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ORIGINAL ARTICLE

Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: a case from Murewa District, Zimbabwe

S. Zingore · P. Tittonell · M. Corbeels ·
M. T. van Wijk · K. E. Giller

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Abstract Smallholder farms in sub-Saharan African exhibit substantial heterogeneity in soil fertility, and nutrient resource allocation strategies that address this variability are required to increase nutrient use efficiencies. We applied the Field-scale resource Interactions, use Efficiencies and Long-term soil fertility Development (FIELD) model to explore consequences of various manure and fertilizer application strategies on crop productivity and soil organic carbon (SOC) dynamics on farms varying in resource endowment in a case study village in Murewa District, Zimbabwe. FIELD simulated a rapid decline in SOC and maize yields when native woodlands were cleared for maize cultivation without fertilizer inputs coupled with removal of crop residues. Applications of 10 t manure ha^{-1} $year^{-1}$ for 10 years were required to restore maize productivity to the yields attainable under native woodland. Long-term application of manure at 5 and 3 t ha^{-1} resulted in SOC contents comparable to zones of high and medium soil fertility observed on farms of wealthy cattle owners. Targeting manure application to restore SOC to 50–60% of contents under native woodlands was sufficient to increase productivity to 90% of attainable yields. Short-term increases in crop productivity achieved by reallocating manure to less fertile fields were short-lived on sandy soils. Preventing degradation of the soils under intensive cultivation is difficult, particularly in low input farming systems, and attention should be paid to judicious use of the limited nutrient resources to maintain a degree of soil fertility that supports good crop response to fertilizer application.

Keywords Soil fertility gradients · Resource allocation · Modelling · Maize production · FIELD model · NUANCES-FARMSIM

Introduction

Despite a generalized trend of decreasing soil fertility in sub-Saharan Africa (Stoorvogel et al. 1993), rates of change in soil nutrient stocks differ between farms and fields within farms (Haileslassie et al. 2007;

S. Zingore (✉)
Tropical Soil Biology and Fertility Institute of CIAT,
P.O. Box 158, Lilongwe, Malawi
e-mail: szingore@ipni.net

P. Tittonell · M. T. van Wijk · K. E. Giller
Plant Production Systems, Wageningen University,
P.O. Box 430, 6700 AK Wageningen, The Netherlands

P. Tittonell · M. Corbeels
Unité de Recherche Systèmes de Culture Annuels,
Centre de Coopération Internationale en Recherche
Agronomique pour le Développement (CIRAD), Bâtiment
27, 2 place Viala, 34060 Montpellier Cedex 2, France

M. Corbeels
Tropical Soil Biology and Fertility Institute of CIAT,
P.O. Box MP228, Mt Pleasant, Harare, Zimbabwe

Zingore et al. 2007a). Smallholder farmers typically have limited amounts of nutrient resources that are preferentially used on fields closest to homesteads, leading to steep gradients of decreasing soil fertility with increasing distance from homesteads (Prudencio 1993). This, combined with inherent variation in soils, results in complex variability in soil fertility between fields on the same farm or between farms differing in access to resources for crop production. In Zimbabwe, striking gradients of soil fertility caused by differential management have been documented on small farms of less than three hectares and within short distances of less than 50 m from the homesteads (Carter and Murwira 1995; Mtambanengwe and Mapfumo 2005; Zingore et al. 2007a). Such differences in soil fertility within and between farms have considerable effects on resource use efficiencies and crop production (Tittonell et al. 2008a).

Field experiments show that when soil fertility gradients are steep, nutrient resources, especially mineral fertilizers, are used most efficiently when applied on more fertile homefields than on depleted outfields (Wopereis et al. 2006; Zingore et al. 2007b). This is because the depleted soils of the outfields suffer multiple nutrient deficiencies and have poor physical structure. Applications of large amounts of organic resources, such as animal manure, over several seasons may be required to restore productivity. However, animal manure, which is a key organic matter and nutrient resource to sustain soil productivity, is currently in short supply given the decreasing ratios of cattle population to area of cropland (Zingore et al. 2007a). Refocusing resource management to apply large amounts of manure to restore productivity in depleted fields without immediate yield benefits, coupled with a decline in productivity in the more fertile fields may result in a yield penalty at farm scale in the short term (Zingore et al. 2007b).

Current fertilizer and manure recommendations in Zimbabwe are based on potential yields determined by rainfall, but ignore actual resource availability and farmer management practices. For example, in Murewa application of 10 t manure ha^{-1} year^{-1} is recommended for maize production (Grant 1981), although availability of manure varies substantially among farmers and average application rates are less than 2 t manure ha^{-1} year^{-1} (Zingore et al. 2007a). Fertilizer use in Murewa is also often less than half the blanket recommendation of 120 kg N ha^{-1}, 30 kg P ha^{-1} and 25 kg K ha^{-1} (Chuma et al. 2000). Many studies have focused on analysis of strategies for efficient use of nutrient resources in individual fields, but there have been few attempts to assess management practices for improving the efficiency with which scarce nutrients resources are used at the farm and village scales taking into account heterogeneity in resource availability and soil fertility between farms.

Productivity of limited nutrient resources can be maximized at the farm scale by targeting application of fertilizers or manure to fields that give the largest yield increases per unit input, but restricting application rates to maintain high marginal responses. We hypothesized that: (1) strategic resource management of limited nutrient resources by farmers is a key driver of heterogeneity in soil fertility within and across farms; (2) management-induced heterogeneity in soil fertility strongly affects crop productivity and response to application of nutrient resources, making it necessary to fine-tune soil fertility management recommendations to different soil fertility zones; (3) sustained investment in nutrient resources in depleted fields is necessary to restore their productivity; (4) substantial productivity gains at the farm and village scales can be achieved with the same amount of nutrient resources by changing nutrient allocation to individual fields; and (5) options for redistribution of nutrient resources across soil fertility gradients that are most productive in the short-term, may not necessarily be attractive in the long-term, as the resulting shift of soil fertility gradients may lead to inefficiencies in resource use. In this study we applied the model FIELD (Field-scale resource Interactions, use Efficiencies and Long-term soil fertility Development, Tittonell et al. 2007, 2009) to explore the short- and long-term impacts of resource allocation strategies in spatially heterogeneous farms on crop productivity and nutrient use efficiencies at the farm and village scale. Our objectives were to conduct model-based assessments of: (1) the impact of fertilizer and manure applications on long-term soil organic carbon (SOC) contents and maize productivity; (2) the effects of soil fertility variability on the short- and long-term response of maize to mineral and organic fertilisers; and (3) the short- and long-term changes in maize productivity at the farm and village scales as a result of reallocation of the same amount of nutrient resources to fields varying in soil fertility.

Materials and methods

The site and the farms under study

Murewa district (17°49′S, 31°34′E) is one of the earliest settled and most densely populated smallholder farming areas in Zimbabwe, with up to 120 inhabitants km^{-2}. For this study, we selected Chiwara in northern Murewa as a case study village, building on previous research done in the area. Chiwara village has a total of 120 households and a total surface area of 600 ha under two major land-use systems: about 400 ha are under natural Miombo woodland used for communal grazing and the remaining 200 ha are under crop cultivation. The dominant soils in Murewa are sandy (>85% sand) derived from granite, with a low inherent fertility and classified as Lixisols (FAO 2006). 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 in Murewa are found on more fertile red-clay soils derived from dolerite (Luvisols). Climatic conditions in Murewa are favourable for intensive crop production with total annual rainfall ranging between 750 and 1,000 mm, distributed in a unimodal pattern (November–April). Farmers practice a mixed crop-livestock system with maize (*Zea mays* L.) as the dominant staple crop. Other crops commonly cultivated on small areas include groundnut (*Arachis hypogaea* L.), sweet potato (*Ipomoea batatas* L.), sunflower (*Helianthus annuus* L.) and paprika (*Capsicum annuum* L.). Local and mixed cattle breeds constitute the main type of livestock in the area, grazing freely in communal rangelands during the day and tethered in kraals close to the homesteads at night. Less than 50% of the farmers own cattle and average cattle ownership in the village is about three animals per farm. Manure is also the major source of organic matter inputs into the soil as crop residues are removed from the fields to feed livestock or grazed in situ after harvesting.

The households in the village vary considerably in access to resources for crop production. Zingore et al. (2007a) grouped farms into four resource endowment groups (RG) using indicators that were identified by farmers, such as cattle ownership, size of arable land, production orientation (subsistence or commercial) and use of mineral fertilizers (Table 1). Farmers in the RG1 (very wealthy) and RG2 (wealthy) categories owned cattle, whilst farmers in the RG3 (poor) and RG4 (very poor) categories did not. Wealthier farmers also owned more land and used more mineral fertilizers than poor farmers.

At village scale, livestock play an important role in transfer of nutrients from communal rangelands to fields of wealthy farmers. In addition, cattle freely graze stover left in the fields following harvest, leading to net transfer of nutrients from the poor farms without cattle to farms of cattle owners. Cattle manure is used exclusively by cattle owners as it is a non-tradable commodity in Murewa. On average cattle owners use between 5–10 t manure per farm annually, which provides 50–100 kg N and 15–30 kg P (Zingore et al. 2007a). Many farmers in the area use some N and P fertilizers, but the rates applied are lower than the recommended rates of 120 kg N ha^{-1} and 25 kg P ha^{-1}. The wealthy farmers (RG1 and RG2) use larger amounts of fertilizers (50–100 kg N and 15 kg P per farm; applied at about 40 kg N ha^{-1} year^{-1} and 10 kg P ha^{-1} year^{-1} across the whole farm area compared

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

Farm type	No. of farms	Household size	Farm size (ha)	Cattle	Oxen	Goats	Chickens	Scotch carts	Manure available (t year^{-1})	Labour: land ratio[a]
RG1	8	7	3.1	12	2	2	8	1	10	1.6
RG2	14	5	2.5	7	1	3	5	0.4	6	1.6
RG3	12	6	2.2	0	0	2	6	0	0	1.8
RG4	16	4	1.0	0	0	0	3	0	0	2

[a] Land:labour ratio calculated as number of household members working on the farm over farm size

Table 2 Description of the different zones of fertility on smallholder farms in Murewa, Zimbabwe; (*a*) their occurrence and soil properties, and (*b*) proportion of the area covered by zones of fertility on farms differing in wealth status

Description		Sandy soil					Clay soil				
		Village area (%)	SOC		N	Avail. P	Village area (%)	SOC		N	Avail. P
			(g kg^{-1})	t ha^{-1}	(g kg^{-1})	(mg kg^{-1})		(g kg^{-1})	t ha^{-1}	(g kg^{-1})	(mg kg^{-1})
(*a*)											
FZ 1	Uncultivated woodland soils. Mainly used as communal grazing lands.	53.6	12	34	1.2	14	14.0	21	55	1.6	18
FZ 2	Most fertile fields where large amounts of manure were applied, typical homefields on RG1 and RG2 farms.	5.6	8	22	0.8	12	1.5	16	42	1.2	12
FZ 3	Fields with moderate fertility where small amounts of manure were used. This zone of soil fertility covers mid-fields (FZ3a) and outfields (FZ3b) on RG1 farms and midfields on RG2 farms.	6.1	5	14	0.6	7	1.6	10	26	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.	14.6	3	8	0.3	3	3.9	7	18	0.5	5

Farm type	FZ2 (%)	FZ3 (%)	FZ4 (%)
(*b*)			
RG1	32	68	0
RG2	42	21	37
RG3	0	0	100
RG4	0	0	100

with the poor farmers (RG3 and RG4) who use <40 kg N and <10 kg P, applied at rates of about 20 N kg N ha^{-1} year^{-1} and 5 kg P ha^{-1} year^{-1} across the whole farm area.

Plots with different fertility status and located at variable distance from the homestead were identified and mapped on farms representative of the different wealth categories, giving rise to several farm type and plot type combinations that constitute different soil 'fertility zones' (see below, Table 2). A more detailed description of the farm and plot typologies is given by Zingore et al. (2007a). Farms in Murewa consist of contiguous fields (0.8–3.1 ha) which were demarcated into plots with varying soil fertility status based on management history. On wealthy farms, soil fertility decreases with distance from homesteads resulting in distinct zones: homefields, midfields and outfields. Most plots on poor farms received no manure and small rates of fertilizer and exhibit poor soil fertility irrespective of distance from homesteads.

The grouping of homefields, midfields and outfields (14 in total on each soil type) for farms of different wealth categories were classified into soil fertility zones (FZs) with similar soil characteristics (Table 2). One of the FZs represented the virgin woodland soils at the inception of cultivation (FZ1), and all of the fields across the farm types were represented within three fertility zones (FZ2-4) that captured the wide variability within and across farms. Midfields and outfields on RG1 farms are categorized as FZ3, but distinguished as FZ3a and FZ3b respectively. More than 50% of the cultivated area in the village fell in the FZ4 category, consisting of infertile fields that were cultivated for long periods with little addition of mineral fertilizers or organic nutrient resources, from where crop residues were removed or grazed after harvest. Only a small proportion of grazed nutrients or C are recycled directly in the FZ4 fields, as manure is mostly deposited in the kraals where cattle are tethered at night.

Model overview

FIELD is the crop and soil module of the farm-scale dynamic simulation model NUANCES-FARMSIM, where it is linked with other modules that simulate farmers' resource allocation, animal production and the dynamics of nutrients via manure (van Wijk et al. 2009). FIELD simulates long-term changes in soil fertility (C, N, P and K), interactions between nutrients that determine crop production, and crop responses to management interventions such as mineral fertilizer and/or manure application. For this study, we used FIELD decoupled from the other models. Yet FIELD has a modular structure in itself, with modules that calculate crop production, soil C dynamics, and soil available water, N, P and K. These modules have been documented (Tittonell et al. 2007, 2008a, b, 2009). Here, we provide an overview of the central crop production module that links the other modules.

Crop production in FIELD is determined by the interaction of resource availabilities (light, water, nutrients) calculated over a seasonal time step (Fig. 1). 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 recoveries—cf. Chikowo et al. 2010). Functional relationships expressed as either response curves or response surfaces (e.g. rainfall capture efficiencies as affected by soil fertility and rainfall amount) are derived from empirical data or generated using more detailed crop growth models parameterized for a certain agroecogical zone and built into FIELD (e.g. Chikowo et al. 2008).

Light-determined crop production represents the 'potential' production (of total aboveground biomass) of a certain crop genotype in a certain environment, as affected by management decisions such as planting date and plant density. Water-limited crop production is calculated on the basis of seasonal rainfall and a site- and crop-specific rainfall use efficiency coefficient. Total amounts of nutrients available for crop uptake in a given season are calculated from total supplies in soil and from added mineral and organic nutrient resources, considering losses through erosion, leaching, denitrification or volatilization in each particular case.

Nutrient conversion efficiencies (kg DM kg^{-1} nutrient taken-up) are the inverse of the weighted-average nutrient concentrations in grain, straw and roots, and range between crop-specific minimum and maximum values (Janssen et al. 1990). FIELD simulates resource conversion efficiencies following the approach of Liebscher's 'Law of the Optimum': as the amount of a certain nutrient X available to the

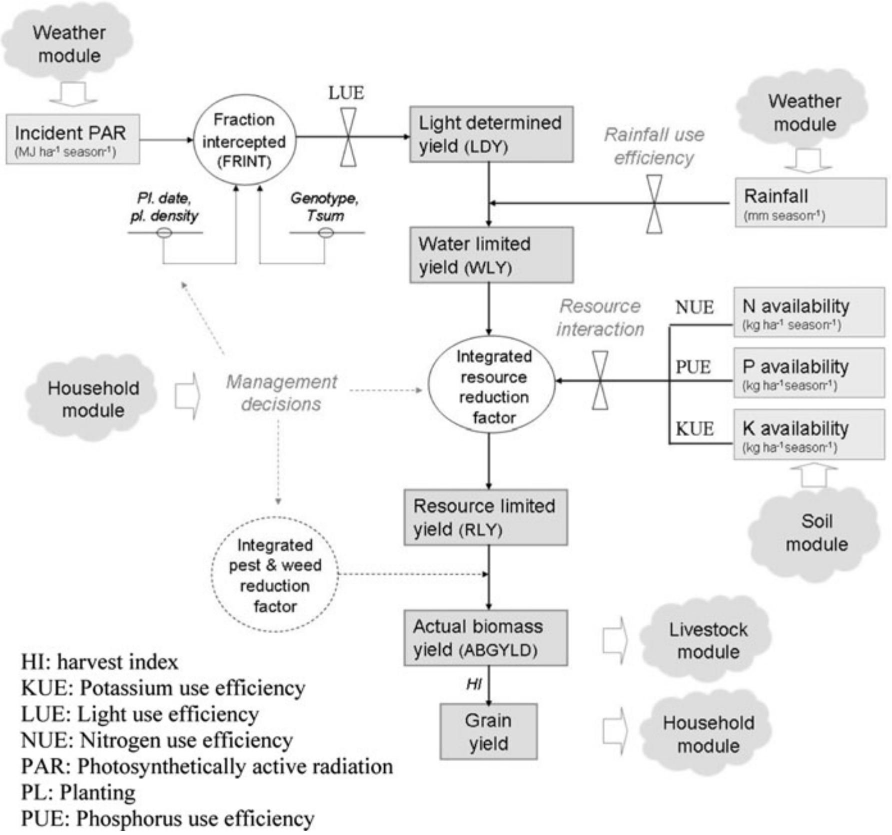

Fig. 1 Schematic representation of the way in which crop production is calculated in FIELD, indicating the links with other modules of the NUANCES-FARMSIM model

crop declines, long before it becomes limiting, the efficiencies with which other nutrients *Y*, *Z*, etc. are used by the crop are gradually affected. Such interactions between available nutrients and water, which are regulated by weighing coefficients specific for different crops, lead to an integrated reduction factor for the light-determined yield to calculate a resource-limited yield (Fig. 1).

Model parameterization and testing

FIELD was used in this study to simulate different resource management strategies for different field plots of farms located on the granitic sandy (Lixisol) and red-clay (Luvisol) soils in Murewa. In the simulations of this study we only considered N and P, nutrients most commonly limiting in these soils. FIELD was calibrated using measured changes in SOC from chronosequences of cultivated land following woodland clearance in Zimbabwe (Zingore et al. 2005), and further tested against experimental data on crop responses to different combinations of N, P and manure applications to maize in homefields and outfields of smallholder farms on clayey and sandy soils in Murewa (Zingore et al. 2007b). Key results of the calibration of FIELD for these cropping situations are illustrated in Fig. 2. The model produced satisfactory predictions (r^2 0.6–0.9) of long-term changes in SOC and simulated accurately the response of maize to different management interventions.

Scenario analysis

Scenario analysis focused on how the scarce resources available to farmers in the various RGs can be most efficiently allocated to fields varying in soil fertility. The performance of various resource allocation strategies were assessed considering different time horizons at farm scale—the scale of decision-making, and at village scale, recognizing social interactions and livestock-mediated nutrient flows. Different indicators of land productivity and nutrient use efficiency were used, focusing indicators of land productivity and nutrient use efficiencies focusing on maize production, as this is the main crop

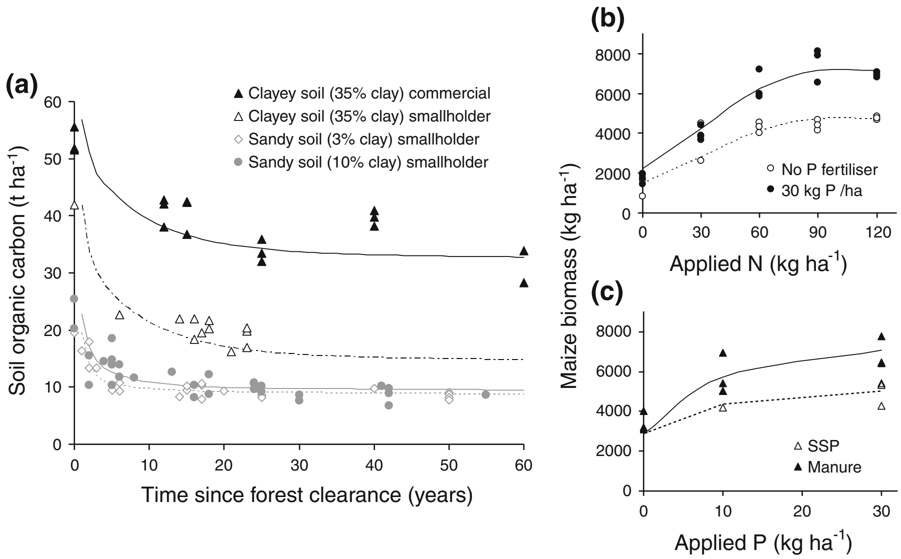

Fig. 2 Selected results showing the calibration of FIELD for clay and sandy soils of northern Zimbabwe: **a** Chronosequences of soil carbon after forest clearance in soils of different texture and under commercial and smallholder farming; **b** Response of maize to N applied as mineral fertilizer with and without addition of P on a sandy soil; **c** Response of maize to P applied as mineral (SSP) and organic (Manure) fertilizer on a sandy soil receiving 100 kg N ha^{-1} (further details are given in Zingore et al. 2005, 2007a, b; Tittonell et al. 2007)

grown for food and the market. None of the scenarios analysed here consider options such as changing crop types, use of green manures or cereal-legume rotations. We focused on exploring options for efficient use of existing nutrient resources (manure and mineral N and P fertilizers) in the predominantly maize monoculture cropping systems in Murewa.

Data required to simulate the different scenarios were: (1) soil properties: soil particle size distribution, SOC, soil N, and extractable P; (2) amount and quality of manure: total C, total N, and total P contents; (3) amounts and nutrient composition of mineral N and P fertilizers; and (4) crop type. Values for soil particle size distribution on different plots of the same soil type varied little and 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. Chemical soil properties varied for the different soil fertility zones (cf. Table 2). The parameters for manure used in the model were taken from average values calculated for manures at the study site: 30% C; 1% N; and 0.2% P (Zingore et al. 2007a). Default crop parameters for maize as provided by FIELD were used. In all scenarios, 90% of the maize residues were removed from the field at harvest to mimic farmers' management practice of removing stover to feed livestock (for wealthy farmers) and in situ grazing of crop residues for poor farmers without cattle. All simulations are based on long-term (1964–2002) mean monthly rainfall (average 810 mm $year^{-1}$) for Murewa district.

Scenario set I: The development and distribution of soil fertility gradients

The first hypothesis (1), was tested: that strategic resource management of limited nutrient resources by farmers is a key driver of heterogeneity in soil fertility within and across farms. FIELD was run to simulate changes in SOC and maize yields for 30 years following clearance of native woodland soils (FZ1) for cultivation of maize. The model was run using soil fertility parameters for FZ1, and used to simulate maize mono-cropping under different combinations of mineral N and P fertilizer and manure applications as follows: no fertilizer inputs; 100 N + 20 kg P ha^{-1} $year^{-1}$; 100 N ha^{-1} + 10 t manure ha^{-1} $year^{-1}$; 100 N ha^{-1} + 5 t manure ha^{-1} $year^{-1}$; and 100 N ha^{-1} + 3.3 t manure ha^{-1} $year^{-1}$. The highest rate of manure simulated was 10 t ha^{-1}, based on a generally recommended manure application rate (Grant 1981), and medium or low application rates

(5 and 3.3 t ha^{-1} $year^{-1}$, respectively) were also simulated. We only present N and P application rates of, respectively, 100 kg N ha^{-1} and 20 kg P ha^{-1}, which are the maximum rates applied by the farmers (Zingore et al. 2007a), to estimate the corresponding maximum yields and SOC contents that can be sustained in the long-term with mineral fertilizers alone. Other scenarios in which no manure or fertilizer is applied were relevant for FZ4 (all the fields on RG3 and RG4 farms, or the outfields on RG2).

Scenario set II: variable crop responses across soil fertility gradients

Hypothesis (ii) was tested: that heterogeneity in soil fertility strongly affects crop productivity and response to application of nutrient resources making it necessary to fine-tune soil fertility management recommendation to different soil fertility zones. Maize response to application of different rates of N (0, 30, 60, 90, and 120 kg ha^{-1}), with different rates of P (0, 10, and 20 kg ha^{-1}) or manure (0, 3.3, 5.0, and 10.0 t DM ha^{-1}) were simulated to establish the baseline and attainable yields and yield responses on the different FZs. The rates of fertilizer were chosen to generate response curves within the range of fertilizer rates used by farmers. Simulated manure application rates aimed at representing the rates applied by RG1 and RG2 farmers to the different fields.

Scenario set III: Restoring soil productivity

Hypothesis (iii) was tested: that sustained investment in nutrient resources in depleted fields is necessary to restore their productivity. FIELD was used to estimate the amounts of manure, and the timeframe required to replenish SOC (used as a proxy for soil fertility in relation to potential supply of multiple nutrients and regulation of soil biophysical properties that determine crop response to addition of N and P) and improve maize yields. The model simulated the effects of different rates of manure, ranging from low (3.3 t ha^{-1}), medium (5 t ha^{-1}), and high (10 t ha^{-1}).

Scenario set IV: Evaluating nutrient allocation strategies at farm and village scales

This scenario tested hypotheses that (iv) substantial productivity gains at the farm and village scales can be achieved with the same amount of nutrient resources by changing management of individual fields; and (v) options for redistribution of nutrient resources across soil fertility gradients that are most productive in the short-term, may not necessarily be attractive in the long-term, as the resulting shift of soil fertility gradients may lead to inefficiencies in resource use. The maize yield responses to manure and fertilizer application that were generated by the model in Scenario set II were used to evaluate different strategies for resource use by farmers of different wealth status (RG1-RG4), taking into account the resources available to farmers, the type of soil cultivated, farm sizes and the area of the different FZs within the farms (Table 2). For RG1 and RG2 farms, the maximum mineral N and P sources of nutrients were restricted to 100 kg N and 20 kg P $farm^{-1}$ $year^{-1}$ and the total amounts of manure were restricted to 10 t $farm^{-1}$ $year^{-1}$ on the RG1 farms and 5 t on the RG2 farms (based on actual amounts of fertilizer and manure used on RG1 and RG2 farms). For each farm type RG1 and RG2, the best strategies for application of available nutrient resources were determined maximizing nutrient use efficiencies (based on agronomic P use efficiency, calculated as kg yield increase kg^{-1} P applied) and thus the total crop production per fertility zone. Nitrogen, P and manure were first applied to the FZ that gave the highest agronomic efficiencies, up to rates that allowed the resources to be used most efficiently. The amount of fertilizer and/or manure used in the first step was subtracted from the total resources available, and the balance applied to the remaining FZ in the order of decreasing agronomic N and P use efficiency. For the RG3 and RG4 farms where no manure and very little fertilizer were used, the model simulation for FZ4 without fertilizer or manure was the practical scenario. The best-performing strategies were simulated for five seasons to determine their suitability for total farm maize production over multiple seasons.

The impact of various resource management strategies on maize production and food sufficiency at the village scale was calculated considering the distribution of farmers of different wealth status within the village, occurrence of soil fertility zones and the total village population. At the village scale, we also explored the impact of best resource allocation strategies at the farm scale.

Maize self-sufficiency (defined here as the capacity of farmers or village to produce sufficient maize required annually) was used as an indicator of food security status, and used to assess the combined effects of the different soil fertility status and availability of resources for crop production on farmers' livelihoods. It was calculated using the households' annual requirement of maize, which differed according to household size and age distribution. On average, annual maize consumption per individual was estimated at 100 kg maize per person (Zingore et al. 2009).

Results and discussion

Long-term effects of differential resource management on SOC and maize productivity (Scenario set I)

The simulations with FIELD indicated that variability in SOC in the soil types studied was driven by application of manure at different rates, with mineral fertilizer having small effects due to removal of crop residues after harvest (Fig. 3). On the sandy soil, application of about 10 t manure ha^{-1} each year was required to prevent decline of SOC when land-use changed from native woodland to maize cultivation (Fig. 3a). Lower applications (5 and 3.3 t ha^{-1}) resulted in SOC contents of 22 and 19 t C ha^{-1} from the initial of 26 t C ha^{-1} on the sandy soil, and 38 and 33 t C ha^{-1} from the initial of 59 t C ha^{-1} on the clay soil, which corresponds well with SOC contents measured in the FZ2 and FZ3, although simulated differences between the fertility zones are smaller than measured (Table 2a). The simulated SOC contents for fields under permanent cultivation without manure or fertilizer also closely matched the SOC contents measured in the FZ4.

Farmers who have access to manure (albeit insufficient to apply at high rates across their farms) preferably use it on homefields, as this requires less labour, and is more convenient (Misiko 2007) than transporting to outfields. Fertile fields receiving about 5 t manure ha^{-1} year^{-1} are found close to the homestead on wealthy farms (FZ2), which cover about 23% of the area under cultivation in the village. Cultivation of maize year-after-year with little

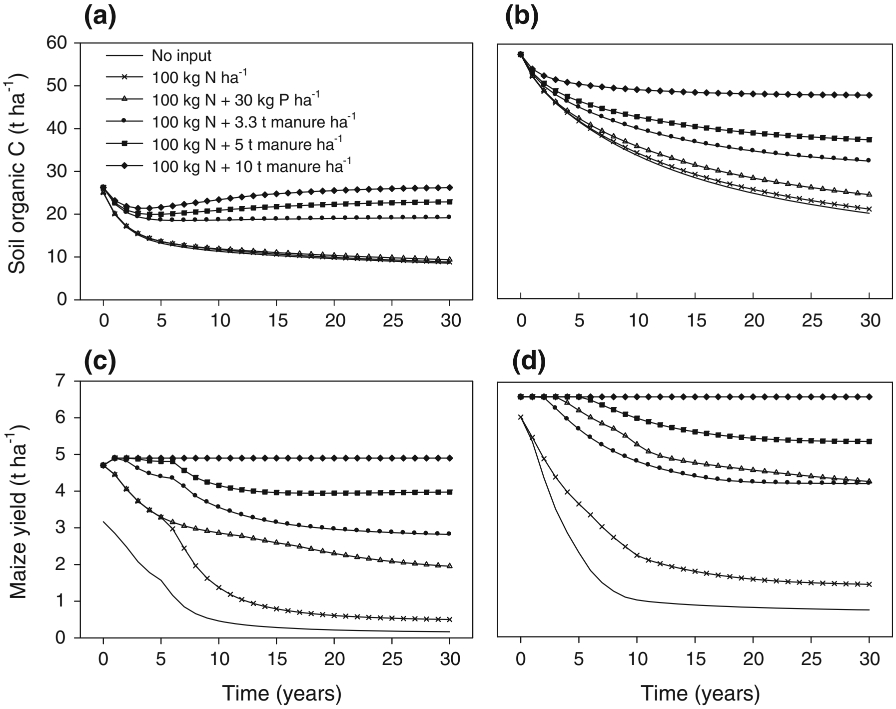

Fig. 3 Simulated effects of N, P and different rates of manure application on long-term dynamics of SOC on the sandy (**a**) and clay soils (**b**), and maize grain yields on the sandy (**c**) and clay (**d**) soils

fertilizer input is typical management of all fields on poor farms (RG3 and RG4) without cattle and outfields on RG2 farms, leading to a large area (about 55% of the area under cultivation) of depleted soils. The larger loss of SOC simulated for the clay than the sandy soil is attributed to the originally larger amounts of ‘active’ organic matter in the clay soil under woodland. In uncultivated soils, particulate organic matter is protected in macroaggregates, but is rapidly lost when those aggregates are disturbed by tillage. Despite the greater losses of SOC in the clay soil, equilibrium was attained at substantially larger contents than those for sandy soil due to greater physical stabilization capacity of the clay soil.

The FIELD simulations predicted that maize yields with mineral N and P fertilizers remain better than without fertilizer (especially with combined N and P), but their simulated effects on SOC were small, as the larger amounts of crops residues produced were not returned to replenish SOC. The beneficial effects of mineral fertilizers in maintaining SOC have been demonstrated in commercial farming systems in Zimbabwe, where large contents of organic matter in the soil was maintained by using mineral fertilizers which gave large yields, and large amounts of stover concomitantly returned (cf. Fig. 2a). Incorporating crop residues is not a practical option for maintaining SOC on smallholder farms, particularly on the mixed crop-livestock RG1 and RG2 farms, because crop residues are an important source of cattle fodder during the dry season. However, recycling of C and nutrients through manure is highly inefficient, as large losses occur during storage, handing and application to the fields (Rufino et al. 2007). Increased C input from root biomass with mineral fertilizers contributed little to SOC, as C derived from maize roots is highly labile, and thus much of it enters the active SOC pool with a rapid turnover, particularly in coarse textured soils that are ploughed.

Crop responses across soil fertility zones (Scenario set II)

On the sandy soil, simulated maize yield response to addition of N, P, and manure declined from FZ2 to FZ4 (Fig. 4). On the most fertile fields (FZ2), the

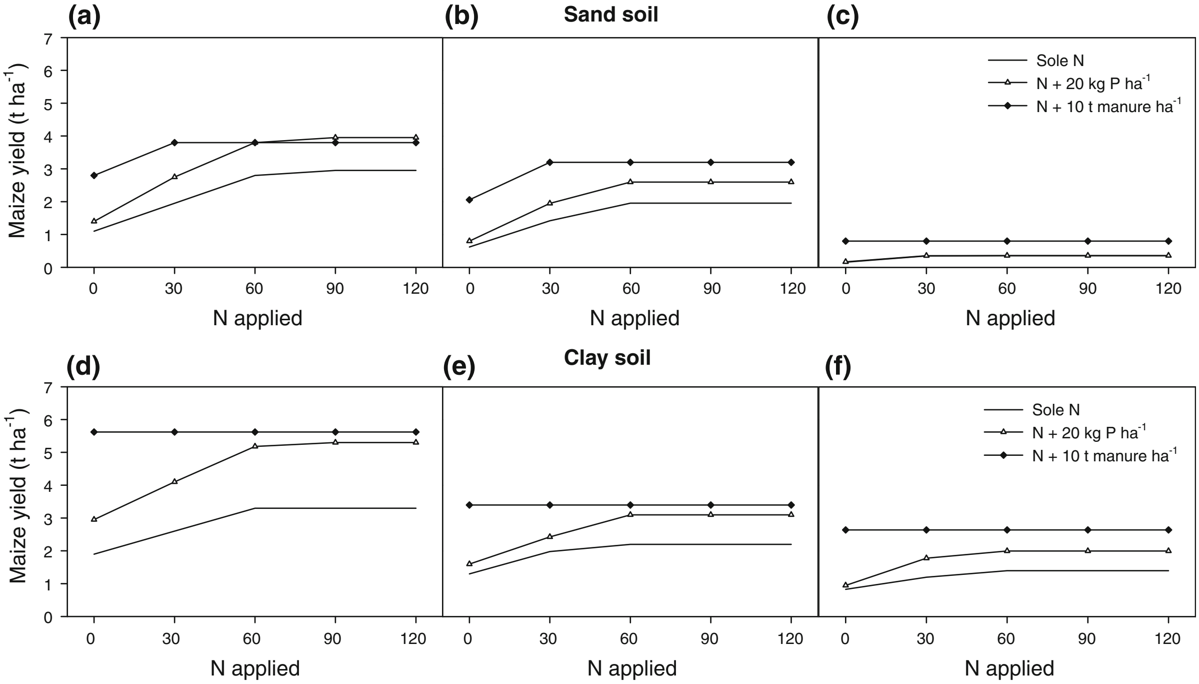

Fig. 4 Simulated maize yield response to application of N with different rates of P and manure on different soil fertility zones (FZ) on the sandy soil (FZ2, **a**; FZ3, **b**; FZ4, **c**) and clay soil (FZ2, **d**; FZ3, **e**; FZ4, **f**) at Murewa

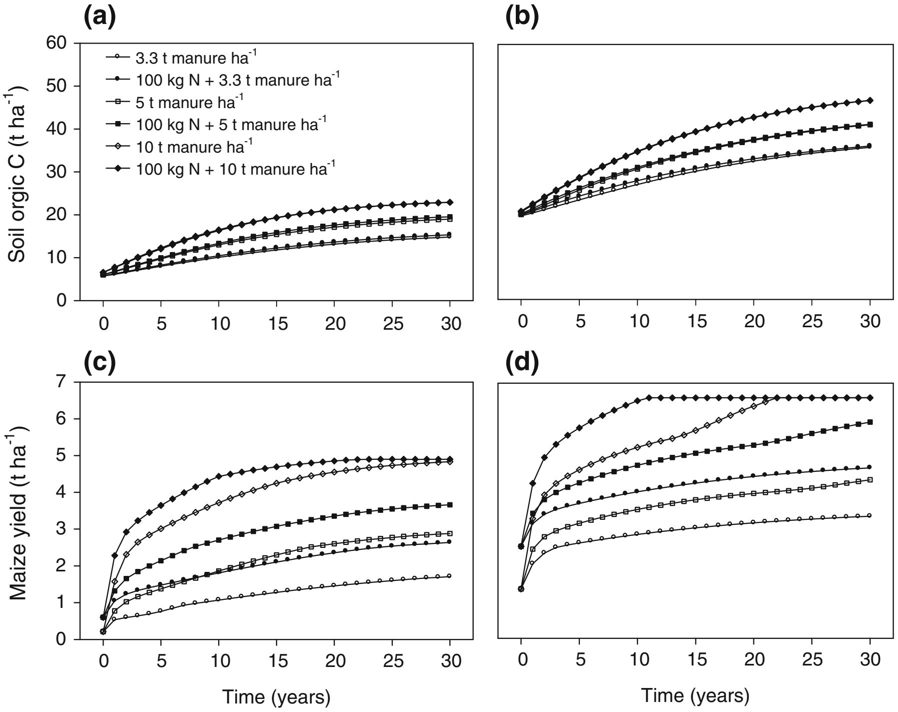

Fig. 5 Simulated effects of long-term application of different rates of manure on replenishment of SOC on degraded sandy (**a**) and degraded clay (**b**) soils and restoration maize productivity on the sandy (**c**) and clay (**d**) soils

simulated yields attainable with mineral P matched those with manure, but higher rates of N were required when P fertilizer was used (Fig. 4a). On FZ3, manure had larger effects on maize yields than P fertilizer, even when N was applied at high rates. Due to the smaller SOC contents, FIELD predicted that manure plays an increasingly important role for maize production. Poor yields (<1 t ha^{-1}) were simulated for FZ4, even with manure application (Fig. 4c). The extremely low SOC contents on FZ4 of the sandy soil are associated with multiple constraints to maize productivity, including multiple nutrient deficiencies, high acidity and low water availability (Mtamabengwe and Mapfumo 2005) and this restricted maize yields to <1 t ha^{-1}, even with manure and N application.

On the clay soil, FIELD predicted strong maize yield responses to application of N and P fertilizer on the FZ2 (Fig. 4d). FIELD predicted no additional response to mineral N on the clay soil when manure was applied at 10 t ha^{-1}. Nutrients were used less efficiently on the FZ3 than FZ2 due to the smaller yield responses (Fig. 4d, e). The responses generated by FIELD showed a succession of constraints to crop production with decreasing soil fertility status, increasing the complexity of soil fertility management options required to increase productivity.

Restoration of depleted soils (Scenario set III)

Simulations showed that addition of 10 t manure ha^{-1} year^{-1} for 10 years was required to raise attainable maize yields to those simulated for FZ1 (Fig. 5c, d). However, application of 10 t manure ha^{-1} year^{-1} for 30 years was insufficient to restore SOC to contents under woodland on both the sandy and clay soils (Fig. 5a, b). Mtambanengwe and Mapfumo (2005) observed that maize response to fertilizer on granitic sandy soils was directly linked to SOC contents, with insignificant responses when SOC fell below 0.46%. Maize yield response to N and P in depleted fields was limited by deficiency of other nutrients, as demonstrated experimentally for Ca and Zn on these sandy soils by Zingore et al. (2009). Restoration of soil fertility in degraded fields is a major challenge due to scarcity of organic resources and high costs of fertilizers that supply multiple nutrients. Cattle manure, where available, is a key resource in restoration of soil fertility (Bayu et al. 2005; Murwira et al. 1995), supplying macro- and micro-nutrients, raising soil pH, and contributing SOC. By raising soil organic matter, it provides cation exchange capacity and improves soil physical properties, such as rainfall infiltration. The challenge for restoration of soil fertility is that poor farms with the most depleted fields and the smallest areas of land are also the ones without access to manure. Alternative management that could be used by poor farmers to restore soil fertility in the depleted fields include low-external-input soil fertility improving technologies that require little cash investment, such as establishment of indigenous legume fallows (Mapfumo et al. 2005). The drawbacks of such technologies is that they cannot supply nutrients other than N, and they require farmers to invest in restoring soil fertility in the long-term without immediate food provision, and are also highly demanding for labour. Use of fertilizers that supply multiple nutrients required to address the deficiencies of both macro- and micronutrient in the degraded soils (FZ4) coupled with use of resilient crop cultivars and incorporation of crop residues can gradually replenish SOC and nutrients and improve productivity in the degraded soils on farms without livestock (Tittonell et al. 2008b).

Strategies for improving nutrient resource use efficiency at farm and village scale (Scenario set IV)

Farm scale

To maximize efficient use of limited nutrient resources, emphasis must be placed on targeting nutrients to zones that give the highest efficiencies, but avoiding application rates that over-supply nutrients to prevent decreasing marginal returns. At farm scale, simulated total maize production was largest on the RG1 farms (Table 3). This is due to a combination of large farm size and more fertile soils. On the sandy soil, the short-term production on the RG1 and RG2 farms was largest when manure was applied to the FZ3 plots, and mineral N and P applied to the most fertile FZ2 plots. However, yields simulated for this strategy after 5 years showed that production at farm scale would decrease (Tables 4, 5). This is because the yield increases in the FZ3 plots with repeated additions of manure were smaller than the yield decreases in the FZ2 plots with mineral N and P added for 5 years. Shifting gradients of soil fertility by redirecting manure application to fields of medium fertility led to increased maize production in the short term, but this did not lead to sustained high production in the medium or long-term. The best strategy simulated for

Table 3 Potential maize productivity (t ha^{-1}) and P use efficiency for farms in different wealth categories as affected by soil type, farm size, within-farm variability of soil fertility, amount of resources and resource allocation strategies

Farm	Soil type	FZ2		FZ3a		FZ3b		FZ4		Total farm production
		Yield (t ha^{-1})	PUE[a] (kg grain kg^{-1} P)	Yield (t ha^{-1})	PUE (kg grain kg^{-1} P)	Yield (t ha^{-1})	PUE (kg grain kg^{-1} P)	Yield (t ha^{-1})	PUE (kg grain kg^{-1} P)	Yield (t $farm^{-1}$)
RG1	Sand	3.5[b]	80	3.2[d]	60	2.6[c]	30	–	–	9.3
	Clay	5.7[d]	120	3.1[c]	45	2.6[b]	40	–	–	11.4
RG2	Sand	3.5[b]	80	3.2[d]	60	–	–	0.6[b]	20	5.7
	Clay	4.7[d]	140	3.1[c]	45	–	–	1.7[b]	30	8.0
RG3	Sand	–	–	–	–	–	–	0.4[b]	20	0.9
	Clay	–	–	–	–	–	–	1.7[b]	30	3.7
RG4	Sand	–	–	–	–	–	–	0.4[b]	20	0.4
	Clay	–	–	–	–	–	–	1.7[b]	30	1.7

[a] Agronomic P use efficiency calculated as additional kg grain produced per kg of P applied

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

[c] P applied at 20 kg ha^{-1}

[d] Manure applied

Table 4 Effects of the best resource allocation strategies on maize productivity in the first year in individual plots and whole RG1 and RG2 farms in Murewa

Farm	Soil type	FZ2 (t ha^{-1})	FZ3a (t ha^{-1})	FZ3b (t ha^{-1})	FZ4 (t ha^{-1})	Total farm production (t $farm^{-1}$)
RG1	Sand	3.5[b]	3.2[d]	2.6[c]	–	9.3
	Clay	5.7[d]	3.1[c]	2.6[b]	–	11.4
RG2	Sand	3.5[b]	3.2[a,d]	–	0.6[b]	5.7
	Clay	4.7[d]	3.1[a,c]	–	1.7[b]	8.0

[a] Area of field is 0.5 ha; hence maize production per plot is 50% of the productivity

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

[c] P applied at 20 kg ha^{-1}

[d] Manure applied

Table 5 Maize productivity after 5 years of implementing the initially best fertilizer and manure allocation strategies in individual plots and whole RG1 and RG2 farms in Murewa

Farm	Soil type	FZ2 (t ha^{-1})	FZ3a (t ha^{-1})	FZ3b (t ha^{-1})	FZ4 (t ha^{-1})	Total farm production (t $farm^{-1}$)
RG1	Sand	2.2 (−1.3)	4.2 (+1.1)	1.4 (−1.2)	–	7.8 (−1.5)
	Clay	6.4 (+0.7)	2.6 (−0.5)	2.1 (−0.5)	–	11.1 (−0.3)
RG2	Sand	2.2 (−1.3)	4.2 (+1.1)[a]	–	0.4 (−0.2)	4.7 (−1.0)
	Clay	4.7 (0)	2.6 (−0.5)[a]	–	1.5 (−0.2)	7.5 (−0.5)

Yield changes after 5 years are shown in parenthesis

[a] Area of field is 0.5 ha; hence maize production per plot is 50% of the productivity

the RG1 farm on the clay soil was when manure was concentrated to the most fertile plot (FZ2) and mineral N and P applied to the two plots in the FZ3 (Table 3). This implies that current management of targeting high rates of manure to FZ2 plots and mineral fertilizers to FZ3 plots is the best option to sustain maximum maize productivity at the farm scale.

Options for improving productivity and resource use efficiency were limited on the RG3 and RG4 farms with depleted plots and without access to manure. On the sandy soil, maximum yields achievable with mineral N and P fertilizers on the RG3 and RG4 farms were only 0.4 and 0.9 t $farm^{-1}$ respectively. Maize production was greater on the RG3 and RG4 farms on the clay soil due to higher soil fertility status.

Village scale

Preventing a decline in SOC after land is cleared for cultivation by applying large amounts of manure (>10 t ha^{-1}) is not feasible, as the total amounts of manure produced annually at village scale are about 350 t, sufficient to cover only 35 ha (about 18% of the total arable area) if applied at 10 t ha^{-1}. Attention should be paid to judicious use of the limited nutrient resources to maintain a level of soil fertility that supports good crop response to fertilizer application (Mtambanengwe and Mapfumo 2005). Targeting manure application to restore SOC to about 60 and 50% of maximum contents was sufficient to increase productivity to 90% of attainable yields on the sandy and clay soils, respectively. At village scale, the current farmer management practice of applying manure at 5 t ha^{-1} into FZ2, 3.3 t ha^{-1} in FZ3, and none in FZ4 (Fig. 6) resulted in an aggregate maize production of 334 t $year^{-1}$, at an average yield of 1.7 t ha^{-1} $year^{-1}$. The largest contribution came from FZ2, despite the area under FZ2 being less than half of that under FZ4. This highlights the important contribution of the small zones of high soil fertility near homesteads of wealthy farmers (FZ2) to maize

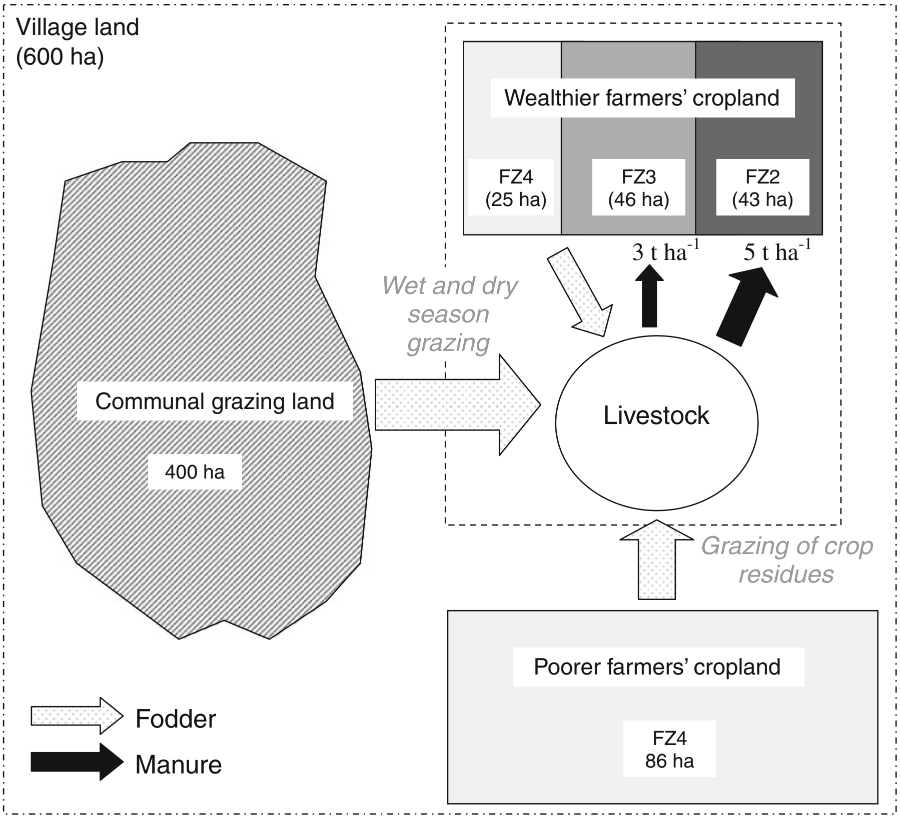

Fig. 6 Livestock-mediated nutrient transfers driving heterogeneity in soil fertility at the farm and village levels, including model estimates of long-term manure applications that have created existing soil fertility gradients in Murewa, Zimbabwe. Through manure, cattle transfer nutrients from communal grazing lands and cropping fields to home- and midfields belonging to wealthy farms leading to creation of 'islands' of fertile fields on homefields of wealthy farmers. See Table 2 for description of soil fertility zones (FZ)

production at village scale. The best strategies for nutrient resource allocation at the farm scale increased maize production at village scale by 41 t above the current management. This increase in maize production at village scale was mainly due to yield increases by reallocating manure from FZ2 to FZ3 on the sandy soil. As shown earlier in the analysis at farm scale, the increased production by reallocation the same amount of fertilizer and manure may not be sustained.

A previous study that sought to design sustainable farm units in Zimbabwe, established that cropping could not be sustained 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 with crop residues removed, which agrees well with the results we simulated for the sandy soil using FIELD. This reinforces the results produced by FIELD showing that redistribution of the same amount of limited nutrient resources only led to a short-term increase in productivity, and increased investment in nutrient resources is necessary for sustainable increase in productivity.

Implications for food sufficiency at farm and village scale

Under current management, maize productivity on RG4 farms on the sandy soils is slightly below the annual maize requirements of 0.5 t year^{-1}, even when maize is grown on the whole farm (Table 6). The RG4 farms on the clay soil can potentially produce 1.2 t maize each year in excess of that required for household consumption. Despite cultivating poor soils and lack of nutrient resources, RG3 farmers on

Table 6 Potential maize production, maize requirement and excess maize for sale (assuming maize was the only crop cultivated) on farms in various resource groups on a sandy and clay soil in Murewa

	Sandy soil			Clay soil		
Farm type	Maximum production (t farm^{-1} year^{-1})	Maize requirement (t household^{-1} year^{-1})	Excess maize for sale (t farm^{-1} year^{-1})	Maximum production (t farm^{-1} year^{-1})	Maize requirement (t household^{-1} year^{-1})	Excess maize for sale (t farm^{-1} year^{-1})
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	0.7	0.2	3.7	0.7	3.0
RG4	0.4	0.5	0.0	1.7	0.5	1.2

the clay and sandy soils can potentially produce sufficient maize to meet their annual requirements because they own larger farms than RG4 farmers. RG1 and RG2 farms can potentially produce at least 5–11 t of maize each year above what they require for consumption, due to a combination of fertile soils, relatively large farm sizes and use of greater amounts of mineral fertilizers and manure. Land area cultivated by farmers, soil types and soil fertility status due to management history are key factors determining the capacity of farmers to produce sufficient maize, an important indicator of food security in the area (Waithaka et al. 2006; Zingore et al. 2009).

The poorest (RG4) farmers commonly work for the wealthy farmers to supplement food produced on their own farms. The key synergies between farmers at village scale are to a large extent influenced by resource endowment: crop production on wealthy farms is ensured by nutrients recycled from rangelands and fields of poor farmers, and by labour supplied by poor farmers. On the other hand, the poor farmers who have no capacity to grow sufficient maize for home consumption on their own farms benefit from the excess maize production at the village scale in return for the labour they sell to wealthy farmers (Zingore et al. 2009).

How to target the allocation of nutrient resources to spatially variable soil fertility conditions within and across smallholder farms?

Current blanket fertilizer recommendations are based on maximum achievable yields, as determined by rainfall received, but they ignore heterogeneity in soil fertility at farm and village scale. Variable responses to mineral fertilizers due to differences in soil fertility and other factors such as seasonal variation in rainfall are inevitable, and are given as major reasons limiting use of mineral fertilizers in smallholder farming systems (Nandwa and Bekunda 1998). We propose a simple approach for targeted allocation of nutrient resources that recognizes the inherent and management induced variability in soil fertility at the farm and village scales. Firstly, soil types are distinguished due to the strong influence of inherent soil properties on soil physical and chemical processes. For each soil type, historical management is then brought into perspective, mainly on the basis of manure application, since manure is the key resource driving variability in soil fertility (Fig. 3). The rates of manure applied are then used as the third criteria to delineate zones of soil fertility. These criteria are based on factors influencing soil fertility variability that are readily recognizable by farmers and can be used in situations where high costs and small fields prevent wide scale soil analysis for fertilizer recommendations.

Further model development and refinement of management of nutrient resources

The type of analyses performed above are useful conceptual exercises to illustrate the impact on different biophysical aspects of the system that certain resource allocation strategies may have, or to explore options for soil fertility maintenance in the medium to long-term. To develop recommendations and/or design alternative management strategies with the aid of model-based studies, it is necessary to consider explicitly also the socio-economic constraints faced by farmers. For example, reallocation of manure from FZ2 to FZ3 may not be feasible due to lack of labour. 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 required 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.

Farmers' decision making on allocation of their limited resources is influenced by multiple factors, corresponding to both the socio-economic and biophysical environments in which farmers operate, including village scale negotiations, potential conflict and local traditions regulating the use of communal resources. This implies the need of using integrative models that consider multiple household activities at farm and village scales (e.g., Rufino et al. 2010). The effects of crop rotation and competition by weeds are some of the important factors not yet incorporated in the model.

Conclusions

In crop-livestock mixed farming systems in northeast Zimbabwe, preferential application of manure to fields closest to homesteads has created gradients of decreasing soil fertility with increasing distance from homesteads on farms of cattle owners, or prevalent poor soil fertility in fields of non-cattle owners, following prolonged cultivation with small applications of fertilizer and no organic nutrient resources. Exclusive use of fertilizer without paying attention to soil organic matter resulted in a sharp decline in maize productivity. Model simulations showed a succession of constraints to crop production with decreasing soil fertility status, increasing the complexity of soil fertility management options required to restore productivity. Targeting manure application (>5 t ha^{-1} year^{-1} for about 10 years) to restore SOC in depleted fields to about 60 and 50% of its content under native woodlands was required to increase maize productivity to 90% of attainable yields on the sandy and clay soils, respectively. Limited nutrient resources were used most efficiently at the farm scale by targeting nutrients to the fields of higher fertility, but limiting application rates to avoid decreasing marginal responses. There is scope to improve productivity of smallholder farms by targeted application of limited mineral and organic nutrient resources to fields varying in soil fertility, although this would have greater impact on wealthier farmers who have more fertile soils and greater access to fertilizer and manure. The increase in crop productivity by reallocating a limited amount of resources at the farm scale were not sustained on the sandy soil, and increased investment in organic nutrient resources is necessary to sustainably increase crop productivity.

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