Influence of soil fertility variability and nutrient source on maize productivity and nitrogen use efficiency on smallholder farms in Zimbabwe

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Abstract
Poor soil fertility is a major constraint to crop productivity on smallholder farms in sub-Saharan Africa. This study evaluated the effects of soil type, soil fertility status and nutrient source on maize productivity and partial factor productivity (PFP_N) of fertilizer N in north-east Zimbabwe. Four on-farm sites representative of major soil fertility categories in the region were selected for the study: (i) depleted sandy soil (DSS); (ii) sandy soil (SS); (iii) depleted clay soil (DCS); and clay soil (CS). Fertilizer and manure treatments were applied over nine cropping seasons as follows: (i) no fertilizer; (ii) 100 kg N/ha; (iii) 100 kg N/ha + cattle manure (15 t/ha); (iv) 100 kg N/ha + 30 kg P/ha in combination with 20 kg Ca/ha, 5 kg Zn/ha and 10 kg Mn/ha. Initial maize yields were in the order DSS<DCS<SS<CS. Across all trials, maize grain yield response and PFP_N values in the sole N-fertilizer (100 kgN/ha) treatment were low, indicating multiple constraints to crop productivity. Yields on the sandy soils were marginally increased with balanced fertilizer application. Across all fields, the highest yields and PFP_N after nine seasons were achieved with application on N in combination with manure, indicating the importance of manure in maintaining soil fertility, maize productivity and optimum PFP_N levels in smallholder farming systems where crop residues are removed to use as livestock feed.

Key Words
Soil fertility, maize, nitrogen, manure, nutrient use efficiency

Introduction
Most of the soils in sub-Saharan Africa (SSA) are inherently infertile, and poor agricultural management practices over many decades have led to a severe decline in their productive capacity (Sanchez 2002). The amounts of organic resources and fertilizers used in crop production are extremely low in much of the region and this is recognized as one of the main factors underlying low crop productivity and widespread land degradation. Yields of cereal crops have stagnated at less than 1.6 t/ha over the past 5 decades, despite increasing demand for food due to a rapidly growing population (World Bank 2008). As a direct result of low rates of fertilizer use and high rates of nutrient mining, nitrogen (N) balances are highly negative and partial factor productivity values for N fertilizer use in cereal crop production are unsustainably high, exceeding 120 kg grain per kg N applied (Fixen et al. 2015).

Nitrogen is recognized as the most limiting nutrient to cereal crop production in SSA, accounting for 40-100% of the nutrient-limited yield gaps. Soils in the region that are exposed to long-term cultivation with little addition of nutrient resources are characterized by poor yield responses to N due to the interaction of multiple constraints to crop production, particularly in poorly buffered sandy soils. Management of N in the predominant coarse textured sandy soils is particularly difficult due to high susceptibility to losses by leaching and erosion. Large quantities of manure are necessary to achieve and sustain high crop productivity in smallholder cropping systems, where fertilizer application rates are low and crop residues are removed from the field and used as fodder (Zingore et al. 2007). However, manure is often only available in limited quantities and the quality is often low, so that significant rates of manure application rates only possible on small fields of farmers who own many livestock.

Despite the overall patterns of soil fertility depletion, smallholder farms in SSA exhibit a high degree of soil fertility variability, and as a consequence, crop yields and yield responses to applied nutrients vary considerably between fields (Zingore et al. 2007; Tittonell et al. 2005). Management-induced soil fertility variability is driven by shortages of labor, fertilizer and manure, leading to preferential allocation of nutrients to fields close to the homestead. The fields located further from the homesteads are typically less fertile and characterized by multiple nutrient deficiencies, high acidity, low soil organic carbon (SOC) and low water holding capacity (Zingore et al. 2007). The differences in soil fertility resulting from variable farmer management practices require adapted nutrient management strategies to improve nutrient use efficiencies and optimize the management of scarce nutrient resources.

Sustainable crop production intensification in SSA will require increased nutrient use in combination with effective strategies for managing of N under variable soil fertility conditions. The need for balanced nutrient management and maintenance of soil fertility to support levels of crop productivity and N use efficiencies that are both agronomically and economically viable is recognized. This paper evaluates the effects of soil type, soil fertility status and nutrient sources maize productivity and N use efficiency of applied fertilizer based on results from multi-location long-term agronomic trials conducted in north–east Zimbabwe.

Methods

The study was conducted in north-east Zimbabwe, a region that receives total annual rainfall ranging between 750 and 1000 mm, distributed in a unimodal pattern (November-April). Farmers practice a mixed crop-livestock system with maize as the dominant staple crop. Cattle manure is an important source of organic matter inputs into the soil, as crop residues are removed from the fields to feed cattle or grazed *in-situ* after harvesting. Manure availability is limited as less than 50% of the farmers own cattle. Two representative farms were selected for the study after a detailed characterization of farm types and soil fertility variability in the region. One farm was located on a sandy soil (Alfisol) and the second on a clay soil (Luvisol). On each of the farms, two fields with contrasting soil fertility conditions were selected depending on the management history. Fields closest to the homestead had in the past received annual additions of at least 5 t/ha manure and 50 kg/ha N fertilizer, while fields furthest from the homesteads had been cultivated continuously with no manure and very little fertilizer (<10 kg/ha N fertilizer). The four fields had variable soil properties determined by soil and management factors and were classified as follows: (i) standard sandy soil (SS); (ii) depleted sandy soil (DSS); (iii) standard clay soil (CS) and; (iv) depleted clay soil (DCS). Sampled soils from each field were analysed for total C and N in soil through dry combustion using a Carbon/Hydrogen/Nitrogen Analyzer (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, CEC by the ammonium acetate method. Soil analysis results showed that management history had a strong influence of soil properties. All fields were low in organic matter and available P (Table 1).

Table 1. Initial soil chemical properties (0-20 cm) on fields with different previous management on sandy and clay soils in north-east Zimbabwe.

Field type	C(%)	N (%)	pH	Avail. P (mg/kg)	CEC ($cmol_c$/kg)	Ca ($cmol_c$/kg)	Mg (cmol/kg)	K ($cmol_c$/kg)
Sandy Standard	0.50	0.04	5.1	7.20	2.2	0.91	0.32	0.21
Sandy Depleted	0.30	0.03	4.9	2.40	1.6	0.26	0.19	0.11
Clay Standard	1.40	0.08	5.6	12.10	24.2	11.50	6.20	0.80
Clay Depleted	0.80	0.05	5.4	3.90	22.0	8.40	6.30	0.30

Experimental treatments were laid out in a randomized complete block design (RCBD) with three replications on 6 m × 4.5 m plots in each field. The experiment was run for nine consecutive seasons starting with the 2002/2003 seasons. The selected treatments presented in this paper were: (i) Control (no amendment added); (ii) 100 kg N/ha (N); (iii) 100 kg N/ha + 30 kg P/ha + 25 kg S/ha + 20 kg Ca/ha + 5 kg Zn/ha + 5 kg Mn/ha (NPSCaMgZnMn) and; (iv) 100 kg N/ha + 15 tons air-dried manure/ha (N+manure). The average concentration of other major nutrients in manure were: 0.2% P; 0.9% N; 0.2% Ca; 0.05% Mg and 0.4% K. Mineral N fertilizer was applied as ammonium nitrate (AN, 34.5% N) and P fertilizer as single super-phosphate (SSP). In treatment 3, Ca, Mn and Zn were applied as sulphates, which together with SSP supplied S. Aerobically composted cattle manure was applied annually on a dry-weight basis. Manure was spread evenly on the surface covering the whole plot and incorporated (0-20 cm) into the soil using hand hoes before planting. The SSP and secondary and micronutrients applied in treatment 3 were spot-applied at each planting hill. In treatments 2-4, ammonium nitrate fertilizer was applied as top-dressing in two 50 kg N/ha amounts at three and six weeks after crop emergence in all plots except the control. A medium maturity maize variety SC525 was planted at a spacing of 90 cm × 25 cm.

Grain yield of maize were determined from net plots measuring 2.7 m × 2 m and expressed at 12.5% moisture content. The partial factor productivity of N (PFP_N) was used as the N use efficiency index, and calculated for each treatment that received fertilizer N as follows:

$PFP_N = Y_N/F_N$
Where Y_N is the yield (kg/ha) in the fertilized plot and F_N is the fertilizer N applied (kg/ha).

Results

The four field types we studied showed strong effects of soil type and fertility status on short- and long-term trends in maize productivity and PFP_N. Maize yields in control plots were lower in the sandy soil and in the depleted fields, and this was associated with lower indigenous nutrient supply capacity. On the SS, a decline of 0.4 t/ha between the first and final season due to lack of nutrient inputs was significant (Table 2). On the DCS, the yield decline due to lack of nutrient inputs was small compared with the other three fields (Table 2). The largest decline in yields in the control treatment was in the CS, where yields declined significantly from 2.1 t/ha in the first season to 0.7 t/ha in the final season (Table 2). On clay soils, in both field types, long-term application of N alone at 100 kg/ha maintained yields of about 2 t/ha. In sandy soils, long-term application of 100 kg N/ha maintained yields below 1 t/ha in the SS and less than 0.5 t/ha in the DSS.

Balanced fertilizer application significantly increased yield in the long-term in the DCS, while yield declined on the CS (Table 2) from the first to the ninth season. This resulted in the reduction of the yield gaps with fertilizer application observed between the DCS and CS in the first season. Long-term changes in yields with combined application of N and other fertilizer nutrients were smaller on the sandy soils, and the large yield gap initially observed between the DSS and the SS fields was still evident after nine cropping season (Table 2).

Table 2. Initial, final and cumulative maize yields as influenced by long-term application of fertilizer and manure under variable soil fertility conditions in Zimbabwe

Soil type	Field type	Treatment	Yield (t /ha)		
			2002/03	2010/11	Cumulative*
Clay	Standard	Control	2.13	0.69	10.78
		N	2.90	2.33	17.04
		NPSCaMgZnMn	6.18	2.95	29.69
		N+manure	4.24	7.34	37.09
	Depleted	Control	0.74	0.60	6.61
		N	0.82	2.17	12.34
		NPSCaMgZnMn	2.12	3.77	25.02
		N+manure	3.56	5.57	34.49
Sandy	Standard	Control	0.95	0.56	5.37
		N	1.52	0.94	8.78
		NPSCaMgZnMn	2.33	2.00	16.33
		N+manure	3.35	3.85	23.77
	Depleted	Control	0.24	0.14	1.15
		N	0.31	0.57	2.24
		NPSCaMgZnMn	0.81	1.10	6.26
		N+manure	0.98	2.28	12.43
	SED		0.24	0.29	2.57

*Exclude data for one season that was unavailable due to late harvesting.

The restoration of crop productivity in the DSS was only significant when a combination of N fertilizer and manure were used (Table 2), increasing yields from <0.5 t/ha in the control plots to 2.3 t/ha after nine seasons. Despite increased yields with manure, maximum yields achieved in the SS were about 2.3 t/ha, which was significantly less that the yield of 4 t/ha recorded for the corresponding treatment on the SS. After nine seasons, the yields with a combination of N fertilizer and manure were significantly larger than with N alone or N applied in combination with other nutrients in all the four fields (Table 2). On the CS, larger yields were produced in the first year with the mineral fertilizer than manure, but this trend was reversed after nine seasons.

The high PFP_N values that characterize low-input smallholder cropping systems farms were reversed to very low values when high N rates aimed at achieving attainable yield were applied, indicating major soil constraints to N response. In first season, PFP_N were generally low and below the lower limit of common global values (Fixen et al. 2015) across all sites, except on the CS when N was applied in combination with other nutrients and manure (Figure 1). On the CS, there was a drastic decline in PFP_N in the NPSCaMgZnMn treatment, but a substantial increase in the N+manure treatment, indicating the importance of manure in sustaining high yields and high N use efficiency in smallholder farming systems. This is corroborated with PFP_N for the other three fields that also showed significantly higher PFP_N when N was applied with manure than when applied alone or with other fertilizer nutrients. PFP_N was extremely low on the DSS, with values <10 kg/kg in the first season, irrespective of treatment (Figure 1). Although PFP_N on the DSS was significantly increased with long-term application of manure, values achieved remained lower than the other fields and far below the typical lower limit for cereal crops.

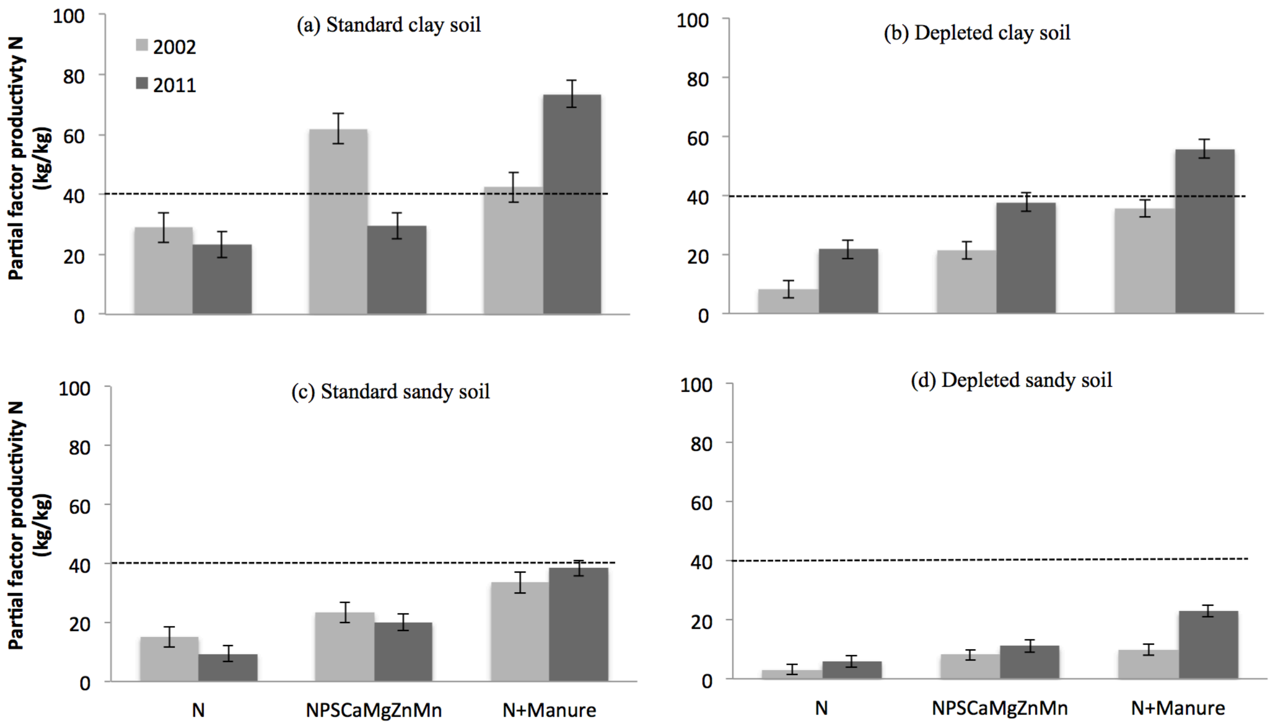

Figure 1. Initial and final partial factor productivity (PFP) of fertilizer N (PFP_N) maize yields following long-term application of fertilizer and manure under variable soil fertility conditions in Zimbabwe. Dotted line represents lower limit of common PFP_N values for cereal crops in global cropping systems (Fixen et al 2010).

Conclusion

Maize yields, yields responses to fertilizer and manure application and PFP_N varied widely in the short- and long-term (9 years) in fields in north-east Zimbabwe, depending on soil type and management history. Yields and PFP_N were very poor on a depleted sandy soil, highlighting challenges for increasing productivity and optimizing N use efficiency in degraded sandy soils that cover large areas of croplands in SSA. Balanced fertilizer application led to higher maize yields over N alone on the clay soils. However, the highest attainable yields and PFP_N in the long-term were achieved when N was applied in combination with manure across fields varying in initial fertility, highlighting the important role of manure in smallholder farming systems where crop residues are removed to use as livestock feed.

References

Fixen P, Brentrup F, Bruulsema T, Garcia F, Norton R, Zingore S (2015) Nutrient/fertilizer use efficiency: measurement, current situation and trends. In Managing Water and Fertilizer for Sustainable Agricultural Intensification. Eds P Drechsel. P Heffer, H Magen, R Mikkelsen, D Wichelns. IFA, IWMI, IPNI, and IPI, Paris, p 8-37.

Sanchez PA (2002). Soil Fertility and Hunger in Africa. Science 295, 2019-2020.

Tittonell P, Vanlauwe B, Leffelaar P.A. Rowe EC, Giller KE (2005) Exploring diversity in soil fertility management of smallholder farms in western Kenya. I. Heterogeneity of region and farm scale. Agriculture Ecosystems and Environment 110, 149-165.

Zingore S, Murwira HK, Delve RJ, Giller KE 2007. Soil type, management history and current resource allocation: Three dimensions regulating variability in crop productivity on African smallholder farms. Field Crops Research 101, 296-305.

Zingore S. Tittonell P, Corbeels M, Wijk van MT, Giller KE (2011) Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: a case from Murehwa District, Zimbabwe. Nutrient Cycling in Agroecosystems 90, 87-103.