Field Crops Research 147 (2013) 40–53

Contents lists available at SciVerse ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Pushing the envelope? Maize production intensification and the role of cattle manure in recovery of degraded soils in smallholder farming areas of Zimbabwe

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ARTICLE INFO

Article history:
Received 1 February 2013
Received in revised form 20 March 2013
Accepted 23 March 2013

Keywords:
Cattle manure
Maize production
Crop–livestock systems
Degraded soils
Nutrient gradients
Integrated soil fertility management (ISFM)
Ecological intensification (EI)

ABSTRACT

Soil fertility decline is a major constraint to crop productivity on smallholder farms in Africa. The objective of this study was to evaluate the long-term (up to nine years) impacts of nutrient management strategies and their local feasibility on crop productivity, soil fertility status and rainfall infiltration on two contrasting soil types and different prior management regimes in Murehwa, Zimbabwe. The nutrient management strategies employed in the study were: a control with no fertiliser, amendments of 100 kg N ha^{-1}, 100 kg N + lime, three rates of manure application (5, 15 and 25 t ha^{-1}) in combination with 100 kg N ha^{-1}, and three rates of P fertiliser (10, 30 and 50 kg P ha^{-1}) in combination with 100 kg N, 20 kg Ca, 5 kg Zn and 10 kg Mn ha^{-1}. Maize grain yields in sandy soils did not respond to the sole application of 100 kg N ha^{-1}; manure application had immediate and incremental benefits on crop yields on the sandy soils. A combination of 25 t ha^{-1} manure and 100 kg N gave the largest treatment yield of 9.3 t ha^{-1} on the homefield clay soils, 6.1 t ha^{-1} in the clay outfield, 7.6 t ha^{-1} in the homefield and 3.4 t ha^{-1} in the eighth season. Yields of the largest manure application on the sandy outfields were comparable to yields with 100 kg N in combination with 30 kg P, 20 kg Ca, 5 kg Zn and 10 kg Mn ha^{-1} in the homefields suggesting the need to target nutrients differently to different fields. Manure application improved rainfall infiltration in the clay soils from 21 to 31 mm h^{-1} but on the sandy soils the manure effect on infiltration was not significant. Despite the large manure applications, crop productivity and SOC build-up in the outfield sandy soils was small highlighting the difficulty to recover the fertility of degraded soils. The major cause of poor crop productivity on the degraded sandy soils despite the large additions of manure could not be ascertained. The current practice of allocating manure and fertiliser to fields closest to homesteads exacerbates land degradation in the sandy outfields and increases soil fertility gradients but results in the most harvest for the farm. On clay soils, manure may be targeted to outfields and mineral fertiliser to homefields to increase total crop productivity. Farmers who owned cattle in the study site can achieve high manure application rates on small plots, and manure application can be rotated according to crop sequences. Consistent application of manure in combination with mineral fertilisers can be an effective option to improve crop yield, SOC and moisture conservation under smallholder farming conditions. Combined manure and mineral fertiliser application can be adapted locally as a feasible entry point for ecological intensification in mixed crop–livestock systems.

1. Introduction

Farming systems in southern Africa exhibit a close integration between crops and livestock. Crop residues are used as livestock feed during the dry season (de Leeuw, 1996), and manure is an important source of nutrients for crop production (Murwira et al., 1995; Zingore et al., 2008). This synergistic relationship is

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http://dx.doi.org/10.1016/j.fcr.2013.03.014

widespread in farming systems, but varied in its ecological and economic complexity (McCown et al., 1979). In the maize-based farming systems of southern Africa, cattle are the main livestock and are grazed in a communal system during the day and kept in kraals close to homesteads at night. Cattle are herded in the communal rangelands during the rainy season and graze freely both rangelands and crop fields during the dry season. Benefits in these mixed crop–livestock systems are skewed towards cattle owners because they have access to crop residues from non-livestock owners; non-livestock owners only benefit if cattle deposit significant amounts of manure whilst grazing in their fields (Rufino et al., 2007). Manure availability is critical in these smallholder systems because mineral fertiliser use, as in the whole of sub-Saharan Africa, has remained far below the amounts required to sustain crop production (Sanchez, 2002; Bekunda et al., 2010). On the other hand household manure production is often insufficient for optimum application to all fields of the farm (Zingore et al., 2007a,b; Rufino et al., 2011).

A combination of shortages of labour, fertiliser and manure often leads to preferential allocation of nutrients to fields close to the homestead resulting in highly nutrient deficient outfields (Mtambanengwe and Mapfumo, 2005; Zingore et al., 2007a). The outfields on sandy soils are typically characterised by deficiencies of N, P and S, high acidity, low soil organic carbon (SOC) and low water holding capacity (Zingore et al., 2007a). These multiple nutrient deficiencies in combination with low organic matter content render these soils non-responsive to application of NPK fertiliser. The differences in soil fertility resulting from variable farmer management practices require adapted nutrient management strategies to improve nutrient use efficiencies (Zingore et al., 2007b; Tittonell and Giller, 2013). A combination of mineral fertiliser and manure has shown promise to improve crop productivity of the nutrient depleted outfields (Dunjana et al., 2012). However restoration of the fertility of degraded soils is likely to be hampered by the need to maximise returns to limited nutrient resources which is assured in homefields compared with the degraded outfields (Zingore et al., 2007a).

Large quantities of good quality manure are necessary to achieve and sustain high crop productivity (Powell and Mohamed-Saleem, 1987; Snapp et al., 1998). Good quality manure should be anaerobically composted with added plant material, contain N greater than 1.8% and be free of sand (Murwira et al., 1995; Rufino et al., 2007; Tittonell et al., 2010). Applications of about 17 t ha^{-1} manure have been found to be effective in the short term in improving SOC, P, pH, base saturation and the restoration of crop productivity of a degraded sandy soil in north-east Zimbabwe (Zingore et al., 2008). In a similar study, annual applications of 3 or 6 t of manure for five years on a sandy soil at Grasslands Research Station, Zimbabwe raised the fertility of the soils by progressively increasing the cation exchange capacity, the exchangeable bases and pH (Grant, 1967). Nyamangara et al. (2001) demonstrated that manure application of 12.5 t ha^{-1} per year or 37.5 t ha^{-1} once in three years significantly improved the structural stability and water retention capacity of sandy soils with low organic matter content. However, such application rates are only possible on small fields (<0.5 ha) or for farmers who own many livestock. Both of the former studies reported results of three year investigations; the long-term recovery of degraded soils and their ability to support sustainable high crop productivity are not fully understood. Our major hypothesis is that long-term application of manure and mineral fertiliser can restore fertility of degraded soils and offset the yield and SOC differences between homefields and outfields which could be a sustainable and feasible entry point for ecological intensification. We also hypothesised that the rate of recovery of degraded soil depends on soil type.

In this paper the results of a 9-year agronomic experiment conducted in north–east Zimbabwe are described and discussed. The results of the first three years of this experiment were reported earlier by Zingore et al. (2007b). The overall objective of the experiment was to improve nutrient use efficiency through strategic application of limiting nutrients, and to identify a pathway to restore soil fertility of degraded outfields using a combination of mineral fertilisers and manure. We measured crop grain yield as it is the basis for household food security and income (Jayne and Jones, 1997), and SOC as it is an important determinant of soil fertility and sustainability (Körschens et al., 1998; Lal, 2006). In addition we measured rainfall infiltration as affected by long-term manure application using simulated rainfall. Water infiltration into the soil is an important soil quality indicator that is strongly affected by land management practices such as organic matter inputs (Lal, 1990; Franzluebbers, 2002), and is especially important under water-limited crop production. Manure availability is a great constraint at farm the scale, thus we quantified feasible manure quantities and the corresponding current manure application rates to various plots across the farm.

2. Materials and methods

2.1. Site description

Manjonjo (17°49′ S; 31°33′ E, 1300 metres above sea level – m.a.s.l.) and Ruzvidzo (17°51′ S; 31°34′ E, 1300 m.a.s.l.) villages are located in Murehwa smallholder farming area, 80 km north east of Harare. Murehwa is located in agro-ecological region II (Vincent and Thomas, 1960) which receives annual rainfall of between 750 and 1000 mm in a unimodal pattern. Mid-season dry spells are common. The soils in the area are predominantly granitic sandy soils (Lixisols: FAO, 1998) of low inherent fertility with intrusions of dolerite derived clay soils (Luvisols; FAO, 1998) that are relatively more fertile (Nyamapfene, 1991). Cattle ownership varies widely among households (Zingore et al., 2007a). Other small livestock such as goats and chickens are also important. Farmers who own cattle use manure together with small amounts of mineral fertiliser they can afford on small areas of the farm resulting in improved crop productivity. Maize (*Zea mays* L.) is the dominant staple crop while groundnut (*Arachis hypogaea* L.), sweet potato (*Ipomoea batatas* (L.) Lam.) and sunflower (*Helianthus annuus* L.) are important crops.

The communal grazing area is characterised by the Miombo woodland dominated by *Julbernardia globiflora* (Benth.) Troupin, *Brachystegia boehmii* (Taub.) and *Brachystegia spiciformis* (Benth.) (Mapaure, 2001). Grass species of the genus *Hyparrhenia* are predominant, and *Andropogon*, *Digitaria*, and *Heteropogon* spp. are also common species. *Sporobolus pyramidalis* (P.) Beauv., a grass of poor grazing quality often dominates in overgrazed areas and perennially wet 'vlei' areas of the veld.

2.2. Experimental design

Initial farming system and field characterisation revealed the occurrence of soil fertility gradients due to previous soil fertility management on both clay and sandy soils (Zingore et al., 2007a). Fields close to the homestead (i.e. 0–50 m) were relatively more fertile and called *homefields*, and those far away from the homestead (i.e. 100–500 m) were relatively less fertile and called *outfields* (Table 1). Thus the experiment was established on fields with contrasting soil types (Manjonjo – sandy soil, Ruzvidzo – red clay soil) and previous nutrient management intensity. The sand plus silt content of clay homefield was 56%, clay outfield 58%, sandy homefield 15% and sandy outfield 12%. Initial characterisation showed

Table 1
Initial and final soil chemical properties after nine seasons of manure and mineral fertiliser application on fields with different previous management (homefield and outfields) on sandy and clay soils at Murehwa, Zimbabwe. The treatments 5TM, 5TM and 25TM refer to manure application rates of 5, 15 and 25 t ha^{-1}.

Soil	Field type	Treatments	C (%)	N (%)	pH	Available P (mg kg^{-1})	CEC (cmol$_c$ kg^{-1})	Ca (cmol$_c$ kg^{-1})	Mg (cmol$_c$ kg^{-1})	K (cmol$_c$ kg^{-1})	BS%
Sandy	Homefield	Initial	0.50	0.04	5.10	7.20	2.20	0.91	0.32	0.21	73.00
		Control	0.40	0.03	5.38	6.62	2.53	1.46	0.45	0.17	57.91
		100N	0.29	0.03	5.26	8.91	2.83	1.06	0.35	0.15	57.84
		100N + 5TM	0.59	0.05	5.43	7.47	5.27	2.29	0.72	0.32	64.77
		100N + 15TM	0.50	0.04	5.29	8.40	4.78	1.90	0.65	0.31	61.52
		100N + 25TM	0.68	0.06	5.47	9.38	6.51	2.91	0.95	0.40	66.83
	Outfield	Initial	0.30	0.03	4.90	2.40	1.60	0.26	0.19	0.11	37.00
		Control	0.34	0.03	5.00	2.01	3.30	0.94	0.36	0.10	45.84
		100N	0.30	0.03	5.08	4.33	2.84	0.92	0.34	0.12	51.74
		100N + 5TM	0.34	0.03	5.05	8.12	3.16	0.98	0.37	0.16	51.16
		100N + 15TM	0.39	0.03	5.12	8.47	3.94	1.29	0.49	0.21	53.21
		100N + 25TM	0.49	0.04	5.26	9.00	4.59	1.72	0.64	0.25	58.24
Clay	Homefield	Initial	1.40	0.08	5.60	12.10	24.20	11.50	6.20	0.80	78.00
		Control	1.38	0.05	6.44	10.39	19.63	10.32	5.38	0.67	83.06
		100N	1.37	0.05	6.47	10.87	22.75	11.53	8.76	0.58	87.76
		100N + 5TM	1.53	0.09	6.50	15.43	22.63	11.66	7.23	1.30	89.41
		100N + 15TM	1.63	0.08	6.52	15.45	24.32	12.86	7.94	1.24	90.52
		100N + 25TM	1.84	0.09	6.50	16.70	25.58	13.68	8.53	1.60	93.47
	Outfield	Initial	0.80	0.05	5.40	3.90	22.00	8.40	6.30	0.30	68.60
		Control	0.67	0.05	6.46	3.83	20.33	8.10	6.07	0.51	72.98
		100N	0.76	0.06	6.52	4.30	27.92	14.69	10.52	0.49	90.53
		100N + 5TM	0.82	0.06	6.51	9.81	30.73	15.71	10.94	0.63	88.19
		100N + 15TM	0.87	0.06	6.51	10.04	28.11	14.62	10.33	0.82	88.98
		100N + 25TM	0.97	0.06	6.44	10.80	23.68	12.23	8.70	0.98	89.51
	*Standard error of mean SEM		0.11	0.00	0.14	0.84	2.51	1.28	0.92	0.09	3.82

that both soils were deficient in N and P, confirming that they were the most limiting nutrients across soil types; whereas K was deficient only in the sandy soils (Table 1). Experimental fields were tilled using an ox-drawn mouldboard plough at the start of the rainy season. All previous crop harvest residues were grazed by cattle during the dry season. The experiment was located on four fields (clay homefield, clay outfield, sandy homefield, and sandy outfield) on two farms, one on each soil type. Experimental treatments were laid out in a randomised complete block design (RCBD) with three replications on 6 m × 4.5 m plots in each field. The experiment was run for nine seasons starting with the 2002/2003 season. No crops were sown in the fourth season (2005/2006) and the seventh season (2008/2009) due to logistical problems, fields had been tilled but weeds were allowed to grow. The initial treatments were:

i. Control (no amendment added)
ii. 100 kg N ha^{-1}
iii. 100 kg N ha^{-1} + 10 kg P ha^{-1} (i.e. 5 t manure ha^{-1})
iv. 100 kg N ha^{-1} + 30 kg P ha^{-1} (i.e. 15 t manure ha^{-1})
v. 100 kg N ha^{-1} + 30 kg P ha^{-1} (i.e. 15 t manure ha^{-1}), dolomitic lime (500 kg ha^{-1})
vi. 100 kg N ha^{-1} + 10 kg P ha^{-1}
vii. 100 kg N ha^{-1} + 30 kg P ha^{-1}
viii. 100 kg N ha^{-1} + 30 kg P ha^{-1}, dolomitic lime (500 kg ha^{-1})
ix. 100 kg N ha^{-1} + dolomitic lime (500 kg ha^{-1}).

Mineral fertiliser N was applied as ammonium nitrate (AN, 34.5% N) and P as single super-phosphate (SSP), 20% P_2O_5). After the first season, the following treatments were modified: treatment (v) was modified to manure equivalent of 50 kg P ha^{-1} plus 100 kg N ha^{-1}, and treatment (viii) was modified to 50 kg P ha^{-1} (SSP) plus 100 kg N ha^{-1}. Application of dolomitic lime was discontinued because it had small effects on maize yield. Results from the initial four years showed no significant grain yield response to addition of N and P alone (Zingore et al., 2007b), and results from a pot experiment suggested that Ca and micronutrient deficiencies limited the response of maize to N and P (Zingore et al., 2008). Treatments that received mineral fertilisers only (AN and SSP) were modified in the 6th season (2006/2007) to include Ca, Mn and Zn. This allowed assessment of the potential to increase maize yields and P use efficiency with Ca and micronutrient additions to mineral fertiliser treatments especially on degraded sandy soils compared with manure treatments. Potassium (K) was not included in the fertiliser treatments, which in retrospect was an oversight in the design. From the sixth season, the treatments were:

i. Control (no amendment added)
ii. 100 kg N ha^{-1}
iii. 100 kg N ha^{-1} + 10 kg P ha^{-1} (i.e. 5 t manure ha^{-1})
iv. 100 kg N ha^{-1} + 30 kg P ha^{-1} (i.e. 15 t manure ha^{-1})
v. 100 kg N ha^{-1} + 50 kg P ha^{-1} (i.e. 25 t manure ha^{-1})
vi. 100 kg N ha^{-1} + 10 kg P ha^{-1} + 20 kg Ca ha^{-1} + 5 kg Zn ha^{-1} + 10 kg Mn ha^{-1}
vii. 100 kg N ha^{-1} + 30 kg P ha^{-1} + 20 kg Ca ha^{-1} + 5 kg Zn ha^{-1} + 10 kg Mn ha^{-1}
viii. 100 kg N ha^{-1} + 50 kg P ha^{-1} + 20 kg Ca ha^{-1} + 5 kg Zn ha^{-1} + 10 kg Mn ha^{-1}
ix. 100 kg N ha^{-1} + 500 kg lime ha^{-1}.

Aerobically composted solid cattle manure was applied annually on a dry-weight basis. Manure was dug and heaped without cover for two months before application to the fields, mimicking local management. To reduce variability, cattle manure was collected from the same farm every year and contained 20% C, 1.1% N, 0.18% P, 0.20% Ca, 0.08% Mg, 0.64% K, 800 mg kg^{-1} Fe, 22 mg kg^{-1} Cu, 280 mg kg^{-1} Mn, 112 mg kg^{-1} Zn (Zingore et al., 2008). Manure was spread evenly on the surface covering the whole plot and incorporated (0–10 cm) into the soil using hand hoes before planting. Basal and top-dressing fertiliser was spot-applied at each planting hill. Ammonium nitrate fertiliser was applied as top-dressing in two 50 kg N ha^{-1} amounts at three and six weeks after crop emergence in all plots except the control. A medium maturity, drought tolerant hybrid maize variety SC525 was planted at a spacing of 90 cm between rows and 25 cm within the row to give a plant population of 44,444 plants ha^{-1}. All plots were weeded manually four times during each season.

2.3. Soil and manure sampling and analysis

In 2002 (baseline) and in 2011 (after nine seasons), soil samples were taken from the experimental fields using an auger (0–20 cm depth), air-dried and, sieved prior to analysis. Total C and N in soil and manure were analysed through dry combustion using a carbon/hydrogen/nitrogen analyser (Leco-CNS2000). Available P was measured by the Olsen method (Olsen et al., 1954). Soil pH was measured with a digital pH metre in a 1:2.5 (w/v) soil: deionised water suspension, Ca and Mg were determined by atomic absorption spectroscopy and K by flame photometry after extraction in ammonium acetate, and cation exchange capacity (CEC) by the ammonium acetate method as described by Anderson and Ingram (1993).

2.4. Rainfall infiltration measurement

Artificial rainfall was generated by a portable rainfall simulator based on single full cone nozzle principle and calibrated following the procedure of Panini et al. (1993) and Nyamadzawo et al. (2003). Simulated rainfall with intensity of 35 mm h^{-1} was supplied from a height of 5 m on a surface area of 2.25 m^2 (1.5 m × 1.5 m). Uniformity of size and distribution of raindrops was achieved at this rainfall intensity. Measurements were taken from the central 1 m^2 confined using metal sheets leaving a single outlet leading into a small gutter where runoff was collected. The nozzle was checked and adjusted; three rain gauges were installed in the wetted buffer area to check the uniformity of rainfall distribution. Water for the simulation experiment was collected from the communal borehole closest to the experimental field. The rainfall simulations were carried out in October 2009 under dry conditions (less than 5% soil moisture); simulations continued until steady state runoff was attained on the clay soils. On the sandy soils, rainfall simulations continued for more than 5 h because it was not possible to reach steady state infiltration. Infiltration was estimated by calculating the difference between applied rain and runoff. The irregular infiltration patterns in sandy soils meant the data could not be modelled. A sigmoidal decay curve characterised by a lag-phase of decrease of initial infiltration was used to describe the clay soil infiltration data. The model had four parameters: $i_t = i_f + (i_i - i_f/1 - (t/t_0)^K)$ where i_i is initial infiltration rate, i_f is final infiltration rate, t_0 is time *at* $i_i/2$, and K is the infiltration rate decay coefficient.

2.5. Crop yield measurement

Maize was harvested after physiological maturity; yield was estimated from a net plot of 5.4 m^2 (2.7 m × 2 m) in the centre of the plot to avoid border effects. Grain was shelled from the cob by hand and separated from stover (leaves stalk and core). Grain weight was measured using a digital scale, and moisture content taken immediately to correct yields to 12.5% moisture. Stover sub-samples were dried in the oven at 70 °C until constant mass to convert fresh stover yields measured in the field to dry matter.

2.6. Manure collection estimates

An on-farm survey was carried out in September 2011 to estimate the amount of manure that households (who owned cattle) collected from their kraal in Manjonjo village. We also estimated the manure application rates for the various plots to which manure was applied. Twenty-five farmers were interviewed, a specific question was asked on the number of carts collected from the kraal per farm. The mass of manure contained in a local standard cart (1 m^3) was measured using a digital scale. Total amount of manure collected was obtained by multiplying the number of carts collected by the standard mass of manure in a cart per farm. Sub-samples of manure were collected, oven dried and moisture content used to express manure on a dry weight basis.

A boundary line was fitted to establish the relationship between amount of manure collected and number of cattle owned per farm. Boundary lines were fitted through boundary points that corresponded to the largest manure quantity (y) at each value of the number of cattle (x) using the model: $y = ax + b$. The most suitable boundary line model was obtained by minimising the root mean squared error (RMSE) between the fitted boundary line and the boundary points using the Solver function in MS Excel.

2.7. Statistical analysis

The generalised linear mixed model (GLMM) in GenStat 14th Edition (VSN, 2011) was used to test the effects of nutrient management treatment, soil and field type, season and their interactions on crop yield. Maize grain yield data were tested for normality and found to be normally distributed using the Shapiro–Wilk W test (Shapiro and Wilk, 1965). Three models were used in the analyses: Model 1 (combined model) was used to describe maize yield across both clay and sandy soils, Model 2 (clay soil) to describe maize yield on clay soils and Model 3 (sandy soil) to describe maize yield on sandy soils. Model 1 aimed at testing the general effect of the factor ‘soil type’ on maize yields. In Model 2 and Model 3, the effect of ‘nutrient management’ and ‘field type’ was further specified for the two soil types in order to test their specific effects on maize yield. In the analysis, nutrient management treatments, soil and field type were considered fixed factors while season was considered a random factor. Nutrient management, soil and field types were considered fixed factors because these were specifically determined and their effects on yield were of major interest. The fixed effects were tested by sequentially adding terms to the fixed model. Season was considered a random factor due to the fact that the effect of season under rainfed conditions is nested in the interaction of amount × distribution of rainfall, and cannot be determined experimentally. It is also unlikely that the duration of the experiment covered all the possible combinations of amount × distribution of rainfall. The major interest on the seasonal effect was also on the variation among them rather than the specific effects of each on crop yield in each treatment. A multiple correlation analysis was performed to understand the relationship between maize grain yield and other measured variables such as soil bulk density, SOC and rainfall infiltration using data from the 2009/2010 season.

3. Results

3.1. Experimental factors on maize grain yield

Total seasonal rainfall did not vary strongly among the seasons with the 2005/2006 season recording the least rainfall (Fig. 1a). However, intra-seasonal rainfall distribution varied strongly (Fig. 1b), there were large differences in rainfall received during the critical grain filling stage, ca. day 80 after planting. Treatment (nutrient management), soil type, field type and season all had significant ($P < 0.0001$) effects on crop grain yield (Table 2). The interaction of all the four factors was also significant on crop grain yield. Analysis of residual variances showed that soil type had the strongest ($F = 426$) effect on yield followed by field type and nutrient management, and lastly season (Model 1). Under

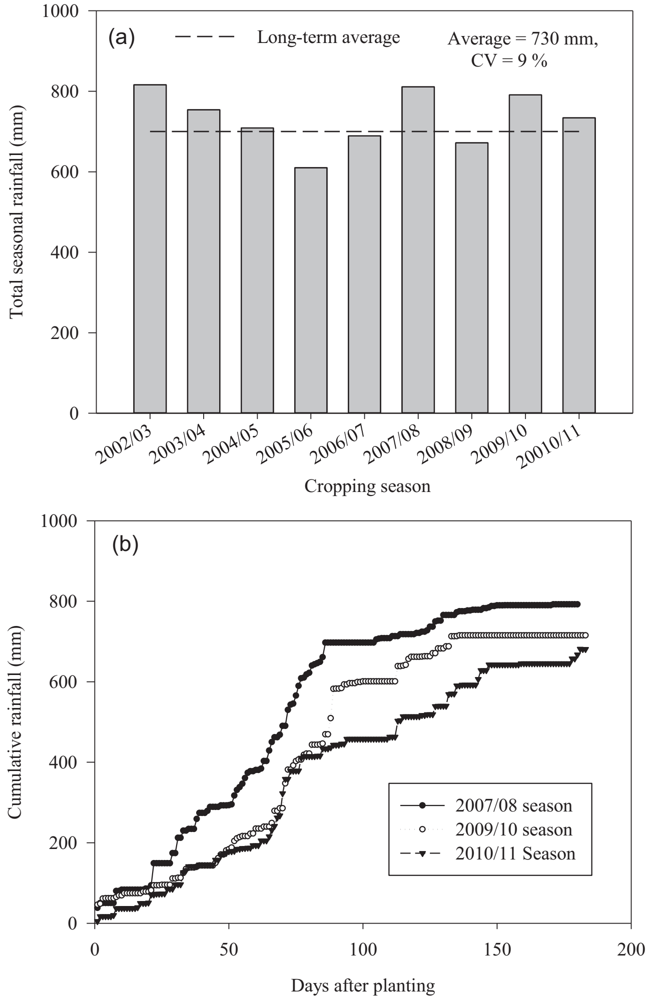

Fig. 1. (a) Measured total seasonal (October–May) rainfall received during the experimental period in Murehwa and (b) seasonal rainfall distribution in the last three seasons standardised by days after planting.

Table 2
Output of the GLMM procedures for explaining variability of maize grain yields in the long-term trial in Murehwa (2002–2011). Model 1 (combined model) was used to test the general effect of the factor 'soil type' on maize yields. The effect of 'nutrient management' and 'field type' was further specified for the two soil types in order to test their specific effects on maize yield in Models 2 (clay soil) and 3 (sandy soil).

Model	DF	*F* Value	*Pr* > *F*
Combined model	**231**	**10.41**	<**0.0001**
Season	6	35.32	<0.0001
Soil	1	426.27	<0.0001
Field	1	298.06	<0.0001
Treatment	8	95.03	<0.0001
Field × Treatment	8	3.54	0.0006
Soil × Treatment	8	6.42	<0.0001
Season × Treatment	43	3.96	<0.0001
Soil × Field	1	2.22	0.137
Soil × Field × Treatment	8	0.78	0.6165
Season × Soil × Field × Treatment	147	1.67	<0.0001
Clay soil	**115**	**7.43**	**<0.0001**
Season	6	21.32	<0.0001
Field	1	90.02	<0.0001
Treatment	8	47.62	<0.0001
Field × Treatment	8	1.46	0.172
Season × Field × Treatment	92	2	<0.0001
Sandy soil	**115**	**11.12**	**<0.0001**
Season	6	19.43	<0.0001
Field	1	294.46	<0.0001
Treatment	8	59.84	<0.0001
Field × Treatment	8	3.88	0.0003
Season × Field × Treatment	92	2.29	<0.0001

Table 3
Correlations between maize grain yield and other measured parameters using data obtained in 2009/2010 season.

Variable	by variable	Correlation	Significance
Soil bulk density	Grain yield	−0.3881	0.3421
SOC	Grain yield	0.9079	0.0018
SOC	Soil bulk density	−0.5921	0.122
Infiltration	Grain yield	0.155	0.714
Infiltration	Soil bulk density	−0.845	0.0083
Infiltration	SOC	0.4843	0.2239

each soil type (Models 2 and 3), field type, cropping season and nutrient management had a significant effect on crop grain yield ($P < 0.001$). On sandy soils (Model 3), field type had a stronger effect on crop yield than on clay soils. As a result, the interactions between field type and nutrient management were weak on clay soils ($P = 0.172$) and stronger on sandy soils ($P = 0.0003$) (Table 2). The strong effects of field type on grain yield suggest that targeting of nutrients to homefields and outfields is important for efficient use of limited nutrient resources at the farm-scale.

A multiple correlation analysis between maize grain yield, soil bulk density, SOC measured in the 8th season and final water infiltration rate showed that maize grain yield was strongly ($P < 0.05$) correlated with SOC and negatively correlated with soil bulk density (Table 3). Final infiltration was positively correlated to SOC but negatively correlated with soil bulk density.

3.2. *Short term (≤3 years) maize grain yields*

On the sandy soils, the effects of nutrient management strategies in the first season on maize grain yield were apparent in the homefield but not in the outfield (Fig. 2a and b). The smallest (<0.1 t ha^{-1}) yields on control plots for the first three seasons were observed on the outfield sandy soil (Fig. 2a). Application of manure had a cumulative effect on crop yield; application of 100 kg N + 25 t ha^{-1} manure in the sandy outfield increased yield from 0.5 t ha^{-1} in the first season to 2.7 t ha^{-1} in the third season. In the sandy homefield, the largest yield was 4.4 t ha^{-1} obtained with 100 kg N + 25 t ha^{-1} manure but decreased to 3.4 t ha^{-1} in the third season although it was still the largest yield among all the treatments (Fig. 2b). In the third season, application of 100 kg N ha^{-1} alone did not increase crop yield significantly on both outfield and homefield sandy soils. In most cases, the yields of NP fertiliser treatments were in between the yields of 100 kg N and 100 kg N + manure treatments.

On the clay soils, there were no significant yield differences between control and application of 100 kg N ha^{-1} in the first three seasons on both field types (Fig. 2c and d). In general, in the first year, control yields in the clay outfields were less than half those in the clay homefields (Fig. 2c and d). The largest control yield of 2.1 t ha^{-1} was recorded in the first season in the homefield but decreased in the two successive seasons. The yield of the control in the outfield was 0.8 t ha^{-1} in the first season and did not change significantly in the second and third seasons. The largest yield (4.3 t ha^{-1}) in the first three seasons in the clay outfield was obtained with 100 kg N + 25 t ha^{-1} manure in the second season, however, yield declined after the second season, as for all treatments. In the first season, yields attained with manure were less than with N + P fertiliser, but by the third season yields attained with manure were larger than with N + P fertiliser in the clay homefield. In the clay outfield, yields from manure treatments were consistently greater than from N and P treatments.

3.3. *Long term maize (>3 years) grain yields*

After the third season, significant yield benefits were recorded in treatments that combined fertiliser and manure, and showed

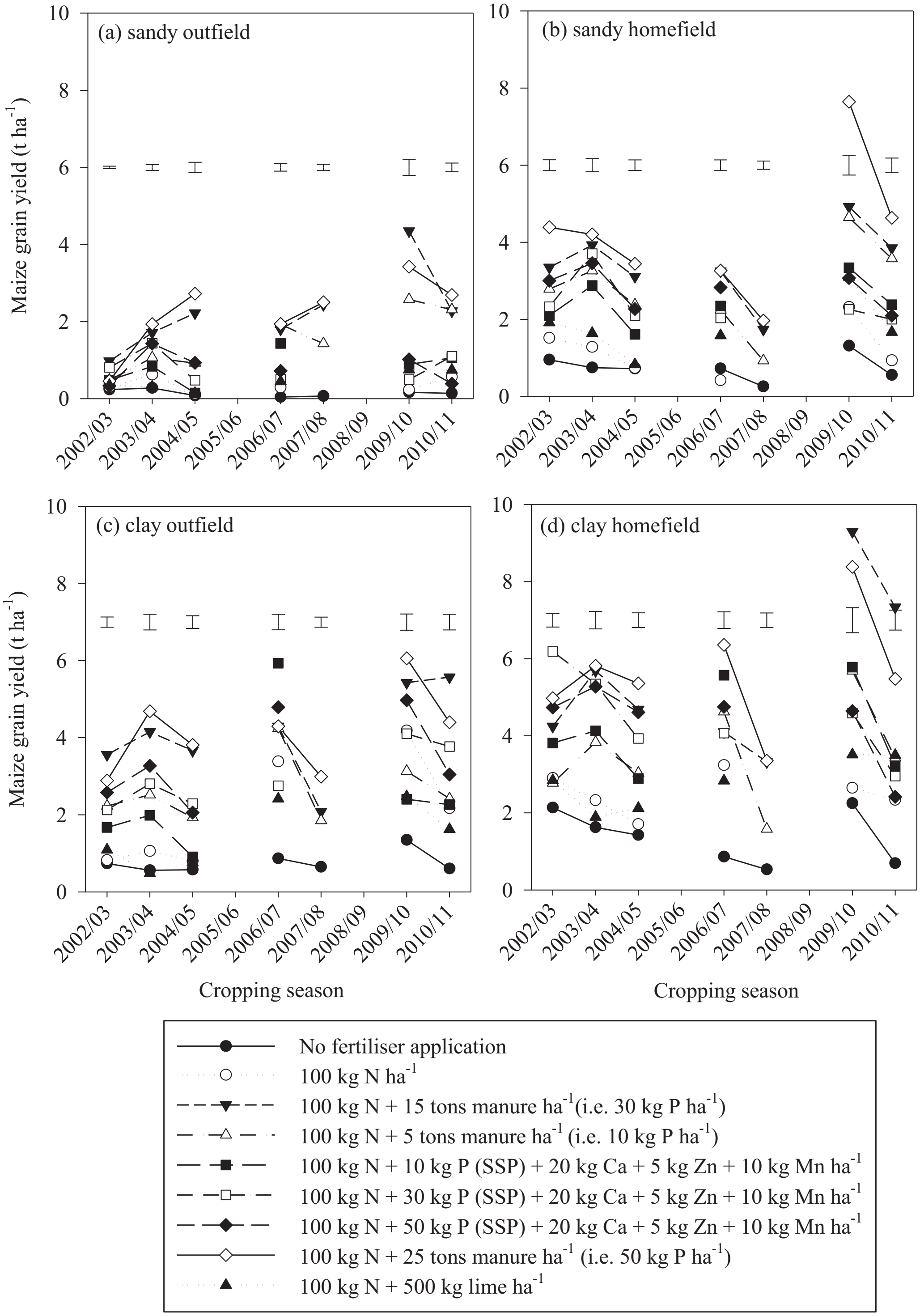

Fig. 2. Nutrient management strategies and seasonal maize grain yield trends in (a) sandy outfield, (b) sandy homefield, (c) clay outfield, and (d) clay homefield in Murehwa. Treatments receiving mineral fertilisers only (AN and SSP) were modified in the 6th season (2006/2007) to include Ca, Mn and Zn. Error bars are the standard error of differences (treatment × season).

incremental benefits in successive seasons (Fig. 2). The largest yields for the experimental period were recorded in the eighth season (a season that had good rainfall distribution); on the homefield sandy soils application of 100 kg N + 25 t ha^{-1} of manure resulted in the largest grain yield of 7.6 t ha^{-1} for the experimental period. The corresponding treatment in the outfield sandy soils yielded only 3.4 t ha^{-1} and was not significantly different from the application of 100 kg N + 15 t ha^{-1}of manure in all seasons. The largest yield in the clay outfield was obtained with application of 100 kg N + 25 t ha^{-1} manure; top yields were 6.1 t ha^{-1} for the outfield and 9.3 t ha^{-1} for the homefield. The largest yield of 6.1 t ha^{-1} in the outfield in the 8th season obtained with the application of 25 t ha^{-1} manure, was the same as yield obtained in the homefield with the application of 100 kg N ha^{-1} + 50 kg P ha^{-1} + 20 kg Ca ha^{-1} + 5 kg Zn ha^{-1} + 10 kg Mn ha^{-1}. In the ninth season, maize grain yields were smaller relative to the eighth season, however, manure based

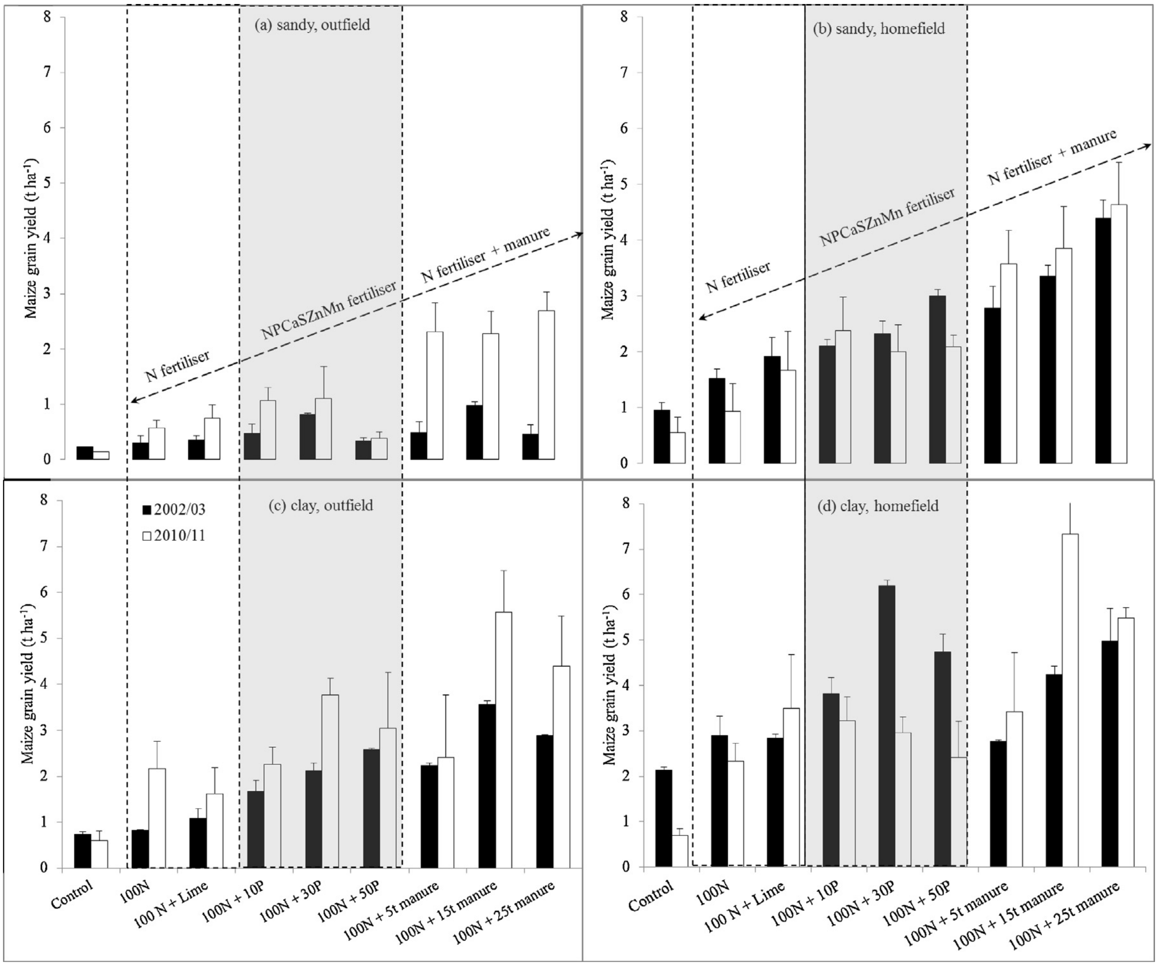

Fig. 3. Maize grain yield gaps in (a) sandy outfield, (b) sandy homefield, (c) clay outfield, and (d) clay homefield under different nutrient management strategies at the start (2002) and end (2011) of the experiment in Murehwa. NPCaSZnMn refer to the treatments which received N, P, Ca, S, Zn and Mn in the form of inorganic fertiliser, error bars are the standard error of mean.

treatments out yielded the fertiliser-based treatments on all fields. The ninth season received less rainfall than the eighth season.

3.4. *Comparison of initial and final seasons*

In the sandy outfield maize grain yield declined by 50% from 0.2 t ha^{-1} in the first season to 0.1 t ha^{-1} (Fig. 3a) in the final season. In the sandy homefield, a loss of 0.4 t ha^{-1} between the first and final season due to lack of inputs was significant (Fig. 3b). In the clay outfields, the yield decline due to lack of inputs was small compared with the other three fields (Fig. 3c). In the clay homefield, lack of nutrients reduced yield significantly from 2.1 t ha^{-1} in the first season to 0.7 t ha^{-1} in the final season (Fig. 3d). On clay soils, in both field types, long-term application of 100 kg N ha^{-1} maintained yields around 2 t ha^{-1}. On sandy soils, long-term application of 100 kg N ha^{-1} maintained yields below 1 t ha^{-1} and approached zero in sandy outfields.

Additions of Ca and micronutrients increased yield in the long term in the outfields for both sandy and clay soils (Fig. 3a and c) compared with the first season. However, the opposite results were recorded in the corresponding homefields, yields declined in the final season with respect to the first (Fig. 3b and d). The restoration of crop productivity on the degraded sandy soils was only substantial when a combination of mineral fertiliser and manure were used (Fig. 3). In the final season, maize grain yields with N + manure application in the outfields were comparable to yield with the equivalent P fertiliser treatment in the homefields. The difference in yield between mineral fertilisers, and a mixture of N fertiliser and manure was largest in the sandy outfields (Fig. 3). Yields of corresponding nutrient management treatments in outfields were significantly smaller than in homefields after nine seasons for both soil types.

3.5. *Comparative yield advantage of manure*

On the sandy soils, manure treatments often yielded better than the equivalent mineral fertiliser treatments, even with Ca and micronutrients (from the sixth season onwards), for the entire experimental period (Fig. 4a and b). The superiority of manure treatments was especially apparent in the long term. On the clay soils the trend was different to that obtained on the sandy soils (Fig. 4c and d). On the homefield clay soils yields from treatments with application of manure were not significantly different from those from treatments with the equivalent mineral fertiliser treatments in the first three seasons. Application of 100 kg N + 5 t ha^{-1} manure resulted in similar grain yields as those from the treatments with the mineral fertiliser equivalent (10 kg P ha^{-1}) for the whole experimental period, whilst the larger manure applications showed larger yields than the equivalent P fertiliser treatments in the eight and nine seasons. In the clay outfields, yields from manure treatments were superior to those from the equivalent mineral P

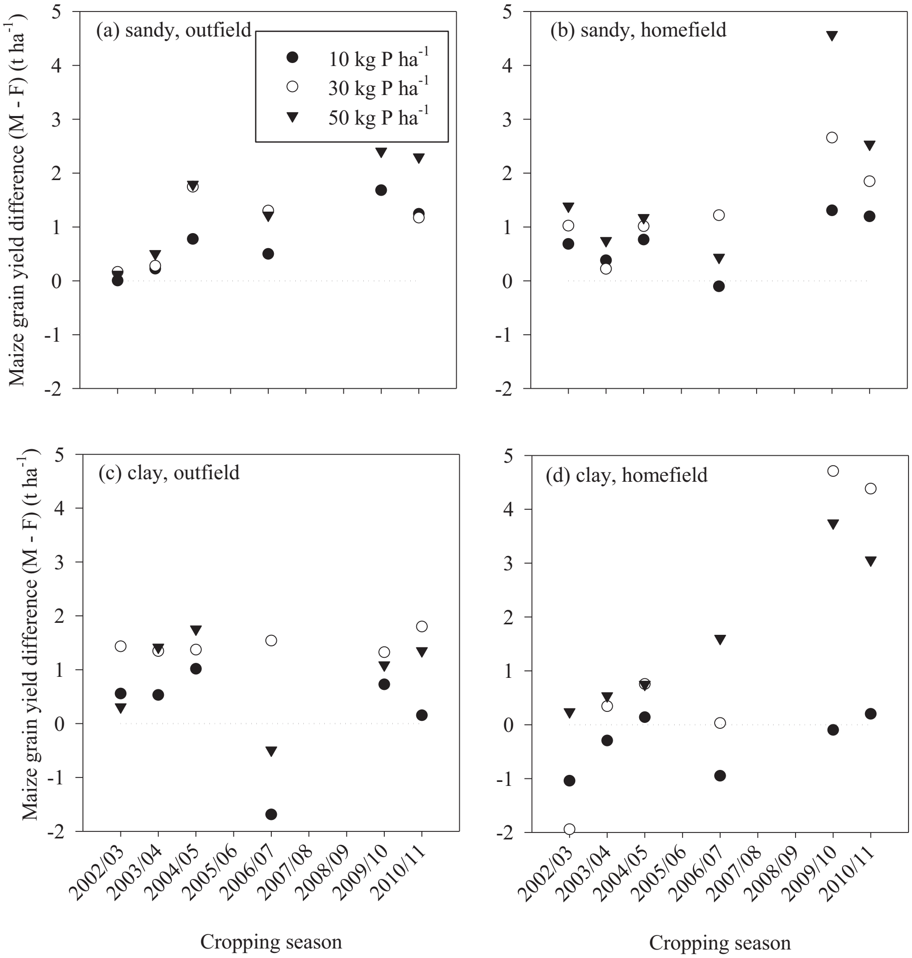

Fig. 4. Seasonal effect on maize grain yield differences between manure (M) and fertiliser (F) treatments at equivalent amount of phosphorus application in (a) sandy outfield, (b) sandy homefield, (c) clay outfield, and (d) clay homefield in Murehwa, dotted line is line of no yield difference.

fertiliser treatments but the magnitude of the difference was fairly constant during the experimental period.

3.6. Maize response to incremental manure and P applications

Maize grain yield generally increased with increased amounts of manure and P applied. In the sandy outfield, response to manure application was poor in the first season; maize yield of 0.3 t ha^{-1} without manure application was only increased to 1.0 t ha^{-1} with application of 15 t manure ha^{-1}, and was 0.5 t ha^{-1} with application of 25 t manure ha^{-1} (Fig. 5a). Response in the homefield was significant; in the first season, application of 5 t manure ha^{-1} doubled maize grain yield compared with where manure was not applied. Manure applications beyond 5 t ha^{-1} did not result in significant yield increase in either the initial or final season on outfield sandy soils. On clay soils, maize grain yield increased significantly with increasing manure application up to 15 t ha^{-1} manure, beyond which yield declined (Fig. 5b). Application of 5 t ha^{-1} manure in the clay homefield depressed yields in the first seasons relative to 100 kg N ha^{-1} only. Generally maize grain yield response to incremental additions of manure in the final season was superior to the response in the first season.

Maize grain yield responses to incremental additions of P fertiliser were similar to the pattern observed with incremental manure additions (Fig. 5c and d). The application of 30 kg P ha^{-1} fertiliser seemed to be the maximum amount of P required to achieve the largest maize grain yield on both clay and sandy soils, field types and first and final season. For example, application of 30 kg P ha^{-1} increased yield from 2.9 t ha^{-1} to 6.2 t ha^{-1}, but declined to 4.7 t ha^{-1} in the clay homefield in the first season. Surprisingly, yield response to P application was poor in the final season compared with the first season in both sandy and clay homefields (Fig. 5c and d).

3.7. Comparison of initial and final soil fertility statuses

Compared with the initial values, most soil properties changed during the experimental period widening the gap between the soil fertility status of the fields and soil types than closing them. Long-term application of manure increased the N concentration in the soils although the changes were not significant relative to the initial status and also to the control treatment across the four fields (Table 1). The pH results were rather inconsistent, pH was larger than the initial years across all treatments although treatment differences were not significant. Available P increased significantly with the application of 100 kg N + 25 t ha^{-1} manure on both soils in all field types while it decreased or remained unchanged in the control and the 100 kg N ha^{-1} treatment. The largest increase in P with application of 100 kg N + 25 t ha^{-1} manure was observed in the outfields, P increased from 3.9 to 10.8 and 2.4 to 9.0 mg kg^{-1} for sandy outfield and clay outfield respectively. Cation exchange capacity increased significantly in sandy soils but increases in clay soils were not significant. Manure application also led to significant increases in base cations and base saturation.

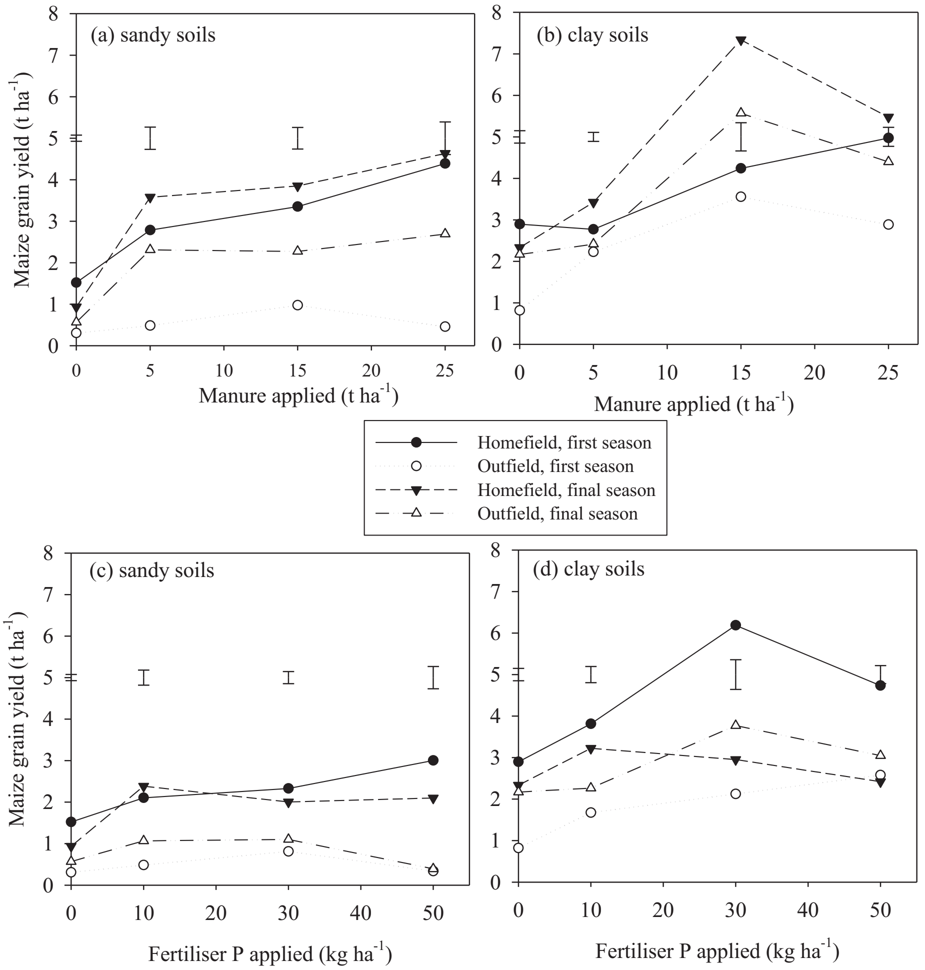

Fig. 5. Maize grain yield response to increasing manure application rates (a) in sandy and (b) clay soil, maize grain yield response to increasing P application rates in (c) sandy soil and (d) clay soil in the first and final season as affected by field type in Murehwa. Error bars are the standard error of differences (s.e.d.).

The change in SOC concentration in the soil (0–20 cm) over time was proportional to the amount of C added in manure. SOC increased significantly with the application of 100 kg N + 25 t ha^{-1} manure on both soils in all field types while it decreased or remained unchanged in the control and the 100 kg N ha^{-1} treatment (Table 1). At the end of the experiment, the treatment with the smallest application of manure (100 kg N ha^{-1} + 5 t manure ha^{-1}) in combination with 100 kg N ha^{-1} resulted in an increase in SOC from 0.5% to 0.8% in the sandy homefield, from 0.3% to 0.5% in the sandy outfield, from 1.4% to 1.53% in the clay homefield, and from 0.8 to 0.82% in the clay outfield. The largest manure application of 100 kg N + 25 t ha^{-1} increased SOC from 0.50% to 0.86% in the sandy homefield, from 0.30 to 0.49% in the sandy outfield, from 1.40% to 1.84% in the clay homefields and from 0.8% to 0.97% in the clay outfield (Table 1).

3.8. Effect of manure application on rainfall infiltration

Water infiltration was difficult to determine on the sandy soils due to excessive drainage and suspected water repellence (Fig. 6a). On the outfield sandy soils, application of 100 kg N + 25 t ha^{-1} manure significantly increased time to run-off from 89 min (control) to 210 min. In the homefield, there was no difference in time to run-off as well as the infiltration patterns between control and application of 100 kg N + 25 t ha^{-1} manure (Fig. 6a). The simulations continued for 5 h, final infiltration was very small (5 mm h^{-1}) and there was no difference in final infiltration between treatments and between fields.

Application of 100 kg N + 25 t ha^{-1} manure on the homefield clay soils led to a final infiltration of 31 mm h^{-1} after 3 h compared with 27 mm h^{-1} for the control. On the outfield clay soils with application of 100 kg N + 25 t ha^{-1} manure, runoff started after 48 min and final infiltration was 29 mm h^{-1} after 2.5 h (Fig. 6b). The difference in infiltration between clay field types was larger for the control treatments but smaller with application of 100 kg N + 25 t ha^{-1} manure.

The irregular infiltration patterns in sandy soils meant the data could not be modelled. On clay soils, the reduction in infiltration rate was not instantaneous resulting in a sigmoidal decay curve (Fig. 6b).

3.9. Farm-level feasible manure quantities

In Manjonjo village, only 38% of farmers owned cattle. Cattle numbers ranged from one to 13 with an average of five per farm for the farmers who owned cattle. Cattle ownership was a major determinant of manure availability. The upper boundary line of the relationship between the amount of manure measured and number of cattle owned per farm was linear: *manure* (*t year*$^{-1}$) = 0.94 × *number of cattle* (Fig. 7a). Results suggest that at least six heads of cattle were required to achieve the minimum application of 5 t ha^{-1} used in the experiment if the target on the

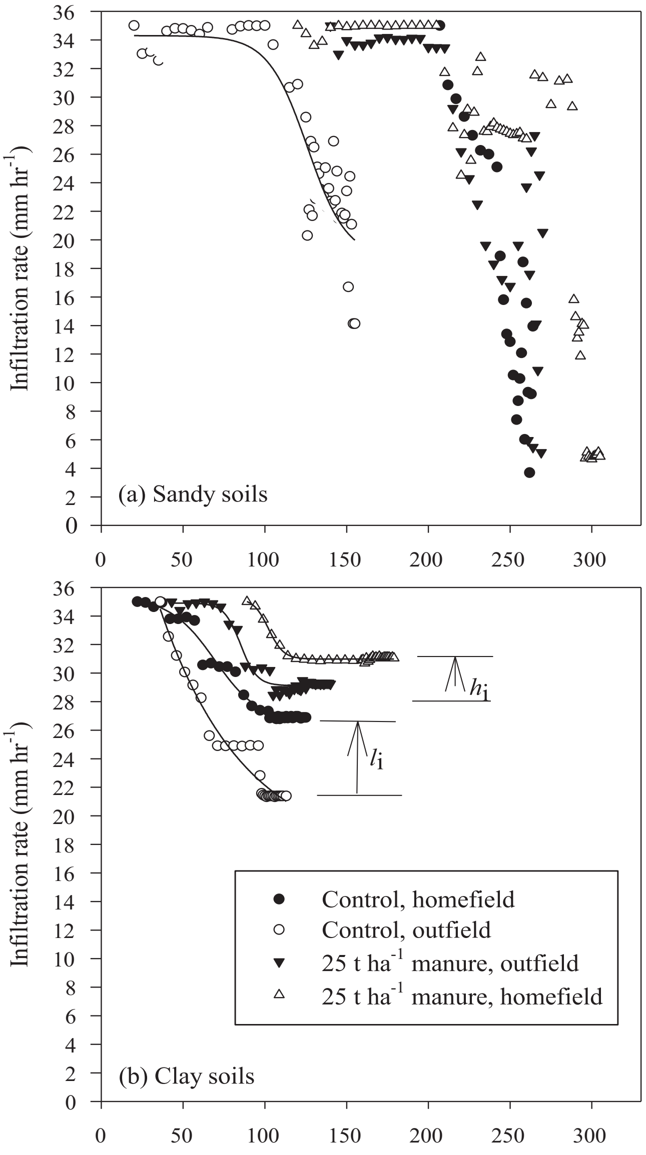

Fig. 6. Rainfall infiltration in a sandy soil (a) and clay soil (b) as affected field type and manure application in Murehwa. Degradation caused by previous management diminishes at larger organic inputs (h_i) and worsen without organic inputs (l_i). The sigmoidal model with four parameters: $i_t = i_f + (i_i - i_f/1 - (t/t_0)^K)$ where i_i is initial infiltration rate, i_f is final infiltration rate, t_0 is time *at* $i_i/2$, and K is the infiltration rate decay coefficient, was used to describe infiltration in clay soils.

farm is a hectare each year. The lower boundary line showed that the amount of manure collected under poor management is sometimes very small despite relatively large cattle numbers. Thus the amount of manure available per farm varied across households even with the same number of cattle. Beyond cattle ownership, manure application rates varied greatly between fields mainly due to management decisions and availability of mineral fertilisers. A greater proportion of the cultivated land in the village was subdivided into plots of sizes of between 0.1 and 0.5 ha (Fig. 7b). It was estimated that on average 30% of the cultivated plots of cattle owners received manure every season at an average application rate of 4.1 t ha^{-1} with a range of 0.4–17.5 t ha^{-1} (Fig. 7b). The application rates achieved by farmers suggest that the yield improvements we have reported especially related to effects of 5 t ha^{-1} manure are possible on some fields for farmers who own cattle.

4. Discussion

4.1. Management and biophysical factors

The variability in fertility status of fields due to previous management and its effects on crop productivity were apparent on both clay and sandy soils. Cropping season, nutrient management strategies and their combinations also had significant effects on maize grain yield (Table 2). The variability in total rainfall between seasons was small (Fig. 1), which suggested that the effect of season on crop yield could have been due to differences in intra-seasonal rainfall distribution. Rainfall in the study region is often poorly distributed over the season with periods of both low and high rainfall which result in yield fluctuations across seasons (Challinor et al., 2007). The yield data reported here were recorded in trials that were generally well managed, planting was with the first effective rains each season, plots were kept weed free and fertilisers were applied at the right time. Nitrogen fertiliser was split applied to avoid losses and improve nutrient use efficiency which is critical especially in the sandy soils characterised by rapid drainage.

Crop productivity differed strongly between soil types as expected because the sandy soils had very low nutrients and organic matter content compared with clay soils that were inherently more fertile (Table 1; Nyamapfene, 1991). On the other hand, soil fertility gradients (homefields vs. outfields) are known to influence the response of crops to added nutrients (Vanlauwe et al., 2006; Zingore et al., 2007b); thus homefields had larger yields than outfields. The differences in crop responses were due to differences in soil organic matter, base cations and micronutrient inputs. In the long term, the history of management as well as the seasonal management and soil type were critical in determining yields agreeing with previous findings on short-term crop responses (Zingore et al., 2007b).

4.2. Response of crop yields to manure versus fertiliser applications

Although fertiliser is considered critical for sustainable crop production, the potential of fertiliser alone to restore soil fertility on the depleted sandy soils was very poor. The delayed response to nutrients often act as disincentive to smallholder farmers because the building of soil fertility takes much more time than is required to deplete it (Tittonell et al., 2012). The delayed increase in crop yields was more pronounced on the outfield sandy soils due to a combination of previous inadequate nutrient management and inherent infertility. The four field types we studied clearly followed different pathways in rebuilding soil fertility as shown by the maize grain yield. It appeared possible to restore soil fertility for the red clay soils in a reasonably short time while it requires much more time to recover degraded sandy soils.

Our results showed the importance of supplementary manure addition on crop productivity, especially on the degraded and non-responsive sandy soils; the core of integrated soil fertility management (Vanlauwe et al., 2010). There was an increase over time in the yield difference between mineral, and combined organic and mineral nutrient management strategies. The long-term relative yield increases of combining manure with mineral fertiliser were much greater on the more degraded outfield sandy soils than fertiliser alone. Results agree with Chivenge et al. (2011) who observed after a meta-analysis a significant yield increases when fertiliser was used in combination with organic matter. Crop yields with manure treatments were always larger than with mineral fertiliser at equivalent P application rate on sandy soils (Fig. 5). This could have been due to potassium (K) deficiencies. Potassium availability was especially poor in the sandy soils (Table 1) but was not included in the treatments; deficiency of K often leads to slow growth and

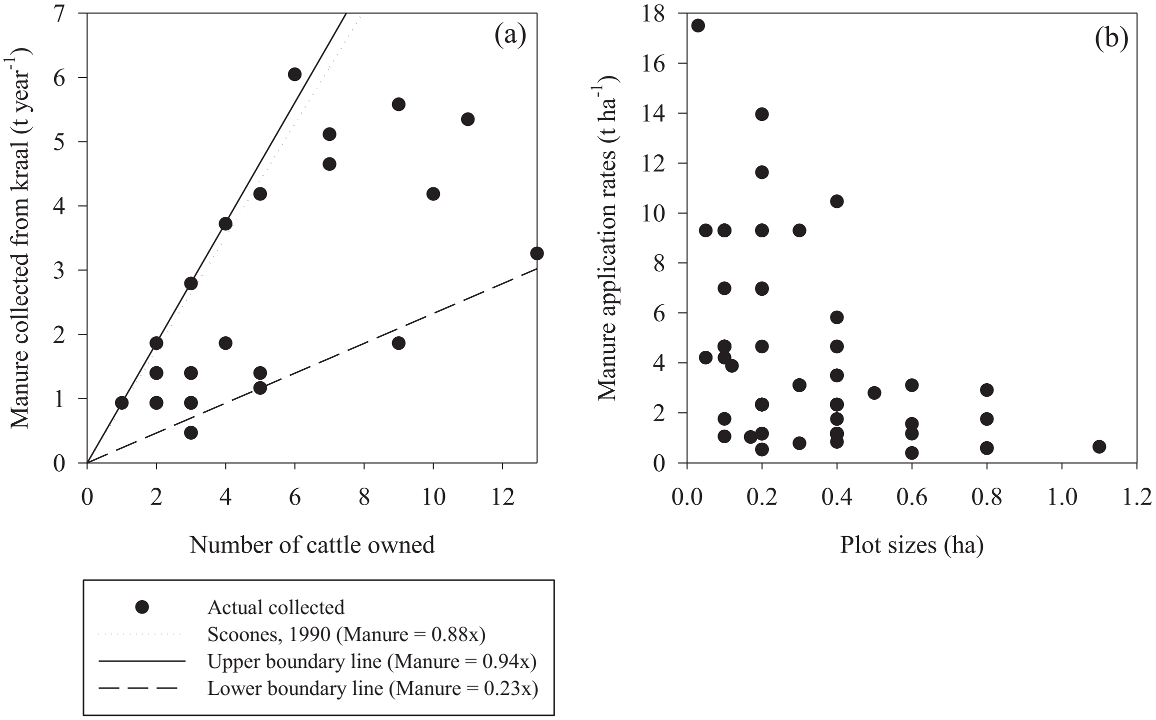

Fig. 7. (a) The relation between livestock ownership and manure collected from the kraal and (b) variations in cultivated field sizes and manure application rates, only for fields where manure was applied in Manjonjo village, Murehwa.

lower yields due to poor water use efficiency and poor N uptake (Leigh and Jones, 1984; Ashley et al., 2006). Results suggest that manure was superior to mineral fertiliser due to increase in soil organic carbon and possibly the supply of K, Mg and micronutrients. The high permeability of sandy soils suggests that there was also a risk of nutrient leaching resulting in small crop yields (Nyamangara et al., 2003; Dempster et al., 2012). Manure allows synchrony between nutrient release and crop uptake in sandy soils of excessive drainage (Murwira and Kirchmann, 1993). The value of manure in conjunction with mineral fertiliser on sandy soils in Zimbabwe has also been noted by other authors (Mugwira, 1984, 1985; Mugwira and Shumba, 1986).

Maize grain yield response to incremental manure inputs was characterised by an exponential rise to the maximum when the amount of manure approached sufficiency for both first and final year yields. Maximum yield was observed to occur at manure application rates of 15 t ha^{-1} y^{-1}. These results were similar to those reported by Nyamangara et al. (2003) who observed that annual application of 12.5 t ha^{-1} of manure in combination with 60 kg N ha^{-1} was the best strategy to ensure large crop yields and small leaching risk on sandy soils. On very sandy soils such as those we studied, the first and last increments of fertiliser inputs were often poorly utilised for increasing growth leading to a sigmoidal response pattern (cf. Mathews and Hopkins, 1999).

4.3. *Soil organic carbon*

Soil organic carbon increased in plots that received manure and was proportional to C input. SOC increases were greater in the clay soil than in the sandy soil. Soil with high clay content has a higher SOC stabilisation rate than soils with low clay content (Zhang et al., 2010). In soils of high clay content, SOC is protected from decomposition through macro- and micro-aggregation and physicochemical binding with silt and clay particles (Six et al., 2002). In general, soil organic matter increases are therefore primarily related to amount of C input in sandy soils and to soil disturbance in clay soils (Chivenge et al., 2007). In a review of long-term experiments, Edmeades (2003) found that manure led to stronger increases in organic matter than inorganic fertiliser application.

We observed a high correlation (r = 0.91, Table 3) between SOC and maize grain yield i.e. plots with large SOC had the largest maize yields especially in the long term. SOC increases crop yield by increasing available soil water capacity in sandy soils, improving supply of nutrients and by enhancing soil structure and other physical properties (Lal, 2006). We conclude that in mixed crop–livestock systems where crop residues are not retained in situ, routine manure application provides one of the most locally adapted pathways to restoring soil organic matter and consequently soil fertility.

4.4. *Rainfall infiltration*

Water infiltration was significantly greater on clay soils than on sandy soils. Differences can mainly be attributed to the structural characteristics of the soils in each field. Time to pond and run-off was shorter on clay than on sandy soils; larger pores in sandy soils allowed water to drain easily. The irregular infiltration pattern on the sandy soil appeared to suggest preferential flow and the rapid drainage characteristics of the soil meant that the soil continuum was not uniformly wet and thus was characterised by uneven water infiltration (Ritsema et al., 1993). The sudden decrease in infiltration on sandy soils could have been caused by some entrapped air which would lower the hydraulic conductivity (Wang et al., 1998), and repellence (Dekker and Ritsema, 1994). Water repellence is the retardation of surface water infiltration due to the hydrophobicity of organic matter in sandy soils (Brandt, 1969). Low pH which is characteristic of the sandy soils of our study sites has been found to increase soil water repellence (Woche et al., 2005). The water supply at a rate of 35 mm h^{-1} coupled with the initial dry conditions (less that 5% soil moisture) was not sufficient to cause immediate surface ponding and run-off. In the end, infiltration decreased substantially which could be a result of surface compaction caused by raindrop impact. The lack of significant difference in final infiltration between homefields and outfields on sandy soils could have been due to the extremely high sand content of 85% and 87% respectively (Table 1).

On clay soils, plots receiving manure had a larger steady state water infiltration rate showing the importance of organic matter inputs in improvement of soil physical properties (Chivenge et al., 2007; Dunjana et al., 2012). Organic matter is important for soil aggregate stability and good soil structure which improve water infiltration (Franzluebbers, 2002). The decrease in infiltration rate was more consistent on the clay soils than on sandy soils; the relatively high SOC content and uniformity of pores ensured that steady-state infiltration could be established within a relatively short time from dry conditions. The significantly different infiltration rates between homefields and outfields in clay soils could have been due to differences in SOC. Nyamadzawo et al. (2003) observed that the amount of C in the top 0–5 cm soil was the single largest determinant of variation in steady state infiltration rates, suggesting that soil C was an important factor in soil properties. Annual application and residual effects of manure have been observed to reduce runoff significantly by between 2 and 62%; a strong relationship was observed between amount of manure application and run-off (Gilley and Risse, 2000).

The correlation coefficient between maize yield and water infiltration was small ($r = 0.15$, Table 3) mainly due to lack of significant difference in infiltration rates between plots on sandy soils yet large differences in grain yield. Large infiltration rates may also lead to small yields as they may lead to waterlogging especially on shallow soils and leaching of crop nutrients beyond the root zone. However, in this agro-ecological zone, large rainfall infiltration is desirable to store moisture in the soil and offset the negative effects of poor rainfall distribution on crop yields.

4.5. Applicability and limitation of results

We sought to explore the potential to recover degraded soils using cattle manure i.e. “pushing the envelope” – what options are available to facilitate innovations around manure use and go beyond current crop productivity. The results after 9 years of substantial (minimum 5 t manure y^{-1}) organic inputs did not show a breakthrough. The fertility of the outfields still could not be brought equal to the homefields (Table 1). In most cases, the initial soil fertility differences were maintained between fertile homefields and degraded outfields. Potassium concentration remained small and could have been limiting crop productivity in the fertiliser treatments especially on the sandy soils. However, in the combination of manure and N treatments, sufficient K was applied through manure but yields remained much smaller on the outfields compared with homefields. The sandy soils were deeper (ca. 150 cm) than the clay soils (ca. 68 cm), and not susceptible to waterlogging, thus it appears that the failure to recover crop productivity was not linked to soil depth. The initial SOC in the sandy outfields may have been too small to achieve large yields: Kay and Angers (1999) suggested that irrespective of soil type, if SOC contents are below 1%, it may not be possible to achieve maximum yields. The SOC on sandy soils and clay outfields were below this value and maize grain yield and SOC were correlated (Table 3). However a comprehensive review of literature by Loveland and Webb (2003) suggested that a threshold SOC value for maximum crop production is elusive as it depends on management and other biophysical limitations such as rainfall and soil type.

The clay soils maintained a larger potential for sustaining crop productivity than the sandy soils. Considering the relevance of the results, the sandy soils are of great importance in the study site because they occupy approximately 75% of the land area. Moving from 1 t ha^{-1} of maize grain yield in the first year to 2.7 t ha^{-1} in the ninth season represented a 170% increase in crop productivity for the sandy outfield for the best performing treatment. However, 2.7 t $ha^{-1}$was significantly smaller than yields obtained in other fields e.g. 4.6 t ha^{-1} in the sandy homefield, 5.6 t ha^{-1} in the clay outfield or 7.3 t ha^{-1} in the clay homefield. Results suggest recovery of severely degraded sandy soils may be beyond the reach of the majority of smallholders who face resource constraints.

Manure availability is the critical factor that determines how the results we reported here can be deployed by the majority of smallholder farmers in mixed crop–livestock systems (Rufino et al., 2011). In one of the villages of the study, about 38% of the farmers owned cattle, and roughly 30% of the fields received manure every season. Cattle ownership is locally considered among farmers as an epitome of development thus the integration of crop and livestock is important to these farming systems. Roughly close to a tonne (0.94 t) of manure per animal per year can be generated for recycling under current management (Fig. 7a). Our estimates of manure collected per animal were similar to that reported by Scoones (1990), who obtained a relationship of 0.88 t per animal per year. Cattle spend much of the time during the day in non-arable areas where excretion of more than half of the manure takes place reducing the amount of manure available (Rufino et al., 2011). The combination of manure availability and average farm size suggest that there is insufficient manure for all fields every season. Improved crop productivity with manure use will depend on how much mineral fertiliser individual farmers can access, and on farm and field specific management related to application rates and crop sequences.

The central question remains: where can farmers best allocate manure on the farm, in outfields or homefields to maximise benefits? Recommended figures of 10 t ha^{-1} y^{-1} (Grant, 1981) are only possible on small areas of land. Farmers in our study site demarcated their fields into manageable plots of about 0.1–0.5 ha (Fig. 7b) in which larger manure rates were applied every other year. On smaller plots, larger and more effective manure application rates are feasible (Zingore et al., 2008). Our results suggest that crop productivity was greater in the homefields than outfields after nine years of applying manure which shows a constraint to recovery of degraded soils. Farmers already target manure to fields close to the household to ensure food self-sufficiency (Mtambanengwe and Mapfumo, 2005; Zingore et al., 2007a). Thus the limited quantities of manure available can be targeted to small plots and not the whole farm to improve its effectiveness on crop productivity.

Beyond crop yields, we have seen that manure increased rainfall infiltration in clay soils and C sequestration. This aligns the paradigm of ecological intensification (Cassman, 1999), where crop production systems need to go beyond increasing crop productivity to address undesirable environmental consequences. The integrated nature of most smallholder production systems (Thornton and Herrero, 2001), suggest that the results reported here are widely relevant to the majority of smallholder farming systems, and it is imperative to find locally adapted strategies to improve manure use.

5. Conclusions

Manure application in combination with mineral fertilisers resulted in larger yields on clay than on sandy soils both in the short and long term. The potential for soil fertility restoration was poor if only mineral fertilisers were added. Yields of the largest manure application in the outfields were comparable with yields with the largest fertiliser P application in the homefields. Yields on sandy outfields remained significantly smaller than on the other field types despite the substantial manure inputs. Our results suggest that at farm scale, manure is used more efficiently in the homefields. Increased SOC resulted in improved rainfall infiltration in the clay soils; the SOC increase in sandy soils did not increase infiltration. Manure application rates we used are feasible in Murehwa because farmers manage small (0.1–0.5 ha) fields, but the amounts of manure available are insufficient for the area of cropland at village scale. We conclude that consistent application of manure in combination with mineral fertiliser improves crop productivity in both short and long term and is a sustainable locally adapted option for ecological intensification in mixed crop–livestock systems of smallholder farmers.

Acknowledgements

Financial support for this work was made possible by a grant to TSBF-CIAT through the sub-Saharan Africa Challenge Program supported by the Forum for Agricultural Research in Africa (FARA). We are grateful to Francis Muranganwa Dzvene and Erikana Chitopo for technical assistance in trial management and data collection.

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