0.40	Maize/sunflower	Urea (15), CPD (10)
5	mid-field	0.50	Lent out		5	garden	0.05	Assorted vegetables	Leaf litter (120), chicken manure (400)
6	outfield	0.60	Maize	AN (70), CPD (30)					
7	outfield	0.30	Fallow						
8	garden	0.05	Assorted vegetables	Manure (1200), leaf litter (1000), AN (40)					

[1]Plot is used here to represent a 'management unit' consisting of a piece of land where the same type of crop with similar fertilizer, planting, weeding and harvesting regimes.
[2]AN = ammonium nitrate
[3]CPD = compound D fertilizer (7%N, 14%P_2O_5, 8%K)

into the arable fields and those of products removed. Since the nutrient balances calculated in IMPACT were partial, they did not consider inputs from biological N_2-fixation and atmospheric deposition and outputs through leaching, erosion and gaseous losses (Defoer et al., 1998).

7.2.3. Analysis of resource use options

Resource use optimization by the Household model

IMPACT was used to generate data input for the Household model, which in turn was used to optimize the net cash balance for different resource use scenarios under the conditions on the two farms during the 2003/4 cropping season. Full details of the model's activities and constraints are described in Herrero et al. (2006b). A brief description of the objective function and major constraints in the Household model used to produce model results for the case study farms is as follows:

Net cash balance was maximized and the performance of the farms assessed in terms of (i) net cash balance, (ii) labour demand and (iii) farm nutrient balance.

The objective function is represented as:

$$\text{maximize} \quad \sum_{y}^{YEAR} \sum_{m}^{MONTH} \left(income_{y,m} - expense_{y,m} \right) \qquad 1$$

Net income was calculated on a monthly (*m*) basis for three categories: cropping, livestock and non-farming or off-farm activities. The annual (*y*) net cash income was calculated from the monthly net income. Total net income for the cropping activities was obtained from income (sale of produce) and production costs (hired labour and inputs) for each plot. Net income for livestock was also computed per livestock type.

Constraints imposed on variables were selected based on information obtained from the farmers. These were:

(i) Constraints on plot size, cropping option and productivity:

$$\forall y \in YEAR, p \in PLOT : plotsize_{y,p} \geq \sum_{o}^{OPTION} \left(LAND_{y,p,o} \right) \qquad 2$$

The size of each plot (p) was fixed in the particular year (y) of analysis and only one optimal cropping option (o) could be allocated to a plot for each scenario evaluated. In analysis of the current land-use, the options for each plot were restricted to those observed on the farms (Table 1). In analysis of optimization of land use, the best option was assigned to a particular plot, depending on production, profitability and household dietary requirement. There is provision for different production levels for a particular option on different plots due to differences in soil fertility. For the wealthy farm, yield indices (0-1) for each cropping strategy for each plot were generated using APSIM. When the index was as 1 for the homefield different options, the indices for the midfields ranged from 0.7 to 0.9 and those for the outfield from 0.6 to 0.8. There were small differences in productivity between the different types of fields on the poor farm and we thus used similar production for each cropping strategy on the different field types.

(ii) Constraints on energy and protein requirement, and diet:

Energy and protein requirement were assessed both on a monthly and annual basis:

$$\forall y \in YEAR, m \in MONTH : \sum_{c}^{COMMOD} \sum_{n}^{NUTR} \left(commodnutr_{n,c} \times DECISION_{y,Eat,c,m} \right) \geq \left(nutrientreq_{y,n} \times nutritionslack_{n} \right) \quad 3$$

The energy or protein contents (*NUTR*) of commodities selected by the model for consumption in a particular month and year ($DECISION_{y,Eat,c,m}$) were greater or equal to the energy or protein required by the household ($nutrientreq_{y,n}$) on the basis of WHO. A coefficient ($nutritionslack_{n}$) was used to adjust the general amount of energy and protein consumption recommended by WHO, to intake specific to the site. Food intake in sub-Saharan Africa is about 70% of WHO requirement (FAO, 1998) and we constrained energy and protein consumption on this for each household ($nutritionslack_{n} = 0.7$).

Restrictions were placed on the importance ($dietimportance_{c,m}$) of commodities consumed ($dietcurrent_{c,m,y}$), both produced from the farm and purchased, which formed the basis of the diet selection ($DECISION_{y,Eat,c,m}$) by the model:

$$\forall y \in YEAR, c \in COMMOD, m \in MONTH : DECISION_{y,Eat,c,m} \geq \left(dietcurrent_{c,m.y} \times dietimportance_{c,m} \right) \quad 4$$

The relative importance of commodity (c) in the family's diet during month m (from 0 to 1) indicates how much the consumption of commodity c can vary between the optimized diet and the observed one: 0 = not important, 1 = important and cannot be substituted from the diet. Values attached to important commodities were: Maize (0.9), groundnut (0.7), vegetables (0.7), and sweet potato (0.5). This constraint allowed the model to maximize net income by varying the diet within the boundaries representative of the local diet (instead of the model only suggesting the cheapest commodity for consumption).

(iii) Constraint on labour:

Labour demand was also calculated on a monthly basis for the cropping system (per plot [p] per activities [o]), livestock (per livestock type) and for other non-farming activities. The model constrained annual labour use to total farm labour and hired labour:

$$\forall y \in YEAR, m \in MONTH:$$
$$\sum_{p}^{PLOT}\sum_{o}^{OPTION}\left(optionlabour_{y,m,o} \times LAND_{y,p,o}\right) + \sum_{l}^{LVSTCK}\left(lvstcklabour_{y,m,l} \times ANIMAL_{y,l}\right) + otherlabour_{y,m}$$
$$\leq HIRELABOUR_{y,m} + \sum_{w}^{WORKGROUP}\left(family_{w} \times availablelabour_{w,m}\right) \quad (5)$$

Where In analyses done in this paper, labour was not selected as an activated constraint (therefore options for resources use were not restricted by availability of labour). We, however, set the model to calculate periods and activities for which labour required was greater than the permanent labour available on the farms. This allowed the model to select options on the basis of farm gross income and to indicate additional labour requirements.

The management scenarios tested by the Household model for the poor and wealthy farms are presented in Tables 2 and 3 respectively (Scenarios A and B). All scenarios were initially proposed by the researchers, but refined by farmers during focused group meetings. The impact of increasing the area under groundnut was assessed due to the perception that increasing grain legume production is a key to approach food security and sustainable soil fertility management on smallholder farms (Snapp et al., 2002). Sensitivity analyses were carried out to assess the effect of changes in energy and protein consumption and changes in prices of fertilizer and grain on net cash balance.

Optional crop-soil management strategies simulated using APSIM

APSIM was used to generate data for optional scenarios of targeting the main crops (i.e. maize and groundnut) to different fields and different options for distributing fertilizer resources between the different crops and fields. Soil N, C and P contents were measured in the different field types on the wealthy and poor farms and these values were used to initialise soil parameter files in APSIM with different fertility levels. For the wealthy farm with steep gradients of soil fertility within farm, APSIM was used to generate response curves for crop production for the different zones of soil fertility (homefield, midfield and outfield) (Figure 2). Crop responses were similar on different plots on the poor farm which had small differences in fertility (Figure 2). For the scenarios of resource use, the APSIM maize and groundnut modules were linked to the surface residue module, soil water module, the soil N module (Probert et al., 1998) and the recently developed soil P module (Probert, 2004). Soil water parameters previously estimated for granitic sandy soil in Murewa were used (Chivenge et al., 2004).

Management details for the options explored using APSIM for the poor and wealthy farms are presented in Tables 2 and 3 respectively. The options were in two categories: (i) distribution of nutrient and labour (poor farm only) resources on maize across farms (scenario C) and (ii) allocation of groundnut on different zones of fertility and targeting basal fertilizer and manure to groundnut on the wealthy farm (scenario D). For each scenario, APSIM was used to predict yields for maize and groundnut depending on nutrients applied and weeding intensity. Optimal weeding of plots was assumed for the wealthy farm, but different weeding intensities were simulated, using the WEED module in APSIM, for the poor farm which was more labour-constrained.

Optional livestock feeding strategies simulated using RUMINANT

The RUMINANT model was used to simulate effects of feeding groundnut stover to lactating cows on milk production. Groundnut residues were fed to cows for six months starting at the beginning of the dry season in May (after groundnut harvest), until October when the rains start, and forage is abundant. Different amounts of groundnut stover, depending on amount of groundnut stover produced were fed to cows, as a supplement to rangeland grass in the communal grazing area. Maize residues were exclusively used as fodder. Details of management options evaluated by RUMINANT for the wealthy farm are presented in Table 3.

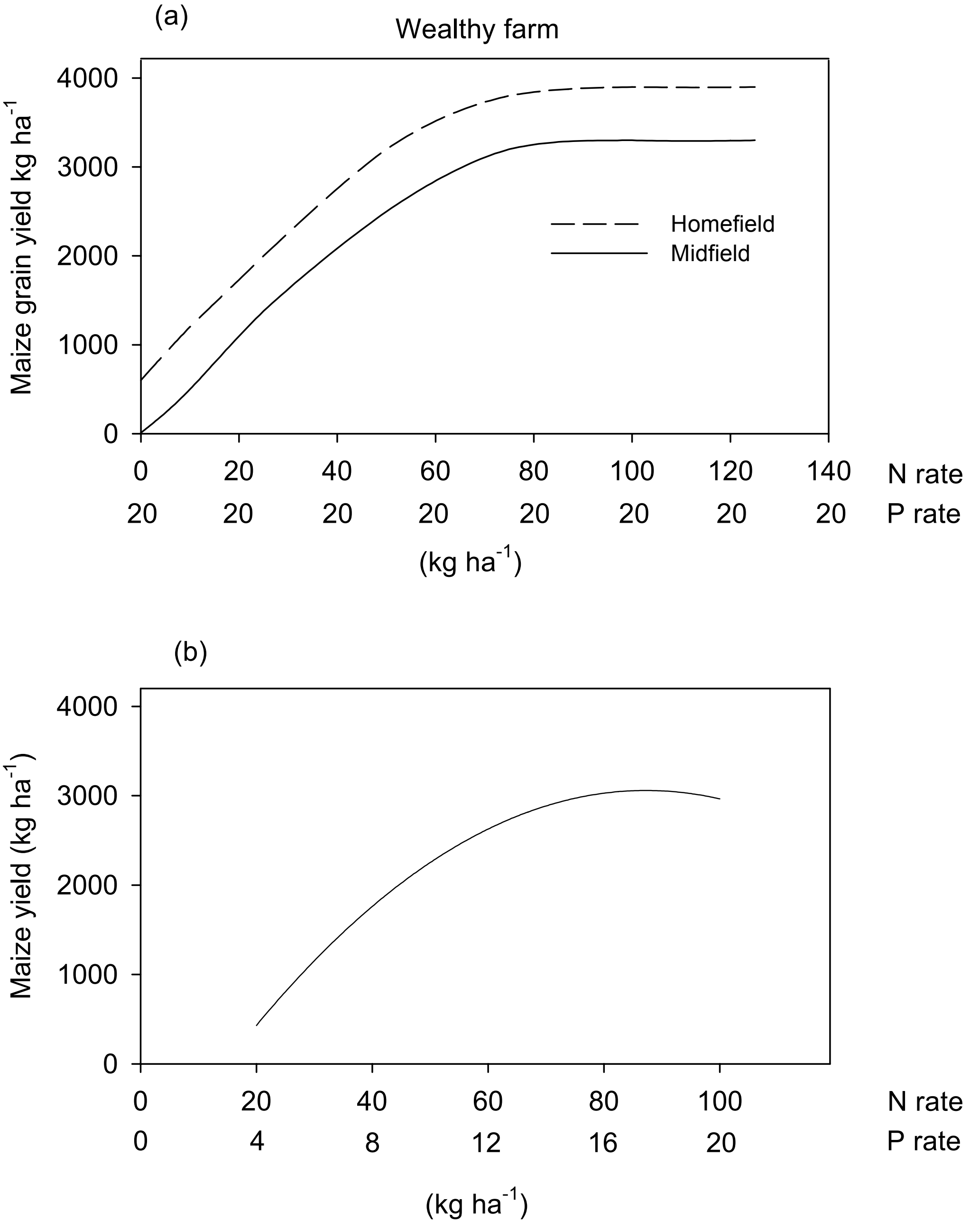


Figure 2. Examples of simulation of maize responses to N for different fields on the wealthy farm at 20 kg P ha^{-1} (a) and response of maize to different N rates at incremental rates of P (0 to 20 kg ha^{-1}) on the poor farm at Murewa, Zimbabwe.

Table 2. Resource use options evaluated for the poor farm in Murewa.

Scenario	Management	Description
Poor-A	Current management	(a) Family's annual energy and protein demand throughout the year met 70% WHO requirement without any land-use changes.
Poor-B	Changing land-use	(a) Household model selected the best land-use activities based on current crop management options and energy and protein requirement by the family.
		(b) Expansion of the area under groundnuts (to about a third of the farm) at the expense of the area under maize.
Poor-C	Options for targeting N and P fertilizers across the plots on the farm.	(a) All fertilizers applied to a third of the area under the maize crop, two-thirds of the area under maize uncultivated.
		(b) Fertilizer applied at equal rates to two-thirds of the maize area, optimal weeding in these plots, a third of the maize area uncultivated.
		(c) Fertilizer applied at equal rates to two-thirds of the maize area, optimal weeding in one-third, 50% optimal weeding in the other third. A third of the maize area uncultivated.
		(d) Fertilizer inputs distributed equally across all the maize area, optimal weeding in all plots.
		(e) Fertilizer inputs distributed equally across all the maize area, optimal weeding in one-third, 50% optimal weeding two-thirds.

Table 3. Resource use options evaluated for the wealthy farm in Murewa.

Scenario	Management	Description
Wealthy-A	Current management	(a) Family's annual energy and protein demand throughout the year met 70% WHO requirement without any land-use changes.
Wealthy-B	Changing land-use	(a) Household model selected the best land-use activities based on current crop management options and energy and protein requirement by the family.
		(b) Expansion of the area under groundnuts (to about a third of the farm) at the expense of the area under maize.
Wealthy-C	Options for targeting N, P and cattle manure to maize across different field types simulated by APSIM	(a) All fertilizers concentrated on maize in the homefield. Other plots cultivated without fertilizer inputs.
		(b) All fertilizers targeted to maize and distributed evenly across all fields.
		(c) Mineral P targeted to maize on homefield; manure targeted to the outfield.
		(d) Mineral P targeted to maize on outfield; organic P from manure targeted to the homefield.
Wealthy-D	Groundnut management in relation to maize (APSIM) and milk production (RUMINANT)	(a) Groundnut grown on the [1]PT1: (i) residues incorporated, (ii) residues fed to livestock.
		(b) Groundnut grown on the PT3: (i) residues incorporated, (ii) residues fed to livestock.
		(c) Current area allocated to maize and groundnut, basal fertilizer and manure at equal rates for maize and groundnut: (i) residues incorporated., (ii) residues fed to livestock.

PT1 - most fertile plot closest to the homestead; PT2 – mid-field; PT3 - outfields, lowest in fertility.

7.3. Results and discussion

7.3.1. Baseline analysis of net revenue, food security and nutrient balances in IMPACT

The overall annual revenue on the poor farm was negative under existing resource management. This was as a result of the negative cash balance from the cropping system that outweighed the small amounts of cash provided by livestock products (sale of eggs and chickens) and other non-farm activities, e.g. sale of labour (Figure 3). In contrast, the wealthy farm had a positive annual net revenue of US$210 per year, mainly from the cropping system (Figure 3). Livestock and other non-farm activities on the wealthy farm had a negative cash balance, due to high costs for purchase of chemicals for treating animals and payment for labour. The wealthy farm had few off-farm activities to generate cash, but spent substantial cash on school fees, health care and purchase of food, hence the negative revenue from other off-farm activities.

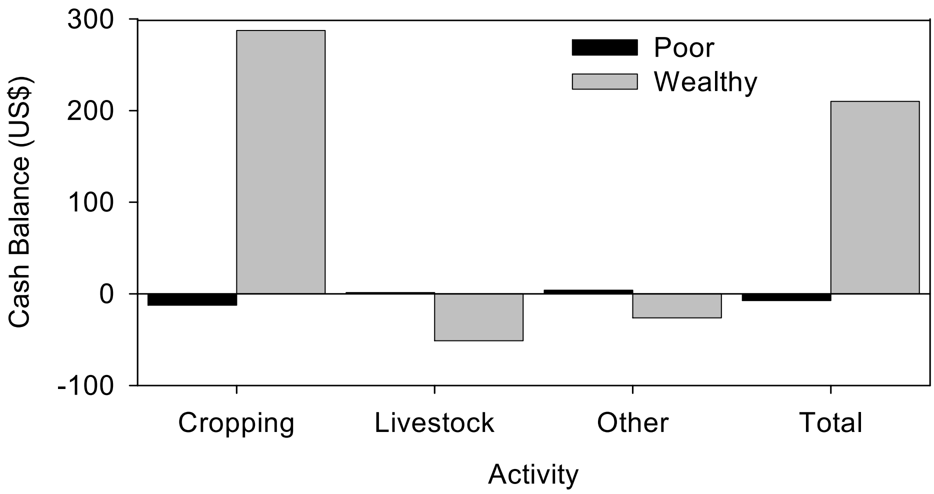


Figure 3. Cropping, livestock, off-farm activities and farm level cash balances for the poor and wealthy case study farms at Murewa, Zimbabwe.

Monthly cash balance for the poor farms was positive only for five months: four months during the cropping season when she sold labour and one month after harvest when she sold some of her groundnut grain. The annual and monthly cash balance for the poor farm clearly indicated the farmer's reliance on selling unskilled labour to generate income. The poor farmer was disadvantaged in that she had to sell labour at planting and weeding, thus compromising the productivity of her own farm due to delays in planting and timely weeding. The poor farmer worked for other farmers about 10 days a month during six months of the crop-growing season. An important trade-off in utilization of labour thus existed on the poor farm where one person worked full-time – should she sell labour for cash or invest it on her farm and improve production. The farmer invested in expensive hybrid seed but applied insufficient amounts of fertilizers and failed to adequately weed some plots, which led to negative returns from the cropping system. Under the existing management there was little leeway for the poor farmer to invest in inputs for the following season, or invest in livestock.

Much of the cash generated on the wealthy farm came from the cropping activities, indicating that livelihoods in Murewa can be sustained by on-farm production if farmers have adequate resources. Monthly cash balance for the wealthy farm was high in the two months after harvest, when grain maize grain was sold, but was low for the other months of the year, although always positive. For good crop yields on sandy soils, good management including investment in mineral fertilizers, use of manure and sufficient weeding of plots is essential. Despite the negative cash balance for the livestock sub-system dominated by cattle, it should be noted, however, that cattle supported the productivity and profitability of the cropping systems through manure and draught power. Cash from sale of farm crops was also used to maintain the herd of cattle. A farm cash balance of US$210 per year is sufficient for the farmer to invest in fertilizers and seed for the following season and purchase cattle to build up the herd (NB: the US$ has a strong value in the local market). The wealthy farmer thus had several options for consolidating the productivity of his farm.

Energy and protein consumption for both farms revealed a major imbalance in relation to the food requirements indicated by WHO. The protein consumption on both farms was equal to the recommended values. Energy intake on the poor farm was about 70% of that recommended, but the energy consumption on the wealthy farm was about 60% of the recommended values. Although the energy consumption levels were far below intake recommended by WHO, the consumption is comparable with actual consumption levels for sub-Saharan Africa (FAO, 1998). The results indicate that the poor farm was more food secure in relation to energy and protein than the rich farm, but in actual fact, a large proportion of the food consumed on the poor farm came from food relief following a drought the previous season. Food donations contributed about 50% of the diet, implying that the poor farmer could only meet about 35% and 50% of energy and protein requirement respectively for the family from her own farm. Distribution of food donations was done by the local rural district council, which decided on recipients based on information provided by the chiefs. The wealthy farm did not receive food relief, which was only given to the poor households. Crop products dominated the diet on the wealthy farm (45%), followed by purchased products (40%) and animal products (15%).

Partial balances for N were positive but small (+7 kg ha^{-1}) on the poor farm, whilst the P balance was nil, which could be attributed to little fertilizer inputs. The partial N and P balances would be expected to be negative if there were no fertilizer donations. The wealthy farm was characterised by positive partial N and P balances (86 and 8 kg ha^{-1} respectively) due to large amounts of manure and mineral fertilizers used.

7.3.2. Resource use optimization by the Household model

Net revenue on the poor farm remained negative when the Household model maximized net cash balance under the current resource use, with the constraint of 70% WHO requirement for energy and protein (Scenario Poor-A) (Table 4). The small influence of diet selection on net cash balance on the poor farm was due to the small amounts of food produced on-farm or purchased, and the heavy reliance of this farm on food donations. A similar analysis for the wealthy farm showed that net cash balance increased from US$210 to US$290 per year when diet was optimized (Figure 4; Table 5). This indicates that the there is flexibility for the wealthy farm to improve cash income by adjusting diet through reduced intake of protein rich foods, which were more valuable, and increased intake of foods with more energy.

Sensitivity analysis of net cash balance to changes in diet showed that it will cost the wealthy farm about US$40 per year to attain the energy and protein consumption level recommended by WHO (Figure 4), which is within the capacity of this farm as it recorded a net cash balance of about US$290 per year at 70% of the WHO requirement. The poor farm, which had a negative net margin of about US$7 per year at 70% of energy and protein recommended by WHO would need a further US$10 to attain 100% (Figure 4a). Net revenue on the wealthy farm was more sensitive to changes in food intake due to the larger family size, the large quantities of food purchased off-farm and consumption of food grown on-farm, which could either be consumed or sold.

The net cash balance on the wealthy farm was also highly sensitive to prices of mineral N fertilizer and price of maize grain sold, but the net cash balance was at least US$150 per year even under stringent ranges of prices, indicating the resilience of the wealthy farm to possible

Table 4. Evaluation of the effects of current and optional fertilizer use and crop allocation strategies on net cash balance, labour demand and nutrient balances on the poor farm in Murewa (See Table 2 for description of scenarios).

Scenario	Annual net cash balance (US$)	Labour deficit (man-days)	Partial nutrient balance (kg ha^{-1})		Specific activities requiring hiring labour
			N	P	
Poor-A	-7	3	7	0	Labour deficit during weeding period
Poor-B (a)	81	211	18	-2	Extra labour required for all activities (planting: 24 days, weeding: 60 days, harvesting and processing: (127)
(b)	72	46	10	-1	Extra labour for all activities (planting: 4 days, weeding: 29 days, harvesting and processing: (13)
Poor-C (a)	21	3	-4	5	Labour deficit during weeding period
(b)	40	29	-35	3	Labour deficit during weeding period
(c)	26	13	-26	5	Labour deficit during weeding period
(d)	23	56	-24	6	Labour deficit during weeding period
(e)	10	26	-17	7	Labour deficit during weeding period

Table 5. Household model evaluation of current and different resource use strategies on net cash balance, labour demand and nutrient balances on the wealthy farm in Murewa (see Table 3 for description of scenarios).

Scenario		Annual net cash balance (US$)	Labour deficit (man-days)	Partial nutrient balance ($kg\ ha^{-1}$)		Specific activities requiring hiring labour.
				N	P	
Wealthy-A		290	43	86	8	Labour hired for harvesting maize.
Wealthy-B	(a)	756	153	357	38	Labour for harvesting increased, and also extra labour required for manure application.
	(b)	279	198	84	9	Extra labour required for planting and harvesting groundnut.
Wealthy-C	(a)	160	18	104	25	Reduced labour requirement for harvesting.
	(b)	200	99	96	29	Labour for harvesting increased, and also extra labour required for manure application.
	(c)	285	90	75	24	Labour for harvesting increased, and also extra labour required for manure application.
	(d)	275	56	78	26	Labour hired for harvesting maize.
Wealthy-C	(a) (i)	235	194	100	29	(i) Extra labour required for planting and harvesting groundnut. (ii) Four extra days required for feeding livestock in June, when maize is harvested.
	(a) (ii)	278	198	94	30	
	(b) (i)	219	198	100	31	(i) Extra labour required for planting and harvesting groundnut. (ii) Two extra days required for feeding livestock in June, when maize is harvested.
	(b) (ii)	248	200	98	31	
	(c) (i)	290	145	105	32	(i) Extra labour required for planting and harvesting groundnut. (ii) Five extra days required for feeding livestock in June, when maize is harvested.
	(c) (ii)	334	150	101	31	

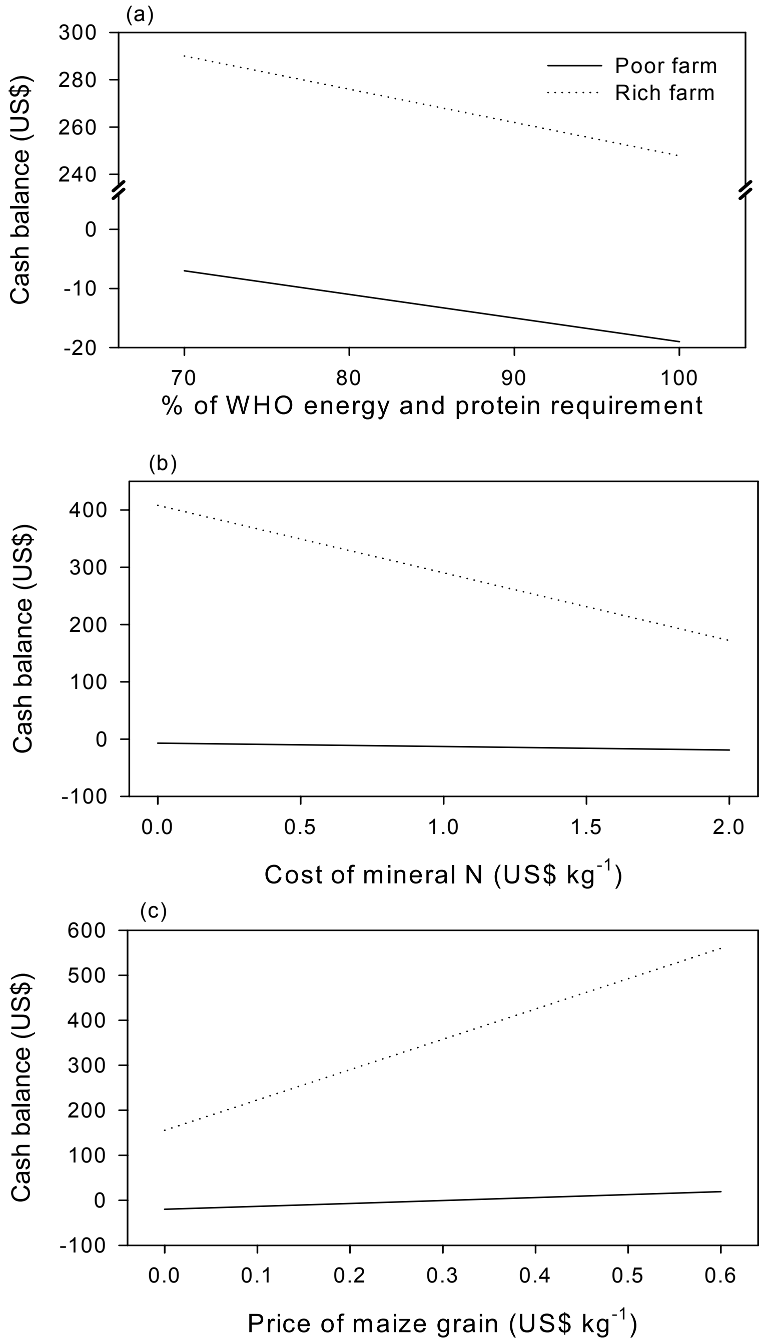


Figure 4. Sensitivity of net cash balance to food consumption (a) price of mineral N fertilizer (b) and price of maize grain (c) for the rich and poor farms in 2003/04 at Murewa, Zimbabwe.

changes in commodity prices (Figure 4b). The high sensitivity to the changes in N fertilizer prices was due to the large amounts of purchased mineral fertilizers used. At the current price of about US$1 kg^{-1} N, the net cash balance was US$290 per year; if the farmer was to receive free fertilizer the net cash balance would rise to US$408 per year, but doubling of fertilizer prices would reduce the current net cash balance by more than US$100 per year. The sensitivity of the net cash balance on the wealthy farm to maize grain prices (Figure 4c) was due to the large amounts of grain sold. Failure of the maize market would significantly reduce the net cash balance, but replacement of maize by other crops would secure a net cash balance of US$150 per year. The poor farmer used little purchased fertilizers and sold small amounts of grain and as a result the sensitivity of net cash balance to changes in prices of N fertilizer and maize grain was low.

The current practice has a labour deficit of 3 man-days for the poor farm and a deficit of 43 man-days for the wealthy farm. The poor farmer had a labour shortfall during the weeding period, the period she usually sold labour. For the wealthy farmer, the period when labour required was in excess of that on the farm was during harvesting and processing grain. The poor farmer could have worked extra hours during periods of peak labour demand, whilst excess labour on the wealthy farm was met by hired temporary labour.

The Household model was set to reallocate crops across the different plots on the basis of net cash balance, potential performance of each cropping strategy and household dietary requirement. This raised the net cash balance on the poor farm by US$81 per year by increasing the area under groundnut and beans at the expense of maize (Table 5). It would be more advantageous for the poor farmer to sell groundnuts and beans and buy maize for consumption, as groundnuts grown without fertilizer inputs are more profitable than maize grown with sub-optimal amounts of N. Increasing the area under groundnut would also increase the N balance by 11 kg ha^{-1}, but reduce the P balance by 2 kg ha^{-1}.

In practice, adjusting land-use in this way is not feasible for the labour-constrained poor farm due to the additional labour demand which exceeds annual available labour by 211 man-days. The farmer is also unlikely to substitute all the maize plots for groundnut and beans, as maize is the staple and food security crop. A more likely crop allocation where a third of the farm arable land is allocated to the groundnut showed that a net cash balance of US$71 per year could still be attained, with a reduced labour deficit of 46 man-days (Table 4).

Optimization of crop allocation revealed that the wealthy farmer would increase net cash balance from US$290 to US$756 per year by changing cropping strategies, by expansion of the area of maize grown with cattle manure and mineral N fertilizer, and elimination of the sweet potato, groundnuts and other maize plots (Table 5). This management may lead to more sustainable soil fertility management as indicated by increased nutrient balances (Table 5). There are two major limitations to expansion of the maize area fertilized with manure and mineral N. Firstly, large quantities of manure are required and the challenge would be for the farmer to source more manure. Secondly, applying manure more widely will require an extra 110 man-days labour compared with the current strategy, which is above the limit the farmer was able to hire. The limited amounts of manure and labour available were some of the factors that explained the commonly observed trend whereby farmers concentrate the manure on small areas close to the homesteads (Rowe et al., 2006; Tittonell et al., 2005). The usable manure produced under current management was about 8 t per year, and at least 40 t per year would be required to cover the farm at the rate used in plot 1. Use of such large amounts of manure is doubtful, as it would require increasing the cattle herd five-fold. The problem of restricted manure availability could be partly solved by improving the capture of manure and reducing nutrient losses during the processes of storage, handling and application (Rufino et al., 2006).

Expansion of the area on which groundnut was grown in the mid-field without fertilizer inputs to a third of the farm arable land was unfavourable as shown by the reduced net cash revenue, the huge labour demand associated with groundnut production and the small effect on N and P balances (Table 5). Groundnut production was poor relative to maize mainly due to farmers' preference to apply fertilizers to maize and little to groundnut, which was grown on residual fertility. Groundnut was also grown on the less productive field. The limited impact of groundnut on the N balance was due to removal of the residues for feeding cattle.

7.3.3. Analysis of optional nutrient resource management strategies using APSIM and RUMINANT

Analysis for the poor farm

Assessment of the opportunities to improve net cash balance by targeted application of mineral fertilizers to maize plots was analysed by linking the crop yields simulated by APSIM to the IMPACT and the Household model (Scenario-C). On the poor farm, fertilizers were used most efficiently when applied to two-thirds of the current maize area, rather than concentrated on one-third or spread across the whole maize area when optimal weeding was assumed (Table 4). APSIM predicted poor grain production at low nutrient application rates (when fertilizers are spread across the whole farm) due to poor internal nutrient use efficiencies (conversion of nutrients taken up into grain) by the maize (Figure 2). Agronomic nutrient use efficiencies were lower at high application rates due to diminishing returns. However, optimal weeding of two-thirds of the maize area would require the poor farmer to hire 29 man-days of labour. To address this limitation, an alternative scenario of optimal weeding on part (50%) of the two-third area and 50% weeding on the other part (50%) reduced annual net cash balance by US$14, and showed that labour could still be a limitation as 10 extra days were required. The partial N and P balances were highest for the fertilizer allocation patterns where fertilizers were either concentrated on a third of the maize area or applied to all plots, indicating poor nutrient uptake efficiencies associated with these strategies, as much of the N is lost from the system.

According to the model results, labour and fertilizer resources were used most efficiently when concentrated rather than spread. Since labour is a major constraint on the poor farm, this would allow the farmer to expand groundnut production or sell labour to raise cash for other needs. The poor farmer could then use inexpensive soil fertility improving technologies such as establishment of indigenous legume fallows (Mapfumo et al., 2005), to assist in restoring soil fertility in the uncultivated fields.

Analysis for the wealthy farm

Limiting the fertilizers used to those available on the wealthy farm, results from the APSIM and Household models suggested that spreading the mineral and organic fertilizer resources evenly across the farm was more efficient than concentrating the resources on the plot closest to the homestead. Spreading the resources across the maize plots would require the wealthy farmer to invest 99 man-days of hired labour compared with the 18 man-days that would be required when fertilizers are concentrated on the plot closest to the homestead (Table 5). Such an investment in labour is not justified since the benefit is less than the cost of additional labour. A more favourable P balance could however add additional reason to spread the fertilizer resource across the farm (Table 5).

The other option available to the wealthy farmer was targeting manure and basal fertilizer to the homefield and outfield, whilst mineral N was applied to both fields. Application of basal mineral fertilizer to the homefield, and manure to the outfield, produced a larger net cash balance compared with the reverse (Table 5). But again, the benefits of targeting manure to the outfield would demand an extra 34 man-days of labour, which are more costly than the accrued benefits.

The major disincentive of expanding of the area under groundnut on the wealthy farm is the associated increase in the labour required (Table 5). Expansion of the area under groundnut to a third of the farm could only match the net cash balance of targeting organic and mineral fertilizers on maize if the groundnut was allocated to the homefield and residues fed to livestock. Allocation of an expanded area under groundnut to the outfield was less profitable, as well as more laborious (Table 5). Analysis of groundnut management strategies for the wealthy farm (Scenario-D) showed that maintaining the current area allocated to groundnut, but distributing the basal fertilizers and manure at equal rates for maize and groundnut would be a more appropriate groundnut intensification strategy, in terms of net cash balance and labour requirement and nutrient balances.

According to RUMINANT output linked to the Household model, there is potential to increase the annual net cash balance by between US$29 and US$44 through enhanced milk production from supplementing the diet of the cows with groundnut residues, depending on the groundnut intensification strategy chosen (Table 5). Removal of the groundnut residues to feed livestock had a small negative effect on the N balance of the cropping systems overall (reduced by 2-6 kg N ha^{-1}) but the impact on N balance on the particular plots on which groundnut was grown could be large (N balance reduced by 6-20 kg ha^{-1}). The gap in the N balance between strategies in which residues were left in the field or removed could be reduced if some of the groundnut N fed to cattle is recovered in urine and manure and returned to the fields. Directly incorporating high quality residues may lead to higher N recovery by maize compared with cycling of the residues through cattle (Delve et al., 2001). Farmers could opt for feeding the groundnut residues to cattle to improve milk production, then allow maize to benefit from N recycled through manure. This would enhance the productivity of both livestock and crops, although it could lead to large N losses from the system during handling and storage of manure (Rufino et al., 2006).

7.4. Conclusions

The modelling approach of linking different existing component models through a farm-level database used in this study was very useful for integrating biophysical and socio-economic factors influencing decision making on smallholder farms and evaluating trade-offs for resource use in terms of nutrient balances, labour use, food sufficiency and cash balance. These broader based models still need good user skills, and experience in their use, to be able to generate meaningful additional information, but we have shown that this approach works at the farm-level and that generated data can contribute to more accurately analysing trade-offs of resource use in smallholder farming systems. This study underscores the need to carefully consider site-specific conditions at the farm level when designing interventions for improving efficiency of resource use, as some options have opposing effects, especially when comparing farms of contrasting wealth. For example, expansion of the area under groundnut was more profitable on the poor farm, but less profitable on the wealthy farm. Also, spreading fertilizer resources across the maize plots was more profitable on the rich farm, but less profitable on the poor farm.

The poor farm faced multiple constraints including poor availability of cash and labour, and lack of manure and draught power. Under these conditions resources would be used more efficiently if maize was grown on smaller, well-managed areas and the mineral fertilizers concentrated rather than spread widely across the farm. Other interventions for resource management suitable to the poor farm must be cheap and demanding little labour. On the wealthy farm, expansion of the area fertilized with manure would be ideal, although this would be highly labour demanding and require large amounts of manure. Net cash balance would be higher if manure was targeted at the outfield and basal mineral fertilizer on the homefield, rather than the reverse. Intensification of groundnut production on the wealthy farm should focus on targeting some of the P fertilizers and manure on the groundnut, rather than increasing the area cultivated. Feeding groundnut residues to a lactating cow is attractive for short-term household economics, although it reduces the N available to the cropping systems and should be weighed against the long-term effects of incorporating the residues on crops grown in subsequent seasons. Availability of nutrient resources and labour were identified as major factors determining feasibility of resource management options; hence targeted and strategic use of nutrients and labour is required for efficient management of smallholder farms.

CHAPTER 8

Long-term and short-term nutrient allocation strategies and their impact on spatial variability of soil fertility, crop yields and resource use efficiencies in African smallholder farms

To be submitted to *Plant and Soil* in a modified form as:

Zingore, S., Tittonell, P., van Wijk, M., Delve, R.J. and Giller, K.E. Long-term and short-term nutrient allocation strategies and their impact on spatial variability of soil fertility, crop yields and resource use efficiencies in African smallholder farms.

Abstract

In this chapter, a simple dynamic model (FARMSIM) is applied to synthesize the results from the different sections dealing with spatial and temporal variability in soil fertility and its effects on maize production. FARMSIM simulated the rapid decline in soil organic C (SOC) and the rapid development of gradients in SOC on plots that received different rates of manure. Manure also stabilized yields in the long-term, which decreased when mineral N and P fertilizers alone were used. About 10 t manure ha^{-1} yr^{-1} was required to maintain SOC at original contents under woodland. On the clay soil, the model suggested that maintaining SOC at original contents under woodland vegetation was not efficient for maize production, as it led to oversupply of nutrients. Starting from woodland clearance, manure was used more efficiently when applied at 5 t ha^{-1}. On the sandy soil, model results indicated that resources are used most efficiently across soil fertility gradients when manure is applied to plots with medium fertility and mineral fertilizers to the best fields. In the medium term, this strategy resulted in decline of overall farm productivity, as yield gains on the plots with medium fertility were not able to compensate for yield decreases with mineral fertilizers on the best fields. The nutrient stocks on the clay soil were more resilient and there were small changes in overall farm productivity for different resource management strategies in the medium-term. Assuming that farmers grew maize on all their plots, wealthy farmers who owned cattle could potentially produce more than 5 t maize grain per farm above their maize requirement for household consumption. The poor farmer without cattle can potentially produce only 0-3 t maize per farm due to poor soil fertility from poor past management, inadequate nutrient resources for the current season and the small farm size. The model highlighted the essential role of manure as a resource driving variability of soil fertility and maize yields on smallholder farms.

8.1. Introduction

Cultivation of crops for prolonged periods with little addition of nutrient resources has led to depletion of soil fertility on smallholder farms in sub-Saharan Africa (Sanchez et al., 1997). Assessment of changes in soil nutrient stocks in sub-Saharan Africa has shown large negative balances for N, P and K, indicating rapid depletion of soil fertility for individual countries and the region as a whole (Stoorvogel et al., 1993; Van den Bosch et al., 1998). However, several studies have revealed contrasting trends of nutrient balances for wealthy and poor farms or for different plots on the same farms (Elias et al., 1998; Esilaba et al., 2005; Haileslassie et al., 2005), indicating that the changes in soil fertility at the farm and plot levels are not homogeneous. Nutrient balances at the farm-level are mostly positive on wealthy farms that own livestock and use large amounts of animal manures and mineral fertilizers, but tend to be negative on poor farms without access to manure and mineral fertilizers, as they are unable to compensate for nutrients removed in harvested products and those lost through different soil processes. Within farms, zones of active nutrient accumulation are often found on fields closest to homesteads on wealthy farms, where farmers preferably apply nutrients, whilst fields far from homesteads show negative balances.

As a consequence of differential resource management and inherent differences in soil properties, smallholder farms are characterised by steep gradients of decreasing soil fertility with increasing distance from the homesteads (Prudencio, 1993; Tittonell et al., 2005; Giller et al., 2006). Such gradients occur even on small farms of less than three ha and within short distances of less than 500 m from the homesteads in Zimbabwe (Mtambanengwe et al., 2005; Zingore et al., 2000a). Differential resource allocation on smallholder farms is influenced by several biophysical and socio-economic factors that include size of farms, availability of nutrient resources and labour, minimizing risk associated with erratic rainfall, and concentrating resources on fields less prone to theft and grazing by livestock (Carter et al., 1995; Chikuvire, 2000). The striking differences in nutrient balances and soil fertility at the farm and plot levels calls for the need to match fertility management interventions to particular zones of fertility within farms, rather than considering different farms and fields as homogeneous units that require blanket recommendations.

The variability in soil fertility within farms gives opportunities for farmers to improve total farm crop production and resource use efficiencies by maintaining within-farm variability or reducing the gradients by spreading nutrient resources evenly across their farms. Rowe et al. (2006) indicated that nutrients in organic form (i.e. manure) could be used most efficiently in maize production when spread evenly across uniform farms, on the basis that marginal nutrient use efficiencies are greatest when nutrients are applied at low rates (Lopez-Ridaura et al., 2006). However, other studies (including that of Rowe et al., 2006) have shown that when soil fertility gradients are steep, nutrients resources, especially mineral fertilizers, are used most efficiently when applied on more fertile homefields than depleted outfields (Vanlauwe et al., 2006; Wopereis et al., 2006; Zingore et al., 2006b), suggesting that current farmer management practices are rational. This is because in many cases, the outfields are severely depleted in soil fertility and suffer multiple nutrient deficiencies, which can only be rectified through repeated applications of large amounts of animal manure (Zingore et al., 2006b). Productivity of grain legumes on smallholder farms also depends strongly on variability of soil fertility within and between farms. Production of grain legumes on depleted fields is often constrained by soil acidity and deficiency of nutrients, especially P.

There is growing awareness of the profound effects of soil fertility gradients on resource use efficiencies on smallholder farms, and the need to evaluate appropriateness of soil fertility management options taking cognisance of soil fertility differences between plots on the same farm or on different farms. The complex spatial variability in soil fertility and its implications on resource use efficiency necessitates the application of systems analysis tools to comprehensively evaluate the short-term and long-term implications of resource management for individual plots and whole farms. Both short and long-term implications of strategies of soil fertility management must be taken into account, because an optimal strategy for a given situation in one season, is not necessarily optimal for farm-productivity in the longer-term. At the plot level, production is mainly affected by soil fertility status. At the farm level, availability of nutrient resources, labour and differences in soil fertility are important factors that determine feasibility of resource management options. The farm level is considered the main unit of analysis as it is at this level that farmers decide on resource allocation strategies, depending on their objectives, resource endowment and constraints. One approach for farm level modelling is to use existing crop-soil simulation models to simulate management effects on individual plots, and to aggregate output from the plots using optimization models to assess the impact at the farm level (Castelan-Ortega et al., 2003; Zingore et al., 2006d). Whilst this approach is robust for evaluating resources use options for specific farms within a given season, its application for wide-ranging conditions and for multiple year simulations is difficult due to the large data requirements for parameterization of existing complex crop-soil models. To overcome this limitation, simple dynamic models that only consider the main processes affecting heterogeneity of soil fertility and crop production can be effectively applied to simulate the effects of different resource management strategies across soil fertility gradients on smallholder farms (Shepherd et al., 1998; Rowe et al., 2006).

A simple model which requires relatively little data input, (FARMSIM), has been developed with the objective of simulating key processes affecting crop responses for fields with different soil fertility conditions and a variety of resource allocation strategies, thus reducing data required for parameterization (Tittonell et al., 2006). The model was parameterized and validated against data from different experiments in Zimbabwe and showed good ability to simulate the effects of soil fertility and application of mineral and organic nutrient resources on maize and soyabean yields. The model was applied in this paper to explore the long-term and short-term consequences of different resource use strategies on variability of soil fertility and crop yields on smallholder farms in Zimbabwe.

8.2. Materials and Methods

8.2.1. The study site

Murewa district (17°49'S, 31°34'E) is one of the earliest settled and most densely populated smallholder-farming sites in Zimbabwe. The soils in Murewa are mainly sandy soils (>85% sand) derived from granite (Lixisols), which are low in inherent fertility. The granitic sandy soils are the most widespread soils in Zimbabwe, covering about 70% of the area cultivated by smallholder farmers (Nyamapfene, 1991). Smaller areas cultivated by smallholder farmers in Murewa are found on more-fertile red clay soils derived from dolerite (Luvisols). Total annual rainfall ranges between 750 and 1000 mm, distributed in a unimodal pattern (November-April).

Farmers practice a mixed crop-livestock system with maize as the dominant staple crop. Other crops commonly cultivated in Murewa include groundnut, sweet potatoes, sunflower, and vegetables. Cattle are the main livestock and graze freely in communal rangelands during the day and are tethered in kraals close to homesteads at night. Less than 50% of the farmers own cattle, and cattle ownership rates are less than three animals per farm. Manure is a key nutrient resource, due to its multiple soil fertility benefits and is used together with small amounts of mineral fertilizers. Manure is also the only major source of organic matter inputs into the soil as crop residues are removed to feed livestock or grazed *in-situ* after harvesting.

8.2.2. The FARMSIM model

In brief, FARMSIM is an explorative dynamic model running on a seasonal time-step, designed to simulate effects of different resource management strategies across soil fertility gradients on smallholder farms in sub-Saharan Africa. The version of the model applied in this study simulates crop production and changes in soil fertility status on different plots using a crop and soil sub-model named FIELD. Crop yields for different plots are determined by the interaction of nutrient and water availability. The utilization efficiency of the various resources by the crop is the result of two separate components: resource capture and resource conversion efficiencies. The simulation of resource capture efficiencies is largely empirical, derived from experimental data (e.g. nutrient recovery) and/or from modelling exercises using (parameterized) process-based models. As opposed to previous approaches that fit case-specific empirical functions (QUEFTS – Janssen et al., 1990) or consider crop growth as determined by the individual most limiting resource (SCAN – van Keulen, 1995), FARMSIM simulates resource conversion efficiencies in a simple mechanistic way following the approach of Liebscher's 'Law of the Optimum'. By doing so, crop responses to combined applications of different types and sources of plant nutrients can be better explored. Total amounts of nutrients available in the soil in a given season are calculated from total mineral forms available in the soil, nutrients mineralized from soil organic matter and those added in mineral and organic nutrient resources. Nutrients available for crop uptake are determined by the difference between total nutrients available and those lost through erosion for N and P, and through leaching and gaseous losses for N. The model also simulates effects of K on crop production, but K was not considered in the simulations for Murewa, as K is not a common limiting nutrient in soils in that area. Crop available water is simulated using total seasonal rainfall, and infiltration and drainage calculations based on soil particle size distribution and soil organic matter content. FARMSIM is capable of simulating different soil fertility management scenarios including productivity of different crops and their response to application of mineral and organic sources of nutrients. A more detailed description of the model and its parameterization for conditions on smallholder farms in Zimbabwe is presented in a paper attached as Appendix 1.

8.2.3. Scenario Analysis

The model was used to simulate different resource management strategies for farms located on sandy and clay soils in Murewa. The data requirements for simulating different scenarios of resource use after model parameterization are as follows: (i) soil properties; (ii) amount and quality of manure; (iii) amount of mineral N and P fertilizers; (iv) crop type. The soil parameters required are: soil particle size distribution, soil organic C (SOC), soil N, and extractable P. To simplify scenario analysis, typical zones of soil fertility were constructed for farms in different wealth categories (Table 1), based on gradients of soil fertility observed in the resource flow mapping exercise and field experiments (Zingore et al 2006a; Zingore et al 2006b). Detailed description of farm wealth categories is presented in Chapter 3. Farm resource groups (RG) were mainly based of cattle ownership and land availablity. RG1 (very wealthy, farm size 3.0 ha) and RG2 (wealthy, farm size 2.5 ha) farmers owned cattle, whilst RG3 (poor, farm size 2.2 ha) and RG4 (very poor, farm size 1 ha) farmers did not own cattle and had no access to manure (Table 1). Soil parameter settings for different zones of soil fertility are given in Table 2. Values for soil particle size distribution on different plots of the same soil type were assumed to be similar: 10% clay, 5% silt and 85% sand on the sandy soil and 35% clay, 15% silt and 50% sand on the clay soil. Data required for manure quality include total C, total N and total P contents. The manure parameters used were: 30% C; 1% N and 0.2% P. Default crop parameters as provided by FARMSIM were used. The first set of scenarios simulated dealt with resource allocation strategies driving variability of soil fertility and maize yields.

Table 1. Mean resource endowment for the farms in the different farmer resource groups (RG) in the Chiwara village, Murewa (Total sample size is 50 farms).

Farm type	No of farms	Household size	Farm size (ha)	Cattle	Oxen	Goats	Chickens	Scotch carts	Manure available (t)	Labour:Land ratio[a]	Average maize yields ($t\ ha^{-1}$)[b]
RG1	8	7	3.1	12	2	2	8	1	10	1.6	3.6
RG2	14	5	2.5	7	1	3	5	0.4	6	1.6	1.7
RG3	12	6	2.2	0	0	2	6	0	0	1.8	0.9
RG4	16	4	1.0	0	0	0	3	0	0	2	0.7

Adapted from Zingore et al. 2006a.

[a]Land:labour ratio calculated as number of household members working fulltime on the farm per farm size.
[b]Calculated as total maize production per farm area sown to maize, based on data collected from case study farms for three seasons (2001/01-2003/4).

Table 2. Description of the different zones of fertility, their occurrence and soil properties on smallholder farms in Murewa, Zimbabwe.

Fertility Zone	Description	Sandy soil			Clay soil		
		SOC ($g\ kg^{-1}$)	N ($g\ kg^{-1}$)	Avail. P ($mg\ kg^{-1}$)	SOC ($g\ kg^{-1}$)	N ($g\ kg^{-1}$)	Avail. ($mg\ kg^{-1}$)
FZ 1	Virgin soils under woodland vegetation.	14	1.2	14	21	1.6	18
FZ 2	Most fertile fields where large amounts of manure were applied, typical homefields on RG1 and RG2 farms.	10	0.8	12	16	1.2	12
FZ 3	Fields with moderate fertility where small amounts of manure were used. This zone of soil fertility covers mid-fields and outfields on RG1 farms and outfields on RG2 farms.	7	0.6	7	10	0.8	10
FZ 4	Fields with low fertility mostly cultivated with little fertilizer inputs. Fields in this category include all fields on RG3 and RG4 farms and outfields on RG2 farms.	4	0.3	3	7	0.5	5

Table 3. Different nutrient resource use strategies simulated using FARMSIM: (a) For long-term simulation starting with a virgin soil (FZ1); (b) Different combinations for N, P and manure on the different zones of fertility (FZ1-FZ4).

(a)

Resource management
1. No fertilizer inputs
2. 100 N ha^{-1} yr^{-1}
3. 100 N + 20 kg P ha^{-1} yr^{-1}
4. 100 N ha^{-1} + 10 t manure ha^{-1} yr^{-1}
5. 100 N ha^{-1} yr^{-1} + 5 t manure ha^{-1} yr^{-1}
6. 100 N ha^{-1} yr^{-1} + 3.3 t manure ha^{-1} yr^{-1}
7. 100 N ha^{-1} yr^{-1} + 10 t manure ha^{-1} applied every three years
8. 10 t manure ha^{-1} yr^{-1}
9. 5 t manure ha^{-1} yr^{-1}
10. 3.3 t manure ha^{-1} yr^{-1}

(b)

N (kg ha^{-1} yr^{-1})	P (kg ha^{-1} yr^{-1})	Manure (t ha^{-1} yr^{-1})
0, 30, 60, 90, 120	0	0
0, 30, 60, 90, 120	10	0
0, 30, 60, 90, 120	20	0
0, 30, 60, 90, 120	0	3.3
0, 30, 60, 90, 120	0	5
0, 30, 60, 90, 120	0	20

Table 4. Different scenarios for strategies of allocation of mineral fertilizers and manure evaluated for farms in different resource groups, taking into account soil type, farm sizes and sizes of plots with different fertility status. (a) Resource group 1; (b) Resource group 2; (c) Resource groups 3 and 4.

(a)

Scenario	Description
1	Baseline yields without application of nutrient resources
2	Optimal fertilizer distribution with 180 kg N and 50 kg P per farm
3	Manure applied evenly across the farm without mineral N
4	Manure applied to two plots without mineral N
5	Manure concentrated on one plot without mineral N
6	Manure applied evenly across the farm with mineral N
7	Manure applied to two plots with mineral N
8	Manure concentrated on one plot with mineral N
Best strategy	Best strategy with 10 t manure; 180 kg N and 30 kg P per farm

(b)

Scenario	Description
1	Baseline yields without application of nutrient resources
2	Optimal fertilizer distribution with 180 kg N and 50 kg P per farm
3	Manure applied evenly across the farm without mineral N
4	Manure concentrated on one plot without mineral N
5	Manure applied to two plots with mineral N
6	Manure concentrated on one plot with mineral N
Best strategy	Best strategy with 10 t manure; 180 kg N and 30 kg P per farm

(c)

Scenario	Description
1	Baseline yields without application of nutrient resources
2	Maximum yield obtained with mineral N and P fertilizers
3	Manure applied at 3.3 t ha^{-1}

The model was applied to simulate effects of applying different manure per year, which is all used on a plot of 1 ha^{-1}. The effect of smaller rates of manure application was simulated to assess the implications of spreading the same amount of manure across two plots of 1 ha each and to three plots of 1 ha. Other scenarios in which no manure is applied are also relevant for management of plots on RG3 and RG4 farms where no cattle manure was used. Maize responses to different rates of N, P and manure application on the different zones of fertility were simulated in a second category of scenarios (Table 3b). This set of scenarios explored the questions on how limited fertilizer resources can be judiciously allocated across plots with different soil fertility.

Crop yield responses generated by the model were then applied to estimate crop production potential for RG1-RG4 farms on the clay and sandy soils taking into account the type of soil cultivated, farm sizes and size and fertility status of plots within farms (Table 1). On the RG1 and RG2 farms, maximum mineral N and P sources of nutrients were restricted to 200 kg N and 50 kg P per farm per season in scenarios in which no manure was used (based on total application rates of N and P that are typical of RG1 and RG2 farms) (Table 4). When manure was applied, the total amount of mineral N was restricted to 100 kg N and <20 kg P per farm per season. The best strategies for application of nutrient resources were determined using the total production per plot and efficiencies of nutrient use (based on agronomic P use efficiency). Labour productivity (maize production per unit invested labour) was also calculated for different manure application strategies. The best-performing strategies were simulated for five seasons to determine their suitability for total farm maize production in the medium term. The granitic sands are the predominant soils cultivated by the farmers in the study village (about 80% of the arable area); hence the results simulated for the sandy soil are widely relevant.

8.3. Results and discussion

8.3.1. The development of soil fertility gradients through differential management

Soil organic C declined rapidly when land-use changed from natural woodland to cultivation of maize for all simulations without application manure (Figure 1a, 2a). A new equilibrium was reached in about 15 years of cultivation on the sandy soil and in 30 years on the clay soil. SOC declined from 30 t ha^{-1} to less than 10 t ha^{-1} on the sandy soil and from about 55 t ha^{-1} to 16 t ha^{-1} on the clay soil. Although larger SOC equilibrium contents were attained on the clay soil under cultivation, about 40 t C ha^{-1} was lost from inception of cultivation to new equilibrium, compared with only 20 t ha^{-1} lost on the sandy soil. The simulated SOC depletion under rates of manure and mineral N and P fertilizers for 30 years, starting with virgin soils (Table 3a). A

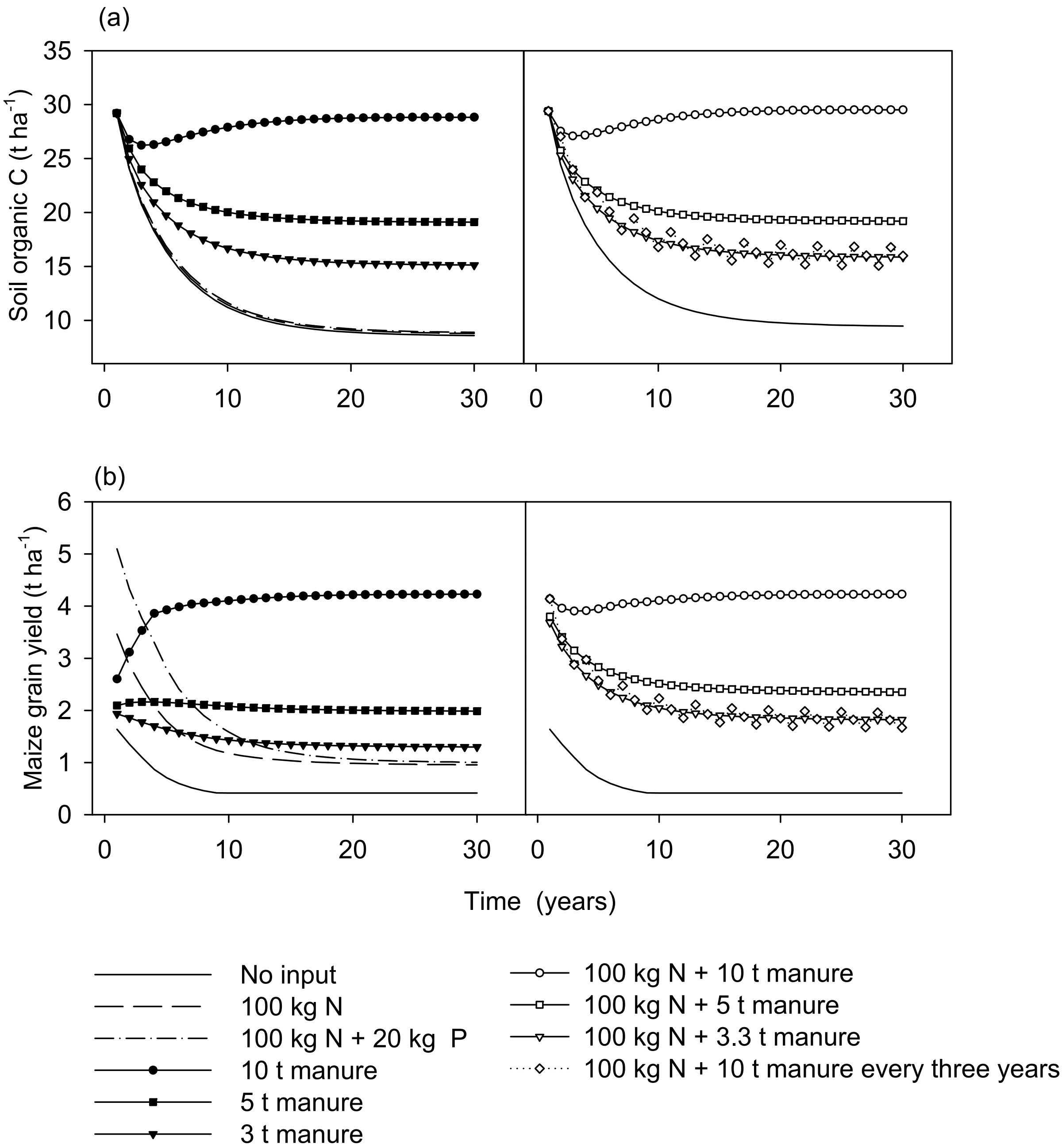


Figure 1. Effects of different resource management options on long-term dynamics of (a) SOC and (b) maize grain yields following woodland clearance for maize cultivation simulated by FARMSIM for the sandy soil.

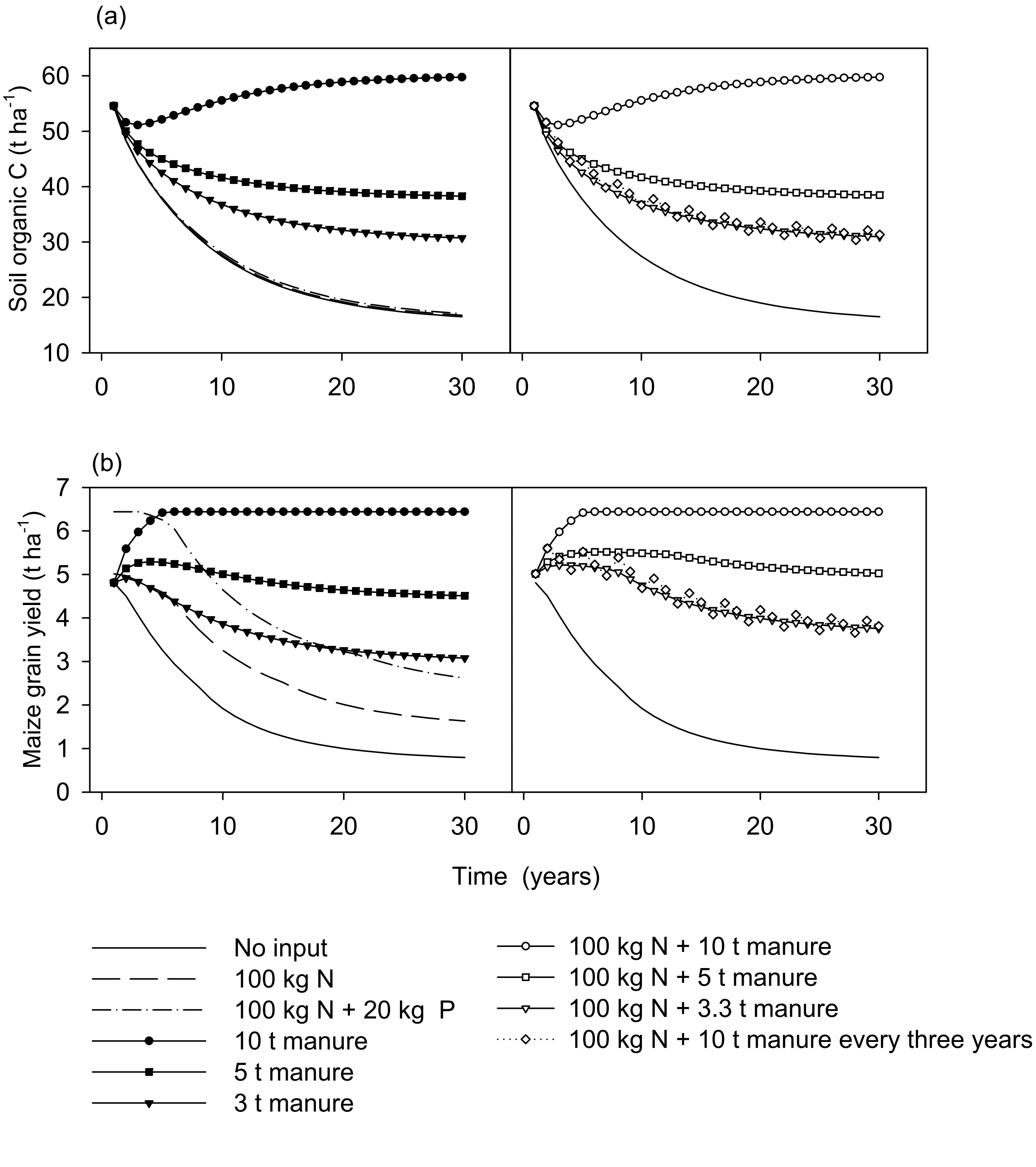


Figure 2. Effects of different resource management options on long-term dynamics of (a) SOC and (b) maize grain yields following woodland clearance for maize cultivation simulated by FARMSIM for the clay soil.

chronosequences on similar soil types (Zingore et al., 2005). Such management is typical of fields on poor farms (RG3 and RG4) without cattle and outfields on RG2 farms (Zingore et al., 2006a). The decline in SOC without fertilizer inputs is caused by poor productivity and removal of stover. Mineral fertilizers contribute little to SOC due to removal of the larger amounts of stover initially produced with mineral fertilizers. Commercial farmers were able to maintain large contents of organic matter in the soil by using mineral fertilizers which gave large yields, and concomitantly returning large amounts of stover (Zingore et al., 2005). The incorporation of crop residues is unlikely to be a practical option for maintaining SOC on smallholder farms because crop residues are an important source of fodder during the dry season. Increased C input from root biomass when mineral fertilizers were used also contributed little to SOC as C derived from maize roots it is highly labile (Balesdent and Balabane, 1992), and thus much of it enters the active SOC pool with a rapid turnover time.

According to FARMSIM, variability in SOC on smallholder farms is driven by use of manure, which is the only major organic nutrient resource used by farmers (Murwira et al., 1995). Application of 10 t manure ha^{-1} each year was required to maintain SOC contents at values initially present under uncultivated woodland soils (Figure 1, 2). Application of manure at 5 and 3.3 t ha^{-1} led to an equilibrium SOC content of 16 and 14 t C ha^{-1} on the sandy soil, and 28 and 30 t C ha^{-1} on the clay soil, respectively. Due to removal of maize residues addition of fertilizers with manure had no significant effect on equilibrium soil C contents. The model results suggested that differences in SOC due to application of manure at different rates develop within a few years of cultivation, and maximum differences are reached in about 20 years on the sandy soil and more gradually after 30 years on the clay soil. Field measurements showed that plots closest to homesteads on RG1 and RG2 farms where large amounts of manure were used had greater contents of SOC than fields further away and all plots on RG3 and RG4 farms (Zingore et al., 2006a, b). Gradients of soil fertility were not observed on the RG3 and RG4 farms, as they did not use manure or substantial amounts of other organic resources.

Simulated yields declined with time of cultivation for all resource use strategies, except with 10 t manure ha^{-1} on the sandy soil and with 5 t and 10 t manure ha^{-1} on the clay soil (Figure 1b, 2b). The recommended manure application rate for maintaining soil fertility and large maize yields on the sandy soil is 10 t ha^{-1} yr^{-1} (Grant, 1981), which is in agreement with the model output. Yields were sustained with manure because repeated application led to maintenance of SOC and build-up of N and P. Larger amounts of manure were required to maintain yields on the sandy soil due its small capacity to store SOC (Six et al., 2002). Mineral N and P initially gave larger yields than manure on the sandy soil, but these declined over time as SOC declined. FARMSIM maximum of 10 t manure ha^{-1} is simulated, assuming that a farmer in the RG1 had 10 t of continuous cultivation without fertilizer inputs is consistent with trends observed along cultivation simulations used SOC as a surrogate for other factors limiting response to N and P, such as, poor water use efficiency and deficiency of other nutrients besides N and P (Zingore et al., 2006b).

At equilibrium, maize yields on the clay soil were 6.5 t ha^{-1}, 4.5 t ha^{-1} and 3 t ha^{-1} with manure applied at 10 t ha^{-1}, 5 t ha^{-1} and 3.3 t ha^{-1} respectively (Figure 1d). Given that maize yields without fertilizer inputs were about 1 t ha^{-1} and assuming that no mineral fertilizers are applied, manure would be used efficiently on a 3 ha RG1 farm (three plots of 1 ha) with 10 t of manure when appliesd to two plots (total maize production = 10 t ha^{-1}), followed by manure applied to all three plots at 3.3 t ha^{-1} (total maize production = 9 t ha^{-1}), and least when concentrated on one plot (total maize production = 8.5 t ha^{-1}). Although 10 t manure ha^{-1} was required to maintain SOC at the original contents under woodland, this was not efficient for crop production as it led to over-supply of nutrients. Without considering the labour requirements, it could be sensible for farmers on the clay soil to spread manure evenly across the whole farm to maintain soil fertility of all fields. There were small differences in overall farm production between the different strategies for manure use for a similar scenario on the sandy soil with low SOC threshold levels. The strategy of applying manure at 10 t ha^{-1} every three years had similar effects on maize yields to the strategy in which manure (3.3 t ha^{-1}) was applied evenly across all the plots every year (Figure 1b, 2b).

The type of analyses performed above are useful conceptual exercises to illustrate the impact on different biophysical aspects of the system that some of the resource allocation strategies may have, or to explore options for soil fertility maintenance in the long term. To develop recommendations and/or design alternative management strategies with the aid of model-based studies, it is necessary to consider also the socio-economic aspects of the system. For example, the different strategies for the spatial allocation of 10 t of manure on clay soils would be restricted to only the RG1 farms, where such amounts of manure may be available (cf. Table 1). Without considering the labour requirements, it could be sensible for these farmers to spread manure evenly across the whole farm to maintain soil fertility of all fields. However, the yield increase brought about by manure applications should also be analysed in light of the variability in the prices of maize, manure and labour for its application, including the trade-offs in the allocation of labour force to competing activities, by which the conclusions of the analysis may change.

The model results also aided the classification and grouping of fields (plots) from the different farm types, which were potentially 10 potentially (4 farm types x 3 plot types (RG1-RG3 farms) or 2 plot types (RG4 farm farms), plus initial woodland soils. Four fertility zones were identified (Table 2). One of the fertility zones represented the virgin soils under woodland, and all of the fields across the farm types could be represented within three fertility zones that captured the wide variability in soil fertility (Table 2).

8.3.2. Maize responses to N, P and manure across soil fertility gradients

The second set of scenarios explored using FARMSIM concerned allocation of nutrient resources across existing soil fertility gradients (Figures 3 and 4). On the clay soil, maize responded poorly to N at the two extremes of soil fertility conditions, i.e. immediately following woodland clearance (FZ1) and for the depleted soil fertility zone (FZ4) (Figure 4a, d). Lack of maize yield response to N for the FZ1 on the clay soil can be explained by large amounts of N mineralized from the SOC, which could support a yield of 4.5 t ha^{-1} without any P added and about 6.4 t ha^{-1} when P was added at 20 kg ha^{-1}. P was thus more limiting than N, and its supply, both from manure and SSP increased maize yield at agronomic P use efficiency of about 100 kg grain kg^{-1} P supplied. On the FZ4, maize response to mineral N and P was constrained by other factors such as poor water availability due to low SOC content. The simulation results showed poor response of maize yields to P and N, and maximum yields achieved with mineral fertilizers alone were less than 2 t ha^{-1} when all crop residues were removed. Manure applied at 10 t ha^{-1} was required to substantially increase maize yields above the limit of 2 t ha^{-1} achieved with mineral N and P. Decline in SOC from FZ1 to FZ2 on the clay was associated with a decline in baseline maize yields from 4.8 t ha^{-1} to 2 t ha^{-1} (Figure 4a, b). However, attainable yields declined by only 0.5 t ha^{-1}. Nutrients were thus used most efficiently on the FZ2 on clay soil due to the large gap between baseline yields and attainable yields. No additional mineral N was required to improve yields when manure was applied at 10 t ha^{-1}, whilst 30 kg N ha^{-1} was required to reach maximum yields attainable with 5 and 3.3 t manure ha^{-1}. The FZ2 on the clay soil was characterized by a strong interaction between N and P. With P applied, maize grain yields increased linearly up to 60 kg N ha^{-1}. This is because the interaction of resources in FARMSIM is simulated by following Liebscher's 'Law of the optimum'. Agronomic P use efficiency was greatest (about 150 kg grain kg^{-1} P applied) when 10 kg P ha^{-1} was applied with more than 60 kg N ha^{-1}. Agronomic N use efficiency was greatest at 30 and 60 kg N ha^{-1} with 20 kg P ha^{-1} applied. Nutrients were used less efficiently on the FZ3 than FZ2 due to the smaller attainable yields (Figure 4c).

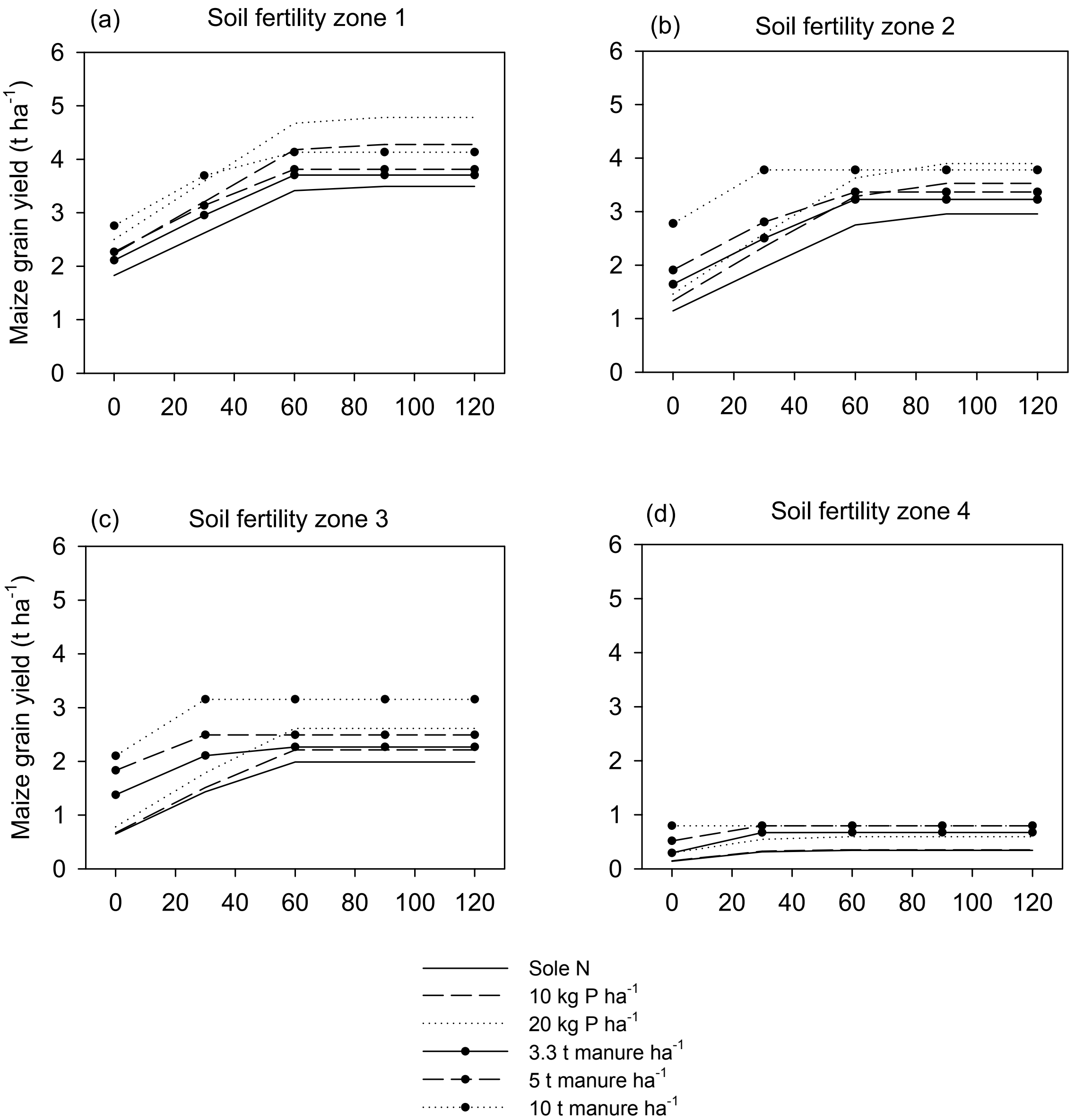


Figure 3. Simulated maize yield response to application of N with different rates of P and manure on different soil fertility zones on the sandy soil at Murewa.

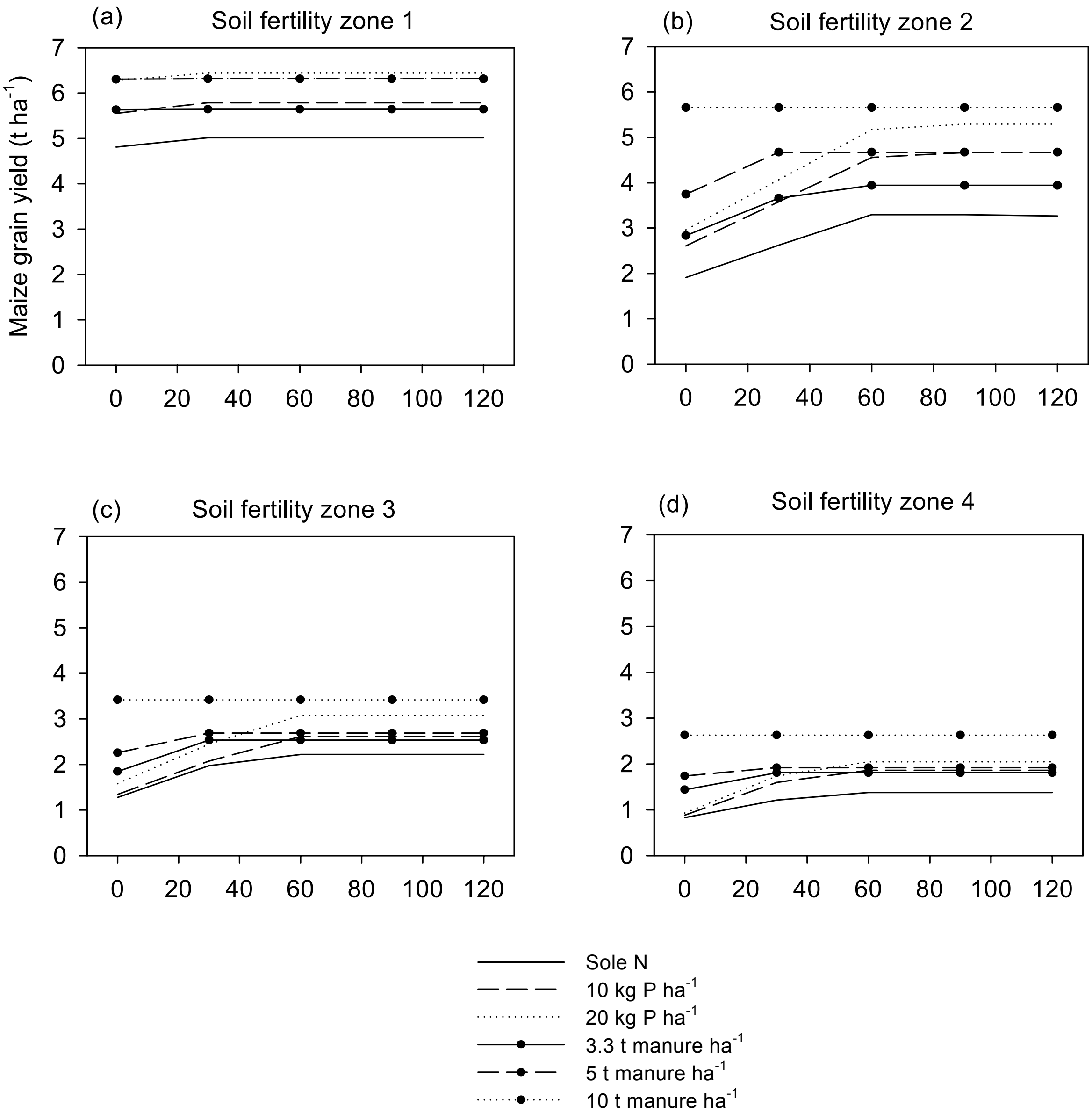


Figure 4. Simulated maize yield response to application of N with different rates of P and manure on different soil fertility zones on the clay soil at Murewa.

Model output indicated that the red clay soil was more productive than the sandy soil assuming optimal weeding. In practice, the red clays are difficult to manage, especially when wet, which may lead to yield reduction. This was a possible reason for the similar yields estimated during resource flow mapping for farms in the same resource group, but on different soil types (Zingore et al., 2006a).

On the sandy soil, yields without nutrients input, attainable yields and maize yield response to addition of N, P and manure declined from FZ1 to FZ4 (Figure 3). The baseline yields simulated for the FZ1 on the sandy soil were within the range of 2-3 t ha^{-1} reported by Grant (1981). There was a strong response to mineral N without P applied on FZ1 on the sandy soil, suggesting that N and P could be deficient even in the uncultivated sandy soils that contain the largest contents of organic matter (Figure 3a). Also, 10 t ha^{-1} manure could not supply sufficient N; hence combined use of N with manure was required for substantial instantaneous increases in yields across all fertility zones on the sandy soil. As shown already in Figure 1, a 5 year build-up of 10 t ha^{-1} yr^{-1} manure input is needed for substantial yield increases. The yields with SSP matched those with manure on FZ2, but higher rates of N were required when SSP was used (Figure 3b). On FZ3, manure had larger effects on maize yields than SSP, even when N was applied at high rates. Due to the decreasing SOC, manure played an increasing important role for maize production with time. Poor yields (<0.2 t ha^{-1}) were simulated for the FZ4 without fertilizer inputs as soil N and P were severely depleted. FARMSIM simulated poor responses in the FZ4 as it considered poor nutrient recovery efficiencies, using empirical functions (Appendix 1). The actual factors constraining yields in the depleted sands are multiple deficiencies of nutrients including Ca and Zn (Zingore et al 2006c). Modelling effects of base cations and micronutrients could be too complicated; hence for the purpose of simplicity we considered it sufficient to describe nutrient responses in different fertility zones to SOC, which indicated the extent of soil fertility depletion.

8.3.3. Restoration of depleted soils

A major challenge in soil fertility management on smallholder farms is restoration of the depleted fields with poor physical structure and multiple nutrient deficiencies. Simulations for repeated applications of manure to replenish organic matter in FZ4 on the sandy and clays indicated that 10 t manure ha^{-1} for ten years was required to replenish SOC and maize yields to contents similar to those simulated for FZ1 (Figure 5a, b). Ten years of application of manure at 10 t ha^{-1} was also required on FZ4 on the clay soil to restore productivity to that of the original virgin soil, but simulated SOC contents showed that a longer time frame (>30 years) was necessary to replenish organic matter to be equal to the original contents under woodland vegetation (Figure 5c, d). Manure applied at 20 t ha^{-1} for three seasons on an outfield did not substantially increase SOC. In the long-term, addition of N and P together with manure had small effects on SOC, but improved maize yields, except with 10 t manure ha^{-1} on the clay soil. The dilemma for restoration of soil fertility is that poor farms with the most depleted fields are also the farms without access to manure. There is, therefore, little possibility for the poor farms without cattle to raise sufficient amounts of manure or other organic resources to restore soil fertility in depleted fields.

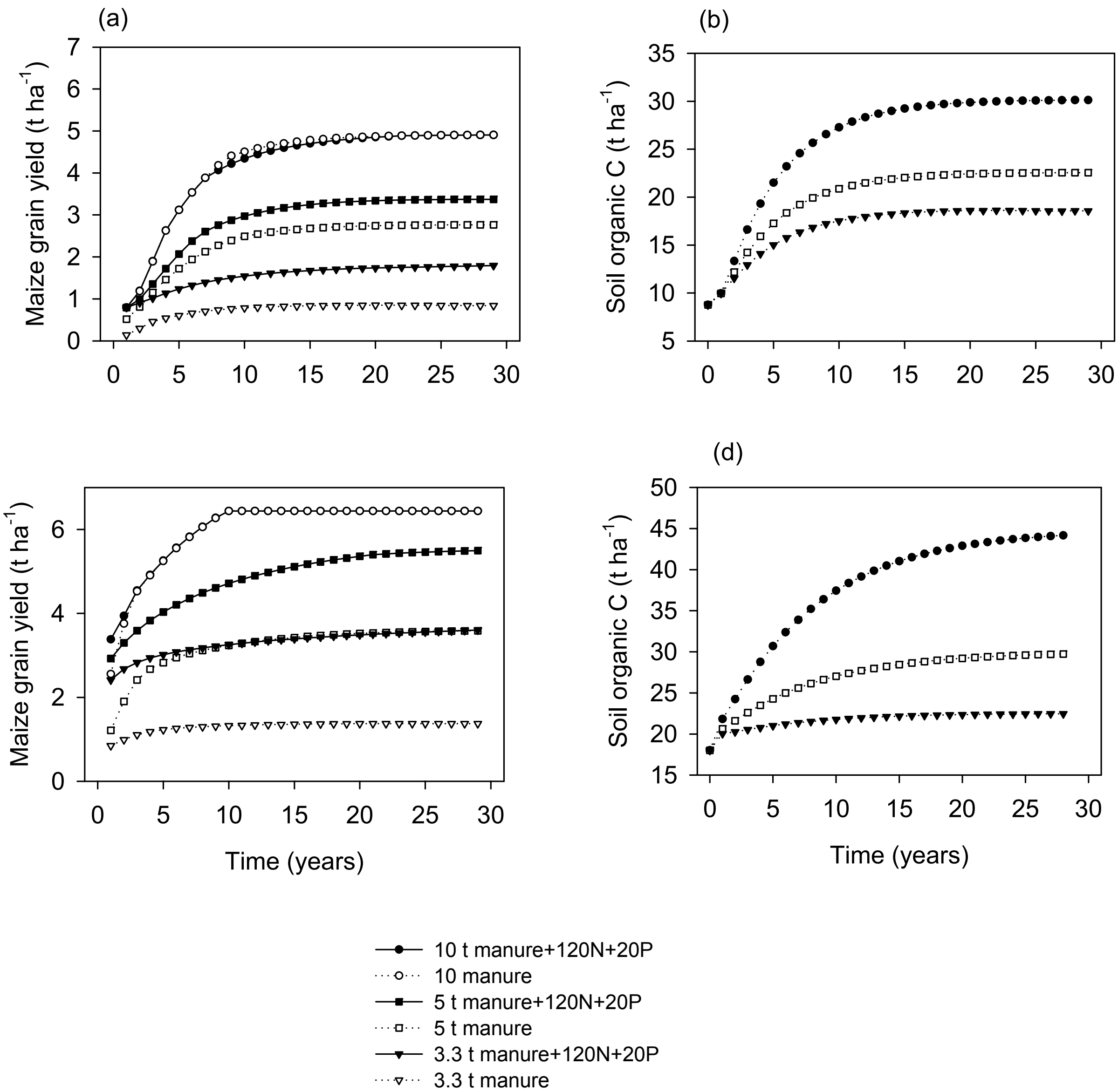


Figure 4. Effects of addition of different rates of manure on restoring SOC and productivity of a depleted sandy soil (a and b) and a depleted clay soil (c and d).

8.3.4. Resource use efficiencies and production potential for farms with different access to resources

Simulated yields and agronomic P use efficiencies (PUE) decreased with decreasing soil fertility, and on this basis, it is sensible for farmers to preferentially apply limited nutrient resources to zones of high fertility. The notable exception was on the sandy soil where manure without mineral N was used more efficiently on FZ3 than on FZ2 (Table 5a).

Without addition of any nutrients, total maize production on the RG1 farms of 3 ha was estimated at 2.5 and 4.5 t per farm on the sandy and clay soils respectively (Table 5a, b). The largest total farm production without nutrient inputs was on the RG1 farms and this is caused by the larger farm size and more fertile soils. The largest total farm maize output with mineral fertilizers on the RG1 farms without manure was 8.7 t per farm on the sandy soil and 10 t per farm on the clay (Table 5a, b). Under this scenario, overall farm resource use efficiency was highest on the sandy soil when P was applied to the plots in the FZ3 at 20 kg ha^{-1} and to the FZ2 at 10 kg^{-1}. This level of production would require an investment of 180 kg N and 50 kg P $farm^{-1}$, which is about double the amounts of N and P used on RG1 farms (Zingore et al., 2006a). In reality, the RG1 farms would require less mineral fertilizers as they also used large amounts of manure.

Considering that the RG1 farmers had access to 10 t manure each year, total farm output and PUE on the sandy soil did not vary substantially with strategies of manure allocation to different plots, both when manure was used alone or in combination with mineral N fertilizer. The efficiencies of the different manure allocation strategies on the clay soil were dependent on the use of mineral fertilizers. Concentrating manure on the most fertile plots on the clay soil out-performed the options for applying manure to two plots or spreading the manure evenly across the farm, both when manure was used alone or in combination with mineral N (Table 5b). When applications of both mineral and organic nutrient resources was considered, production was largest (9.3 t per farm) on the RG1 on sandy soil when manure was concentrated on one of the plots in FZ3, and mineral N and P applied to the most fertile plot (Table 5a). Yields simulated for this strategy after 5 years showed that production would decrease to 7.9 t per farm (Table 6a). This is because the yield increases in the plots with manure were smaller than the decrease in the plots with mineral N and P. The best strategy for the RG1 farm on the clay soil was simulated when manure was concentrated to the most fertile plot (FZ2) and mineral N and P applied to the two plots in the FZ3 (Table 5b). After five seasons, maize production in the best strategy decreased marginally, due to the slower decline in responses to N on the plots without manure

(Table 6b). These results show clearly that optimal strategies for nutrient allocation for one season based on short term response trials are not necessarily optimal in the medium term.

Productivity and PUE between plots varied most on RG2 farms, which consisted of plot types of all three fertility zones (Table 7). Applying nutrient resources on the FZ4 led to marginal yields gains and poor resource use efficiency, hence model output suggested that nutrient resources should be targeted to the FZ2 and FZ3. Since the RG2 farmers had only 5 t manure, they are unlikely to compromise production on the homefields and mid-fields by applying manure to outfields for several seasons to restore fertility and productivity. Production potential on the RG2 farms with a maximum of 50 kg P and 180 kg N per farm from mineral fertilizers alone was about 5.4 t and 8.5 t per farm on the sandy and clay soils respectively. This was less than the production with similar N and P application rates on the RG1 farms due to the poor productivity on the outfields and the smaller sizes of mid-fields on the RG2 farms. On the RG2 farm on clay soil, 5 t of manure was used most efficiently when concentrated on the most fertile field, with or without N (Table 7b). Distribution of manure between the homefield and mid-field had small effects on total farm production and PUE on the clay soil. The maximum maize production on the on the sandy soil was found when manure targeted to the plot in FZ3 and mineral N and P to the plot in FZ2. Whilst this strategy was initially the most productive, it was not appropriate in the medium term as it led to a yield reduction of 1 t per farm on the sandy soil and 0.5 t per farm on the clay soil after 5 years (Table 8a, b).

Without addition of nutrient resources, maize production on a typical RG4 farmer on the sandy soil was only 0.2 t maize farm^{-1} if all arable land is sown to maize (Table 9). Maize yields increased to only 0.4 t farm^{-1} with mineral fertilizers. Assuming an optimistic scenario where 3.3 t manure was available, the maximum maize production was less that 1 t farm^{-1} (Table 9). The small yields and poor response to mineral fertilizers were similarly observed in experiments on depleted sandy soils. Maize production without fertilizer inputs for an RG4 farm on the clay soil was estimated at 0.8 t farm^{-1}. Total farm production increased to 1.7 and 1.8 t farm^{-1} with mineral fertilizers and manure respectively. The yields were larger on the clay soil due to higher inherent fertility. Maize production on the RG3 farms was greater than on the RG4 farms on a similar soil type due to larger farm sizes (Table 9).

Table 5. Maize production (t ha^{-1}) and PUE (kg grain kg P applied^{-1}) for typical RG1 farms as affected by soil type, farm size, within-farm variability of soil fertility, access to resources and resource allocation strategies: (a) sandy soil; (b) clay soil.

(a) Sandy soil

Strategy	FZ2 (1 ha)		FZ3 (1 ha)		FZ3 (1 ha)		Total farm production
	Yield	PUE	Yield	PUE	Yield	PUE	Yield
1	1.1	-	0.7	-	0.7	-	2.5
2	3.5^{1}	80	2.6^{2}	30	2.6^{2}	30	8.7
3	1.6	71	1.4	100	1.4	100	4.4
4	1.1*	-	1.8	110	1.8	110	4.7
5	2.8	85	0.7*	-	0.7*	-	4.2
6	3.2	71	2.3	43	2.3	43	7.8
7	3.4	70	2.5	50	2.0^{0}	-	7.9
8	2.7^{0}	-	3.2	60	2.0^{0}	-	7.9
Best strategy	3.5^{1}		3.2		2.6^{2}		9.3

(b) Clay soil

Strategy	FZ2 (1 ha)		FZ3 (1 ha)		FZ3 (1 ha)		Total farm production
	Yield	PUE	Yield	PUE	Yield	PUE	Yield
1	1.9	-	1.3	-	1.3	-	4.5
2	5.2^{2}	95	3.1^{2}	45	2.6^{1}	40	10.0
3	2.8	128	1.9	85	1.9	85	6.6
4	3.7	180	2.3	100	1.3*	-	7.3
5	5.7	190	1.3*	-	1.3*	-	8.3
6	4.0	100	2.7	71	2.7	71	9.4
7	4.7	140	2.7	50	2.2^{0}	-	9.6
8	5.7	120	2.2^{0}	-	2.2^{0}	-	10.1
Best strategy	5.7		3.1^{2}		2.6^{1}		11.4

See Table 4 for description of scenarios.

*Plot not selected for manure application; ^{0} No P applied, ^{1}P applied at 10 kg ha^{-1}; ^{2}P applied at 20 kg ha^{-1}.

Table 6. Maize productivity (t ha^{-1}) of the different plots and whole farms for the RG1 farms after five years of cultivation: (a) sandy soil; (b) clay soil.

(a) Sandy soil

Strategy	FZ2 (1 ha)	FZ3 (1 ha)	FZ3 (1 ha)	Total farm production
	Yield	Yield	Yield	Yield
1	0.5	0.4	0.4	1.3
2	2.2	1.4	1.4	5.0
3	1.8	1.8	1.8	5.4
4	0.5	2.1	2.1	4.7
5	3.4	0.4	0.4	4.2
6	2.4	1.9	1.9	5.7
7	3.4	2.7	1.1^{0}	7.2
8	2.0	4.3	1.1	7.4
Best initial strategy	2.2	4.3	1.4	7.9

(b) Clay soil

Strategy	FZ2 (1 ha)	FZ3 (1 ha)	FZ3 (1 ha)	Total farm production
	Yield	Yield	Yield	Yield
1	1.5	0.9	0.9	3.3
2	4.6^{2}	2.6	2.1	9.3
3	3.3	2.5	2.5	8.3
4	4.6	3.2	0.9	8.5
5	6.4	0.9	0.9	8.2
6	4.0	2.6	2.6	9.2
7	4.7	3.2	1.7	9.6
8	6.4	1.7	1.7	9.8
Best initial strategy	6.4	2.6	2.1	11.1

See Table 4 for description of scenarios.

Table 7. Maize production (t plot^{-1}) and PUE (kg grain kg^{-1} P applied) for typical RG2 farms as affected by soil type, farm size, within-farm variability of soil fertility, access to resources and resource allocation strategies: (a) sandy soil; (b) clay soil.

(a) Sandy soil

Strategy	FZ2 (1 ha)		FZ3 (0.5 ha)		FZ4 (1 ha)		Total farm production
	Yield	PUE	Yield	PUE	Yield	PUE	Yield
1	1.1	-	0.6	-	0.2	-	1.9
2	3.5^{1}	80	1.3^{2}	30	0.6^{2}	20	5.4
3	1.6	71	0.7	100	0.2	-	2.5
4	1.9	80	0.4*	-	0.2*	-	2.7
5	3.2	71	1.2	43	0.2	-	4.6
6	2.7^{0}	-	1.6	60	0.2^{0}	-	4.5
Best strategy	3.5		1.6		0.6		5.7

(b) Clay soil

Strategy	FZ2 (1 ha)		FZ3 (0.5 ha)		FZ3 (1 ha)		Total farm production
	Yiel d	PUE	Yield	PUE	Yield	PUE	Yield
1	1.9	-	0.7	-	0.8	-	3.4
2	5.2^{2}	95	1.6^{2}	45	1.7^{1}	30	8.5
3	2.8	128	1.0	85	0.8*	-	4.6
4	3.7	180	0.7*	-	0.8*	-	5.2
5	4.0	100	1.4	71	1.4^{0}	-	6.8
6	4.7	140	1.1^{0}	-	1.4^{0}	-	7.2
Best strategy	4.7		1.6		1.7		8.0

See Table 4 for description of scenarios.

*Plot not selected for manure application; ^{0} No P applied,^{1}P applied at 10 kg ha^{-1}; ^{2}P applied at 20 kg ha^{-1}.

Table 8. Maize productivity (t ha^{-1}) of the different plots and whole farms for the RG2 farms after five years of cultivation: (a) sandy soil; (b) clay soil.

(a) Sandy soil

Strategy	FZ2 (1 ha)	FZ3 (0.5 ha)	FZ4 (1 ha)	Total farm production
	Yield	Yield	Yield	Yield
1	0.5	0.2	0.2	0.9
2	2.2	0.7[2]	0.4	3.5
3	1.8	0.9	0.2	2.9
4	3.4	0.4	0.2	4.0
5	3.4	1.0	0.2	4.6
6	2.2	2.1	0.2	4.3
Best strategy	2.2	2.1	0.4	4.7

(b) Clay soil

Strategy	FZ2 (1 ha)	FZ3 (0.5 ha)	FZ3 (1 ha)	Total farm production
	Yield	Yield	Yield	Yield
1	1.5	0.5	0.8	2.8
2	4.6[2]	1.3	1.5	7.4
3	3.3	1.2	0.8	5.3
4	4.6	0.5	0.8	5.9
5	4.0	1.3	1.0	6.3
6	4.7	0.8	1.0	6.5
Best strategy	4.7	1.3	1.5	7.5

See Table 4 for description of scenarios.

Table 9. Maize production (t ha^{-1}) and PUE (kg grain kg^{-1} P applied) for typical RG3 and RG4 farms as affected by soil type, farm size, within-farm variability of soil fertility, access to resources and resource allocation strategies

Strategy	RG3 Sand (2.2 ha)		RG3 Clay (2.2 ha)		RG4 Sand (1 ha)		RG4 Clay (1 ha)	
	Yield	PUE	Yield	PUE	Yield	PUE	Yield	PUE
1	0.4	-	1.8	-	0.2	-	0.8	-
2	0.9[1]	20	3.7[1]	30	0.4[1]	20	1.7[1]	30
3	1.5	71	4.0	57	0.7	71	1.8	57

[1]P applied at 10 kg ha^{-1}

8.3.5. Labour productivity for application of manure to different plots

On the sandy soil, labour productivity was least on the depleted fields (FZ4), but there was a small difference between FZ2 and FZ3 (Table 10). The poor labour productivity for use of manure on the depleted outfields on the sandy soil is due to the small yield response to manure applied and large amounts of labour required to transport manure to fields furthest from homesteads, which is a disincentive for farmers to apply manure to FZ4 for the purpose of restoring soil fertility. Labour for manure application was used most efficiently on FZ2 on clay soil (45-48 kg maize $manday^{-1}$) and this was at least 20 kg maize $manday^{-1}$ greater than the labour productivity on FZ3 and FZ4 on the same soil type (Table 10). When labour is a major constraint, RG1 and R2 farmers should therefore focus application of manure on the best fields where returns to labour invested are highest.

Table 10. Labour productivity for different rates of manure applied to the different fertility zones on a hactare basis.

Manure application rate (t ha^{-1})	Labour productivity (kg maize $manday^{-1}$)					
	Sandy soil			Clay soil		
	FZ2	FZ3	FZ4	FZ2	FZ3	FZ4
3.3	25	29	3	45	25	20
5	20	23	5	45	21	15
10	21	15	5	48	22	15

8.3.6. Implications of farm maize production for food sufficiency

The poor farms with an average household size of 4 people require at least 400 kg of maize for consumption annually, without considering other food requirements. The poor farmer on the sandy soil cannot meet their annual maize requirement, even when the maize is grown on the whole farm (Table 11). The RG4 farmers usually work for the wealthy farmers to supplement income from their own farms, which further compromised their own production. The RG4 farm on the clay soil has potential to produce 1.3 t maize each year in excess of that required for household consumption. RG1 and RG2 farms can potentially produce at least 5 t of maize each year above what they require for consumption, which makes maize production more viable for the farms that owned cattle.

Table 11. Potential maize production (t $farm^{-1}$), maize requirement (t $household^{-1}$) and excess maize (t $farm^{-1}$) for sale (assuming maize was the only crop cultivated).

	Sandy soil			Clay soil		
Farm type	Maximum production	Maize requirement	Excess maize for sale	Maximum production	Maize requirement	Excess maize for sale
RG1	9.3	0.8	8.5	11.4	0.8	10.6
RG2	5.7	0.6	5.1	8.0	0.6	7.4
RG3	0.9	0.6	0.3	3.7	0.6	3.1
RG4	0.4	0.4	0	1.7	0.4	1.3

8.3.7. Further model development

Farmers' decision making on allocation of their limited resources is influenced by multiple factors, corresponding to both the biophysical and the socio-economic environments in which farmers operate. Among the biophysical factors, competition by weeds, long-term changes in weed infestation levels as affected by management (e.g. rotations, fertilizer applications, weeding), and the relationship between labour invested and weed reduction represent important aspects not yet accounted for in the model. As mentioned before, resource management practices such as transport and incorporation of manure require much labour, precluding their suitability for the socio-economic conditions on smallholder farms (Zingore et al., 2006a). On mixed farms, farmers are also faced with difficult choices on investing cash, labour and organic nutrient resources to competing crop and livestock production activities. These aspects will be considered in future versions of FARMSIM, which is currently being further developed.

8.4. Conclusions

The dynamic but simple modelling approach using FARMSIM was sufficient to capture the main effects of resources use on SOC and maize production. The model demonstrated that soil fertility gradients develop rapidly when different rates of manure are applied following change of land-use from native woodland to maize cultivation. Soil organic C, maize production and maize yield response to mineral N and P fertilizers declined rapidly without application of manure. Large amounts of manure were required over several seasons to restore productivity. About 10 t manure ha^{-1} yr^{-1} were required to maintain SOC at original content under woodland. Results for the clay soil indicated that it is not necessary to maintain SOC at contents originally found under woodland, as this was not efficient for crop production with limited nutrient resource. Desirable contents of SOC, based on productivity, were achieved in the long-term with manure applied at 5 t ha^{-1}. On the sandy soil with a small capacity to store SOC, efficiency of maize production in the long-term differed little with manure application rate. Most efficient strategies of use of organic and mineral fertilizers differ depending on resource availability and soil fertility status of plots. Strategies effective in the short-term may not be effective in the medium/long-term, as shown by the decline in overall farm production on RG1 and RG2 farms on the sandy soil after 5 seasons of employing the strategy that was initially most efficient. A simple analysis taking into account the amount of labour needed for implementing the different strategies showed that if labour is a major constraint, concentration of resources on the fields closest to the homestead is the best option. Simulations with FARMSIM showed that the consequence is then a rapid development of strong SOC gradients within the farm, similar to the current situation of smallholder farms in reality.

CHAPTER 9

Concluding Remarks

9.1. Concluding Remarks

Soil fertility on different plots varied considerably within and across smallholder farms in Zimbabwe. The wide differences in soil fertility were due to three factors: (i) inherent differences in soil fertility (clay and sandy soils); (ii) the number of years fields have been under cultivation and; (iii) management practices. Soil organic C (SOC) declined rapidly when native woodlands were cleared for subsistence cultivation of maize without addition of nutrient resources, coupled with removal of residues to feed cattle (Chapter 2). Maize contributed little to SOC under such management due to small amounts of residues returned, especially in the coarse-textured soil where this small input was combined with a small capacity of the soil to stabilize SOC physically. A substantial fraction of SOC originally present in woodland soils remained in the soil after long-term cultivation suggesting that this fraction was chemically stabilized. Organic material with large contents of polyphenols and lignin could be important for sustainable SOC management on coarse-textured soils.

Spatial variability in soil fertility within farms, on plots of the same soil type and cultivated for similar periods, was driven by differential management of nutrient resources. Farmer surveys and resource flow mapping provided insight into nutrient resource allocation strategies by smallholder farmers in different wealth categories in Murewa, Zimbabwe (Chapter 3). Farmers identified cattle ownership as the main indicator of wealth status, due to the many roles that cattle play in the household economy. In addition to cattle ownership, wealthy farmers had larger farm sizes and used larger amounts of mineral fertilizers than poor farmers. Wealthy farmers typically concentrated manure on fields closest to homesteads and little on fields further away and this explained, to a large extent, the steep gradients of decreasing soil fertility with increasing distance from homesteads observed. Such gradients were not observed on poor farms that had no access to cattle manure and used small amounts of mineral fertilizers. During resource flow mapping exercises and focused group discussions, the following emerged as the major issues that need consideration for improving efficiency of resource use on smallholder farms in Murewa:

- Evaluation of the efficiencies with which different types of mineral fertilizers and manure are used across the soil fertility gradients and assessment if the current strategies whereby farmers concentrate nutrient resources on homefields are the most suitable in terms of resource use efficiency, productivity and profitability.
- Implications on farm-level productivity of moving resource allocation to plots of lower fertility for one or more seasons, rather than keeping adding large amounts of nutrients to the more fertile plots.

- Except on the richest farms, grain legumes are mostly targeted to the less fertile plots with few nutrient inputs. The grain legumes only benefit from residual benefits of fertilizers directly applied to the maize crop in the preceding season. There is thus need to assess if the benefits of biological N_2-fixation, and productivity on farms could be improved by increasing the area under grain legumes on the more fertile plots.

These issues were investigated in field experiments, which revealed large gaps in yields and nutrient use efficiencies across different fields on the same soil type or fields on contrasting soils. For fields on a similar soil type, maize yields were larger and nutrient use efficiencies higher on the homefields than the outfields (Chapter 4). It is therefore rational for farmers to concentrate resources on homefields. This is attributed to the high soil fertility status of the homefields following many years of addition of large amounts of manure and mineral fertilizers. On sandy soils, large amounts of manure applied over several seasons were required to significantly improve maize yields on the depleted outfields. Given low availability of manure, there are limited opportunities for farmers to apply large amounts of manure for several seasons on the outfields to restore soil fertility without getting immediate crop yield benefits. The poor maize yields on these depleted sandy soils, even with large amounts of mineral N and P fertilizers, were due to deficiencies of other nutrients including Ca and Zn (Chapter 5).

Soyabean yields were poor across depleted sandy soils due to the multiple nutrient deficiencies (Chapter 6). Manure application significantly increased soyabean yields and N_2-fixation. On such soils, applying mineral P and manure to maize led to greater economic and nutrient use efficiencies. On a clay soil with moderate fertility, applying manure to soyabean was economically more viable than applying it to maize, indicating that farmers can benefit by targeting nutrients to grain legumes. For smallholder farmers to benefit substantially from production of grain legumes, they need to apply nutrient resources on these crops, especially manure. They also need expand the areas grown to the grain legumes on the more fertile plots, although production should be optimised in relation to maize, which is the food security crop.

Different modelling approaches were used to explore strategies for use of nutrient resources. An analysis of trade-offs of resource management strategies was done using a modelling approach of linking different existing models (linear programming and simulation models) through a farm-level database (Chapter 7). The analysis showed that availability of labour and nutrient resources and economic performance of management options were the major factors that determined feasibility of different resource management options. Exploring long-term resource management strategies with a simple but dynamic model, FARSIM, showed that manure was the resource driving the variability of soil fertility and maize yields (Chapter 8). The model results highlighted the need to consider both short-term and long-term impact of resource management strategies on maize productivity, as some strategies that performed best in the short-term were not ideal for the medium-term or long-term.

Manure is an essential resource for sustainable maize production on the sandy soils and for rehabilitation of degraded fields due to its capacity to improve SOC and supply multiple nutrients. A previous study that assessed suitability of resource management options on smallholder farmers in Zimbabwe about three decades ago, established that cropping was not sustainable on the granitic sands without integrating crops with livestock (Rodel and Hopley, 1973). They suggested that at least 24 t of manure was required every season on a three ha farm (applied at 8 t ha^{-1} in combination with 90 kg N and 20 kg P ha^{-1}) for optimal crop production, which is in agreement with the results for effects of manure we simulated for the sandy soil using FARMSIM. However, our simulation results indicate that smaller amounts of N are required when applied in combination with manure. Three decades ago, average manure application rates were about 3.3 t ha^{-1}, which meant that cattle ownership had to increase threefold to achieve the target of 8 t ha^{-1}. This was not possible for several reasons. Firstly, farmers lacked capital to invest in livestock and the high labour demand for managing the large amounts of manure. Secondly, the cattle stocking rates were already in excess of the carrying capacity of the communal grazing areas. Recommended stocking rates in the smallholder farming areas are 8-11 ha per livestock unit (livestock unit is equivalent 250 kg live body weight), but stocking rates were 3 ha per livestock unit (Shumba, 1984). Conditions on smallholder farms in Zimbabwe have worsened over the past decades. Due to increasing population, farms are smaller and livestock ownership has decreased, except with the rich farmers. This implies that there are limited opportunities for the farmers to increase manure use by investing in cattle, as increasing pressure on communal grazing land leads to degradation. Farmers considered soil fertility gradients as a temporary feature of their farm and assumed that these gradients could be reduced if mineral fertilizers are available at affordable prices. The analysis in thesis suggests that mineral fertilizers have a small effect on heterogeneity of soil fertility in farming systems where stover is removed to feed livestock. As manure use was the principal factor inducing differences in soil fertility between different plots, under the current management gradients of soil fertility are likely to be a permanent feature due to limited amounts of manure available.

Basal fertilizer containing Zn (Compound Z: 8%N; 6%P; 6%K; 6.5%S; 0.8% Zn) was produced in Zimbabwe and commercial farmers applied it on maize to correct Zn deficiencies (G.

Hutchinson, personal communication). Use of Zn fertilizers has not been promoted in the smallholder sector, which has led to severe Zn deficiencies on fields without a history of manure use. We observed symptoms of zinc deficiency in outfields in Murewa, and that maize biomass was improved by addition of zinc in a greenhouse experiment.

9.2. Further Research

Further research is required to explore resource use at the village level, taking into account the interactions between farms, for example, in terms of flow of nutrient resources between farms and from communal grazing areas to arable fields. This can be useful to identify opportunities for poor farmers who do not own cattle to benefit from communal resources and their association with wealthy farms.

This study mainly focused on soil fertility and crop production across soil fertility gradients and paid limited attention to livestock. A more detailed analysis of the contribution of cattle to the household economy is required to better guide farmers' decisions on investment in cash, labour and nutrient resources between the cropping system and the livestock system.

Further experiments are required to assess the merits of adding zinc to depleted fields on sandy soil under field conditions and evaluate if that is economically viable, especially for the poor farmers. Studying interaction between water and nutrient use efficiencies across soil fertility gradients can also be an important area for further experimental work.

Analysis at the farm-scale has indicated the limited scope for improvement of productivity of smallholder farms with the current resources available. This is particularly true for the poorer farmers. Attention to pricing and markets for nutrient inputs and produce, and other policies to support the smallholder farmers will be required to allow improvements of productivity. Such approaches will undoubtedly favour those farmers who already have access to more land and labour.

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Summary

Soil fertility on smallholder farms in Africa varies considerably between different plots on the same farm or on different farms due to differences in soil type and management. Improved understanding of the socio-economic and biophysical variability and functioning of smallholder farming systems is required for improved targeting of soil fertility management interventions. The overall objective of this thesis was to characterize the spatial variability of soil fertility on smallholder farms in Zimbabwe and resource management patterns driving this variability. Appropriateness of resource management strategies for the heterogeneous biophysical and socio-economic conditions on the smallholder farms was also assessed in field experiments and explored using different modeling approaches.

Long-term changes in soil organic C and N were measured in fields cultivated for different years after woodlands were cleared for smallholder maize production without fertilizer inputs. Soil organic matter declined rapidly in the initial 5 years of cultivation due to small amount of inputs and removal of stover to feed livestock. Less than 35% of the soil organic C was derived from maize, even after prolonged maize cultivation. Commercial farming with intensive use of mineral fertilizers and incorporation of maize stover led to more gradual decline of soil organic matter: at equilibrium, contents of SOC in a clay soil were 15 t C ha^{-1} greater than the contents in similar soils on smallholder farms and maize contributed 67% of the soil organic C.

Resource flow mapping was used to characterize differential management of nutrient resources between and within farms for three seasons. Wealthy farmers who owned cattle concentrated large amounts of manure on fields closest to their homesteads, which led to gradients of decreasing soil fertility with increasing distance from the homesteads. Soil available P was more concentrated on the plots closest to homesteads on wealthy farms (8 to 13 mg kg^{-1}), compared with plots further from the homesteads and all of the plots on poor farms (2-6 mg kg^{-1}). Partial nutrient balances on the wealthy farms were largest on the homefield. N and P partial balances differed little across plots on the poor farms (–5 to +5 kg per plot) due to limited nutrients applied and small off-take from small harvests. Maize was grown on large areas on the best fields, and also received the largest amounts of nutrients, as it is the food security crop.

Experiments were conducted for three seasons to assess maize yields following application of 100 kg N ha^{-1} with different rates of P (0, 10, 30, 50 kg ha^{-1}) from two sources (single super phosphate and cattle manure) on homefields and outfields of smallholder farms on a granitic sandy soil and a red clay soil. Maize yields without nutrient inputs were larger on the homefields

than outfields for both soil types in the order: homefield clay (1.5-2.1 t ha^{-1}) > homefield sand (0.8-1.0 t ha^{-1}) ~ outfield clay (0.6-0.8 t ha^{-1}) > outfield sand (0.1-0.3 t ha^{-1}). Maize yield responses and nutrient use efficiencies were greater on the homefields that outfields. Maize responded poorly to application of mineral fertilizers or manure on the outfields on the sandy soil. Application of manure at a rate of more than 15 t ha^{-1} yr^{-1} was required to restore productivity of the outfields on the sandy soil. In a pot experiment, it was established that the depleted sandy soil was deficient in many nutrients including N, P, Ca and Zn.

Soyabean yields were also poor on the depleted sandy soil (<0.2 t ha^{-1}) and responded little to SSP due to deficiency of other nutrients. Manure application significantly increased soyabean 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 most efficiently in maize-soyabean rotations, when SSP was applied to maize. Soyabean yields were larger on clay soil with moderate fertility (0.4-0.7 t ha^{-1}) and were significantly increased by application of both SSP and manure. On the clay soil soyabean fixed more than 67% of its N, except with SSP (40%). Within soyabean-maize rotations, P use efficiency was higher when manure and SSP were applied to maize (43 and 25%) than when applied to soyabean (20 and 19%). In a farmer managed experiment, soyabean and groundnut grain and stover yields varied widely across different plots on farms in different wealth categories. Yields were largest (~1 t ha^{-1} for soyabean and ~0.8 t ha^{-1} for groundnut) on homefields of wealthy farms which were more fertile due to good past management. Yields were poor (< 0.5 t ha^{-1}) on the mid-fields and outfields on the wealthy farms and all fields on poor farms. Soyabean and groundnut yields correlated well with available P (R^2 = 0.5-0.7) and soil organic C contents (R^2 = 0.4-0.6), but yields also varied widely for fields with similar fertility due to differences in management by farmers.

A farm characterization tool linked to optimization and simulation models was used to analyze trade-offs between resource use options on farms in contrasting wealth categories. Crop production was not viable on a poor farm without cattle, which relied on selling labour to meet food security. Although the performance of the poor farm could be improved by expanding the area sown to groundnut, this was not feasible due to large labour requirements. On a wealthy farm, maize was most productive when manure was applied in combination with cattle manure. Without constraining nutrient resources farm income was increased substantially by expanding the management strategy where maize was grown with a combination of cattle manure and ammonium nitrate fertilizer. Groundnut intensification on the wealthy farm would be more economic and labour-effective if a small area is grown with basal fertilizer (7%N, 14%P_2O_5,

8%K), rather than expanding the area sown to groundnut without fertilizer inputs. Despite reducing nutrient balances for the arable plots, feeding groundnut residues to lactating cows increased net cash balance by 12-18% for the current year through increased milk production.

A simple dynamic model (FARMSIM) was used to explore long-term effects of resource management strategies on variability of soil fertility and maize yields. Simulations with FARMSIM showed a rapid development of gradients of soil organic matter and maize yields within the farm when different rates of manure were applied. About 10 t manure ha^{-1} yr^{-1} applied was required to maintain soil organic matter at the original contents under woodland. Results for the clay soil indicated that it is not necessary to maintain SOC at levels originally under woodland, as this was not efficient for crop production with limited nutrient resources. Desirable contents of soil organic matter, based on crop productivity, were achieved in the long-term with manure applied at 5 t ha^{-1}. Strategies effective in the short-term may not be effective in the medium/long-term, as shown by the decline in overall farm production on RG1 and RG2 farms on the sandy soil after 5 seasons of employing the strategy that was initially most efficient. A simple analysis taking into account the amount of labour needed for implementing the different strategies, showed that if labour is a major constraint, concentration of resources on the fields closest to the homestead is the best option. The study highlights the need to consider the wide biophysical and socio-economic variability on smallholder farms for designing appropriate strategies for soil fertility management.

Samenvatting

De bodemvruchtbaarheid op kleine boerderijen in Afrika varieert aanzienlijk tussen verschillende plots op dezelfde boerderij en tussen verschillende boerderijen als gevolg van verschillen in bodem type en beheer. Beter begrip van de socio-economische en biofysische variabiliteit is noodzakelijk voor een verbeterde doelgerichtheid van interventies in het beheer van de bodemvruchtbaarheid. Het doel van dit proefschrift was de karakterisering van zowel de ruimtelijke variabiliteit van bodemvruchtbaarheid op kleine boerderijen in Zimbabwe als van de patronen binnen het beheer van de beschikbare middelen die deze variabiliteit sturen. De geschiktheid van strategieën om de beschikbare middelen te gebruiken binnen de heterogene biofysische en socio-economische omstandigheden zijn verder ook getest in veldexperimenten en verkend met behulp van verschillende simulatie-studies.

Lange termijn veranderingen in bodemorganisch C (koolstof) en N (stikstof) werden gemeten in velden onder cultivering voor verschillende duren sinds boskap, terwijl de kleine boeren maïs verbouwden zonder bemesting. Het bodemorganisch materiaal nam snel af in de eerste 5 jaar van cultivering door de geringe hoeveelheid inputs en de verwijdering van maïs resten welke gebruikt werden als veevoer. Minder dan 35% van de C in het organisch materiaal kwam van maïs, zelfs bij langdurige cultivering van maïs. Velden van commerciële boeren met intensief gebruik van minerale meststoffen en en met onderwerking van de maïs residuen, lieten een meer geleidelijke afname van het bodem organisch materiaal zien: bij evenwicht waren de hoeveelheden bodem organisch C in een kleibodem 15 ton C per hectare groter dan die in vergelijkbare bodems bij de kleine boeren, en maïs was verantwoordelijk voor 67% van het bodemorganisch C.

Karteringen van hoe de boer de beschikbare middelen gebruikt en hergebruikt binnen zijn boerderij zijn toegepast om de verschillende beheerstypen van de beschikbare nutriëntbronnen te karakteriseren tussen en binnen boerderijen over drie seizoenen. Rijke boeren in het bezit van vee concentreerden grote hoeveelheden mest op de velden het dichtst bij hun huis, wat leidde tot gradiënten van afnemende bodemvruchtbaarheid met toenemende afstand tot hun woonhuis. Bodembeschikbare P (fosfaat) was meer geconcentreerd op de velden het dichtst bij het woonhuis bij de rijke boeren (8 tot 13 mg kg^{-1}), vergeleken met velden verder van het huis bij de rijke boeren en alle velden van de arme boeren (2 – 6 mg kg^{-1}) . Gedeeltelijke nutriënt balansen van de rijke boerderijen waren het hoogst op het thuisveld (20 tot 30 kg N en 13 kg P per veld), maar namen af tot 10 tot 20 kg N en 6 tot 9 kg P per veld in de middenvelden en -7 tot +10 kg N en -1 tot +1 kg P per plot op de buitenvelden. De balansen van N en P verschilden weinig van plot tot plot op de arme boerderijen (-5 tot + 5 kg per plot) omdat weinig nutriënten gegeven werden en er weinig biomassa van het veld weggenomen werd van de kleine oogsten die werden behaald. Maïs werd verbouwd op grote oppervlaktes op de beste velden, en deze maïs kreeg ook de grootste hoeveelheden nutriënten, omdat dit het gewas is dat voor voedselzekerheid moet zorgen.

Experimenten werden uitgevoerd gedurende drie seizoenen om de maïs oogst te kunnen bepalen bij toepassing van 100 kg N ha^{-1} bij verschillende hoeveelheden van P (0, 10, 30, 50 kg ha^{-1}) van

twee verschillende bronnen (enkelvoudig super fosfaat (SSP) en dierlijke mest). Het experiment werd uitgevoerd op thuisvelden en buitenvelden van kleine boerderijen op zowel zandbodems als op rode kleibodems. De maïsoogsten zonder gebruik van nutriënten waren groter op de thuisvelden vergeleken met de buitenvelden op beide bodemtypes. De volgorde was van de grootte van de oogst was: thuisveld klei (1.5 – 2.1 t ha^{-1}) > thuisveld zand (0.8 – 1.0 t ha^{-1}) ~ buitenveld klei (0.6 – 0.8 t ha^{-1}) > buitenveld zand (0.1 – 0.3 t ha^{-1}). De respons van zowel de maïsoogst als de efficiëntie van nutriëntgebruik was groter op de thuisvelden dan op de buitenvelden. Maïs reageerde weinig op de toevoeging van zowel minerale meststoffen als dierlijke mest op de buitenvelden op zandige bodem. Toevoeging van dierlijke mest met een hoeveelheid van meer dan 15 t per hectare per jaar was nodig om de productiviteit van de buitenvelden op zandige bodem tot significante niveaus te herstellen. In een pot experiment werd vastgesteld dat de gedegradeerde zandige bodem tekorten vertoonde in veel nutriënten waaronder N, P Ca (Calcium) en Zn (zink).

De oogst van soja was ook laag op de gedegradeerde buitenvelden op zand (<0.2 t ha^{-1}) en ze reageerde weinig op SSP als gevolg van het gebrek aan andere nutriënten in de bodem. De toepassing van dierlijke mest leidde tot een significante toename van sojaoogst, een stabilisatie van de oogst over drie seizoenen en ook tot een significante toename van de proportie van N_2 gefixeerd door soja (gemeten met behulp van de natuurlijke hoeveelheid van ^{15}N) van 60% naar 83%. Op de zandige bodem werd P het meest efficiënt gebruikt in maïssoja rotaties als het werd toegevoegd aan maïs. Soja oogsten waren groter op kleibodems met gemiddelde vruchtbaarheid (0.4 – 0.7 t ha^{-1}) en ze werden significant verhoogd door de toevoeging van SSP en dierlijke mest. Op de kleibodem fixeerde soja meer dan 67% van zijn N, behalve als SSP toegevoegd werd (40%). Bij sojamaïs rotaties was de P gebruiksefficiëntie hoger wanneer dierlijke mest en SSP werden toegepast op maïs (43 en 25%; bij toepassing op soja werden de waardes 20 en 19%). In een experiment beheerd door boeren varieerden de oogsten van soja en pinda korrel en overige biomassa sterk over de verschillende velden op boerderijen in verschillende klassen van rijkdom. De oogsten waren het hoogst (~ 1 t ha^{-1}) voor soja en ~0.8 t ha^{-1} voor pinda) op de thuisvelden van rijke boeren, die een betere bodemvruchtbaarheid hadden als gevolg van het goede beheer in het verleden. De oogsten waren laag (< 0.5 t ha^{-1}) op de midden en buitenvelden op de rijke boerderijen en op alle velden op de arme boerderijen. De oogsten van soja en pinda vertoonden goede correlaties met beschikbare P (R^2 = 0.5 – 0.7) en bodemorganische C hoeveelheden (R^2 = 0.4 – 0.6), maar de oogsten varieerden sterk in velden met vergelijkbare bodemvruchtbaarheid als gevolg van verschillend beheer door boeren.

Een software programma waarmee boerderijen gekarakteriseerd kunnen worden gekoppeld aan software voor optimalisatie en simulatiemodellen werd gebruikt om de uitruil te analyseren tussen bron gebruiksopties op boerderijen in contrasterende categorieën van rijkdom. Gewasproductie was niet levensvatbaar op boerderijen zonder vee, die afhankelijk waren van de verkoop van hun arbeid om voedselzekerheid te bereiken. Alhoewel de prestatie van de arme boer verbeterd kon worden door de oppervlakte waarop pinda verbouwd werd uit te breiden, was dit geen optie vanwege de grote hoeveelheid benodigde arbeid. Op een rijke boerderij was maïs het meest productief wanneer minerale meststoffen werden toegepast in combinatie met dierlijke mest. Zonder de beschikbare nutriëntbronnen te beperken nam het bedrijfsinkomen significant toe door de beheersstrategie waarin maïs wordt verbouwd onder de toepassing van een combinatie van dierlijke mest en ammonium nitraat meststoffen breder toe te passen. Pinda intensificatie op de rijke boerderijen zou meer efficiënt zijn vanuit het economisch oogpunt en vanuit het oogpunt van arbeid wanneer een kleine oppervlakte verbouwd zou worden met toepassing van minerale meststoffen (7% N, 14% P2O5, 8% K) vergeleken met het uitbreiden van de oppervlakte waarop pinda verbouwd wordt zonder toepassing van meststoffen. Ondanks het feit dat het de nutriënt balans van een veld reduceert, is het gebruik van pinda gewasresten als voer voor lacterende koeien positief voor de netto geld balans (+12 – 18%) voor het lopende jaar doordat de melkproductie toeneemt.

Een eenvoudig dynamisch model (FARMSIM) is gebruikt om de lange termijn effecten van beheersstrategieën voor de beschikbare middelen op de variabiliteit van de bodemvruchtbaarheid en de maïsoogst te verkennen. Simulaties met FARMSIM lieten een snelle ontwikkeling zien van sterke gradiënten van bodemorganisch materiaal en maïsoogsten binnen een boerderij wanneer verschillende hoeveelheden dierlijke mest werden toegepast. Ongeveer 10 t dierlijke mest per hectare per jaar was nodig om het bodemorganisch materiaal op het originele niveau bij bosgebruik te houden. De resultaten voor de kleigrond wezen erop dat het niet nodig is om het bodemorganisch C op het niveau bij bosgebruik te houden, omdat dit niet efficiënt was voor gewasproductie bij limiterende nutriëntbeschikbaarheid. De gewenste gehaltes van bodemorganisch materiaal, gebaseerd op gewasproductie, werden bereikt op de lange termijn met dierlijke mest toepassing op een niveau van 5 t per hectare per jaar. Strategieën die effectief zijn op de korte termijn hoeven niet effectief te zijn op de middellange tot lange termijn, zoals het afnemen van de totale boerderij productiviteit op RG1 en RG2 boerderijen op zandige bodem aantoont na het 5 jaar lang toepassen van een strategie die initieel op seizoensbasis het meest efficiënt was. Een simpele analyse die de hoeveelheid arbeid meeneemt die nodig is voor het uitvoeren van de verschillende strategieën liet zien dat, als arbeid een belangrijke beperkende factor is, het concentreren van de beschikbare middelen op de velden het dichtst bij het huis van de boer de beste optie is. Deze studie benadrukt de noodzaak om de brede biofysische en socioeconomische variabiliteit op kleine boerderijen mee te nemen wanneer men de juiste strategieën van bodem vruchtbaarheidsbeheer wil ontwerpen.

Appendix 1

Nutrient use efficiencies and crop responses to N, P and manure applications in Zimbabwean soils: exploring management strategies across soil fertility gradients

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Abstract
Spatial variability in crop yields within smallholder farms of Sub-Saharan Africa is caused by gradients of declining soil fertility with increasing distance from the homestead. Due to this heterogeneity, soil management recommendations based on regional soil surveys are of limited value. The variability in soil qualities within-farms should be considered when designing management strategies, and their feasibility analysed by integrating results at the farm livelihood scale. FARMSIM is a dynamic bio-economic model for analysis and exploration of tradeoffs in resource and labour allocation in heterogeneous smallholder farms. Focusing on farm-scale strategies, the approach to simulation of soil and crop processes in FARMSIM (the sub-model FIELD) is aimed for simplicity, but keeping the necessary level of complexity to capture heterogeneity in resource use efficiencies. To test this approach, the sub-model FIELD was calibrated against chronosequences of woodland clearance in three agroecological zones of Zimbabwe (with soil textures of 3, 10, 35% clay), and used to simulate the creation of soil fertility gradients and different strategies of N, P and manure applications to maize and soyabean rotations in homefields and outfields of smallholder farms on clayey and sandy soils (CH, CO, SH, SO, respectively). The results of the simulation of management strategies were tested against on-farm experimental data from Murewa, Zimbabwe. The model produced satisfactory predictions (r^2 0.6 – 0.9) of long-term changes in soil organic C, and of crop responses to N and P and nutrient use efficiencies in the different field types. However, the model results were less accurate to predict crop responses to N and P applications in the SO. Experimental evidence indicated yield limitation by Ca and Zn deficiencies in highly depleted SO, which were not covered in the current version of FIELD. Repeated applications of 16 t ha^{-1} $year^{-1}$ of manure allowed larger responses to applied N and P after 3 years of experiment; such corrective effect of manure was simulated as improved N and P recovery efficiencies in the model. The simulation results in combination with the experimental data suggested that soil fertility gradients affect nutrient use efficiencies operating mostly on the efficiencies of nutrient capture. A typology of fields according to the type of management interventions needed is introduced, based on a generic application of FIELD with this parameterisation.

Keywords: Sub-Saharan Africa, FARMSIM, resource use efficiency, rotations, maize, soyabean

1. Introduction

Spatial variability in crop yields within smallholder farms of Sub-Saharan Africa is caused by gradients of declining soil fertility with increasing distance from the homestead (Zingore et al., 2006a; Tittonell et al., 2005b). Such heterogeneity in soil fertility within the farm is caused largely by the differential long-term management of the various production units (fields). The limited labour and nutrient resources are preferentially allocated to fields close to the homestead by smallholders. The large variability in the calculations of nutrient stocks for different units within heterogeneous farms led Smaling et al. (2002) to conclude that regional soil surveys are of limited value at the farm level, and that variability at farm scale should be considered when designing soil management strategies. While some studies suggested the need for designing management strategies to reduce the magnitude of the soil fertility gradients, homogenising productivity within the farms (Mtambanengwe and Mapfumo, 2005), others showed that preferential allocation – concentration – of limited resources such as manure and mineral fertilisers to the more fertile fields gave greatest aggregate yields at farm scale (Rowe et al., 2006). However, unravelling such discrepancies requires going beyond the aggregation of results from single fields and focusing analysis at the farm scale, considering multiple indicators of success meaningful to farmers.

Crop production in smallholder systems is limited by multiple resources that operate simultaneously, and cause resource imbalances that eventually lead to poor yields (Kho, 2000). In such sense, Lopez-Ridaura et al. (2006) indicated that options for more sustainable management of resource-poor farming systems should be designed pursuing maximum marginal use efficiencies for the most limiting resources, and maximum absolute use efficiencies for resources locally in more abundant supply. This translates, for the smallholder systems under study, as the need for identifying the most limiting resources for crop production, which are likely to vary across soil fertility gradients. For example, large differences in the efficiency of use of nutrient resources (N, P, K and manure) by maize, soyabean and groundnuts grown on home gardens as opposed to outfields of small farms of Kenya (Vanlauwe et al., 2006) and Zimbabwe (Zingore et al., 2006b) suggest different limiting factors for crop yield. N and P fertiliser applications led to better results in terms of maize yield and nutrient recovery for infields as compared to outfields of smallholder farms in the Sudan savannah zone of Togo, and the results varied strongly between dry and wet years in an experiment over several years (Wopereis et al., 2006). However, not only soil fertility but also the diversity in the intensity and timing of certain agronomic practices (e.g. planting and weeding), which are often associated to the perceived fertility of different fields (Tittonell et al., 2005b), are key factors influencing on-farm crop yield variability (Mutsaers et al., 1995).

A recent study in western Kenya pointed to the existence of resource use efficiency gradients associated with soil and management diversity within smallholder farms, and suggested that a proper analysis of ‘efficiency’ indicators such as N use efficiency, labour productivity and/or benefit:cost ratios in relation to different management practices should also consider the long-term dynamics of the system (Tittonell et al., 2006). Dynamic simulation models offer opportunities for the integrated analysis of different options available to smallholder farmers to improve productivity of their land, while considering the spatial heterogeneity of their farms, the long-term impact of their operational and strategic management decisions, changes in the biophysical and socioeconomic scenarios, and monitoring multiple indicators of sustainability at different scales. A number of studies are available in which modelling approaches were used for designing sustainable management systems for African smallholders. For example, Diels et al. (2004) explored the potential of different crop rotational and fertilisation schemes to build up soil C and its associated soil properties in southern Benin, using the dynamic soil C model ROTHC (Coleman and Jenkinson, 1995). Jagtap et al. (1999) used the CERES-maize crop growth model to investigate N management and maize variety technologies in three agroecological savannah zones of Nigeria, testing the model against data from international testing nurseries. Several examples of application of the APSIM crop growth model to the plot-scale analysis of different crop and soil management alternatives in low inputs systems are available (e.g. Carberry et al., 1996), including simulations of intercropping, weed management, crop rotation and nutrient management.

In the examples reviewed above, relatively complex, process-based mechanistic models were used. However, the performance of such models may be poor in the data-scarce environments of the tropics (Smaling et al., 1997). Simpler modelling approaches that consider the main factors limiting crop production in smallholder systems may yield sufficiently accurate results to aid decision making on resource allocation (e.g. Janssen et al., 1990) – particularly when the long term is considered (e.g. Abegaz et al., 2006). Ten years ago Van Keulen (1995) summarised the three major disadvantages of using detailed process-based models in such systems, which are: (i) extensive data requirements that often cannot be satisfied; (ii) difficulty of validation since many variables may not have been measured, and certainly not over the time-span necessary to judge their long-term behaviour; and (iii) partial knowledge of many of the underlying processes leading to unbalanced descriptions; i.e. much detail on well-known processes but gross generalisations of other processes that are poorly understood. Thus, modelling for long-term analysis of farming strategies by smallholders, with emphasis on livelihood, requires simple approaches to avoid being overwhelmed by detail, but that are sensitive enough to capture the spatial and temporal variability of the systems, and the impact of proposed technologies for improvement (Giller et al., 2006).

We hypothesised that between- and within-farm heterogeneity in resource use efficiency and in the performance of technological interventions for smallholder systems can be satisfactorily analysed by identifying key determining factors and simulating their interaction using simple models, able to capture the variability of such factors. FARMSIM (FArm-scale Resource Management SIMulator – Tittonell et al., 2005c) is a farm-scale bio-economic model that is developed with the aim of analysing tradeoffs around farming systems and the environment, focusing on strategic decision-making and embracing the spatial and temporal variability of smallholder systems. In this paper we briefly describe the soil and crop modules of FARMSIM and apply them to a case study in Zimbabwe. These modules constitute simple approaches to simulate water and macronutrient dynamics in the soil and supply to crops, next to monitoring indicators of resource degradation, such as soil organic matter dynamics and soil erosion. Our objectives were: (i) to calibrate and test a simple crop-soil model for exploration of soil fertility management (SFM) options available to farmers for later use as an integrated part of farm-scale analysis of livelihood issues; (ii) to analyse the main factors affecting resource use efficiency and crop responses to nutrient management strategies and their interaction; and (iii) to analyse the scope for developing recommendations and technological interventions accounting for the heterogeneity in soil quality within smallholder farms, using the model in combination with experimental data from different soil fertility experiments at Murewa, Zimbabwe. This paper is complementary to a companion paper by Zingore et al. (2006 e), in which the model and concepts discussed here are applied to the long-term analysis of soil fertility management and crop rotational strategies across soil fertility gradients.

2. Materials and methods

2.1 Model description

FARMSIM constitutes a farm-scale decision making shell, where household objectives, constraints and resource allocation patterns are simulated and economic balances calculated, linking the simulation results from different sub-models (Figure 1 A). Crop and soil modules are combined at field plot scale in the sub-model FIELD (Field-scale resource Interactions, use Efficiencies and Long-term soil fertility Development). This model can be parameterised for a variety of crops and soil types. Different combinations of crops and soils can be run to explore the interactions occurring within the farm for different field types (e.g. infields and outfields, annual and perennial crops, etc.). LIVSIM (LIVestock SIMulator) is a sub-model that simulates animal production and maintenance requirements, considering different livestock units characterised by production objectives (dairy, meat, manure, traction), animal species and breeds. The dynamics of nutrients via manure collection, storage and use as well as changes in quality due to management are simulated by the sub-model HEAP, which considers the transfer efficiencies for the different processes under different livestock production systems, types of storage and handling facilities, etc. (Rufino et al., 2006). The variability of the weather and market conditions, as well as the dynamics of resource availability from common lands constitute inputs to FARMSIM that are accounted for and/or modified for scenario simulation, or simulated using auxiliary models.

Experimental data and, when possible, calibrated process-based models are used to generate functional relationships that are built into the various sub-models of FARMSIM. Thus, these sub-models constitute summary models that incorporate processes and interactions in a descriptive rather than an explanatory way, disregarding within season dynamics and operating with time steps of one season. For exploration of medium- to long-term changes in crop productivity and soil quality such summary models may suffice (Bouman et al., 1996). The data requirements of these models can be easily satisfied for most of the African farming systems under study, and their results can be used for exploration of long-term management strategies since the dynamic character of the combined FARMSIM model allows simulation of interactions and feed-backs. A detailed description of the FIELD sub-model, and the derivation of parameters and functional relationships used in the model can be found in Tittonell et al. (2005 c). In the following section, we only describe the key aspects of the simulation of soil C dynamics and soil N and P supply.

Soil organic matter dynamics

Three C pools are considered in the model: C in crop residues and other soil amendments (e.g. manure), C in the active, decomposing organic matter pool (N.B. not synonymous with the microbial biomass), and C in the humified, soil organic matter (Figure 1 B). The active pool represents the 'unprotected' organic matter; on seasonal time steps it can be assumed that the microbial biomass is in a steady-state, so we considered it as an implicit part of the active pool. The humified soil pool represents stabilized (physical + chemical) organic matter. We assumed that all pools decompose following first-order kinetics. For each pool, there is a constant maximum decomposition rate (k_R, k_A and k_S) and a stabilisation fraction (e_A, e_H and e_S) or partitioning coefficient (1 – CO_2-C release). The coefficient e_A represents the growth efficiency of the microbes; e_H is the humification coefficient (chemical stabilisation) and e_S represents the physical stabilisation of C in the soil (the turnover rate k_S is affected by soil texture). Thus our approach follows the conceptual model of soil organic matter stabilisation of Six et al. (2002). A fraction of soil C is considered inert, and a certain amount is seasonally lost by soil erosion (calculated in a soil erosion module). The C/N ratios of the different pools are introduced as model parameters. Other quality aspects of the soil amendments such as lignin and polyphenol contents (Palm et al., 2001) are considered to calculate potential decomposition rates.

Without considering erosion losses, and assuming that the value of the fraction inert is zero, the amount of C in the soil C pool is calculated as:

$$C_S = C_{S(i)} + dC_S/dt * t \qquad \textit{Eqn. 1}$$

The rate of change of soil C is then:

$$dC_S/dt = C_A * k_A * e_A - C_S * k_S + C_S * k_S * e_S \qquad \textit{Eqn. 2}$$

Both k_S and e_S may be integrated in one single rate as:

$$dC_S/dt = C_A * k_A * e_A - k'_S * C_S \qquad \textit{Eqn. 3}$$

Where k'_S represents: $(1 - e_S) * k_S$. This function was fitted to experimental data on long-term changes in soil C, as explained later. The loss of C by water erosion (E_i) is estimated in relation to soil loss (A):

$$E_i = [C_i] * A * Er_i \qquad \text{Eqn. 4}$$

where $[C_i]$ is the concentration of organic C in the soil pool i and Er_i is enrichment ratio of eroded soil (Van Keulen, 1995). Soil loss is calculated according to the Universal Soil Loss Equation (USLE), adapted to tropical conditions (Roose, 1983).

Soil N and P supply

Gross nitrogen mineralisation follows C decomposition, considering the C/N ratios of the different C pools. The C/N ratio of the active OM ($C:N_{AOM} \sim 8$) determines the magnitude of the immobilisation flow from mineral soil N. The net rate of change of mineral nitrogen in the soil can be generically expressed as:

$$dN_{min}/dt = NetN_{min} + N_{fert} - N_{upt} - N_{lost} \qquad \text{Eqn. 4}$$

Where, $NetN_{min}$ is the difference between gross N mineralization and mineral N immobilisation by the decomposing organic pool. N_{lost} is the fraction of total soil mineral N lost by denitrification, volatilisation and leaching. The amount of mineral N available in the soil is partitioned between crop uptake, N immobilisation by microbes and N losses by different processes. This partitioning determines the priority for N allocation to the different processes. In models for high-input farming situations, losses and immobilisation are first discounted, and then the remaining N is assumed to be taken up by the crop (e.g. Wolf et al., 1989). Under low-input conditions, plant N uptake or immobilisation may have priority over leaching (Chikowo et al., 2004).

The potential availability of P from organic sources is treated in a similar way to N, using C:P ratios, particularly for P released from organic amendments and from the decomposing organic material or active OM ($C:P_{AOM} \sim 40$). For inorganic P a simplistic approach is used, in view of the limited knowledge on the transfer rates between stable and labile P pools in the soil, the occurrence of P sorption in tropical soils and the mismatch between labile P and available P observed in several studies (Keating et al., 2003). Total soil P is the sum of the organic and inorganic P pools in the soil, and in the model it constitutes a state variable used to keep track of soil P balances in the long-term. A fraction of the total soil P becomes potentially available, and this corresponds to the amount of available P measured using Olsen extractions (a method widely used for tropical soils – Anderson and Ingram, 1993). The ratio total-to-extractable P has been derived from experimental data for a number of case studies encompassing tropical soils with clay contents ranging between 12 and 44%; this empirical relationship varies for soils of different texture and predicts Olsen-P values satisfactorily ($r^2 > 0.6$) for Acrisols and Nitisols of western Kenya with organic C > 8 g kg^{-1} in the topsoil (Tittonell et al., 2006 b). Similar approaches proved satisfactory for modelling maize response to P in Zimbabwean soils (A. Whitbread, pers. comm.). However, when not enough data is available or when soils out of the tested range are studied, and particularly when the model is used to simulate crop responses to nutrient applications without considering long-term dynamics, the empirical equation developed by Janssen et al. (1990) can be used, which estimates potential soil P supply as a function of (measured) average soil C, extractable P and pH values.

Crop dry matter production and grain yield

Resource-limited total dry matter and grain production are calculated in FIELD on the basis of seasonal resource (light, water, nutrients) availabilities through application of crop-specific resource use efficiencies. For each resource, use efficiencies are disaggregated into resource capture and conversion efficiencies. From the total amount of incident photosynthetically active radiation (PAR) during the season only a fraction is captured (intercepted) by the crop, and this is converted into biomass through a light conversion efficiency coefficient. A simple water balance is used to derive crop-available water, and the water-limited production is calculated using a water use efficiency coefficient. Nutrient-use efficiencies determine nutrient-limited crop production. Nutrient captures are represented by the recovery efficiencies, which are highly affected by the type of nutrient considered, soil properties, crop type and management decisions (e.g. type of nutrient resource used, application rate, method, timing, etc.). Nutrient conversion efficiencies are the inverse of the weighted average nutrient concentrations in grain, straw and roots, and range between crop-specific minimum and maximum values.

Actual crop production in FIELD is calculated as the minimum of water-limited production and production determined by the availability of nitrogen or phosphorus. Since the use efficiency of a certain resource (e.g. N) is affected by correction factors calculated on the basis of the availabilities of complementary resources (P, water), the approach to the simulation of resource interactions follows Liebscher's 'Law of the Optimum'; i.e. as availability of resource A becomes restricted and sub-optimal, the slope of the response to resource B may become less steep before resource A becomes completely limiting for plant growth. Total crop biomass is partitioned between grain, stover and root production through application of crop-specific harvest indexes and shoot to root ratios. The concentration of nitrogen and phosphorus in the crop products is derived from the yield and the uptake of both elements. The nutrient that is limiting is diluted to its minimum value, while the concentrations of other nutrients are derived from uptake and total dry matter yield.

2.2 The case study area

The study focused on the Murewa smallholder farming area (population density 104 km^{-2}), which is located about 80 km east of Harare (17°49'S, 31°34'E), has a sub-tropical climate, and is regarded as a high potential agroecological zone for annual crops production in Zimbabwe. The area receives 750-1000 mm year^{-1} between December and April. The soils in the area are predominantly granitic sandy soils (Lixisols) with low inherent fertility, with dolerite intrusions giving rise to scattered areas of clay soils (Luvisols) in close proximity to the sandy soils (Nyamapfene, 1991). Gradients of decreasing soil fertility are common on the farms in Murewa: soil organic carbon and available P decrease significantly with distance from the homesteads, particularly on farms with cattle, due to preferential application of manure and mineral fertilizers on fields closest to the homesteads (Zingore et al., 2006a). Maize is the main crop grown for food and the market, and strong crop-livestock interactions characterise the farming systems (Mtambanengwe and Mapfumo, 2005): livestock provide draught power and manure to arable fields while crop residues are removed and used as feed during the dry season. Communal grazing is common during the dry season. Manure is collected from kraals where the cattle are kept during the night.

2.3 Model parameterisation

We first calibrated the soil C module of FIELD against data from chronosequences of woodland clearance for arable cropping on different soil types occurring in three agro-ecological zones of Zimbabwe encompassing a wide range of environments (Table 1): Mafungautsi, Masvingo and Chikwaka (Zingore et al, 2005). Fields sampled to build the chronosequences were from outfields on smallholder farms (small to no input use) except in Chikwaka, where also a chronosequence with arable fields from commercial (high input use) farms was built. Subsequently, three experimental datasets (Experiments I to III, Table 2) from Murewa were used to test the model performance to simulate crop responses to applied nutrients and to analyse resource interactions within heterogeneous farms. These data were taken from a series of on-farm studies undertaken in Murewa by Zingore et al. (2006 b, c). Soil data from these experiments that was used to initialise the model included textural composition (sand, silt and clay contents), soil bulk density, carbon and extractable P contents, soil pH, and topsoil and rooting zone depths. Crop-specific values for minimum and maximum concentrations of nitrogen and phosphorus in grain, straw and roots, harvest index (i.e. the ratio of economic yield to total aboveground dry matter production), shoot/root ratio, light and water use efficiencies were derived from different sources in the literature (e.g. Nijhof, 1987; van Keulen and van Heemst, 1982). Nutrient recovery efficiencies were derived from analysis of these datasets (Experiments I and II) in combination with others from Kenya (Vanlauwe et al., 2006), and incorporated in the model as empirical relationships.

To calibrate the soil C module, a correction factor f accounting for external factors affecting the decomposition rates was introduced as a multiplier of k_i, and C losses by soil erosion were simultaneously considered. We first calibrated the model for the sandy soils (3% and 12% clay), whereby we set for convenience the rate modifier, f, to 1. We assumed that the turnover time of the active, non protected pool ($1/k_A$) was 1.44 years, a sensible value for particulate organic matter in a sandy soil under tropical conditions (Bostick et al., 2006). Parameter e_A (set to 0.6) as well as the expression to estimate the enrichment ratios [$Er_i = 7.4 * \text{Soil loss (kg ha}^{-1})^{-0.2}$] were taken from the literature (Van Keulen, 1995). The remaining parameters were calibrated against the measured data. Subsequently, the model was calibrated for the soil with 35% clay content by simultaneously optimizing the rate modifier f and the stabilisation coefficient e_S. The rate modifier f integrated the effects of altered water, temperature and texture in a clayey versus sandy soil. A values < 1 indicated slower decomposition rates in clayey soils, presumably due to the overriding texture effect. The value of e_S was larger in the clayey compared to a sandy soil, reflecting higher C stabilisation capacity of these soils.

The chronosequence data used for model calibration included measurements of natural ^{13}C signatures, which allow differentiation of C derived from plants with C3 or C4 metabolic pathways (i.e. woodland- and maize-derived C, respectively) (Jolivet et al., 2003). Using these markers, Zingore et al. (2005) calculated the amount of recalcitrant woodland-derived C at equilibrium (i.e. after 50 years of cultivation) and the annual amounts of maize-derived C entering the soil C pool at equilibrium (i.e. the term $C_A * k_A * e_A$ in Eqn. 2). These ^{13}C data were used here to calibrate the fraction of recalcitrant C and the stabilisation rate of the decomposing organic matter, which at equilibrium is dominated by maize residues. However, different assumptions were necessary to initialise and run the model for calibration, in relation to the bulk density of the soil, the annual amounts of C inputs into the soil as crop residues and C outputs as soil erosion, and the C:N ratio of the soil organic matter. In long-term simulations using FARMSIM, the C inputs and outputs and the C:N ratio of the soil organic matter are normally calculated in different sub-models. For model calibration we used only measured values related to soil dynamics to reduce number of parameters required

The bulk density (BD) of the soil is used to calculate the soil mass stocks of C (t ha^{-1}), and it was expected to change throughout the chronosequence. Simple empirical relationships were sought to adjust the value of BD as soil C decreased. However, although there was a trend of declining BD with time, the slope of such declines was 0.0004 t m^{-3} $year^{-1}$ for Mafungautsi and Masvingo, and 0.001 t m^{-3} $year^{-1}$ for Chikwaka (between 0.04 and 0.1 t m^{-3} in 100 years), which were smaller than their standard deviation (Figure 2 A). Therefore, average BD values were adopted and kept constant throughout the simulation: 1.53 +/-0.07, 1.46 +/-0.06 and 1.29 +/-0.04 t m^{-3} for Mafungautsi, Masvingo and Chikwaka, respectively.

The annual amount of C inputs to the soil throughout the simulation period was derived from field data consisting of grain yield measurements at different points in the chronosequence (Zingore et al., 2005), and summarised as follows:

- on sandy soils, grain yields start at 2 t ha^{-1}, by 15 years they are 1 t ha^{-1}; by the 50^{th} year they are around 0.5 t ha^{-1};
- on clayey soils, they start at 3.5 t ha^{-1}, fall to 2.2 t ha^{-1} in 10 years, to 1.5 t ha^{-1} in 25 years, to 1.2 t ha^{-1} in 50 years and to 1 t ha^{-1} by 100 years.

The potential amount of crop residues (stover) was calculated using the harvest index (HI = grain biomass / total aboveground biomass). However, HI is also a function of maize yield, decreasing with decreasing yields for the typical range of biomass measured on smallholder farms. Empirical relationships between grain yield and HI were derived from the available data (Table 3) and introduced in the model. Thus, large yields at the beginning of the chronosequence were associated with HI values around 0.5, which decreased as grain yields dropped (e.g. to 0.3 after 15 years and to 0.2 at 100 years, for sandy soils). From all the crop residue (stover) produced, only a certain fraction is incorporated in the soil during ploughing; that fraction varies also according to yield (good yielding crops produce high quality stover for cattle feeding or domestic use, so less is incorporated). Two functions (for sandy and for clayey soils) were derived from field data on residue management (Zingore et al., 2006a) to reflect the change in the fraction of residues incorporated as a function of maize yield (over time); the average fraction incorporated up to equilibrium was 0.25. C inputs to the soil through manure applications are only relevant for fields close to the homestead, which were not sampled for the chronosequences described by Zingore et al. (2005).

The amount of C lost by runoff and soil erosion was also accounted for to calculate the overall C decline rate. A version of the Universal Soil Loss Equation (USLE) adapted for tropical conditions (Roose, 1983) is used in FARMSIM to calculate soil losses. C losses by erosion are expected to increase as the amount of soil organic matter decreases due to less structure, soil compaction, surface crusting and hence less water infiltration (the 'erodibility' factor K of the USLE increases), while declining maize yields lead to less soil cover (factor C of the USLE increases). The factors K and C of the USLE were thus related to changes in soil organic carbon. Due to lack of reliable data to test the USLE estimates, general values for the region were assumed, of up to 12 t ha^{-1} of soil per year in the worst cases (Elwell and Stocking, 1988; Vogel, 1992). Losses of C (and N) by burning were not considered, as they are not relevant in the study area.

The calculated C:N ratios of the soil organic matter for Mafungautsi, Masvingo and Chikwaka were, respectively: 22.2:1, 15.5:1 and 16.0:1 for the initial situation, and 20.7:1, 13.3:1 and 12.5:1 for the final state after 50 years (18.5:1, 13.4:1 and 11.7:1 on average). Since little change was observed in these values throughout the chronosequence (Figure 2 B), their average values were used in the model. The C:N ratio of the active organic matter pool at equilibrium was set at 8:1 (average C:N ratio of the microbial biomass); since after forest clearance large amounts of woody elements are incorporated in the soil the C:N ratio of the decomposing pool was set at 30:1 at the beginning decreasing gradually to 8 after 10 years of cultivation (van Keulen, 1995). The C:N ratio of maize residues was assumed to be 50:1 throughout the simulated period (assuming 45 % C and 0.9 % N in maize stover).

2.4 Model simulations

Once the model had been calibrated against the chronosequence data, it was run for 50 years for the different soil types (cf. Table 1) assuming different annual application rates of organic amendments (manure, crop residues) . This was done to simulate the creation of soil fertility gradients, initialising the distribution of measured soil C into the various pools assumed in the model, for each of the different field types in which the experiments Experiments I to IV took place (homefields vs. outfields in clayey vs. sandy soils – cf. Table 2) representing the soil fertility gradients. The performance of the model to simulate the value of soil C at equilibrium when large amounts of nutrient inputs are used was tested using the chronosequence data derived from soil measurements and management records from commercial farms in Chikwaka (Zingore et al., 2005). The creation of soil fertility gradients by differential organic input use is illustrated by FARMSIM simulations presented in (Zingore et al., 2006 e). For comparison, soil properties measured for the different fields at the beginning of Experiments I to III are presented in Table 3.

We ran the FIELD sub-model for Experiments I to III and compared modelled output with experimental data. Experiments I and II (cf. Table 2) were used to adjust the values for the potential soil N and P availabilities, the resource capture (recovery) efficiencies and the partition coefficients of the crops in the model, whereas Experiment III was used as independent data-set for model testing. Applications of (i) N as mineral fertiliser (0, 30, 60, 90 and 120 kg N ha^{-1}) with and without simultaneous application of 30 kg P ha^{-1} to maize grown in the CH, CO, SH and SO were simulated and contrasted with experimental data. Maize and soyabean rotations in the CH and in the SO with P applications as mineral (SSP: 30 kg P ha^{-1}) and organic (manure: 16 t ha^{-1}, equivalent to 30 kg P ha^{-1}) fertilisers were also simulated. Both soyabean and maize were subjected to four treatments: (i) continuous cultivation control, (ii) maize/soyabean rotation control, (iii) maize/soyabean rotation with P application as manure, and (iv) maize/soyabean rotation with P application as SSP. Maize also received 70 kg N ha^{-1} in treatments (ii) to (iv). Nitrogen was applied as ammonium nitrate and P as single super phosphate. The applied manure had the following properties: 20 – 25% C, 0.9 – 1.2% N, 0.16 – 0.20% P, and c. 40% water content on average.

Several indicators of nutrient use efficiency were calculated from the measured and simulated data, as described in Table 4. We used the mean difference between measured and simulated values, the mean square error and the root mean square error as statistics for assessment of model performance. For the crop response simulations, the comparison between observed and simulated data was done by analysing the different components (intercept, plateau) of the crop response curves separately. Regression and correlation analysis were done to examine the relationship between variables in the data, between certain observed and simulated variables, and to derive empirical relationships to use in the summary models. All statistical analyses were performed using Genstat 8th.

3. Results

3.1 Long-term changes in soil organic carbon

The model simulated the decline in the soil organic C (0-20 cm) following clearance of native savannah for arable cultivation over 60 years satisfactorily (Figure 3). The performance of the model to simulate soil organic C decline under smallholder management, as compared with the available data, was better for the sandy soils of Mafungautsi and Masvingo than for the clayey soils of Chikwaka. Focusing on the smallholder systems, a comparison was also done for the overall decay rate of soil C, by summing up the multiples of each initial C pool times its relative decomposition rate, and comparing it against the decay rate calculated with the measured values from the chronosequence (Table 5). The discrepancies between modelled and measured values found for the clay soils of Chikwaka may be due to the shorter (20 year) time span of the chronosequence soil data available. Model simulations suggested that soil C reached equilibrium after about 12 to 15 years in the sandy soils, whereas for the clayey soil it took more than 40 years to reach equilibrium. The estimated amount of soil organic C in the upper 0.2 m of a soil of such texture, using the empirical relationship of Feller and Beare (1995) for cultivated soils would be ca. 15 t ha^{-1}: in agreement with the amount of soil C at equilibrium simulated by the model. Equilibrium soil C levels were higher under under commercial compared to smallholder farming (Figure 3 D), because of the higher C returns to soil via crop residues and roots as a resulted of the higher crop productivity on these plots. Similar results in terms of comparisons between simulated and measured values throughout the chronosequence were observed with total soil N. Again, the simulation results compared better with the measurements for the sandy soils (Table 6).

In the current setting of the model the active pool had a residence time of about 1.5 years ($1/k_A$), whereas the soil organic matter (minus the recalcitrant fraction) decomposed with a life time of less than 5 years ($1/k_S$); a realistic value for these sandy soils (with poor protection capacity) (Janssen, 1984). However, whereas less than 20% of the decomposing soil C was re-stabilised in the sandy soils (cf. e_S in Eqn. 2 and Figure 1), about half of it was retained in the clayey soil. The amount of C entering the soil C pool every year at equilibrium ($C_A * k_A * e_A$ in Eqn. 2) was calibrated against ^{13}C data; thus, the annual amount of maize-derived C added to the soil at equilibrium (40 years after cultivation) was 33.6, 45.1, and 126.9 kg C ha^{-1} $year^{-1}$ for Mafungautsi, Masvingo and Chikwaka (commercial farms), respectively. Soils derived from cleared savannah vegetation may contain large amounts of charcoal C, which is inert. The model assumes a recalcitrant fraction of the total soil organic C that includes also inert C (cf. Figure 1), which is not a constant proportion but increases as soil C decreases throughout the chronosequence. This corresponds to the woodland-derived C identified through the ^{13}C signatures that were used to initialise and test the model. The recalcitrant fraction represents between 30 and 50% of the initial soil C in these soil types under woodland vegetation, and between 50 and 95% of the soil C at equilibrium for these soils under high-input (commercial) or low-input (smallholder) C management, respectively (Zingore et al., 2005). Higher fractions of originally highly lignified woodland-derived C were observed for the coarser soils, in agreement with the higher C:N ratios measured in these soils throughout the chronosequence (cf. Figure 2)

The model was run to equilibrium for the clay and sandy soils (Table 3), assuming (i) additions of 10 t ha^{-1} yr^{-1} manure and (ii) no manure input, to initialise the soil conditions for the four sites in the experiments: clay homefield (CH), clay outfield (CO), sandy homefield (SH) and sandy outfield (SO). The simulated size of the total organic C pool in the upper 20 cm of the soil at equilibrium was 26.6, 16.0, 15.7 and 8.8 t ha^{-1}, whereas for the active C pool it was 0.79, 0.14, 0.19, 0.04 t ha^{-1}, for the CH, CO, SH and SO, respectively. Considering bulk density values of 1.3 and 1.5 t m^{-3} for the clay and sandy soils, respectively, the amounts of total soil C simulated by the model correspond to 10.2, 6.1, 5.2 and 2.9 g C kg $soil^{-1}$ for the CH, CO, SH and SO, which agreed largely with the measured values (Table 3).

3.2 Crop responses to N, P and manure applications

The variation in the response of maize to N fertilisation rates across soil types and fertility gradients with and without P applications (Experiment I – cf. Table 2) was simulated fairly well by the FIELD sub-model of FARMSIM (Figure 4, Table 7). In general, crop response to N was better simulated for the sandy that for the clay soils. For the homefields on clay soils (CH) the model tended to overestimate total aboveground biomass yields when 0 to 60 kg N ha^{-1} were added in combination with 30 kg P ha^{-1}; for the outfields on the clay soil (CO), simulated biomass yields with high application rates of N and without P were less than the corresponding measured yields. The simulated response to N for the homefields on sandy the soil (SH) was in the order to that of CO. On the sandy outfields (SO), yields were strongly limited by P for the whole range of N application rates; the lack of response to P in such fields was due to the poor P recovery efficiency and to limitation of crop growth by water availability. Besides, maize crops grown in the sandy outfields showed clear symptoms of Zn and Ca deficiencies that were later confirmed by chemical analysis and pot experiments (Zingore et al., 2006 d); such deficiencies are, however, not explicitly considered in FIELD. To further test the performance of the model to simulate crop responses, a comparative analysis was done on the different components of the response curves (Table 7). In general for the response of maize to N, there was better agreement between measured and simulated values for the plateau of the curves, both with and without P, than for the intercepts. The simulated P intercepts (i.e. 30 kg P ha^{-1} with no N) showed the widest differences with respect to the corresponding measurements; these discrepancies were largely influenced by the overestimation of the response to P in the clay homefields (cf. Figure 4 A), since no limitations other than water, N and P were considered in the model.

Figure 5 shows observed and simulated grain yields of maize and soybean under a 3-year rotation across soil types and fertility gradients with and without SSP and manure application (Experiment II – cf. Table 2) Maize and soyabean yields were better simulated for the clay homefields than for the sandy outfields (Figure 5). In general, yields of soyabean when manure was applied tended to be overestimated by the model, whereas those obtained with and without application of SSP were more accurately simulated. For both maize and soyabean, FIELD simulated increasing responses to manure applications from year 1 to year 3, although such an effect was not evident from the data in the case of soyabean. On the clay homefields, the simulated response of maize to SSP was larger than to manure in the first year, but smaller in the third year. On the sandy soils, simulated maize responses to manure were higher than those to SSP throughout the rotation period. In the third season, maize yields simulated on sandy soils with manure were more than double those simulated with application of SSP, and were 5 times larger than for the control (which received also 70 kg N ha^{-1}), reflecting the effect of soil organic C build-up after repeated manure applications (of 16 t ha^{-1} year^{-1}). The residual effect of soyabean on maize yields in the rotation was barely evident from the observed data except in the clay homefield during the third season, when better maize yields were attained than in the control treatment. However, such an effect was masked by the application of 70 kg N ha^{-1} to maize in each season (Table 2).

Figure 6 shows the model results on aboveground maize yield together with the observed data for Experiment III (cf. Table 2). As this dataset was not used to derive any of the empirical relationships incorporated in FIELD, and as the experiment conducted in different farms than Experiments I and II, this simulation can be considered as an independent test of the model. FIELD was initialised with the soil values presented in Table 3 for the home- and outfields on clay and sandy soils, with P applications of respectively 0, 10 and 30 kg ha^{-1} as manure or as SSP in the presence of 100 kg N ha^{-1} (cf. Table 2).The response to P sources was well simulated by the model for the clay outfields and for both field types on the sandy soils (Figure 6). For the homefields on the clay soil (CH) the observed data indicated poor response to P applied as manure and a linear response to P applied as SSP. The model results for the CH overestimated the response to manure-P at 10 kg ha^{-1} and underestimated the response to SSP-P at 30 kg ha^{-1}. Yields simulated by the model were limited by P availability in the CH; however, when 10 or 30 kg ha^{-1} P were applied the simulated yields became limited by N. Since additions of P as manure also adds more available N for the crop, yields were larger than those obtained with P applied as SSP. These modelling results did not match the response data observed for the first season – although they did for the subsequent seasons (data not shown), but they are illustrative of how the sub-model FIELD of FARMSIM simulates the effect of interacting resources (N and P in this case).

3.3 Biomass production and nutrient use efficiencies across soil fertility gradients

In spite of the large variation in the treatments simulated and in the background soil properties, the simulated total aboveground biomass and grain yields were in reasonable agreement with the measured yields for both maize and soyabean (Figure 7 A - D); r^2 values for simulated vs. observed biomass and grain yields were 0.81 and 0.82 for Experiment I, 0.72 and 0.71 for Experiment II-maize, 0.86 and 0.81 for Experiment II-soyabean, and 0.88 and 0.81 for Experiment III, respectively. Aboveground biomass yields tended to be overestimated by the model, particularly for the range of higher yields. In the case of maize, this is in agreement with the fact that the value of the harvest index (HI) as a function of aboveground crop biomass was better described by a parabolic function (r^2 0.60) as observed earlier for tropical maize genotypes (Tittonell et al., 2005 a); e.g. for Experiment I, the HI started decreasing for biomass values > 10 t ha^{-1} (Figure 8 A). Another possible source of variation in the accuracy of the model to simulate crop biomass resides in the variability of the relationship between nutrient uptake and crop yield, as calculated from measurements of nutrient concentration in the plant, and biomass yield. The data from the three experiments used for our modelling study indicate a narrow variation in the N:P uptake ratios fluctuating around 5.6 +/-1.6 (Figure 8 B), which is in agreement with the values indicated for cereal crops (Sadras, 2005). However, the data from the three experiments also indicate that the conversion efficiency of N and P by the plant was generally poor (Fig 8 C and D). In most cases, the observed points were close to the maximum N and P concentrations in the plant, indicating that other growth factors (e.g. water, micronutrients) were limiting the ability of the crop to convert absorbed nutrients into biomass.

As the coefficient of conversion of nutrients into biomass fluctuated narrowly around the minimum values for all treatments (including soil type, field type, nutrient source and application rate combinations), the main source of variation for the overall N and P use efficiencies across the soil fertility gradients was caused by differences in the interception and absorption of the available nutrients by the crop (capture efficiencies). The recovery of the applied N in Experiment I decreased from the home-fields to the outfields for both soil types and with increasing N application rates, particularly when no P was applied (Table 8). Application of 30 kg P ha^{-1} maintained the recovery of N around relatively high values (c. 0.6 to 1.0) with N rates of up to 90 kg ha^{-1}, except in the sandy outfield. The fate of the fraction of the applied N not taken up by the crop (i.e. 1 – apparent N recovery) depends on the capacity of the soil to retain such N; in these sandy soils, most of it will be lost by leaching (Chikowo et al., 2004). The recovery of P applied at a rate of 30 kg ha^{-1} (cf. Table 2) increased substantially with the application rate of N, particularly in the homefields. Non-recovered P is less prone to losses due to its poor mobility in the soil, and careful management may allow build-up of the P stock in the soil in the long run (Zingore et al., 2006 b). The partial factor productivity or agronomic use efficiency of the applied N was the largest in the homefields on sandy soils, particularly when P was also applied, reflecting the larger responsiveness of the crops grown on these fields (cf.

Figure 4 C). Nutrient recovery efficiencies and agronomic use efficiencies were very poor on the sandy outfields, indicating important potential nutrient losses.

The ability of FIELD to simulate nutrient use (capture and conversion) efficiencies was examined in relation to the independent dataset from Experiment III (Figure 9 A – D). The model results show a constant P capture efficiency close to 1, indicating that maize yields were limited by P for most treatments and soil conditions; i.e. virtually all the available P (as estimated using the Olsen extraction method) from soil and fertiliser sources was taken up by the crop. In case of N, the capture efficiencies were more variable. Whereas the upper boundary line drawn in Figure 9 A represents capture efficiencies of almost 1, points closer to the lower boundary line represent cases of poor capture efficiency and, depending on the extent of N immobilisation by the soil organic fraction, prone to N losses. The uptake of N and P by the crop were fairly well simulated by the model as compared with the measured data for Experiment III (r^2 0.63 and 0.70, respectively, with RMSE's of 30.2 kg N ha^{-1} and 5.9 kg P ha^{-1}). However, the maximum simulated P uptakes in the aboveground biomass were below 30 kg ha^{-1}, whereas the measured P uptake reached 44 kg ha^{-1} (Figure 9 D). Measurements of plant P contents are subject to substantial methodological errors (due to the low P concentrations - <0.2 mg kg^{-1}), and the subsequent calculation of P uptake is also dependent on the value of the harvest index. Despite these uncertainties, the lack of agreement between measured and simulated P uptakes for the higher range of values may also explain the discrepancies between the modelled and simulated yields for the homefields on clayey soils, where the largest maize yields and nutrient uptakes were attained (cf. Figure 6 A).

The range of N and P conversion efficiencies were well simulated by FIELD (Figs. 9 C and D), with a tendency of the model to overestimate the dilution of N and underestimate the dilution of P in the plant tissues. This is because average values for the maximum and minimum N and P concentrations in maize were used, derived from a wide range found in literature (Tittonell et al., 2006 b). Important genotypic differences in N and P concentrations in cereal crops as affected by breeding (i.e. favouring protein content in grain) are known to affect the N:P ratios in the plant (Dudley, 1974). The accuracy of the simulations would be improved by incorporating crop coefficients for specific genotypes. However, while such coefficients may be available for a number of improved cultivars, they are certainly less frequently found for the local varieties grown by smallholder farmers in Africa. Nevertheless, the ranges of N and P conversion efficiencies simulated by FIELD are satisfactory when considered in relation to the wide range of conditions simulated for Experiment III: two soil types (3 vs. 35% clay), two field types (home- vs. outfields), two sources of P (manure vs. SSP) and three application rates of P (0, 10 and 30 kg ha^{-1}).

3.4 Embracing heterogeneity: a conceptual framework for designing management interventions

FARMSIM is being conceived as a model to simulate livelihood strategies at farm scale, including the exploration of alternative soil, crop and livestock management options that have an impact on the welfare of rural households and on the environment. The crop and soil sub-model FIELD is expected to allow exploration of alternative management practices targeting the existing heterogeneity in soil quality within smallholder farms, as well as the creation of such heterogeneity in the long- term. The scheme in Figure 10 illustrates the potential use of FIELD to design management interventions. Figure 10 A shows the relative decrease in organic C stocks of soils having different textures that were cultivated during 40 years without C and nutrient inputs and with little return of crop residues (which are used for livestock feeding) to the soil. The relative decay in soil C was faster for sandy soils, due to less physical protection (Six et al., 2002). The equilibrium soil C under cultivation is also reached at different times for soils of different texture, and the actual loss of C from the clay soil during the 40-year period is larger than for the coarser soils (cf. Table 6).

The existence of different soil types subjected to differential long-term management constitutes the basis for the development of 'fertility niches' within the farm that should be targeted differently when designing management interventions. 'Blanket' recommendations on fertiliser use according to the inherent soil properties (soil maps) and climatic conditions and/or those derived from the results of on-station experiments (e.g. Smaling et al., 1992; Schnier et al., 1997) are of limited use for the farmer, as illustrated in Figure 10 B and C. Disregarding the heterogeneity created by the historical management (i.e. all fields assumed to have received no inputs during the 40 years) and focusing only on the length of the period under cultivation, the response to N applications (0 – 120 kg N ha^{-1}) in the presence of 30 kg P ha^{-1} was simulated using FIELD for clay (35% clay) and sandy (3% clay) soils after 5 years (Figure 10 B) and 15 years (Figure 10 C) of cultivation. Available P in the soils for the simulation was derived from the data in Table 4, corresponding to the home- and outfields on clay and sandy soils (CH, CO, SH, SO), respectively. These simulation results represent a first step in the identification of heterogeneous units within the farm for fine-tuning recommendations (or decision-making by the farmer), as they point to the existence of (i) poorly-responsive fertile fields (CH), (ii) responsive fields (CO and SH) and (iii) poorly-responsive poor fields (SO).

When long-term management is also considered, the distribution of these three field types in terms of the area of the farm they occupy will also vary for farms of different resource endowment, as demonstrated by the contrasting C and nutrient balances and soil properties measured on different farms in Murewa by Zingore et al. (2006 a). Following this typology of fields within smallholder farms different strategies might be pursued, for example:

- Type I (poorly-responsive fertile fields, CH): interventions aimed at conserving/sustaining soil fertility through organic resource management; intensification and optimisation of agronomic practices to increase resource use efficiency (e.g. optimum planting dates, effective weed and pest control, use of improved varieties – representing cash and labour investments); diversification of production activities by growing cash crops (e.g. high value vegetables if markets are accessible);
- Type II (responsive fields, CO and SH): interventions aimed at improving resource capture efficiencies by eradicating resource unbalances and limitations (e.g. using mineral fertilisers); increasing nutrient stocks in the long term and avoiding losses by managing the timing of resource allocation; the success in achieving high resource capture efficiencies determines higher labour productivities, thereby representing an extra incentive for farmers;
- Type III (poorly-responsive poor fields, SO) interventions aimed at rehabilitating/aggrading soil quality, with emphasis on increasing soil organic matter; as high quality organic resources such as cattle manure are not abundant, and given the poor yields obtained in this fields, fallowing the land (or part of it) for a certain period with inclusion of indigenous N-fixing legume species (e.g. "indifallows" – Mapfumo et al., 2005) may be an option; these fields are normally unfenced, allowing free grazing of crop residues, thus residues may be collected and conserved for later incorporation in the soil before planting.

This set of examples on management recommendations is generic and not exhaustive. However, the proper interventions to address productivity of these different field types and their feasibility will vary from farm to farm according to their capacity to invest in resources (labour, cash, nutrients) for crop production.

4. Discussion

4.1 Heterogeneity in soil fertility, nutrient limitations and use efficiencies in time and space

After land has been cleared of native vegetation and brought into cultivation there is a rapid decrease in soil organic matter content (and associated nutrient pools) as a consequence of decreased C inputs to the soil, higher soil temperatures and tillage increasing C mineralisation rates, and of soil C losses by erosion. Labile soil C pools are rapidly depleted and a new soil C equilibrium level is reached, mainly determined by the magnitude of the pool of stabilised organic matter complexed with soil minerals and by the recalcitrant C pools, reaching a new equilibrium soil C level under cultivation. The rates of these changes and the level of soil C equilibrium vary with different soil types (cf. Figs. 3 and 10). Soil recently brought into cultivation has usually a high nutrient status, and water availability may initially be the only limiting factor to crop production. This is followed by a phase when the soil structure is still good and crops respond strongly to fertilisers (cf. Figs. 4, 5, 6 and 10). As the soil degrades further other nutrients, such as P, K and S, become limiting (J. Anderson, pers. comm.). When soils are highly degraded, applications of fertilisers may produce negligible crop responses (cf. Figs. 4 D, 5 B and D, 6 D and 10 C) and organic matter inputs (or fallow) are required to restore soil physical and chemical properties to enable plant roots to exploit the soil volume. These soil degradation processes take place at different rates within the various fields of smallholder farms, leading to their characteristic spatial heterogeneity often referred to as soil fertility gradients.

Such heterogeneity must be considered when designing technological interventions, as illustrated by running simulations with the sub-model FIELD of FARMSIM (Figure 10). For example, the response to fertiliser applications varied for soils with different organic C contents, particularly in case of the sandy soils (Figs. 4 and 6). Similar trends were observed by Vanlauwe et al. (2006) for the finer soils of western Kenya and by Bationo et al. (2004) in West African sandy and loamy soils, comparing degraded and non degraded sites. Mtambanengwe and Mapfumo (2005) indicated a threshold value of 0.46 g C kg^{-1}, for comparable sandy soils from Zimbabwe, below which no responses to mineral fertilisers would be expected. Potentially, soil C thresholds for a significant response to nutrient applications could also be determined by running FIELD for soils cultivated over different periods or subjected to different rates of organic matter amendments (as in Figure 10). However, within-farm soil fertility gradients cannot be exclusively explained by the spatial heterogeneity in soil organic C; as illustrated by the experimental data from Zingore et al. (2006 b and c), that crops often responded positively to mineral P applications (Figs. 4 and 5). Although in sandy soils P availability may be closely associated to their organic C content, high and low P contents were measured in soils with either high or low C contents (cf. Table 3), suggesting that both soil quality indicators (at least) should be considered when designing interventions. Exploring scenarios for allocation of scarce nutrient resources within the farm requires also the different areas (field sizes) of the various land qualities to be included in the analysis, a feature that can be addressed using FARMSIM.

4.2. Limitations of the current approach within FARMSIM

Currently the FIELD sub-model of FARMSIM considers N, P and K as limiting nutrients for plant production, and the effects of other cations and micronutrients are not explicitly simulated. Zingore et al. (2006 d), however, demonstrated that continuous cultivation of the sandy soils without inputs leads to degradation in soil fertility including strong deficiencies of Ca and Zn and increased soil acidity. Responses to applied N and P were only seen in those degraded fields after three years of repeated manure applications (cf. Figure 5). Repeated manure applications over a number of seasons are known to have corrective effects on soil pH, exchangeable bases and micronutrients (e.g. Pichot et al., 1981; Bationo and Mokwunye, 1991). However, as the dynamics of cations in the soil is not considered in the current version of FIELD, the lack of crop responses to nutrient applications simulated for the sandy outfields are basically due to P availability, and essentially to the linkage between P recovery efficiency and soil C which is included in the model as an empirical function. Although this approach produced satisfactory results for this exercise, as well as in previous modelling studies (e.g. Smaling and Janssen, 1993; Pathak et al., 2003), the use of empirical functions makes the model case-specific. To count on a more generic approach that can be applied to the analysis of other farming systems, further efforts linking nutrient recoveries to soil properties that reflect the variability across soil fertility gradients are necessary, and are currently in development. However, a quick glance at the calculated N and P recovery efficiencies in Table 8 suggests that developing generic functional relationships of wide applicability to estimate nutrient capture by different crops on different soil/field types constitutes a major challenge. Such functions should also consider the effect of nutrient application rates and the interaction between different available nutrients (Kamprath, 1987). As the recovery of N and P followed closely the variation in soil C, specially in sandy soils, such a relationship may be further examined and potentially used to generate empirical relationships across a wider range of agroecological conditions.

Unlike the widely-tested QUEFTS approach of Janssen et al. (1990) in which case-specific empirical functions between nutrient uptake and biomass production are fitted to available data, FIELD simulates the interaction between resources in a generic way. Reduction factors are calculated on the basis of the target requirements (light- and/or water-determined) and actual availabilities of other interacting resources, and used to restrict the maximum conversion efficiency of a certain resource, without giving preferential weight to any of these interactions. This approach, although simplistic, proved sufficiently accurate to simulate the range of N and P conversion efficiencies for a wide range of conditions (Experiment I; Figure 9 C and D). In an earlier version of the sub-model FIELD, the concept of N and P stoichiometry in the plant was used to set target N and P uptakes based on an optimum N:P ratio for maximum yields. Experimental data for maize, sorghum and pearl millet under Sahelian conditions in West Africa indicated an optimum ratio of ~ 10 (Penning de Vries and Van Keulen, 1982). However, a recent review by Sadras (2005), including the wider biologically-oriented study of Agren (2004), indicated a wide variation in the N:P ratio of crops (and autotrophs in general) grown under different agroecological conditions, with N:P ratios for cereal crops attaining maximum yields fluctuating between 4:1 and 12:1.

4.3 Potential applications of FARMSIM in exploring future scenarios for African farmers

The agronomic efficiency for maize production of N and P applied as mineral fertilisers varied widely for the different field types in our case study in Zimbabwe (Table 8). However, in their study in the Sudanean zone of West Africa, Wopereis et al. (2005) measured different degrees of variability in the agronomic efficiency of applied N between infields and outfields, although the average values calculated over three years (216 observations) did not differ between field these types: 19.0 vs. 18.7 kg grain kg N^{-1} for the infields and outfields, respectively. Such results may pose a question mark on the capacity of this indicator to reflect efficiency in the use of resources, when average values are considered. A comparison of the agronomic efficiency against the fertiliser:maize price ratio must be considered to derive suitable application rates of nutrients from an economic perspective, within short time horizons. However, the information provided by the efficiency of nutrient recovery may be of greater interest, particularly when more than one season is considered. From economic and environmental perspectives, management strategies should be oriented towards improving the 'capture' of nutrients brought into the system by manure and/or fertiliser applications (Giller et al., 2006), and thus the fate of applied and not recovered nutrients in subsequent seasons becomes relevant.

Therefore, the evaluation of management technologies should be done by considering longer-term horizons and tradeoffs between tactical (over the season) and strategic (over a number of seasons) objectives. Such tradeoffs may involve conflicting efficiency (productivity) and sustainability (stability, resilience) objectives; so that sustainability may be also seen in a broader sense as an indicator of 'efficiency' in the long term. Bio-economic models that retain a proper level of detail on the biophysical processes modelled may play an important role in such analyses (e.g. Zingore et al., 2006 e). The simple and low data-demanding crop and soil modules of FARMSIM produced acceptable results in the simulation of long-term C and N changes in the soil (cf. Figure 3, Tables 5 and 6) and of mid-term crop rotations (Figure 5). Further testing of the model against long-term (i.e. 20 years) experimental data on crop rotations including climatic variability is, however, needed.

The present study illustrated the creation of niches of differential soil fertility within smallholder farms as a consequence of the limited availability of nutrient resources in smallholder farms. Moreover, early prototyping studies in Zimbabwe categorically indicated that farming on sandy soils is unsustainable without integration of the livestock component to provide manure (Rodel and Hopley, 1973). All this reinforces the idea that heterogeneity within smallholder farms in Africa is the created by what Giller et al. (2005) referred to as "the (de)fault of poverty", an allusion to the lack of resources, and in stark contrast with the assumption that farmers purposely create "islands of soil fertility" that contribute to the strategic diversification of their production activities (e.g. Scoones, 2001). In view of the limited access to plant nutrient resources that smallholder farmers face, experimental and/or modelling studies should place more emphasis on the analysis of crop responses to the application of small amounts of nutrients (e.g. micro-doses, point-placement), targeting the inflexion point of the input-output functions (i.e. the point of maximum incremental resource use efficiency). The identification of such a zone of the response curve for the various niches soil of fertility and across seasons of variable rainfall poses a difficult challenge in experimental design, and thus it may be better accomplished by modelling-aided studies.

In conclusion, this modelling approach proved sufficiently sensitive to the heterogeneous conditions of smallholder farms of Zimbabwe. As such, it can be used to explore management strategies and analyse their impact/feasibility at farm-scale considering the long-term dynamics of the system, while complementing parallel analyses of socio-economic constraints. This study also showed that within farm heterogeneity affects nutrient use efficiencies operating mostly on the capture and/or recovery efficiencies of those nutrients. To some extent, this can be manipulated by management, although the result of some of the technological interventions tested here may not be feasible for resource-poor farmers (e.g. 3 years of high rates of manure applications). Recognition of the spatial heterogeneity within smallholder farms will help designing more effective recommendations targeting the referred soil fertility niches (i.e. poorly-responsive fertile fields, responsive fields and poorly-responsive poor fields). However, it is also necessary to develop communication/extension frameworks to build capacity among smallholder farmers for the practical identification of such variability and its effect on the performance of different management interventions. This will allow farmers to fine-tune their decision-making for the allocation of their scarce (labour, cash and nutrient) resources.

Acknowledgements

We thank Nico de Ridder, Herman van Keulen and Bert Janssen for their valuable input during the conceptual model development. We thank the European Union for funding this research through the AfricaNUANCES Project (Contract no INCO-CT-2004-003729).

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Appendix 1

Figure captions:

Figure 1: (A) Schematic representation of the interrelation between the different modules of the model FARMSIM (FArm-scale Resource Management SIMulator); (B) the soil C and N modules of the sub-model FIELD (Field-scale resource Interactions, use Efficiencies and Long-term soil fertility Development). See text for further explanation.

Figure 2: Variability in the bulk density (A) and C:N ratio of the organic fraction (B) of three (top)soils of different texture in Zimbabwe, subject to different periods of cultivation, starting from clearance of woodland vegetation (year 0). Mafungautsi: Aeolian Kalahari sands, 5% clay + silt; Masvingo: Granitic loamy sands, 12% clay+silt; Chikwaka: Dolerite red clays, 51% clay + silt.

Figure 3: Measured and FARMSIM-simulated long-term changes of soil C in three soil types of different texture in Zimbabwe, subject to different periods of cultivation, starting from clearance of woodland vegetation (year 0); all soils under smallholder management systems (poor C and nutrient inputs) except (D), under commercial (high input) management system.

Figure 4: Measured and FARMSIM-simulated maize response to increasing N application rates with and without application of 30 kg P ha^{-1} in home- and outfields on clay and sandy soils of smallholder farms in Murewa, Zimbabwe.

Figure 5: Measured and FARMSIM-simulated maize and soyabean responses to repeated applications of 30 kg P ha^{-1} as organic (manure) and mineral (SSP) fertiliser on three-year rotations on clay homefields (A, C) and sandy outfields (B,D) in smallholder farms of Murewa, Zimbabwe.

Figure 6: Measured and FARMSIM-simulated maize responses to increasing applications rates of P as organic (manure) and mineral (SSP) fertiliser in the presence of 100 kg N ha^{-1} in home- and outfields on clay and sandy soils of smallholder farms in Murewa, Zimbabwe.

Figure 7: Observed versus simulated aboveground and grain biomass yields of maize and soyabean for Experiments I to III (cf. Table 3) on different fields of smallholder farms in Murewa, Zimbabwe.

Figure 8: Biomass production and internal nutrient use efficiencies in maize as derived from measured data from Experiments I to III. Relationships between (A) aboveground biomass and harvest index (grain/aboveground biomass) – regression curve fitted only to Experiment III data (r^2 0.6); (B) N and P uptakes by the crop; (C) N and (D) P uptakes and aboveground biomass, indicating the physiological limits to nutrient dilution and concentration in the plant tissues as assumed in FARMSIM.

Figure 9: FARMSIM simulation of the conditions of Experiment III (cf. Table 3). Nitrogen (A) and phosphorus (B) capture efficiencies: total nutrient availability in the soil vs. nutrient uptake. Simulated and measured nitrogen (C) and phosphorus (D) conversion efficiencies: aboveground biomass production as a function of nutrient uptake.

Figure 10: Schematic representation of the response of maize to N and P applications in different fields along a gradient of soil fertility generated using FARMSIM. (A) relative changes in soil C along a chronosequence (40 years

since woodland clearance), for different soil types from Zimbabwe (Mafungautsi: Aeolian Kalahari sands, 5% clay + silt; Masvingo: Granitic loamy sands, 12% clay+silt; Chikwaka: Dolerite red clays, 51% clay + silt). Maize response to increasing application rates of N in the presence of 30 kg P ha^{-1}, both as mineral fertilisers, in soils of 51% (clay) and 5% (sand) clay+silt content that have been cultivated for 5 (inset B) and 20 (inset C) years under smallholder management (i.e. as outfields).

Tables

Table 1: Description of the chronosequence sites for model calibration (adapted from Zingore et al., 2005).

Site	Mafungautsi	Masvingo	Chikwaka
Location	28° 54'S, 18 24'E	20° 30'S, 30 30'E	17° 42'S, 31 24'E
Rainfall	650 – 800 mm	400 – 750 mm	800 – 1000 mm
Mean annual temperature	25 °C	24 °C	24 °C
Vegetation*	Dry deciduous woodland	Miombo woodland	Miombo woodland
Soil type (FAO)	Luvic Arenosols	Haplic Lixisols	Chromic Luvisols
Parent material	Aeolian Kalahari sands	Granitic loamy sands	Dolerite red clays
Initial soil indicators			
Clay$^{\alpha}$ + Silt (%)	3 + 2	10 + 2	35 + 16
Soil organic C (g kg^{-1})	6.4	7.8	16.2
Extactable P (mg kg^{-1})	11	4	21
pH water (1:2.5)	5.1	5.0	5.6

* In the three sites, the original vegetation is characterized by a dense tree canopy with sparse grass understorey

$^{\alpha}$Clay minerals were dominated by kaolinite.

Table 2: Data sets from Murewa (Zimbabwe) used for model calibration and testing (Zingore et al., 2006 a and b).

Experiment	Period	Description	Treatments
I	2002	Maize response to N with and without P, both as mineral fertilizers, across soil types (clay and sand) and fertility gradients (homefields and outfields)	N: 0, 30, 60, 90 and 120 kg ha^{-1} P: 0 and 30 kg ha^{-1}
II	2002/4	Maize/soybean rotations, with P applications as manure and as simgle super phosphate (SSP), in clay and sandy soils	N: 70 kg ha^{-1} except to control P: 0 and 30 kg ha^{-1} as SSP or as manure (0 and 18 t ha^{-1})
III	2002/4	Maize response to P applied as manure and as SSP, across soil types (clay and sand) and fertility gradients (homefields and outfields)	N: 100 kg ha^{-1} to all treatments P: 0, 10, 30 kg ha^{-1} as SSP or as manure (0, 7 and 18 t ha^{-1})

Rainfall during the growing seasons 2002-4 in Murewa was: 816, 754 and 709 mm.

Table 3: Soil properties of the different fields used for simulation of crop responses to nutrient applications.

Experiment	Soil type	Field type	Clay (%)	Sand (%)	Silt (%)	SOC (g kg^{-1})	TSN (g kg^{-1})	Ext. P (mg kg^{-1})	ECEC ($cmol_c$ kg^{-1})	pH (water 1:2.5)
I	Red clay	Homefield	35	49	16	15	1.0	10.0	30	5.8
		Outfield	38	46	16	8	0.6	5.6	14	5.1
	Granitic sand	Homefield	10	84	6	8	0.9	12.5	3	5.2
		Outfield	11	86	3	2	0.1	1.5	2	4.6
II	Red clay	Homefield	34	48	18	9	0.5	10.0	16	5.6
	Granitic sand	Outfield	3	92	5	4	0.2	2.4	2	4.0
III	Red clay	Homefield	39	46	15	14	0.8	12.1	24	5.6
		Outfield	44	42	14	7	0.5	3.9	12	5.4
	Granitic sand	Homefield	13	85	2	5	0.4	7.2	2	5.1
		Outfield	8	88	4	3	0.3	2.4	2	4.9

SOC: soil organic carbon; TSN total soil nitrogen; Ext. P: Olsen extractable P; ECEC: effective cation exchange capacity.

Table 4: Definition of different indicators of nutrient use efficiency.

Indicator	Unit	Calculation	Type of data
Apparent Nutrient Recovery (ANR, APR)	kg X kg X^{-1}	$(X_{uptake} - X_{uptake\ control}) / X_{applied}$	Measured and simulated
Efficiency of Nutrient Capture (ENCa, EPCa)	kg X kg X^{-1}	$(X_{uptake} - X_{uptake\ control}) / (X_{applied} + X_{soil})$	Simulated
Efficiency of Nutrient Conversion (ENCo, EPCo)	kg DM kg X^{-1}	*Above-ground biomass* / X_{uptake}	Measured and simulated
Partial factor productivity of the applied nutrient* (PFPN, PFPP)	kg DM kg X^{-1}	*(Above-ground biomass – Above-ground biomass$_{control}$)*/ $X_{applied}$	Measured and simulated

X represents either N or P; Above-ground biomass: aboveground biomass production; DM: dry matter
*Often also referred to as agronomic nutrient use efficiency

Table 5: Comparison of overall model simulation results against measurements from chronosequences of woodland clearance.

Site	Overall C decay rate (year^{-1})		Total C decay in 50 years* (t ha^{-1})		Fraction of initial C lost ($1 - C_f/C_i$)	
	Model	Measured	Model	Measured	Model	Measured
Mafungautsi	0.35	0.31	12.2	10.6	0.55	0.54
Masvingo	0.32	0.26	13.2	13.2	0.57	0.58
Chikwaka	0.38	0.29	21.6	22.4	0.66	0.53

*Keeping all rates constant

Table 6: Range of soil C and total N measured at the assumed initial and final stages of chronosequences of woodland clearance, and statistics of comparison between measured and simulated values.

	Soil organic C (g kg^{-1})			Total soil N (g kg^{-1})		
Site	Range (initial – final)	Mean difference	Root mean square error	Range (initial – final)	Mean difference	Root mean square error
Mafungautsi	19.5 – 8.9	0.03	1.4	0.9 – 0.4	-0.03	0.10
Masvingo	22.8 – 9.6	0.07	2.2	1.5– 0.7	-0.01	0.12
Chikwaka	41.9 – 19.5	-1.60	2.6	2.6 –1.6	-0.08	0.19

Table 7: Statistics of comparison between measured and modelled components of the crop yield (kg ha^{-1}) response curves from Experiment I.

Response curve*		*n*	Measured yields			Simulated	Average	RMSE
			Mean	STDV	Range**	yield	difference	
Full experiment	Grain		1821	1228	0 – 5377	2061	273 (0.15)	862
	Above-ground biomass		4276	2572	196 – 11571	5174	1041 (0.24)	2765
N/P intercept	Grain	10	883	507	0 – 1640	949	198 (0.22)	707
	Above-ground biomass	11	2362	1503	820 – 4832	3791	1626 (0.68)	2432
N plateau	Grain	11	1818	1099	308 – 3407	1697	35 (0.02)	415
	Above-ground biomass	11	4488	2514	845 - 7505	2792	1322 (0.29)	1936
P intercept	Grain	12	990	662	135 – 2254	1604	613 (0.62)	1260
	Above-ground biomass	12	2743	1676	816 – 5329	6104	3360 (1.22)	4491
N/P plateau	Grain	12	2275	1546	321 –4951	3185	290 (0.17)	844
	Above-ground biomass	12	5960	2915	780 – 10393	6439	1020 (0.1)	2742

*N/P intercept: 0 kg ha^{-1} N, 0 kg ha^{-1} P; N plateau: 120 kg ha^{-1} N, 0 kg ha^{-1} P; P intercept: 0 kg ha^{-1} N, 30 kg ha^{-1} P; N/P plateau: 120 kg ha^{-1} N, 30 kg ha^{-1} P
**Considering all soils, field types and experimental replicates; crop failures were excluded, and zero grain yields were recorded only when some aboveground biomass was collected

Table 8: Apparent recovery and partial productivity of applied N, and apparent P recovery for an application rate of 30 kg P ha^{-1}, calculated with data from Experiment I. Definitions of the efficiency indicators are given in Table 4.

Soil/field type	Applied N (kg ha^{-1})	Apparent N recovery (kg kg-1)		Partial N productivity (kg DM kg N^{-1})		Apparent P recovery (kg kg^{-1})
		- P	+ P	- P	+ P	
Clay						
Homefield	0	-	-	-	-	0.06
	30	0.67	0.74	58	47	0.07
	60	0.39	0.66	31	45	0.33
	90	0.33	0.64	20	50	0.34
	120	0.32	0.45	25	37	0.43
Clay						
Outfield	0	-	-	-	-	0.09
	30	0.39	0.80	20	50	0.15
	60	0.51	0.54	28	42	0.22
	90	0.46	0.64	31	37	0.20
	120	0.31	0.26	18	18	0.15
Sandy						
Homefield	0	-	-	-	-	0.03
	30	0.89	1.04	73	76	0.13
	60	0.61	0.95	47	77	0.15
	90	0.42	0.81	33	65	0.38
	120	0.41	0.60	27	44	0.34
Sandy						
Outfield	0	-	-	-	-	0.04
	30	0.04	-0.01	-2	-7	-0.01
	60	0.02	0.07	-3	8	0.07
	90	0.01	-0.01	-1	-1	-0.01
	120	0.02	0.08	0	7	0.07

-/+ P indicates absence or presence of 30 kg P ha^{-1}

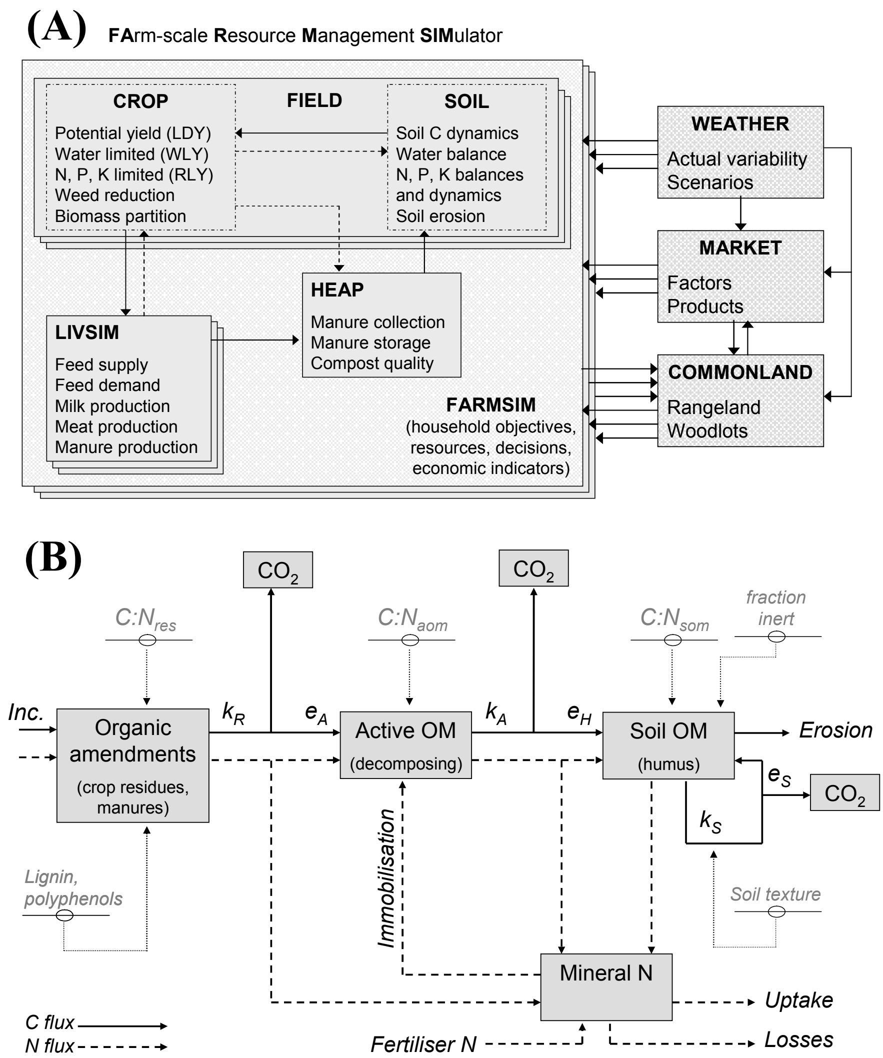

(A)
FArm-scale Resource Management SIMulator
CROP
Potential yield (LDY)
Water limited (WLY)
N, P, K limited (RLY)
Weed reduction
Biomass partition
FIELD
SOIL
Soil C dynamics
Water balance
N, P, K balances
and dynamics
Soil erosion
HEAP
Manure collection
Manure storage
Compost quality
LIVSIM
Feed supply
Feed demand
Milk production
Meat production
Manure production
FARMSIM
(household objectives, resources, decisions, economic indicators)
WEATHER
Actual variability
Scenarios
MARKET
Factors
Products
COMMONLAND
Rangeland
Woodlots
(B)
CO2
CO2
C:Nres
C:Naom
C:Nsom
fraction inert
Inc.
Organic amendments
(crop residues, manures)
kR
eA
Active OM
(decomposing)
kA
eH
Soil OM
(humus)
Erosion
eS
CO2
kS
Lignin, polyphenols
Immobilisation
Soil texture
Mineral N
Uptake
Losses
Fertiliser N
C flux
N flux

Figure 1

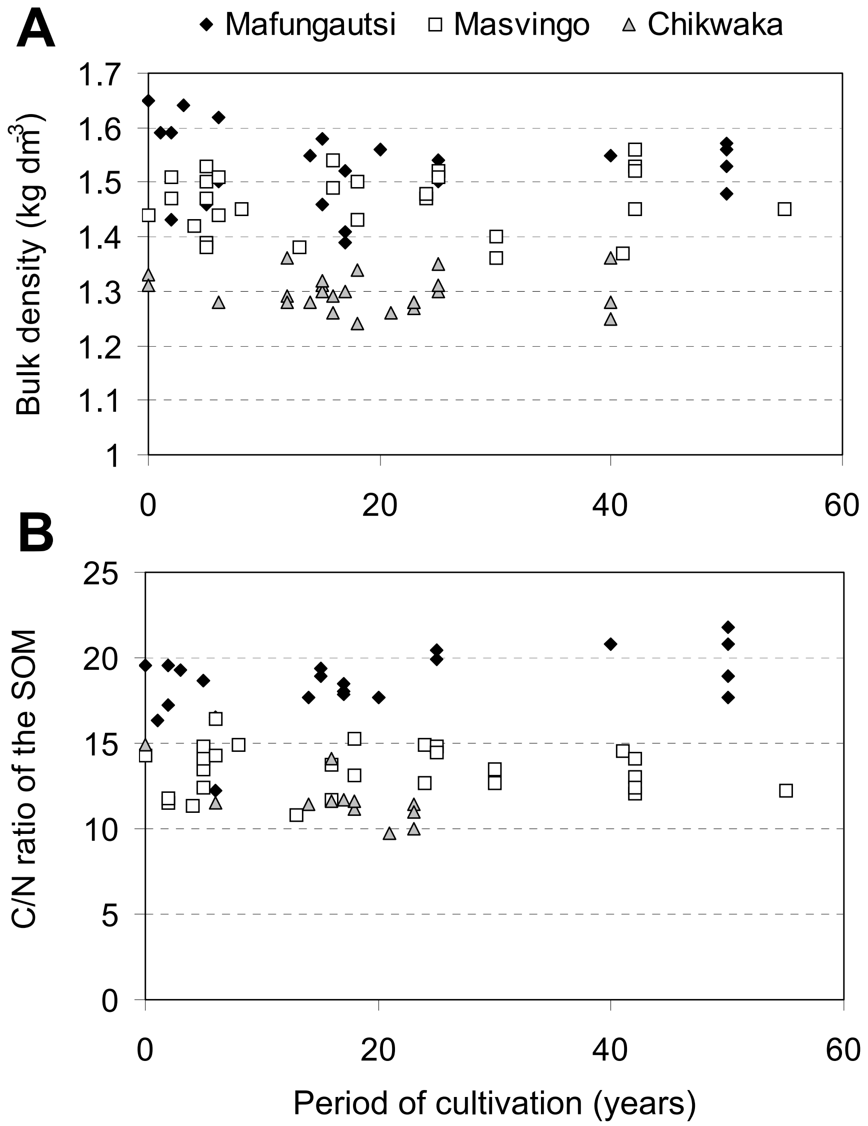

A
Mafungautsi
Masvingo
Chikwaka
Bulk density (kg dm^{-3})
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0
20
40
60
B
C/N ratio of the SOM
25
20
15
10
5
0
0
20
40
60
Period of cultivation (years)

Figure 2

Appendix 1

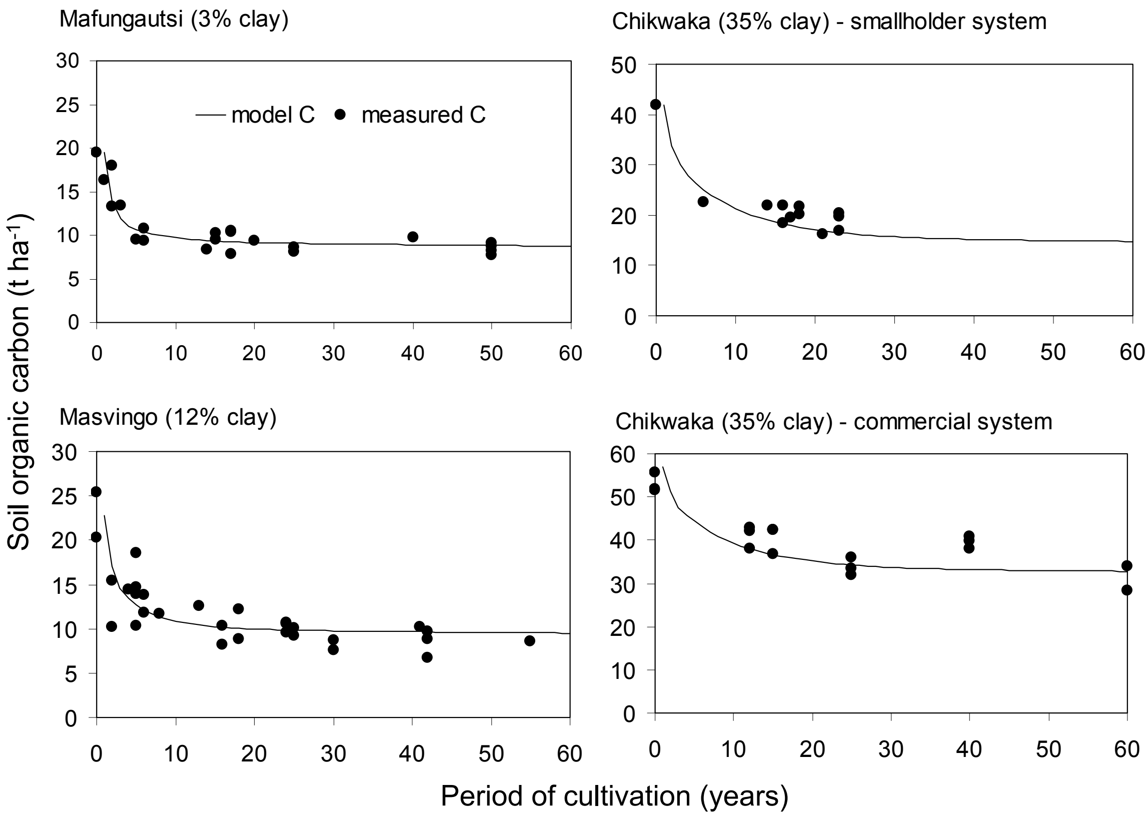
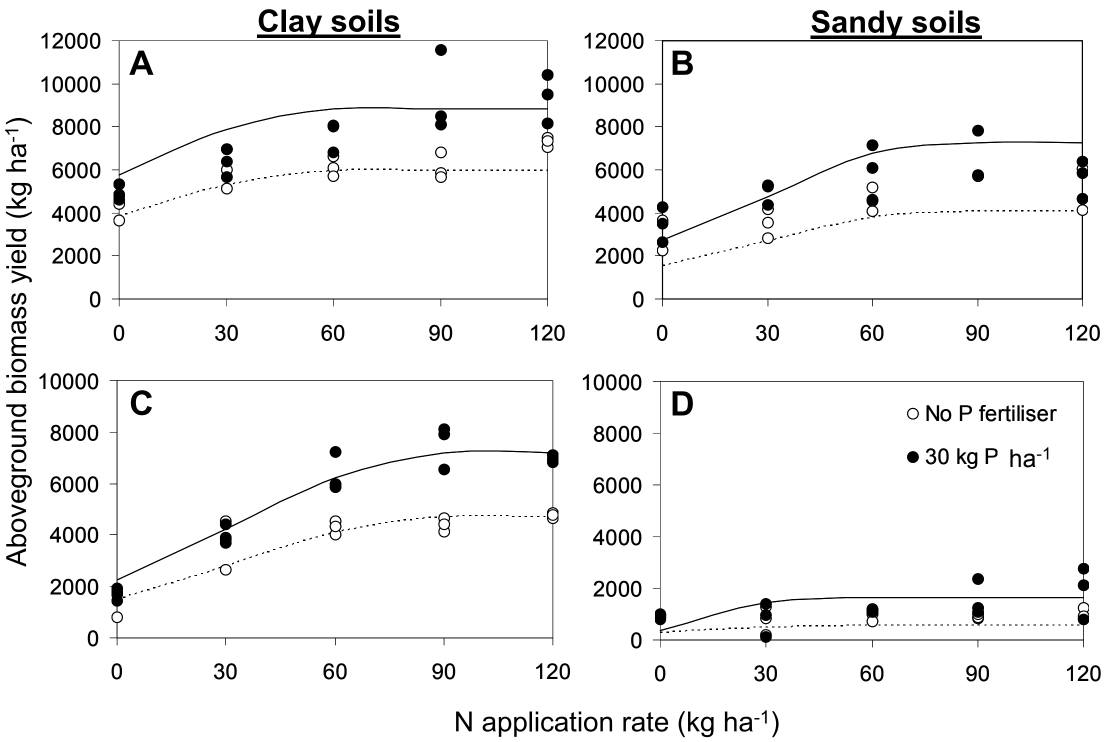


Figure 3



Clay soils
Sandy soils
A
B
C
D
Aboveground biomass yield (kg ha-1)
No P fertiliser
30 kg P ha-1
N application rate (kg ha-1)

Figure 4

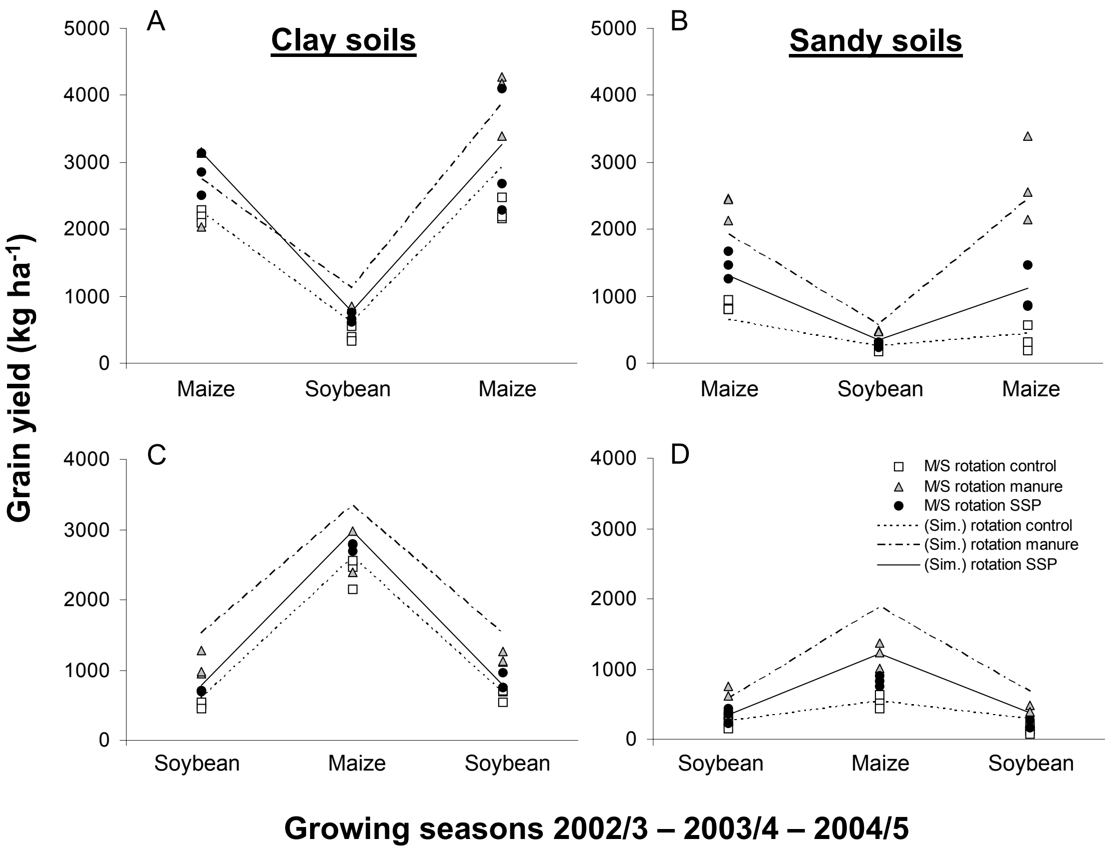

A
Clay soils
B
Sandy soils
C
D
Grain yield (kg ha-1)
Maize
Soybean
Maize
Soybean
Maize
Soybean
5000
4000
3000
2000
1000
0
M/S rotation control
M/S rotation manure
M/S rotation SSP
(Sim.) rotation control
(Sim.) rotation manure
(Sim.) rotation SSP
Growing seasons 2002/3 – 2003/4 – 2004/5

Figure 5

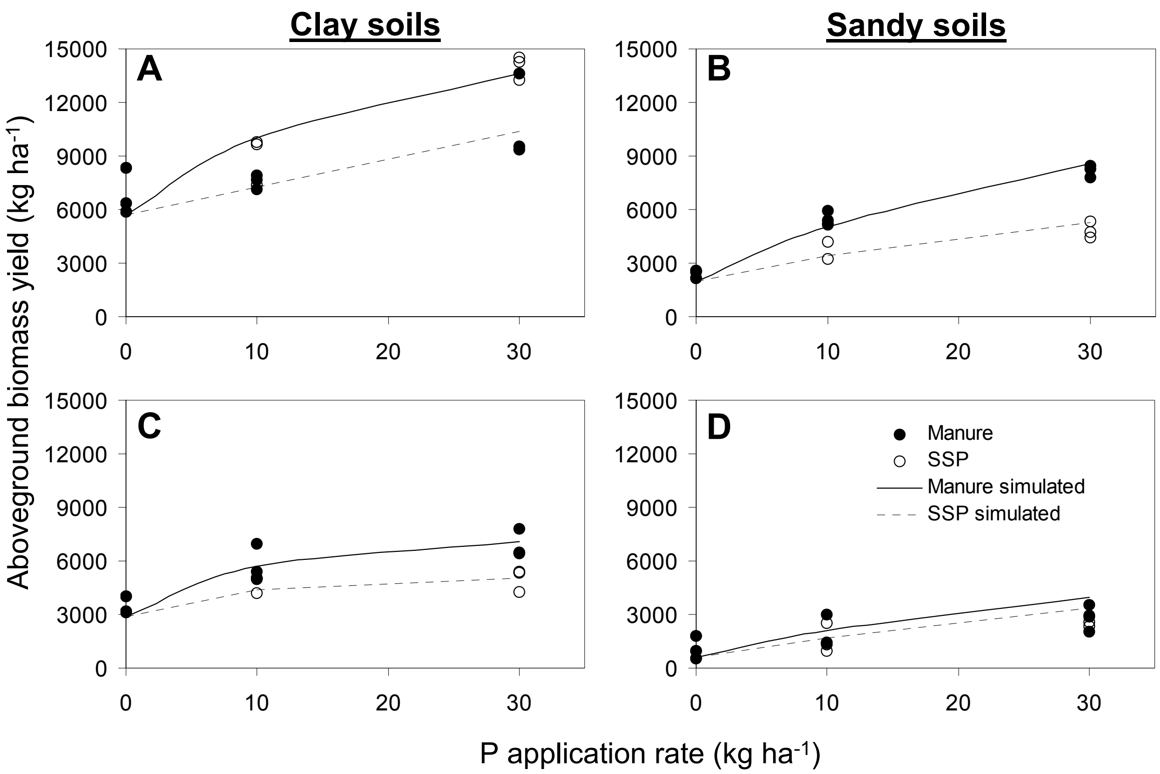
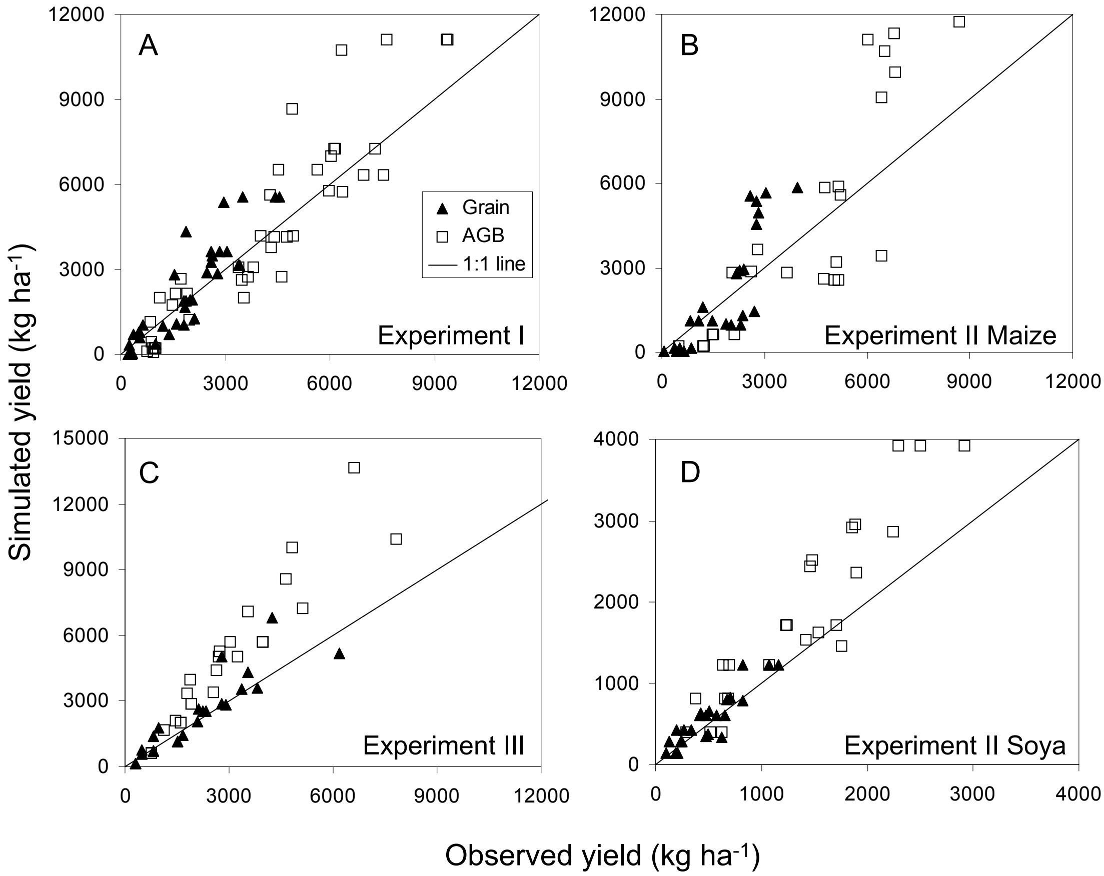

Clay soils
Sandy soils
A
B
C
D
Aboveground biomass yield (kg ha-1)
P application rate (kg ha-1)
0
3000
6000
9000
12000
15000
0
10
20
30
Manure
SSP
Manure simulated
SSP simulated

Figure 6



A
B
C
D
Grain
AGB
1:1 line
Experiment I
Experiment II Maize
Experiment III
Experiment II Soya
Simulated yield (kg ha-1)
Observed yield (kg ha-1)

Figure 7

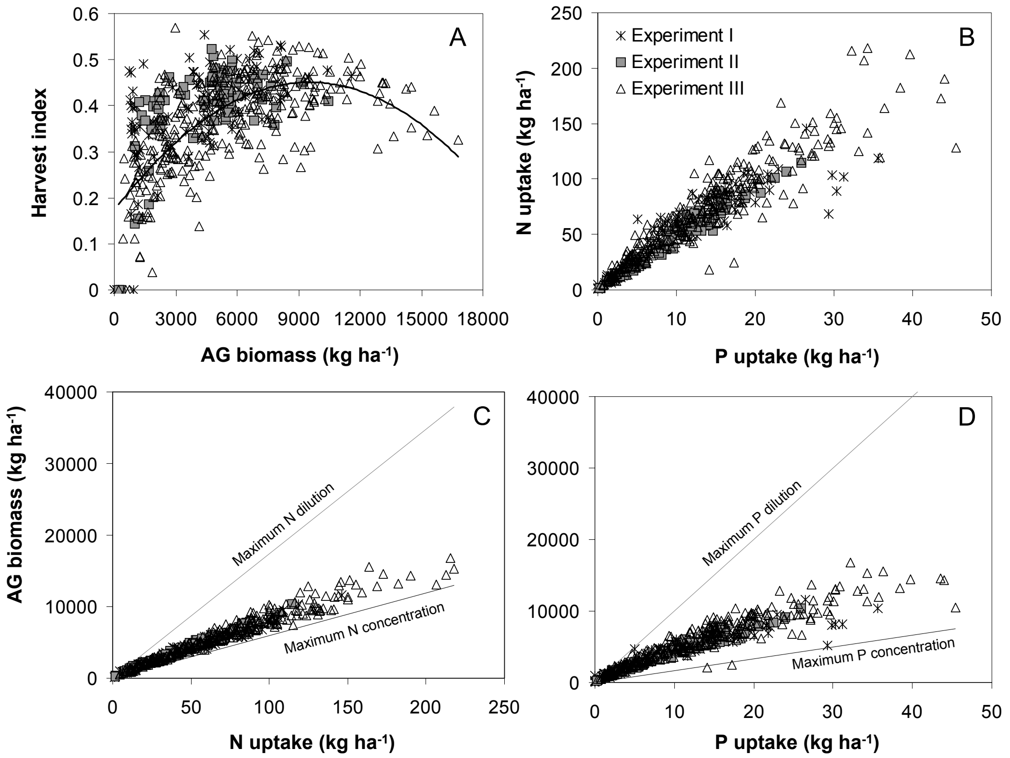
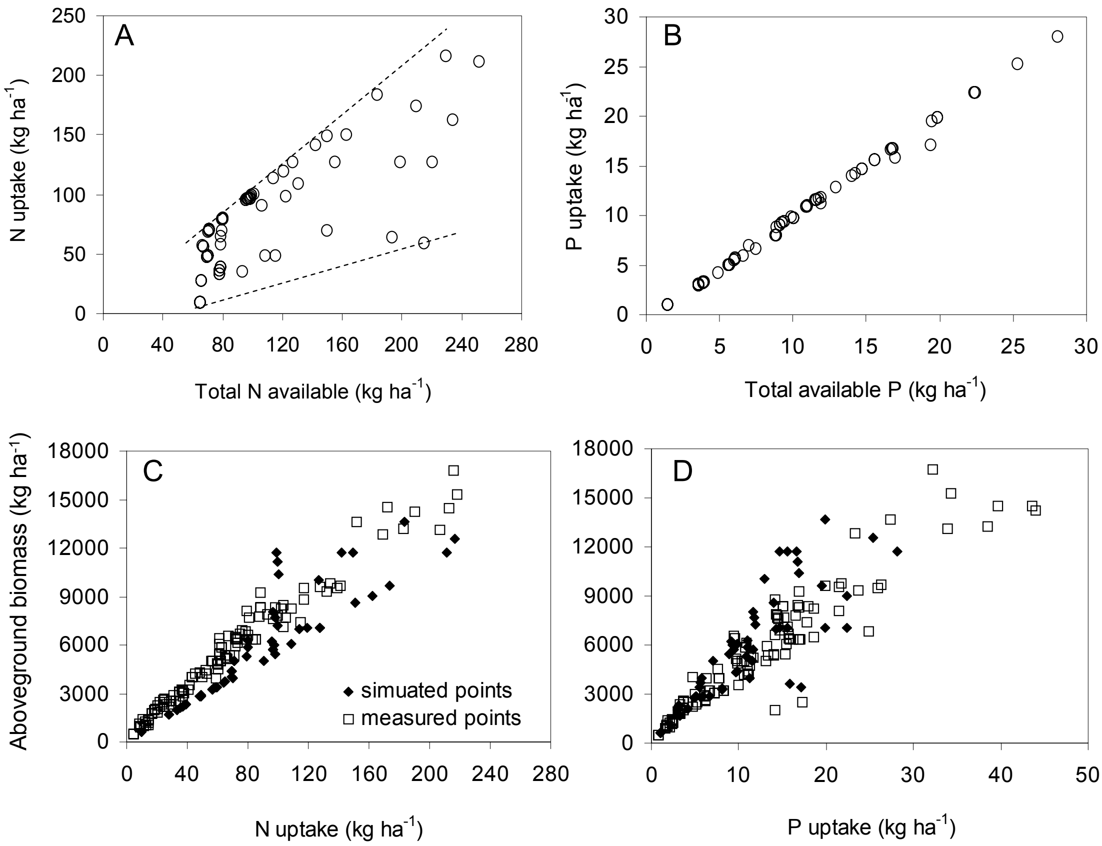
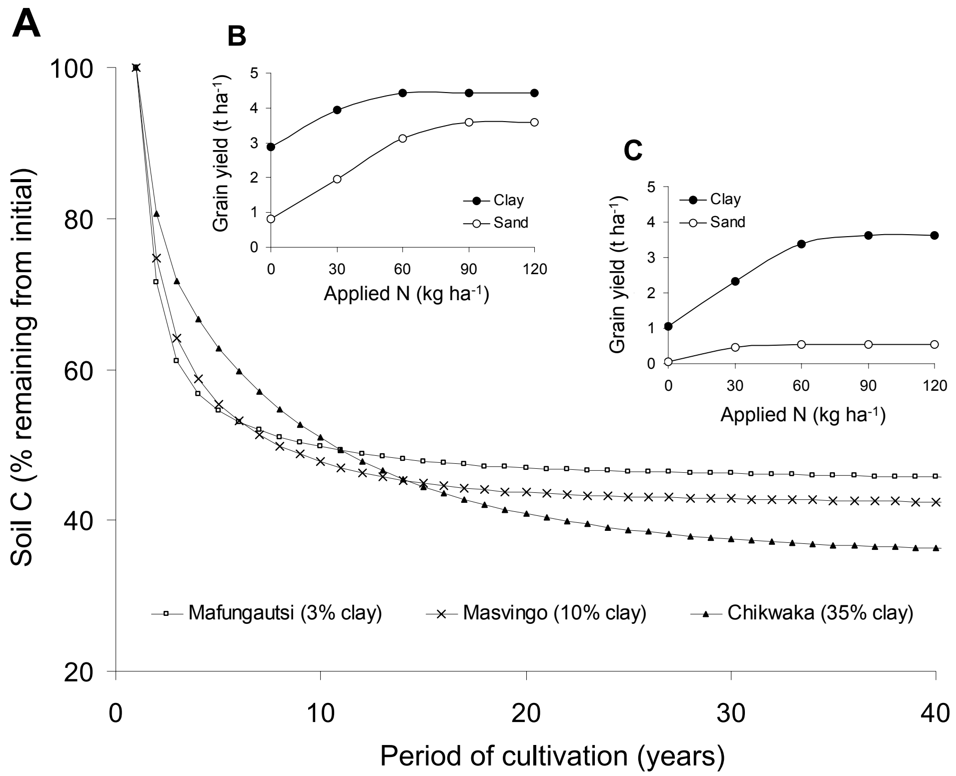

A
Harvest index
AG biomass (kg ha-1)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
3000
6000
9000
12000
15000
18000
B
Experiment I
Experiment II
Experiment III
N uptake (kg ha-1)
P uptake (kg ha-1)
0
50
100
150
200
250
0
10
20
30
40
50
C
AG biomass (kg ha-1)
N uptake (kg ha-1)
Maximum N dilution
Maximum N concentration
0
10000
20000
30000
40000
0
50
100
150
200
250
D
P uptake (kg ha-1)
Maximum P dilution
Maximum P concentration
0
10000
20000
30000
40000
0
10
20
30
40
50

Figure 8



A
N uptake (kg ha-1)
Total N available (kg ha-1)
B
P uptake (kg ha-1)
Total available P (kg ha-1)
C
Aboveground biomass (kg ha-1)
N uptake (kg ha-1)
simuated points
measured points
D
P uptake (kg ha-1)

Figure 9



A
B
C
Soil C (% remaining from initial)
Period of cultivation (years)
Mafungautsi (3% clay)
Masvingo (10% clay)
Chikwaka (35% clay)
Grain yield (t ha-1)
Applied N (kg ha-1)
Clay
Sand

Figure 10

Curriculum vitae

Shamie Zingore was born in Mudzi, Zimbabwe, on 7 November 1976. He finished high school in 1996 and studied for a Bachelor of Science Honour degree in Agriculture, specializing in Soil Science at University of Zimbabwe. After obtaining his first degree in 1999, he worked briefly as a research assistant at the Department of Soil Science and Agricultural Engineering, University of Zimbabwe. In the same year he was awarded a scholarship to study for a Master of Philosophy degree in Soil Science at the same University. He studied under the supervision of Prof. Ken Giller, who was Professor of Soil Science at the University of Zimbabwe at that time. The study was on analysis and modelling of soil organic matter dynamics in maize-based farming systems. He received the Master of Philosophy degree in 2002. Soon after completing the Master of Philosophy degree, he joined the Tropical Soil Biology and Fertility Institute of CIAT (TSBF-CIAT) as a PhD student. Collaboration in farming systems research between TSBF-CIAT and Prof. Ken Giller facilitated his enrolment to study at Wageningen University. His PhD study focused of variability of resource management practices and soil fertility across smallholder farms in Zimbabwe and was supervised by Prof K.E. Giller, Dr. R.J. Delve and Dr H.K. Murwira.

PE&RC PhD Education Statement Form

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 22 credits (= 32 ECTS = 22 weeks of activities)

Review of Literature (4 credits)

- Farm-scale evaluation of nutrient use efficiencies of resource management options in smallholder farming systems of Zimbabwe (2003)

Writing of Project Proposal (4 credits)

- Farm-scale evaluation of nutrient use efficiencies of resource management options in smallholder farming systems of Zimbabwe (2003)

Post-Graduate Courses (2 credits)

- Integrated modelling approaches for systems for smallholder farming systems, Nairobi/Harare (2003/2004)

Deficiency, Refresh, Brush-up and General Courses (9 credits)

- Quantitative analysis of land-use systems (2003)
- Systems analysis, simulation and system management (2003)
- Time planning and project management (2003)

PhD Discussion Groups (5 credits)

- ILRI modelling workshops (2002)
- Soil-crop interactions (2003)
- ILRI modelling workshops (2003)
- ILRI modelling workshops (2005)

PE&RC Annual Meetings, Seminars and Introduction Days (1 credit)

- PE&RC weekend (2003)
- PE&RC annual meeting: "Global climate change and biodiversity"(2003)

International Symposia, Workshops and Conferences (4 credits)

- Use of stable isotopes to study land degradation in Africa, Nairobi, Kenya (2005)
- International soil science society meeting, Philadelphia, USA (2006)