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Effects of cattle manure on selected soil physical properties of smallholder farms on two soils of Murewa, Zimbabwe

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Abstract

The effects of cattle manure and inorganic N-fertilizer application on soil organic carbon (SOC), bulk density, macro-aggregate stability and aggregate protected carbon were determined on clay and sandy soils of the Murewa smallholder farming area, Zimbabwe. Maize was grown in four fields termed homefields (HFs) and outfields (OFs) because of spatial variability induced by management practices and with the following fertility treatments: control (no fertility amelioration), 5, 15 and 25 t/ha cattle manure + 100 kg/ha N applied annually for seven consecutive years. The addition of cattle manure resulted in significant ($P < 0.01$) increases in SOC, macro-aggregate stability and aggregate protected carbon in clay soils from at least the 5 t/ha cattle manure rate and was comparable between HFs and OFs on clay soils. Aggregate protected carbon in clay soils was significantly higher from the 15 and 25 t/ha cattle manure rates compared to the 5 t/ha cattle manure treatment. In contrast, only SOC was significantly ($P < 0.05$) increased with the addition of cattle manure on the sandy soils, while bulk density, macro-aggregate stability and aggregate protected carbon were not significantly changed. Bulk density was also not significantly ($P > 0.05$) different on the clay soils. A significant and positive linear relationship ($r^2 = 0.85$) was found between SOC and macro-aggregate stability, while an r^2 value of 0.82 was obtained between SOC and aggregate protected carbon on the clay soils. However, no regressions were performed on data from the sandy soils because of the lack of significant changes in soil physical properties. Application of cattle manure and inorganic N-fertilizer significantly increased ($P < 0.05$) maize grain yield on both soil types. Results show that inorganic N-fertilizer combined with cattle manure at 5–15 t/ha per yr is necessary to increase maize yields and SOC on sandy soils in Murewa, while at least 15 t/ha per yr cattle manure is required on the clay soils to improve physical properties in addition to maize yields and SOC.

Keywords: Soil organic carbon, macro-aggregate stability, aggregate protected carbon, cattle manure application, homefields, outfields

Introduction

Integrated and balanced application of inorganic fertilizers and organic resources is essential to achieve sustainable increases in crop productivity in smallholder farming systems in sub-Saharan Africa (Zingore *et al*., 2008). The influence of soil organic matter (SOM) on soil biological and physical properties is well documented (Shirani *et al*., 2002; Hati *et al*., 2006; Wang *et al*., 2010). SOM affects crop growth and yield either directly by supplying nutrients or indirectly by modifying soil physical properties such as stability of aggregates, bulk density (Rose, 1991), porosity and water retention, which improve the root environment and stimulate plant growth (Darwish *et al*., 1995).

However, maintaining sufficient SOM to sustain good crop productivity is a challenge in smallholder farming systems because of low quantities of organic manures and rapid turnover rates of green manures and tree legumes under conventional tillage systems (Kwesiga & Coe, 1994; Mtambanengwe & Mapfumo, 2005). Low quality organic resources are good precursors to SOM build-up because of their low turnover rates (Palm *et al*., 1997). Therefore, application of

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low quality cattle manure is often the only organic nutrient resource available to smallholder farmers in substantial quantities to enhance SOM content (Zingore *et al.*, 2008).

Manure is often applied to specific crops or preferentially to fields closer to the homestead (homefields; HFs), while fields further away from the homestead (outfields; OFs) often receive no organic amendments and little mineral fertilizer (Mapfumo & Giller, 2001). This preferential allocation of manure to HFs is driven by the lack of adequate inputs and labour for even application across the farms and security of HFs against grazing by livestock. Consequently, continuous concentration of nutrient resources in the smaller areas around the homestead at the expense of nutrient depletion in larger fields further away culminates in marked gradients of decreasing soil fertility with increasing distance from homesteads (Prudencio, 1993; Tittonell *et al.*, 2005). Mapfumo & Giller (2001) and Zingore *et al.* (2007a) report soil fertility gradients across smallholder farms in Zimbabwe. Similar results are also reported from other parts of Africa (Prudencio, 1993; Woomer *et al.*, 1998; Dembele *et al.*, 2000; Tittonell *et al.*, 2005). However, cases of higher fertility in OFs compared to HFs are also reported (Haileslassie *et al.*, 2007).

This variability within fields is sufficiently great to affect crop response to applied nutrients (Mtambanengwe & Mapfumo, 2005; Zingore *et al.*, 2007b) and also to soil physical properties. Several studies have assessed the impact of farmer-induced soil spatial variability on nutrient uptake and consequent plant growth (Prudencio, 1993; Mapfumo & Giller, 2001; Zingore *et al.*, 2008), but there have been few studies that have assessed the effect of spatial variability on soil physical properties and plant growth.

This study assesses the effects of cattle manure and inorganic N-fertilizer application on soil organic carbon (SOC), bulk density, macro-aggregate stability, aggregate protected carbon and maize grain yield after 7 yr of continuous cropping. We test the hypothesis that HFs and OFs on clay and sandy soils have similar physical properties after receiving the same cattle manure and inorganic N-fertilizer treatments after 7 yr.

Materials and methods

Site description

The experiment was performed in Murewa (17°39′S and 31°47′E), a smallholder farming area in Zimbabwe c. 80 km east of Harare. The area has a sub-tropical climate, receiving a mean annual rainfall of 750–1000 mm, which is distributed in a unimodal pattern between October and April. The area has two main soil types, granite-derived sandy soils (Lixisols; FAO, 1998), which are inherently infertile and dolerite-derived clay soils (Luvisols; FAO, 1998) that are relatively more fertile (Nyamapfene, 1991).

The farming system exhibits much interaction between crop and livestock production. Livestock provide draft power for cropping and manure for soil fertility improvement, while crop residues provide an important source of feed for livestock during the dry season when natural grazing is scarce and of low quality. Cattle constitute the main livestock, although some farmers also own goats and donkeys. The fields are individually cropped but are communally grazed during the dry season. Maize (*Zea mays* L.) is grown as the staple crop and constitutes the main farming area. Other crops including groundnut (*Arachis hypogaea* L.), sweet potato (*Ipomaea batatas* L.) and sunflower (*Helianthus annus* L.) are grown either in rotation with maize or as intercrops.

Selection and characteristics of experimental sites

Field experiments were established in 2002–2003 on two farms, one on the sandy soils and the other on the clay soils. On each of these farms, a field close (< 50 m) to the homestead and another at some distance (100–500 m) were selected as representatives of typical HFs and OFs in the area. Selection of sites was based on the recommendations of Zingore *et al.* (2007a) who found large variability in soil fertility between different fields on the same farm and between farms. The farmers were involved in the demarcation of fields into different plot types in accordance with what they considered as their best, average and worst plots (Zingore *et al.*, 2007a). Physical and chemical properties including texture, SOC and available N were also determined, and SOC and N were found to be higher in HFs than OFs on both soil types (Table 1).

Field management of the experiment

The experiment was laid out in a randomized complete block design (RCBD) with three replications on 6×4.5 m^2 plots in each field. The treatments included a control (no fertility amelioration), and aerobically composted solid cattle manure was applied annually on a dry-mass basis at 5, 15 and 25 t/ha in combination with 100 kg/ha inorganic N for seven consecutive years. At the start of the experiment, cattle manure application rates were based on the amount of phosphorus that the cattle manure could supply over the season. The 100 kg/ha N-fertilizer application rate was chosen to match the 120 kg/ha blanket application recommendation for areas with annual rainfall of c. 800 mm (Zingore *et al.*, 2007b), and the difference was expected to come from the cattle manure through mineralization. The cattle manure generally contained macro- and micronutrients as follows: 1.1% N, 0.18% P, 0.20% Ca, 0.08% Mg, 0.64% K, 800 mg/kg Fe, 22 mg/kg Cu, 280 mg/kg Mn, 112 mg/kg Zn (Zingore *et al.*, 2008), which was medium quality based on the N content (Mugwira & Mukurumbira, 1986). Land

Table 1 Selected initial soil properties for the sandy and clay fields in Murewa in 2002

	Sand (%)	Silt (%)	Clay (%)	C (%)	N (%)	C/N ratio
Sandy homefield	85	2	13	0.5	0.04	12.5
Sandy outfield	88	4	8	0.3	0.03	10.0
Clay homefield	46	15	39	1.4	0.08	17.5
Clay outfield	42	14	44	0.7	0.05	14.0

was first prepared by conventional ploughing using ox-drawn mouldboard ploughs. Maize variety SC525, an early maturing variety with good drought tolerance, was planted at 44 444 plants/ha at 0.9 m and 0.25 m inter- and intra-row spacing, respectively. Cattle manure was first broadcast and then incorporated into the soil (0–10 cm) using hand hoes before planting. Ammonium nitrate (34.5% N) fertilizer was split-applied as top-dressing at 3 and 6 weeks after crop emergence on all fields except the control. Weed was controlled manually using hand hoes just before each top-dressing with ammonium nitrate.

As an ongoing experiment, the initial part of the experiment evaluated changes in soil chemical properties and crop yields over a 3-yr period (Zingore *et al.*, 2008). Therefore, there was a need to further investigate the possibility of other soil attributes that could have changed under the soil fertility management practices. Other than SOC, which was measured at the start of the experiment (Table 1), the soil sampled from the experimental fields after 7 yr was analysed for bulk density, macro-aggregate stability and aggregate protected C for comparison of the treatment effects on the soil physical properties.

Soil sampling, pretreatment and storage

Soil sampling was performed in April 2009 after maize harvesting. One undisturbed soil core (5 cm diameter and height of 5 cm) was collected in each replicate from a depth of 5–10 cm to estimate bulk density. Five sub-samples were randomly collected in each replicate from a depth of 0–15 cm using a spade and composited to obtain representative samples per treatment replicate. The composite samples were used to determine macro-aggregate stability, aggregate protected C and SOC. The samples were air-dried, then sieved through 4.75-, 2- and 0.5-mm sieves before analysis.

Laboratory analyses

SOC and soil physical properties. Soil organic carbon was determined using the modified Walkley–Black method (Houba *et al.*, 1989), and bulk density was determined from soil cores (Okalebo *et al.*, 2002). Macro-aggregate stability was determined following a method by Barthes & Rose (1996). Air-dried samples that passed through a 2-mm sieve were rapidly immersed in de-ionized water for 30 min and wet-sieved through a 0.2-mm sieve using a motor-driven holder with a stroke length of 1.3 cm and immersion frequency of 35 cycles/min for 6 min. After oven-drying (105 °C) and weighing, the aggregate fraction >0.2 mm (F $>$ 0.2 mm) was dispersed by sieving in 0.05 M NaOH solution for 30 min using the same apparatus. The coarse sand fraction (CS) was then obtained after oven-drying at 105 °C. Macro-aggregate stability, defined as the stable macro-aggregate index (Ima), was obtained as:

$$\mathrm{Ima} = 1000\,(\mathrm{F} > 0.2 - \mathrm{CS})/(\mathrm{g} * \mathrm{DM} - \mathrm{CS})$$

where g = mass of air-dried soil sample used in grams and DM = per cent oven-dried sample mass of soil used.

Aggregate protected C was determined only for clay soils owing to inadequate amounts of water-stable aggregates on sandy soils required for the aggregate incubation assay. Fifty grams of air-dried 2–4.75-mm aggregates were placed on 250-μm mesh sieves and wet-sieved using a motor-driven holder with a stroke length of 1.3 cm, immersion frequency of 35 cycles/min for 10 min. After drying at 30 °C, two aggregate treatments from each replicate were established: (i) intact >250-μm aggregates and (ii) crushed >250-μm aggregates (to pass through a 250-μm screen using pestle and mortar) (Beare *et al.*, 1994). The aggregate treatments (5–10 g) were moistened with deionized water to field capacity (55%) obtained from equilibrating saturated soil cores at −10 kPa for the clay soils. The soil samples were incubated in sealed jars containing CO_2 traps (0.1 M NaOH) at 25 °C, and the amount of respired C was determined from the back-titration of NaOH with 0.1-M HCl at intervals of 3, 7, 14 and 21 days (Stotzky, 1965). Three blank titrations of NaOH obtained from jars without soil samples were included each time the CO_2 traps were changed. Barium chloride was used for the precipitation of CO_2, and phenolphthalein was used as the indicator. The respired C content of the soil samples was calculated as follows:

$$\text{mg C} = (B - V)(\mathrm{NE})$$

(Stotzky, 1965)

where B = volume (mL) of the standard acid used to titrate the trap solution from the blanks,
V = volume (mL) of the standard acid used to titrate the trap solution from the jars,
N = Molarity of the acid, in M,
E = 6, the equivalent weight of C in CO_2.

The aggregate protected and unprotected C were then calculated as follows:

$$\text{Unprotected } C_{\min(t)} = \text{intact aggregate } C_{\min(t)}$$

$$\text{Protected } C_{\min(t)} = \text{crushed aggregate } C_{\min(t)} - \text{intact aggregate } C_{\min(t)}$$

where $C_{\min\,(t)}$ is the cumulative C mineralized at time t (days) from uncrushed and intact aggregates (Beare *et al*., 1994).

Grain yield determination

Maize grain for yield determination was collected from the net plots (1.8×2 m^2) for each treatment and weighed using a digital scale. Grain moisture content at harvest was determined using a moisture meter, and grain weight was standardized by adjusting to 12.5% moisture content and expressed in t/ha.

Statistical analysis

Analysis of variance was conducted using the Genstat 7.1 statistical package. A two-way ANOVA was used to analyse differences between fertility treatments, field types and fertility treatment × field type interactions. The least significant difference (LSD) at $P < 0.05$ was used to differentiate between statistically different means. The Pearson's correlation coefficient was used to investigate the relationships between SOC and the physical parameters after which regression functions were performed if correlations were significant.

Results

Soil organic carbon

Cattle manure application for 7 yr on clay and sandy soils increased SOC. Among the cattle manure application treatments, SOC significantly ($P < 0.05$) differed between the control and the different cattle manure rates (Figure 1). Mean SOC obtained from combining all the cattle manure application rates relative to the control treatments was 513, 511 and 489% higher on the clay OF, sandy HF and OF, respectively, while on the clay HF, it was 242%, which was significantly lower. In addition, the control showed a decrease when compared to the initial SOC status of the soils. The decrease was more pronounced on the HFs, which initially had higher SOC contents as a result of long-term application of manure in the past. Initial differences in SOC observed between the HFs and OFs (Zingore *et al*., 2007a) were no longer evident after 7 yr on both soil types.

Bulk density

Bulk density was not significantly ($P > 0.05$) affected by cattle manure application on either clay or sandy soils after 7 yr. Bulk density ranged between 1000 and 1100 kg/m^3 in clay soils, while in sandy soils, it was between 1300 and 1520 kg/m^3 (results not shown).

Macro-aggregate stability

Cattle manure application rates had a significant effect ($P < 0.05$) on macro-aggregate stability as measured by the macro-aggregation index on clay soils (Figure 2a). Macro-aggregate stability increased by 179% and 139% on clay HFs and OFs, respectively, between control and 25 t/ha cattle manure treatments. On the other hand, the cattle manure application did not induce any significant increase in macro-aggregate stability on sandy soils (Figure 2b). There was no significant ($P > 0.05$) effect of farm management (field type) on macro-aggregate stability after 7 yr on either clay or sandy soils.

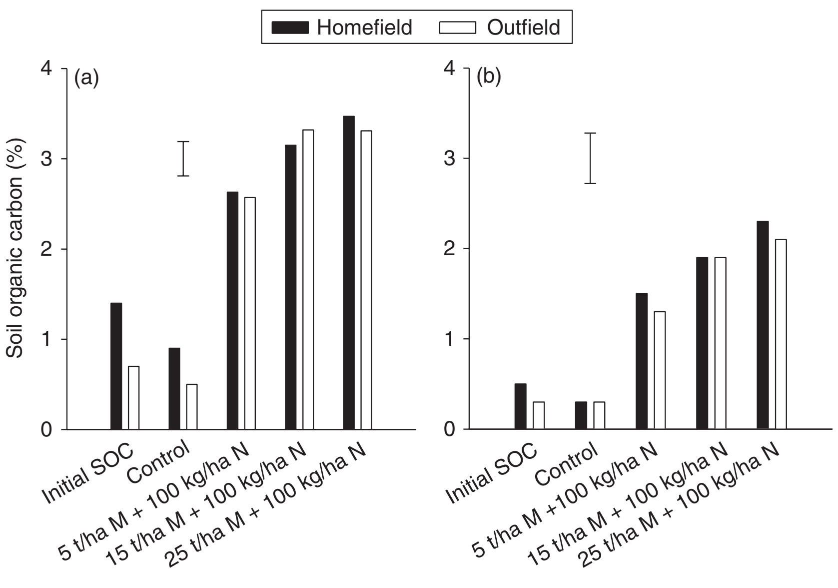

Figure 1 Soil organic carbon (SOC) in (a) clay soil and (b) sandy soil after 7 yr. n is 24 on each soil type. The bar denotes the least significant difference at $P < 0.05$.

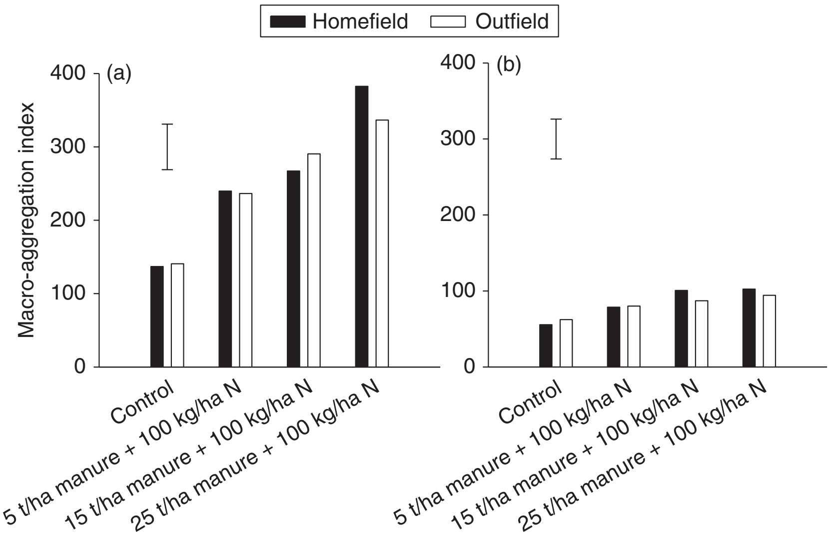

Figure 2 Macro-aggregation indices for (a) clay soils and (b) sandy soils after 7 yr. n is 24 on each soil type. The bar denotes the least significant difference at $P < 0.05$.

Aggregate protected carbon

Cattle manure application rates had a significant effect on aggregate protected C ($P < 0.05$) (Figure 3). The control had the lowest amount of aggregate protected C, which increased with cattle manure application rate. This trend was consistent with results for SOC and macro-aggregate stability.

Regression relationships between SOC, macro-aggregate stability and aggregate protected carbon

Regression functions of SOC with macro-aggregate stability and aggregate protected C were used to analyse the relationship between the soil physical properties and SOC. On the clay soils, macro-aggregate stability and aggregate protected C showed a highly positive linear relationship with SOC explaining 0.85 and 0.82 of the variability, respectively (Figure 4). No regressions were performed for the sandy soils as there was no significant effect on macro-aggregate stability after the cattle manure application.

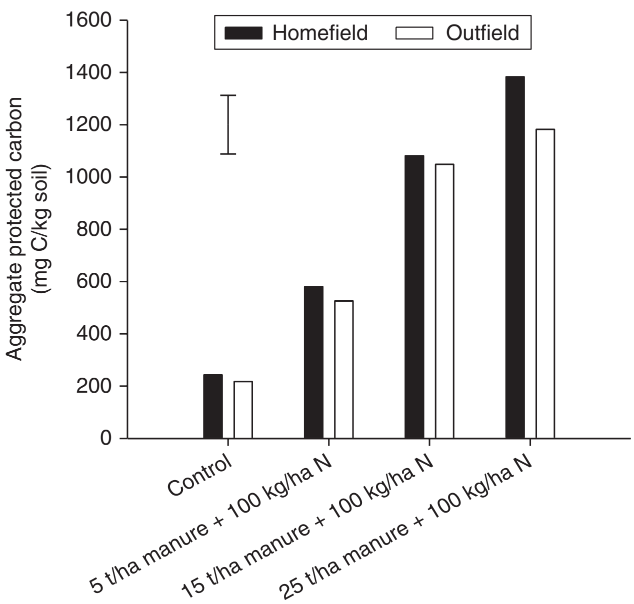

Figure 3 Aggregate protected carbon on the clay soils after 7 yrs. n is 24 and the vertical bar denotes the least significant difference at $P < 0.05$.

Maize grain yield

Cattle manure application rates had a significant effect ($P < 0.05$) on maize grain yield both on clay and sandy soils. Maize grain yield was not significantly different ($P > 0.05$) between the HFs and OFs on clay soils, while on the sandy soils, the HFs had greater yields than the OFs (Table 2). On all field types and both soil types, the control (no amendment applied) yielded < 1 t/ha.

Discussion

The higher SOC and N values observed on HFs than OFs confirm the marked effect of differential management of fields. This is a consequence of long-term use of larger amounts of manure and inorganic fertilizer in the HFs by the farmers and owing to a combination of biophysical and socio-economic factors (Prudencio, 1993). Variability in SOC across fields resulting from field-specific soil management is common across farming systems in sub-Saharan Africa (Tittonell *et al.*, 2005; Bationo *et al.*, 2007).

The significant increase in SOC suggests the importance of cattle manure in SOM enhancement. Similar results are also reported by Shirani *et al.* (2002), Mucheru-Muna *et al.* (2007) and Mugwe *et al.* (2009). Mean SOC increase was higher on clay OFs and sandy soils, while the clay HFs had the least increase, possibly due to the higher initial content. In this study, initial SOC differences between HFs and OFs were no

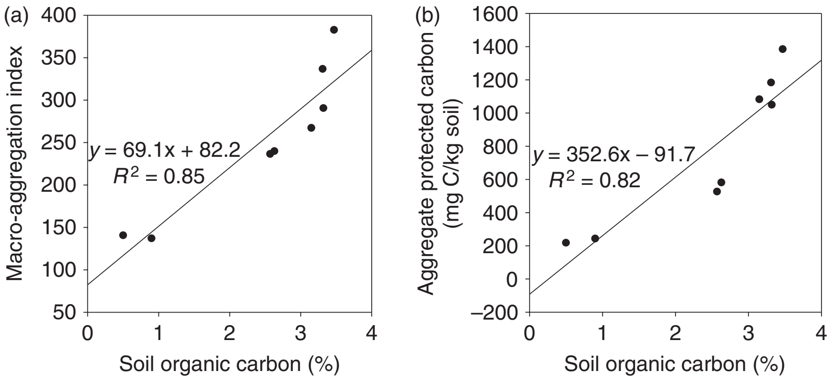

Figure 4 Relationship (R^2) between soil organic carbon (SOC) and (a) macro-aggregation index and (b) aggregate protected carbon on the clay soils. The data points represent the means of the replicates per treatment in each field type.

Table 2 Maize grain yield on experimental sites in Murewa during season 2008–2009

	Maize grain yield (t/ha)			
	Clay soil		Sandy soil	
Treatment	Homefield	Outfield	Homefield	Outfield
Control	0.9^{a}	0.6^{a}	0.4^{A}	0.2^{A}
5 t/ha M + 100 kg/ha N	3.4^{b}	2.7^{b}	2.3^{C}	1.7^{B}
15 t/ha M + 100 kg/ha N	4.5^{c}	4.2^{bc}	3.3^{D}	1.9^{BC}
25 t/ha M + 100 kg/ha N	4.7^{c}	4.3^{c}	3.3^{D}	2.3^{C}
LSD	0.8	0.5		

M, manure; LSD, least significant difference. Values denoted by the same letter in each soil type are not significantly different.

longer evident after 7 yr. This suggests that by uniform application of cattle manure, farmers can reduce the variability in SOC between HFs and OFs within a relatively short period of time.

The increase in macro-aggregate stability on the clay soils is associated with the increases in SOC, probably due to the proliferation of the microbial population and the binding of clay and silt-sized particles and micro-aggregates into macro-aggregates by the mucilages produced by microbes (Oades, 1984; Six *et al.*, 2000). Similar results have also been reported (Shirani *et al.*, 2002; Hati *et al.*, 2006) in systems where farmyard manure and inorganic fertilizer application were applied to increase SOC. Comparable macro-aggregation index values from HFs and OFs indicate that the initial fertility variability is a result of the application of more nutrient resources in the HFs than OFs. Cattle manure and inorganic N-fertilizer application can therefore be considered as an important option of restoring fertility on degraded OFs.

In contrast, the application of cattle manure had limited effects on the physical properties of the sandy soils, possibly due to their very low clay contents (6–13%) that limited the C stabilization capacity of the soils. Regardless of cattle manure application rate, similar macro-aggregation indices were obtained for all cattle manure treatments. These findings are similar to those of Kemper & Koch (1966) who found that aggregate stability increases to a maximum level with higher clay content and free Fe-oxide contents and, consequently, soils with low clay content will have low aggregation indices.

Consistent with the increase in macro-aggregate stability, aggregate protected C increased with the increase in cattle manure application in clay soils. Even though some studies have shown that macro-aggregates ($>250\ \mu m$) give minimal physical protection (Beare *et al.*, 1994; Bossuyt *et al.*, 2002; Alvaro-Fuentes *et al.*, 2009), the dynamics of macro-aggregates are crucial for the sequestration of C (Six *et al.*, 2000). For example, rapid turnover of macro-aggregates reduces the formation of micro-aggregates resulting in lower stabilization of C (Six *et al.*, 2000). The increase in aggregate protected C contributed to a substantial proportion of the SOM in the clay soils.

Positive regression coefficients between SOC, macro-aggregate stability and aggregate protected C confirm the positive relationship between SOC and the measured soil physical properties. Other studies have also reported similar relationships between SOC and soil physical properties (Evrendilek *et al.*, 2004; Wang *et al.*, 2010). The relationship was influenced by the rates of cattle manure used in the experiment. Therefore, increasing cattle manure application rates will enhance soil physical properties depending on the amount of SOC in the soil.

Generally, maize grain yield increased from the control followed by the 5 t/ha cattle manure treatment and then the 15 and 25 t/ha cattle manure treatments, which were not significantly different. However, despite the evident advantages of cattle manure application at high rates such as 15 t/ha on clay soils and at least 5 t/ha in sandy soils, obtaining such quantities is a challenge in smallholder farming areas where the mean application rate is still as low as 2.5 t/ha (Materechera, 2010). The effects of cattle manure on improved crop yields on the sandy soils was possibly through the increased and balanced supply of nutrients, while on the clay soils, improved soil structure (Bationo *et al.*, 2007) and soil physical properties may also be important. The significant increases in grain yield were also partly attributed to the inorganic N-fertilizer applied. Interestingly, Zingore *et al.* (2007b) report an increase in maize yields on clay and sandy HFs in the first season only (2002–2003) with sole N-fertilizer application, which declined thereafter and this is attributed to lack of nutrients other than N, which were supplied by the applied cattle manure.

Conclusion

Initial differences in SOC in fields were eliminated as a result of uniform management for 7 yr, indicating the low resilience of the soil fertility gradients. This study has shown that the combined application of cattle manure and inorganic N-fertilizer improved soil physical properties in the clay OFs after 7 yr, but not in sandy ones. Cattle manure application amounts of at least 15 t/ha per yr are recommended for soil structure improvement and maintenance in clay soils, while in sandy soils, cattle manure rates between 5 and 15 t/ha per yr would be required to increase maize productivity through complementing nutrient supply from mineral fertilizers.

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