Nutr Cycl Agroecosyst (2008) 80:267–282
DOI 10.1007/s10705-007-9142-2

RESEARCH ARTICLE

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

Shamie Zingore · Robert J. Delve · Justice Nyamangara · Ken E. Giller

Received: 22 January 2007 / Accepted: 24 September 2007 /

Abstract Manure is a key nutrient resource on smallholder farms in the tropics, especially on poorly buffered sandy soils, due to its multiple benefits for soil fertility. Farmers preferentially apply manure to fields closest to homesteads (homefields), which are more fertile than fields further away (outfields). A three-year experiment was established on homefields and outfields on sandy and clayey soils to assess the effects of mineral nitrogen (N) fertilizer application in combination with manure or mineral phosphorus (P) on maize yields and soil chemical properties. Significant maize responses to application of N and manure were observed on all fields except the depleted sandy outfield. Large amounts of manure (17 t ha^{-1} year^{-1}) were required to significantly increase soil organic carbon (SOC), pH, available P, and base saturation, and restore productivity of the depleted sandy outfield. Sole N as ammonium nitrate (100 kg N ha^{-1}) or in combination with single superphosphate led to acidification of the sandy soils, with a decrease of up to 0.8 pH units after three seasons. In a greenhouse experiment, N and calcium (Ca) were identified as deficient in the sandy homefield, while N, P, Ca, and zinc (Zn) were deficient or low on the sandy outfield. The deficiencies of Ca and Zn were alleviated by the addition of manure. This study highlights the essential role of manure in sustaining and replenishing soil fertility on smallholder farms through its multiple effects, although it should be used in combination with N mineral fertilizers due to its low capacity to supply N.

Keywords Fertilizer · Manure · Micronutrient deficiency · Multiple nutrient deficiencies · Soil fertility gradients

---

S. Zingore (✉) · R. J. Delve
Tropical Soil Biology and Fertility Institute of CIAT,
P.O. Box MP228, Mt Pleasant, Harare, Zimbabwe
e-mail: s.zingore@cgiar.org

S. Zingore · K. E. Giller
Plant Production Systems, Department of Plant Sciences,
Wageningen University, P.O. Box 430, 6700 AK
Wageningen, The Netherlands

J. Nyamangara
Department of Soil Science and Agricultural Engineering,
University of Zimbabwe, P.O. Box MP167, Mt Pleasant,
Harare, Zimbabwe

Introduction

The predominant soils cultivated by smallholder farmers in Zimbabwe and over large areas of sub-Saharan Africa are inherently infertile, and poor soil fertility is recognized as a major constraint to crop productivity. Vast areas of these soils have critically low concentrations of soil organic carbon (SOC) and nutrients, and are also acidic, due to long-term cultivation with little input of fertilizer (Grant 1981; Nyamangara et al. 2000). Coarse-textured sandy soils are particularly difficult to manage as they easily lose nutrients by leaching and are highly susceptible to erosion due to poor aggregation (Burt et al. 2001). Sanchez et al. (1997) listed low intrinsic soil fertility and depletion of nutrients as major challenges facing farmers throughout sub-Saharan Africa. Cattle manure is a key resource in this regard (Bayu et al. 2005; Murwira et al. 1995), supplying nutrients, raising soil pH, and increasing SOC. By raising soil organic matter, it increases cation exchange capacity and improves soil physical properties, such as soil structure. Smallholder farmers in sub-Saharan Africa typically have limited supplies of organic and mineral fertilizers and tend to use them preferentially on fields closest to the homesteads (homefields) rather than to fields further way (outfields) (Tittonell et al. 2005; Mtambanengwe and Mapfumo 2005; Zingore et al. 2007a). Consequently, nutrients accumulate in small areas and strong nutrient concentration gradients develop within farms. This, combined with the inherent variation in soils, results in complex differences in soil fertility between fields on the same farm or between farms located on different soils (Carter and Murwira 1995; Giller et al. 2006).

We have recently reported on experiments in Zimbabwe that showed strong responses by maize (*Zea mays* L.) to mineral nitrogen (N) and phosphorus (P) on fields closest to homesteads (homefields) that had previously received large amounts of manure (Zingore et al. 2007b). In contrast, on sandy nutrient-poor outfields, maize did not significantly respond to mineral N and P over three seasons. Responses to combined applications of manure and mineral N were also poor in the first two seasons, but significantly improved in the third season. The response of maize on the sandy outfield to N and P was improved after repeated applications of manure and mineral N fertilizer. This indicated that the initial poor response was due to other limiting factors such as deficiency of nutrients besides N and P or to soil physical properties such as low water-holding capacity or poor infiltration due to low SOC, barriers to yield that were overcome by manure. Zinc and boron deficiencies have been shown to occur on granitic sands in Zimbabwe (Rodel and Hopley 1973). Assessment of maize on several outfields in a study by Zingore et al. (2007b) showed nutrient deficiency symptoms: stunted growth and leaves with interveinal chlorosis and dead tips, consistent with Zn deficiency (Marschner 1995). Other studies across sub-Saharan Africa have similarly reported better crop responses to fertilizer application in homefields which receive large amounts of manure compared with outfields (Vanlauwe et al. 2006; Wopereis et al. 2006), but reasons for the poor responses on the outfields remain unclear.

Despite previous research demonstrating large manure-based increases of crop yields in East and West Africa (Bationo and Mokwunye 1991; Bationo et al. 2004) the multiple benefits of manure for soil fertility in low-external-input farming systems are still not fully understood. Research on cattle manure in sub-Saharan Africa has mainly focused on its role in supplying the N required by crops (Delve et al. 2001; Murwira et al. 1995; Nyamangara et al. 2003), with little attention given to its multiple functions on the availability of other nutrients in soils. Studies that examine the long-term effects of manure on soil fertility and crop yields continue to emphasize solely the macronutrients (N, P, K) (Kihanda et al. 2006), neglecting the broader role of manure in plant nutrition. Based on the results reported in Zingore et al. (2007b) and other recent studies, this study aims to extend our knowledge of these functions by quantifying the effects of manure on broad soil chemical properties and its capacity to restore fertility to nutrient depleted soils. Sites with contrasting histories of manure application were selected on two soils, a granitic sand, and a red clay soil. Mineral N fertilizer was applied with or without manure or mineral P fertilizer and after three seasons SOC, N, available P, pH, and exchangeable bases were measured to assess changes due to the treatments. In addition, greenhouse experiments were conducted to assess (i) macro- and micronutrients deficiencies on sandy and clayey homefields and outfields, and (ii) the potential of manure to supply N, P, bases, and micronutrients in the short term.

Materials and methods

Study site, site selection, and field experiments

The characteristics and selection of sites, and field experiments conducted in Murewa (2002–2005), in NE Zimbabwe (17°49′ S, 31°34′ E) are described fully in Zingore et al. (2007b). Briefly, fields closest to the homestead (termed ‘homefields’) and fields at distance from the homestead (termed 'outfields') were selected on two farms: one on a granitic sandy soil (Lixisol) and the other on a clay soil (Luvisol), to provide sites with contrasting histories of manure management on different soil types. The four fields had been mostly under maize cultivation for more than three decades. The homefields received large amounts of manure and mineral fertilizer, whilst the outfields received little mineral fertilizers and had no history of manure application. These sites were carefully selected to be representative of the main categories of soil fertility found in NE Zimbabwe and were typical homefields and outfields in the area (Zingore et al. 2007a; Mtambanengwe and Mapfumo 2005), which are: (i) depleted fields with sandy soils exposed to long-term cultivation with little nutrient inputs (about 60% of the cultivated area), (ii) well-managed sandy soils which had received manure for several seasons (about 20% of the cultivated area), (iii) infertile red clay soil with no history of manure application (about 15% of the cultivated area), and (iv) fertile red clay soils previously fertilized with large amounts of manure (about 5% of the cultivated area).

The experiments assessed the efficiencies of nutrient use by maize on the fields with contrasting histories of management. In the main treatments on the four fields, N was applied as ammonium nitrate (100 kg N ha^{-1}) in combination with different rates of P (0, 10, and 30 kg ha^{-1}), from either single superphosphate (SSP) or cattle manure (Table 1). Farmers typically apply N alone or in combination with basal P fertilizer or manure, and nutrients added in treatments were selected to represent this management pattern. In addition to the target P application, manure also supplied other nutrients (macronutrient contents: 1.1% N, 0.18% P, 0.20% Ca, 0.08% Mg, and 0.64% K; micronutrients contents: 800 mg kg^{-1} Fe, 22 mg kg^{-1} Cu, 280 mg kg^{-1} Mn, 112 mg kg^{-1} Zn). Mineral N was split and applied in equal amounts at about three and six weeks after plant emergence. Manure was applied at 6 and 17 t ha^{-1} year^{-1}, to supply 10 and 30 kg P ha^{-1} year^{-1}, respectively. Manure is generally available in limited quantities as there are relatively few cattle in the smallholder farming systems. Farmers apply their manure at high rates by concentrating in the homefield; often at 17 t ha^{-1} or more (Murwira 1995).

Manure and SSP were incorporated into the top 20 cm of the soil using hoes. In each field, plots (6 × 4.5 m) were arranged in a randomized complete block design with three replicates. All treatments were applied each season. A control plot, on which no nutrients were applied for the three seasons, was also included. A medium maturing maize variety (SC627) was sown at a density of 48,000 plant ha^{-1}. Maize residues were removed after harvesting to mimic management by farmers, who remove the residues to feed cattle. Maize grain and stover yields were determined after five months at the end of the season from net plots measuring 2 × 2.7 m. Moisture contents determined for grain samples were used to correct grain yields to 12.5% moisture content.

Soil sampling and analysis

In each field, three soil samples (0–20 cm) were collected from each block before the start of the

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

Treatment and N applied each season	Source and rate of P applied[a]		
	Year 1	Year 2	Year 3
1 0, control	None	None	None
2 00 kg N ha^{-1}	None	None	None
3 100 kg N ha^{-1}	10 kg P ha^{-1} (manure)	10 kg P ha^{-1} (manure)	10 kg P ha^{-1} (manure)
4 100 kg N ha^{-1}	30 kg P ha^{-1} (manure)	30 kg P ha^{-1} (manure)	30 kg P ha^{-1} (manure)
5 100 kg N ha^{-1}	10 kg P ha^{-1} (SSP)[b]	10 kg P ha^{-1} (SSP)	10 kg P ha^{-1} (SSP)
6 100 kg N ha^{-1}	30 kg P ha^{-1} (SSP)	30 kg P ha^{-1} (SSP)	30 kg P ha^{-1} (SSP)

[a] Manure applied targeting P, but also supplied other nutrients including N, Ca, Mg, K, and Zn

[b] Single superphosphate

experiment using a simple random method from mini-pits. The three samples from each block were bulked to form a composite sample, so that three samples were collected per plot. Soils were sampled again after three years of treatment application. Three samples were collected from each plot and bulked together. Samples were air-dried and passed through a 2 mm sieve and analyzed for SOC (Walkley-Black), total N (micro-Kjeldahl), available P (Olsen), pH (water and 0.01M $CaCl_2$), cation exchange capacity (CEC) (in acidified ammonium acetate), and exchangeable bases (Ca, Mg, and K) (Anderson and Ingram 1993). Water release curves were determined for the soils, and field capacity was taken at a soil pressure of 0.3 bar for the clay soil and 0.1 bar for the sandy soil (Jury et al. 1991).

Greenhouse pot experiments

A greenhouse pot experiment was conducted to determine limiting nutrients in the different fields under controlled moisture conditions. Soil (0–20 cm) was collected from the four different fields described above (homefield and outfield on the sandy and clay soils). The soils were air-dried and sieved through a 2 mm sieve, before weighing into free-draining 2,000 cm^3 pots. The bulk density of the sandy soil was 1.5 g cm^{-3} and that of the clay soil 1.2 g cm^{-3} of which 3 and 2.4 kg were filled in pots, respectively. The treatments for the pot experiment and amounts of nutrients applied are presented in Tables 2 and 3. Deficiencies of K or S were considered unlikely, however, basal K_2SO_4 was applied to all pots to ensure that lack of these nutrients did not limit maize growth. A treatment with dolomitic lime was included to test the effects of increasing pH on maize shoot biomass and nutrient composition. This was important on the sandy soils, where maize growth may be inhibited by soil acidity. The manure used in the greenhouse experiment had a similar chemical composition to that used in the field experiments and was prepared by air-drying and grinding to <0.5 mm.

Table 3 Rates of nutrients applied in the greenhouse pot experiment and their sources

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

[a] Calculation of nutrients applied to the pots was done on a volume basis, assuming an application depth of 20 cm in the field

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

Treatment[a]	Nutrients (no manure)	Manure
1.	Control + (K + S)	Manure
2.	N	Manure + N
3.	N + P	Manure + N + P
4.	N + P + Ca	Manure + N + P + Ca
5.	N + P + Ca + Mg	Manure + N + P + Ca + Mg
6.	N + P + Ca + Mg + micronutrients[b]	Manure + N + P + Ca + Mg + micronutrients
7.	N + P + micronutrients + lime[c]	Manure + N + P + micronutrients + lime

[a] All pots received basal K_2SO_4 at the rates shown in Table 3. Rates of nutrient application are also shown in Table 3

[b] Micronutrients applied are presented in Table 3. Application is based on micronutrients potentially limiting in Zimbabwean soils

[c] Applied as dolomitic lime ($CaCO_3$, $MgCO_3$)

Nutrient solutions were prepared separately for each soil type, due to differences in field capacity, with sufficient distilled water to attain the field capacity for each soil. Manure and dolomitic lime were added directly to the pots before application of the nutrient solutions and were thoroughly mixed with the soils for uniform distribution. The pots were arranged in a randomized complete block design with three replicates. For ease of management, the experiment was done in two phases: pots with sandy soil, both homefield and outfield, were set up first and pots with the red clay soil were set up in the second phase of the experiment. The greenhouse temperature was not controlled, so the first phase of the experiment was conducted under higher temperatures (mean temperature = 29°C) than the second phase of the experiments (mean temperature = 24°C). The objective of the experiment was not to compare maize biomass on the different soils, but to assess nutrient deficiencies in each of the soils.

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

Observations of nutrient deficiency symptoms on unfertilized maize plots (stunted growth of maize and leaves characterized by interveinal chlorosis and dead tips) indicated Zn deficiency. Based on this observation and results from the first pot experiment, a second experiment was conducted to examine if Zn was deficient in the sandy outfield. The treatments were (i) control, (ii) N + P + Ca, (iii) N + P + Zn, (iv) N + P + Ca + Zn, and (v) N + P + Ca + all micronutrients. Similar treatments were also used to test for Zn and Ca deficiency on the soil from the sandy outfield that had received about 17 t of manure ha^{-1} year^{-1} for three seasons to assess the capacity of manure to alleviate deficiencies of Ca and Zn.

Dried manure and maize shoots samples were ground (<0.5 mm) for analysis of nutrient composition. Total N was determined using the micro-Kjeldahl method and total P by ashing and acid extraction; calorimetric determination was carried out using the Mo blue method (Anderson and Ingram 1993). The concentrations of Ca, Mg, K, Zn, Fe, Mn, and Cu were determined by atomic absorption spectrometry after manure and maize biomass samples were dry-ashed at 450°C and extracted with HCl and HNO_3 (Page et al. 1982). Nutrient concentrations in maize shoots were interpreted as deficient, low, or adequate using the values suggested by Mengel and Kirby (2001), Khiari et al. (2001) and Jones (1972) (Table 4).

Statistical Analysis

Analysis of variance (ANOVA) was used to test the significance of the differences between means of soil properties after three seasons of N, SSP, and manure application (model: treatment × field type, for each soil type), maize grain yields (model: treatment × field type × soil type × season), of

Table 4 Values used to interpret the adequacy of nutrients in different fields in Murewa, NE Zimbabwe using nutrient concentration values in maize shoots

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

[a] Mengel and Kirby (2001) (general values for maize)

[b] Khiari et al. (2001) (maize plants at four weeks)

[c] Jones (1972) (maize ear leaf at silking)

maize shoot biomass (model: treatment × field type × soil type) and between means of nutrient composition in maize shoots (treatments on each soil) in the greenhouse experiments. The statistical analysis was performed using the GENSTAT 7.1 statistical package.

Results

Soil chemical properties of homefields and outfields and their response to application of N, P, and manure application

Long-term application of manure to homefields by farmers led to improved soil properties than on outfields on both sandy (Table 5a, b) and clay soils (Table 6a, b). All soil chemical properties measured were significantly higher on a given field type on the clay soil than on the sandy soil.

On the sandy homefield, addition of manure led to a significant ($P < 0.05$) increase in pH, but addition of N fertilizer or N + SSP induced a decline in pH. Available P was significantly higher ($P < 0.05$) in the two treatments in which SSP or the high rate of manure were applied, compared with the control treatment. Application of N fertilizer alone led to a significant decline in available P. On the sandy outfield, addition of N fertilizer together with manure equivalent to 10 kg and 30 kg P ha^{-1} significantly increased SOC contents after three seasons (Table 5b). Manure applied at a rate that supplied 30 kg P ha^{-1} also led to a significant increase in pH, available P, CEC, exchangeable bases (Ca, Mg, and K), and base saturation.

Compared with the initial values, most soil properties remained unchanged on the clayey homefield, except for the substantial decline in available P for the control, sole N, and N + SSP (10 kg ha^{-1}) treatments (Table 6a). Manure applied at 17 t ha^{-1} year^{-1} resulted in significantly greater SOC contents than the control ($P < 0.05$). On the clayey outfield, SOC contents in plots amended with manure (17 t ha^{-1} year^{-1}) was significantly greater than in all plots that did not receive manure. Available P on the clayey outfield was only significantly increased above the control treatment by SSP applied at 30 kg P ha^{-1} year^{-1}.

Maize grain yields on the sandy and clayey homefields and outfields

Maize grain yields for the control treatment decreased in the order: clayey homefield > sandy homefield ~ clayey outfield > sandy outfield, in both the first and third seasons (Fig. 1). Addition of mineral N and P fertilizers significantly increased maize grain yields ($P < 0.05$) on the sandy and clayey homefields in the first season, but their application for three seasons led to a significant decline in maize grain yields. Maize grain yields were significantly increased when N was applied in combination with SSP or manure on all fields except the sandy outfield (Fig. 1b). Contrary to expectations, the response of maize grain yield to N and P was poor on the sandy outfield, irrespective of the source of P. It was only after repeated application of manure (30 kg P ha^{-1}) for three seasons that a significant increase in maize yields was observed. On the clayey homefield, the maize grain yield for the control treatment in the third season was significantly less than that in the first season, indicating a rapid decline in soil fertility.

Despite previous large additions of manure on the homefields, application of manure in experimental plots led to higher maize grain yields than SSP on the sandy homefield. As expected, yields were significantly greater with manure than SSP on the clayey outfield, whilst the maize grain yields with SSP were higher than with manure in the first season on the clayey homefield.

Maize shoot biomass and nutrient composition in pots

On the sandy homefield, maize growth was significantly increased ($P < 0.05$) by the addition of N alone (Fig. 2a), but on the sandy outfield there was poor response of maize growth to the addition of N or N and P (Fig. 2b). A significant increase in maize biomass was observed on the sandy outfield when N and P were applied in combination with Ca. An additional significant increase in maize biomass on the sandy outfield was observed when micronutrients were added. Manure alone (control) had no effects on maize biomass on the sandy soil (Fig. 2a, b), but

Table 5 Soil chemical properties initially and after three seasons of application of N with or without manure or SSP on fields with different initial fertility at Murewa, NE Zimbabwe: (a) sandy homefield, (b) sandy outfield

Treatment	Organic C (%)	Total N (%)	pH (H_2O, $CaCl_2$)	Available P (mg kg^{-1})	CEC ($cmol_c$ kg^{-1})	Exchangeable bases ($cmol_c$ kg^{-1})			Base saturation (%)
						Ca	Mg	K	
(a)									
Initial	0.50	0.04	5.1, 4.9	7.2	2.2	0.91	0.32	0.21	73
Control	0.48	0.03	4.9, 4.5	6.6	2.1	0.75	0.24	0.29	65
100 N	0.48	0.04	4.6, 4.1	2.3	2.1	0.62	0.26	0.32	61
100 N + 10 kg P (manure)	0.52	0.04	5.0, 4.8	5.6	2.4	1.13	0.36	0.35	79
100 N + 30 kg P (manure)	0.58	0.05	5.6, 5.2	12.5	2.6	1.19	0.44	0.50	89
100 N + 10 kg P (SSP)	0.49	0.03	4.5, 4.1	9.3	1.9	0.62	0.22	0.29	63
100 N + 30 kg P (SSP)	0.51	0.04	4.5, 4.2	16.5	2.2	0.76	0.13	0.27	56
SED (treatment)	0.09	0.01	0.2, 0.3	1.7	0.3	0.24	0.19	0.13	12
(b)									
Initial	0.31	0.03	4.9, 4.5	2.4	1.6	0.26	0.19	0.11	37
Control	0.32	0.02	4.9, 4.4	2.5	1.8	0.23	0.21	0.12	33
100 N	0.29	0.03	4.1, 3.5	1.5	1.7	0.15	0.18	0.14	28
100 N + 10 kg P (manure)	0.41	0.03	5.0, 4.7	3.4	1.9	0.31	0.32	0.13	40
100 N + 30 kg P (manure)	0.49	0.04	5.2, 4.9	10.9	2.1	0.53	0.44	0.23	57
100 N + 10 kg P (SSP)	0.29	0.02	4.7, 4.2	4.6	1.6	0.17	0.20	0.12	24
100 N + 30 kg P (SSP)	0.30	0.03	4.6, 4.0	11.5	1.7	0.21	0.27	0.12	29
SED (treatment)	0.05	0.01	0.12, 0.13	1.6	0.4	0.23	0.16	0.11	8

SED = Standard error of differences between means

Table 6 Changes in soil chemical properties following application of N with or without manure or SSP on fields with different initial fertility at Murewa, NE Zimbabwe: (a) clayey homefield, (b) clayey outfield

Treatment	Organic C (%)	Total N (%)	pH (H_2O, $CaCl_2$)	Available P (mg kg^{-1})	CEC ($cmol_c$ kg^{-1})	Exchangeable bases ($cmol_c$ kg^{-1})			Base saturation (%)
						Ca	Mg	K	
(a)									
Initial	1.43	0.08	5.6, 5.3	12.1	24.2	11.5	6.2	0.8	78
Control	1.21	0.07	5.6, 5.2	8.3	23.0	11.8	5.9	0.5	80
100 N	1.26	0.08	5.5, 5.3	7.9	23.1	11.9	5.9	0.6	84
100 N + 10 kg P (manure)	1.45	0.07	5.5, 5.3	9.5	24.0	11.5	6.1	0.9	78
100 N + 30 kg P (manure)	1.64	0.09	5.5, 5.3	10.3	24.8	12.4	6.0	0.7	78
100 N + 10 kg P (SSP)	1.45	0.08	5.6, 5.4	7.3	23.0	11.5	6.0	0.7	88
100 N + 30 kg P (SSP)	1.40	0.08	5.6, 5.2	13.6	23.2	12.1	5.8	0.7	84
SED (treatment)	0.15	0.02	0.2, 0.2	2.6	1.6	0.62	0.44	0.21	12
(b)									
Initial	0.75	0.05	5.4, 5.1	3.9	22.0	8.4	6.3	0.3	69
Control	0.72	0.04	5.5, 5.2	3.7	23.4	8.9	6.5	0.3	68
100 N	0.79	0.05	5.3, 5.0	3.1	23.9	10.4	5.6	0.3	69
100 N + 10 kg P (manure)	0.89	0.07	5.5, 5.3	4.1	22.0	9.6	5.5	0.4	71
100 N + 30 kg P (manure)	0.91	0.07	5.6, 5.3	4.9	23.4	9.6	5.7	0.4	68
100 N + 10 kg P (SSP)	0.72	0.06	5.3, 5.1	4.2	23.2	8.4	5.4	0.3	61
100 N + 30 kg P (SSP)	0.75	0.05	5.4, 5.1	6.7	22.9	9.3	5.6	0.3	67
SED (treatment)	0.08	0.02	0.3, 0.2	1.5	1.1	1.3	0.9	0.1	8

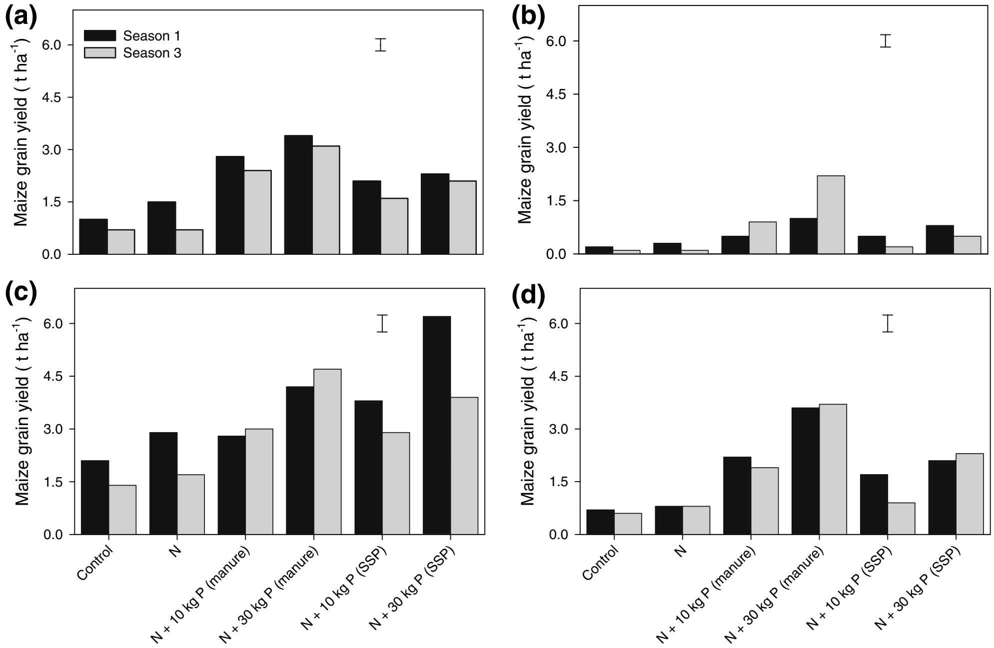


Fig. 1 Maize grain yields on sandy and clayey homefields and outfields at Murewa, NE Zimbabwe, subjected to application of mineral N with different rates of manure or SSP. Bars show SEDs for field × treatment × year interactions

significantly amplified the response to mineral nutrients added. The significant responses to N and P when manure was added sharply contrasted with the lack of response to N and P observed without manure (Fig. 2b), indicating that manure alleviated other deficiencies that limited responses to N and P.

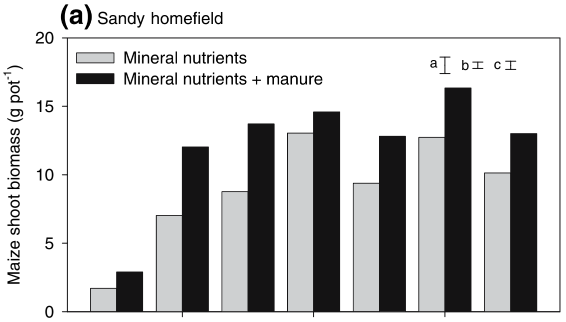
On the sandy homefield and outfield, the concentration of N in the maize shoots in the control treatment was below critical values given for maize (cf. Table 4), both with and without manure (Table 7a, b). The concentration of N in the shoots was significantly increased ($P < 0.05$) with the addition of N, but was significantly reduced with manure in some treatments. On the sandy homefield, the concentrations of all nutrients, except N and Ca, were within the adequate range for maize. On the sandy outfield, the concentrations of P, Ca, and Zn in maize shoots were below the adequate range (low or deficient) in the treatments without the respective nutrients, but concentrations of Ca and Zn were significantly increased with manure application.

The maximum maize biomass obtained for both fields on the clay soil in the greenhouse pot experiment was less than that on the sandy soil, as the treatments with the clay soil were established later in the year when temperatures were lower. None of the major or micronutrients had an effect on maize biomass on the clayey homefield soil (Fig. 3a). On the clayey outfield, there was no response to sole N fertilizer, but there was significant maize growth increase in the N + P treatment, which indicated that either P alone or both P and N were strongly limiting (Fig. 3b).

On the clayey outfield significant effects of manure were expected, but the different combinations of nutrients with manure resulted in maize biomass that was not significantly different from that produced by manure alone or by nutrients without manure (Fig. 3). The significant effects of the N + P + Ca + manure treatment on maize biomass on the clayey outfield was unexpected, as exchangeable Ca in the soil was adequate for maize growth. On the clayey homefield, the concentrations of all nutrients in maize shoots were in the adequate range, although manure significantly reduced N concentration (Table 8a).

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

In the second pot experiment, maize biomass for the N + P + Ca treatment was significantly greater


(a) Sandy homefield

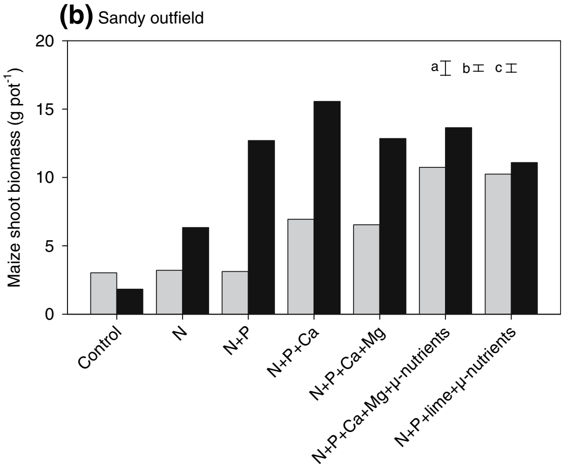

(b) Sandy outfield

Fig. 2 Effects of different nutrients on maize biomass production on sandy soils from Murewa, NE Zimbabwe, in the greenhouse pot experiment: (**a**) sandy homefield; (**b**) sandy outfield. (a) Treatments, (b) field type, (c) soil type. All pots were amended with K and S

than that for the N + P + Zn treatment, suggesting that Ca was deficient on the sandy outfield (Fig. 4). In treatments without Ca, the concentration of Ca in maize shoots was low (<0.3%), indicating that Ca was deficient (cf. Table 4). With 14–19 mg kg^{-1}, the concentration of Zn was low or deficient. The maize shoot biomass for the treatments with N and P, but without Ca or Zn, were greater on the sandy outfield manured for three seasons than on the unamended sandy outfield, suggesting that the manure applications had alleviated deficiencies of Ca and Zn (Fig. 4). In the manured sandy outfield, the concentration of Ca in maize shoots was significantly increased ($P < 0.05$) by an average of 0.05%, although it was still not adequate for maize growth (0.32–0.36%) without the addition of Ca.

Discussion

Differences in soil chemical properties of homefields and outfields subjected to different management

The larger contents of SOC, total N, and exchangeable bases observed on the homefields (Tables 5, 6) can be linked to larger amounts of manure applied over many years (Prudencio 1993; Tittonell et al. 2005). Use of manure has an advantage over basal mineral P fertilizers as it has multiple effects on soil chemical properties (Mapfumo and Giller 2001; Bationo and Mokwunye 1991) and in the Sahelian zone, manure applied at 20 t manure ha^{-1} in one season led to substantial increases in SOC (from 0.29% to 0.58%), total N, available P, and soil pH (Bationo and Mokwunye 1991). Smallholder farmers typically remove stover for use as fodder and manure is the only major source of organic matter returned to agricultural fields. Sandy soils have low capacity to sequester organic matter and as a result soil organic carbon contents were smaller than on the clay soil. On the clay soil, SOC in the homefield was greater than in the outfield by 0.68%, mainly due to the stronger capacity of the clay soil to protect soil organic matter physically, which facilitated greater storage of organic matter from manure on the homefield (Feller and Beare 1997; Zingore et al. 2005).

Manure contains significant amounts of bases, which led to the greater contents of exchangeable bases on the homefield that received manure in the past compared with the outfield. Strong effects of manure on supply of bases were also reported by Lupwayi et al. (2000) and Grant (1967). The higher pH on the homefields than outfield is due to the release of OH$^-$ ions during decomposition of manure and the buffering from organic compounds released from manure applied in the past (Haynes and Mokolobate 2001; Whalen et al. 2000). The higher available P values on the homefields may not be attributable solely to manure, as the farmers also used basal fertilizer (7%N, 9%P, 8%K) on these fields in the past. On the clayey outfield, bases and pH were maintained at high values due to the high buffering capacity of the soil (Table 6b).

Application of mineral N alone as ammonium nitrate led to acidification on the sandy soils

Table 7 Nutrient concentrations of maize plants on the sandy soils from Murewa, NE Zimbabwe, supplied with different combinations of macro- and micronutrients and manure in the greenhouse pot experiment: (a) sandy homefield soil; (b) sandy outfield soil

Treatment[a]	N (%)		P (%)		Ca (%)		Mg (%)		Zn (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Cu (mg kg^{-1})	
	–M	+M	–M	+M	–M	+M	–M	+M	–M	+M	–M	+M	–M	+M	–M	+M
(a)																
1	1.6	1.1	0.26	0.33	0.33	0.44	0.22	0.31	36	41	319	288	127	131	9.6	10.4
2	3.2	2.4	0.25	0.27	0.28	0.41	0.30	0.29	31	37	290	280	120	130	10.2	11.4
3	3.4	2.2	0.37	0.33	0.26	0.39	0.30	0.33	29	31	275	302	122	119	11.1	9.9
4	3.0	2.5	0.31	0.31	0.44	0.53	0.26	0.34	32	45	275	296	132	132	10.6	10.9
5	3.1	3.1	0.34	0.28	0.39	0.44	0.31	0.30	33	44	262	305	121	126	11.0	10.3
6	3.1	2.4	0.30	0.32	0.46	0.55	0.29	0.36	48	44	289	300	139	144	11.5	11.5
7	3.3	2.8	0.29	0.31	0.45	0.53	0.31	0.35	40	43	291	292	143	143	10.2	11.5
SED	0.3		0.07		0.06		0.03		4.2		20		13		1.2	
(b)																
1	1.4	1.4	0.15	0.18	0.28	0.43	0.25	0.24	21	29	250	287	136	136	10.1	10.4
2	3.3	2.1	0.19	0.22	0.21	0.32	0.23	0.28	19	28	274	255	124	116	10.8	10.2
3	3.5	2.7	0.30	0.33	0.25	0.41	0.23	0.25	18	21	278	297	125	106	11.3	10.4
4	3.4	3.0	0.32	0.32	0.36	0.38	0.26	0.26	19	29	265	281	111	124	9.8	10.0
5	3.2	2.8	0.31	0.31	0.40	0.49	0.31	0.33	22	33	276	271	136	121	11.6	10.9
6	3.3	2.5	0.32	0.32	0.42	0.41	0.32	0.33	31	29	280	265	142	139	11.9	11.4
7	3.5	3.1	0.32	0.32	0.51	0.44	0.36	0.35	36	38	282	278	148	157	12.8	11.9
SED	0.4		0.04		0.04		0.05		4.6		29		11		1.0	

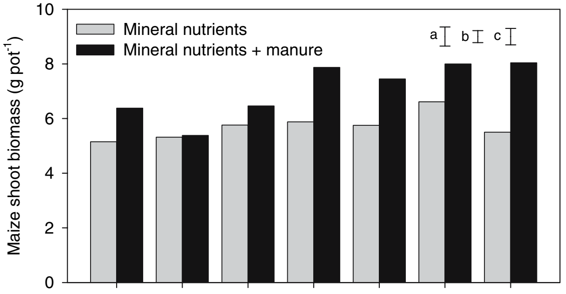
[a] Treatments: 1 = control; 2 = N; 3 = N + P; 4 = N + P + Ca; 5 = N + P + Ca + Mg; 6 = N + P + Ca + Mg + micronutrients; 7 = N + P + lime + micronutrients

(Table 5a, b) but the acidifying effects of ammonium nitrate were less profound on the clay soil, given the stronger buffering capacity of the clay. The other major effect of the sole N treatment was depletion of available P on the homefields, due to increased removal of P. On the clay soil, available P could also have declined due to P fixation without further P addition. Although N is regarded as the most limiting nutrient in Zimbabwe, balanced nutrient application is required, as application of N alone induces depletion of other nutrients (Nyamangara et al. 2000). The relative increases in SOC following manure application were largest on the outfields, which initially contained small amounts of SOC.

The SOC content on the sandy outfield was similar to that of the homefield after three seasons of manure application at 17 t ha^{-1} year^{-1}, indicating that large additions of manure are necessary to reduce the gradients of SOC on the sandy soil. Such application rates were insufficient to raise the SOC of the clayey outfield to the contents found initially on the homefield, suggesting that even larger amounts or a longer time frame of manure application may be required to do the same on the clay soil. The results clearly show that there is limited opportunity for farmers to restore fertility in depleted outfields by refocusing management to apply manure in outfields. Besides SOC and total N, manure had strong effects on available P, exchangeable Ca, Mg, and K, and pH (Tables 5, 6). Field studies in Tanzania showed that manure applied at 20 t ha^{-1} significantly increased available P across depleted farmers' fields (Kaihura et al. 1999). On sandy soils with small total P contents, the effects of manure on P availability are directly related to the release of available phosphates during decomposition (Kaihura et al. 1999). On the clay soil with high P sorption capacity, in addition to direct P supply, organic anions released during the decomposition of manure can compete with P sorption sites and increase the availability of P (Reddy et al. 1999).

Cattle manure generally contains significant amounts of Ca, Mg, and K (De Ridder and Van Keulen 1990), and this led to the increase in exchangeable bases and base saturation on the sandy

(a) Clayey homefield



(b) Clayey outfield

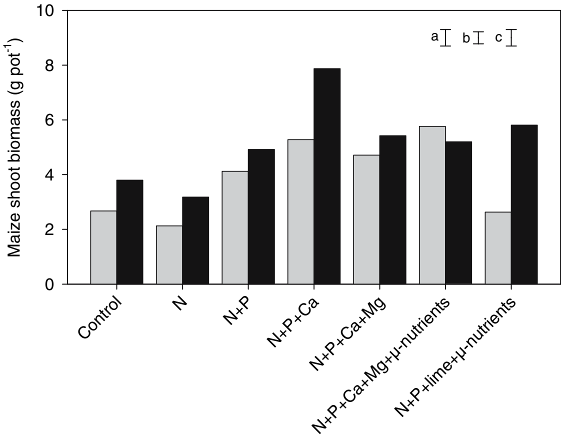


Fig. 3 Effects of different nutrients on maize biomass production on clayey soils from Murewa, NE Zimbabwe, in the greenhouse pot experiment (**a**) clayey homefield; (**b**) clayey outfield. Bars show SEDs for different factors: (a) treatments, (b) field type, (c) soil type. All pots were amended with K and S

outfield. Grant (1967) found similar effects of manure on increasing the supply of bases for maize on granitic sands in Zimbabwe. Application of N and P fertilizers may have an indirect effect on SOC through the production of larger crops and availing larger amounts of crop residues to replenish soil organic matter. This may not be practical on smallholder farms in Zimbabwe, as stover is mostly removed to feed livestock.

Maize grain yields

Large amounts of manure (17 t ha^{-1}) applied each year for three seasons were needed to significantly improve maize yields on the sandy outfield (Fig. 1b). The delay in yield response to manure is possibly due to the need to achieve minimum thresholds for availability of nutrients limiting production in the depleted soil. Manure is key to restoring the productivity of degraded fields as it supplies multiple nutrients, raises soil pH, and improves soil organic matter, which in turn improves the physical properties of the soil (Grant 1981; Gandah et al. 2003). Repeated application of N alone on the sandy homefields led to a decline in the availability of other nutrients and soil acidification on the sandy soil, which explains the lower grain yield responses to N in the third season. Continued addition of manure was required on the sandy homefield to sustain maize productivity. Organic resources are considered crucial for sustainable crop production on smallholder farms and positively interact with mineral N fertilizers to give good yields due to: (i) the addition of multiple nutrients including P, base cations, and micronutrients, (ii) the improvement of the physical properties of the soil, and (iii) the improvement of synchrony between the availability of N and its demand by crops (Giller 2002).

Limiting nutrients on homefields and outfields

To elucidate whether poor yields in sandy outfields were due principally to nutrient problems or water availability, pot experiments were conducted under conditions in which water was not a limiting factor. Manure on smallholder farms is generally poor in N, and this, together with high losses of N from manures applied on fields, may explain the low availability of N on the sandy homefield (Murwira et al. 1995). The sandy outfield, with no history of manure application, suffered multiple nutrient deficiencies, as evidenced by the low concentrations N, P, Ca, and Zn in maize shoots (Table 7b). Zinc deficiencies are associated with extremely low soil fertility conditions (Grant 1981) and have been reported from sandy soil in Zimbabwe and in other parts in Africa (Rodel and Hopley 1973; Van Asten 2003). On the sandy homefield, addition of micronutrients had no significant effect on maize biomass and the concentrations of all micronutrients considered were in the adequate range for maize. This is most likely due to the supply of micronutrients in manure applied to the homefield in the past. Due to its Zn concentration (Lupwayi et al. 2000) manure has been shown to supply significant amounts of Zn to crops (Prasad and Sinha

Table 8 Nutrient concentrations of maize plants on the clay soils from Murewa, NE Zimbabwe, supplied with different combinations of macro- and micronutrients and manure in the greenhouse pot experiment: (a) clayey homefield; (b) clayey outfield

Treatment[a]	N (%)		P (%)		Ca (%)		Mg (%)		Zn (mg kg^{-1})		Fe (mg kg^{-1})		Mn (mg kg^{-1})		Cu (mg kg^{-1})	
	–M	+M	–M	+M	–M	+M	–M	+M	–M	+M	–M	+M	–M	+M	–M	+M
(a)																
1	3.2	2.9	0.31	0.28	0.53	0.55	0.37	0.36	51	42	315	325	127	129	10.3	9.9
2	3.5	3.1	0.30	0.32	0.51	0.57	0.41	0.41	40	42	325	377	130	136	9.5	13.5
3	3.6	3.3	0.34	0.33	0.58	0.63	0.40	0.47	38	43	311	332	131	122	9.1	8.5
4	3.6	3.3	0.34	0.35	0.62	0.65	0.38	0.45	42	41	332	329	125	125	10.9	10.4
5	3.7	2.9	0.32	0.35	0.59	0.61	0.41	0.51	47	49	310	326	126	125	8.7	9.8
6	3.3	3.3	0.34	0.32	0.54	0.69	0.45	0.46	49	51	329	352	134	150	11.5	12.3
7	3.5	3.0	0.36	0.38	0.57	0.55	0.42	0.46	55	53	334	336	123	139	12.1	12.8
SED	0.4		0.02		0.06		0.06		3.3		33		15		2.2	
(b)																
1	2.2	2.6	0.16	0.22	0.43	0.40	0.43	0.43	50	48	350	375	132	129	10.1	11.8
2	3.2	2.9	0.17	0.19	0.45	0.54	0.39	0.42	45	53	375	347	123	123	13.1	11.2
3	3.4	2.9	0.31	0.33	0.43	0.47	0.43	0.44	51	50	352	388	134	125	10.3	10.4
4	3.5	3.3	0.28	0.31	0.49	0.48	0.41	0.40	50	52	320	375	125	140	11.8	10.9
5	3.4	3.2	0.30	0.28	0.56	0.41	0.46	0.42	42	51	323	390	123	129	10.0	10.4
6	2.9	3.1	0.29	0.29	0.48	0.49	0.43	0.36	52	52	401	350	132	141	11.3	13.7
7	3.1	3.2	0.32	0.28	0.53	0.49	0.42	0.40	53	50	350	336	135	145	11.5	12.9
SED	0.2		0.05		0.04		0.03		0.51		44		16		2.4	

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

1982), which explains the significant increase in Zn concentration in maize shoots on the sandy outfield manured for three consecutive seasons. The response of maize shoot biomass to Zn could have been reduced by the lower temperatures under which the second pot experiment was conducted. A compound fertilizer with added Zn (compound Z: 8%N; 6%P; 6%K; 6.5%S; 0.8% Zn) was previously produced in Zimbabwe to redress the problems of Zn deficiency, but has not been widely used by smallholder farmers. Production of compound Z has recently ceased, and fertilizers currently available to farmers only contain the major nutrients (N, P, K, S).

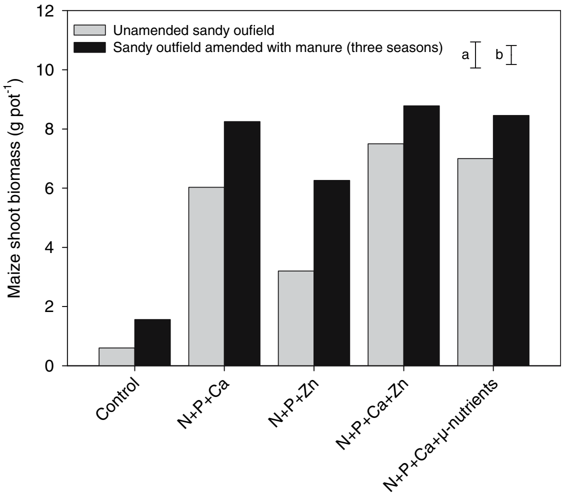


Fig. 4 Effects of Ca and Zn on maize biomass on the sandy outfield soil from Murewa, in NE Zimbabwe in the greenhouse pot experiment. Bars show SEDs for: (a) treatments, (b) the effect of manure applied in the field experiment. All pots were amended with K and S

Despite its significant effects on maize biomass, manure suppressed the N concentration in maize shoots due its low N concentration (Fig. 2a, b; Table 7). Nitrogen immobilization in the short term was likely, due to the low N content of the manure used (Nyamangara et al. 1999). Manure alleviated deficiencies of P, Ca, and Zn in the short term and our results support the observations of Grant (1981) that manure effects on the supply of nutrients other than N may be responsible for the immediate improvements in maize yields. Several studies in different regions in sub-Saharan Africa have shown a strong correlation between SOC and maize response to the addition of mineral N and P fertilizers, with poor responses in soils that contained small contents of SOC (Mtambanengwe and Mapfumo 2005; Vanlauwe et al. 2006; Wopereis et al. 2006). Our results indicate that such poor responses could be linked to deficiencies of other nutrients not commonly promoted for use in smallholder farming systems. No nutrient deficiencies were observed on the clayey homefield due to the high SOC and fertility status. The deficiency of P on the clayey outfield could have been due to the removal of P by crops over many years and the high P fixing capacity of the soil.

Conclusions

This study illustrated that manure is essential for sustainable soil fertility management on smallholder farms, particularly on the poorly buffered, sandy soils that are widespread in southern Africa and much of the Sahel. Homefields that frequently received large amounts of manure had higher contents of soil organic matter, available P, bases, pH, and micronutrients than outfields. Production of maize without fertilizer inputs over many years on the sandy outfield led to multiple deficiencies or low availability of nutrients, notably of N, P, Ca, and Zn. Mineral N and P fertilizers commonly available to smallholder farmers are inadequate to reverse the poor soil fertility status, as they are unable to correct the deficiency of other nutrients (especially bases and micronutrients). Instead, ammonium nitrate led to acidification of the soils. Also, on the depleted sandy soils the response of maize to N and P was poor, as deficiency of other nutrients was overriding. Manure showed potential to restore soil fertility of the depleted sandy soils, as application of manure for three seasons increased soil organic matter, available P, pH, bases, and improved Ca and Zn concentrations in maize shoots in the greenhouse. Large amounts of manure were required over three seasons to restore productivity and produce a significant maize yield response to addition of N in the depleted soil. Manure showed limited potential to meet the N requirement of the crops, due to the poor quality of the manure. Integrated use of manure and mineral fertilizers is therefore required for sustainable soil fertility management on smallholder farms on sandy soils. The results observed on fields with different histories of manure application and in pot experiments reinforce the essential role of manure in supplying multiple nutrients including P, bases, and micronutrients both in the short and long term, which explains the wide differences in maize response to mineral N and P on the smallholders' homefields and outfields. Our analysis shows that large amounts of manure, as currently applied to preferred fields by farmers, are required to sustain productivity. Applying manure to restore productivity in depleted outfields is difficult due to the limited amounts available, but as farmers concentrate these additions on smaller areas (e.g., 0.1 ha) these higher rates are common. Strategies to restore fertility in depleted fields must focus on addressing the multiple constraints on production in such fields, including the correct formulation of fertilizers.

Acknowledgements We thank the International Fund for Agricultural Development (IFAD) and the Department for International Development (DFID) for providing funding for this work. Ken Giller would like to thank the European Union for funding through AfricaNUANCES. The assistance of Francis Dzvene in managing the field experiments and George Gwazawafa in managing the pot experiments is also gratefully acknowledged.

References

Anderson JM, Ingram JSI (1993) Tropical soil biology and fertility: a handbook of methods. CAB International, Wallingford, UK

Bayu W, Rethman NFG, Hammes PS (2005) The role of manure in sustainable soil fertility management in sub-Saharan Africa. J Sust Agric 25:113–136

Bationo A, Nandwa SM, Kimetu JM, Kinyangi JM, Bado BV, Lompo F, Kimani S, Kihanda F, Koala S (2004) Sustainable intensification of crop-livestock systems through manure management in eastern and western Africa: lessons learned and emerging research opportunities. In: Williams TO, Tarawali SA, Hiernaux P, Fernández-Rivera S (eds) Sustainable crop-livestock production for improved livelihoods and natural resource management in West Africa. International Livestock Research Institute and Technical Centre for Agricultural and Rural Cooperation proceedings, Ibadan, Nigeria, pp 173–198

Bationo A, Mokwunye AU (1991) Role of manures and crop residues in alleviating soil fertility constraints to crop production, with special reference to the Sahelian and Sudanian zones of West Africa. Fert Res 29:117–125

Burt R, Wilson MA, Kanyanda CW, Spurway JKR, Metzler JD (2001) Properties and effects of management on selected granitic soils in Zimbabwe. Geoderma 101:119–141

Carter SE, Murwira HK (1995) Spatial variability in soil fertility management and crop response in Mutoko communal area, Zimbabwe. Ambio 24:77-84

De Ridder N, Van Keulen H (1990) Some aspects of the role of organic matter in sustainable intensified arable farming in west-African semi-arid-tropics (SAT). Fert Res 26:299–310

Delve RJ, Cadisch G, Tanner JC, Thorpe W, Thorne PJ, Giller KE (2001) Implications of livestock feeding management on soil fertility in the smallholder farming systems of sub-Saharan Africa. Agric Ecosyst Environ 84:227–243

Feller C, Beare MH (1997) Physical control of soil organic matter dynamics in the tropics. Geoderma 79:69–116

Gandah M, Bouma J, Brouwer J, Hiernaux P, Van Duivenbooden N (2003) Strategies to optimize allocation of limited nutrients to sandy soils of the Sahel: a case study from Niger, West Africa. Agric Ecosyst Environ 94: 311–319

Giller KE (2002) Targeting management of organic resources and mineral fertilizers: can we match scientists' fantasies with farmers' realities. In: Vanlauwe B, Sanginga N, Diels J, Merckx R (eds) Balanced nutrient management systems for the moist Savanna and humid forest zones of Africa. CAB International, Wallingford pp 155–192

Giller KE, Rowe EC, De Ridder N, Van Keulen H (2006) Resource use dynamics and interactions in the tropics: scaling up in space and time. Agric Syst 88:8–27

Grant PM (1967) The fertility of sandveld soil under continuous cultivation. Part I. The effect of manure and nitrogen fertilizer on nitrogen status of the soil. Rhod Zam Mal J Agric Res 5:71–79

Grant PM (1981) The fertilization of sandy soils in peasant agriculture. Zim Agr J 78:169–175

Haynes RJ, Mokolobate MS (2001) Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: A critical review of the phenomenon and the mechanisms involved. Nut Cycl Agro 59:47–63

Jones JB (1972) Plant tissue analysis for micronutrients. In: Mortvedt JJ, Giordano PM, Lindsay WL (eds) Micronutrients in agriculture. Soil Sci Soc Am, Madison, Wisconsin, USA, pp 319–346

Jury W., Gardner WR, Gardner WH (1991) Soil physics, 5th edn. John Wiley and Sons, New York, USA

Kaihura FBS, Kullaya IK, Kilasara M, Aune JB, Singh BR, Lal R, Arshad MA (1999) Soil quality effects of accelerated erosion and management systems in three ecoregions of Tanzania. Soil Till Res 53:59–70

Khiari L, Parent LE, Tremblay N (2001) Critical compositional nutrient indexes for sweet corn at early growth stage. Agron J 93:809–814

Kihanda M, Warren GP, Micheni AN (2006) Effect of manure application on crop yield and soil chemical properties in a long-term field trial of semi-arid Kenya. Nut Cyc Agro 76:341–354

Lupwayi NZ, Girma M, Haque I (2000) Plant nutrient contents of manures from small-scale farms and experimental stations in Ethiopian highlands. Agric Ecosyst Environ 78:57–63

Marschner H (1995) Mineral nutrition of higher plants. Academic Press, London

Mengel K, Kirkby EA (2001) Principles of plant nutrition, 5th edn. Kluwer Academic, The Netherlands

Mapfumo P, Giller KE (2001) Soil fertility management and practices by smallholder farmers in semi-arid areas of Zimbabwe. ICRISAT/FAO, Patancheru, AP. Mimeo

Murwira HK (1995) Ammonia losses from Zimbabwean cattle manure before and after incorporation into soil. Trop Agr 72:269–276

Murwira HK, Swift MJ, Frost PGH (1995) Manure as a key resource in sustainable agriculture: a case study of communal area farming systems in Zimbabwe. A keynote address. In: Powell JM, Fernandez-Rivera S, Williams TO, Renard C (eds) Livestock and sustainable nutrient cycling in farming systems of Sub-Saharan Africa, vol II. International Livestock Centre for Africa (ILCA) Proceedings, Addis Ababa, Ethiopia, pp 131–148

Mtambanengwe F, Mapfumo P (2005) Organic matter management as an underlying cause for soil fertility gradients on smallholder farms in Zimbabwe. Nut Cycl Agro 73:227–243

Nyamangara J, Bergstrom LF, Piha MI, Giller KE (2003) Fertilizer use efficiency and nitrate leaching in a tropical sandy soil. J Environ Qual 32:599–606

Nyamangara J, Mugwira LM, Mpofu SE (2000) Soil fertility status in communal areas of Zimbabwe in relation to sustainable crop production. J Sust Agric 16:15–29

Nyamangara J, Piha M, Kirchmann H (1999) Interactions of aerobically decomposed cattle manure and nitrogen fertilizer applied to soil. Nut Cycl Agro 54: 183–188

Page AL, Miller RH, Keeney DR (1982) Methods of soil analysis Part 2. Chemical and microbiological properties, 2nd edn. Wisconsin, USA.

Prasad B, Sinha NP (1982) Changes in status of micronutrients in soil with long term applications of chemical fertilizers, lime and manure. Plant Soil 64:437–441

Prudencio CF (1993) Ring management of soils and crops in the West African semi-arid tropics: the case of the Mossi farming system in Burkina Faso. Agric Ecosyst Environ 47:237–264

Reddy DD, Rao SA, Reddy KS, Takkar PN (1999) Yield sustainability and phosphorus utilization in soybean-wheat systems on vertisols in response to integrated use of animal manure and fertilizer phosphorus. Field Crop Res 62:181–190

Rodel MGW, Hopley JDH (1973) Investigations into systems of farming suitable for tribal trust land. Rhod Agr J 70:1–18

Sanchez PA, Shepherd KD, Soule MJ, Buresh RJ, Izac AMN (1997) Soil fertility replenishment in Africa: An investment in natural resource capital. In: Buresh RJ, Sanchez PA, Calhoun F (eds) Replenishing soil fertility in Africa. Soil Sci Soc Am Special publication No. 51, Madison, WI, pp 1–46

Tittonell P, Vanlauwe B, Leffelaar PA, Shepherd KD, Giller KE (2005) Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agric Ecosyst Environ 110:166–184

Van Asten PJA (2003) Soil quality and rice productivity problems in Sahelien irrigation schemes. PhD Thesis, Wageningen University, Wageningen, the Netherlands

Vanlauwe B, Tittonell P, Mukalama J (2006) Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. Nut Cycl Agro 76:171–182

Whalen JK, Chang C, Clyton GW, Carefoot JP (2000) Cattle manure amendments can increase the pH of acid soils. Soil Sci Soc Am J 64:962–966

Wopereis MCS, Tamélokpo A, Ezui K, Gnakpénou D, Fofana B, Breman H (2006) Mineral fertilizer management of maize on farmer fields differing in organic inputs in the West African savanna. Field Crop Res 96:355–362

Zingore S, Manyame C, Nyamugafata P, Giller KE (2005) Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe. Eur J Soil Sci 57:727–736

Zingore S, Murwira HK, Delve RJ, Giller KE (2007a) Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. Agric Ecosyst Environ 119:112–126

Zingore S, Murwira HK, Delve RJ, Giller KE (2007b) Soil type, historical management and current resource allocation: three dimensions regulating variability of maize yields and nutrient use efficiencies on smallholder farms. Field Crop Res 101:296–305