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ORIGINAL ARTICLE

Effect of farmer management strategies on spatial variability of soil fertility and crop nutrient uptake in contrasting agro-ecological zones in Zimbabwe

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Abstract Variability of soil fertility within, and across farms, poses a major challenge for increasing crop productivity in smallholder systems of sub-Saharan Africa. This study assessed the effect of farmers' resource endowment and nutrient management strategies on variability in soil fertility and plant nutrient uptake between different fields in Gokwe South (ave. rainfall ~650 mm year^{-1}; 16.3 persons km^{-2}) and Murewa (ave. rainfall ~850 mm year^{-1}; 44.1 persons km^{-2}) districts, Zimbabwe. In Murewa, resource-endowed farmers applied manure (>3.5 t ha^{-1} year^{-1}) on fields closest to their homesteads (homefields) and none to fields further away (outfields). In Gokwe the manure was not targeted to any particular field, and farmers quickly abandoned outfields and opened up new fields further way from the homestead once fertility had declined, but homefields were continually cultivated. Soil available P was higher in homefields (8–13 mg kg^{-1}) of resource-endowed farmers than on outfields and all fields on resource constrained farms (2–6 mg kg^{-1}) in Murewa. Soil fertility decreased with increasing distance from the homestead in Murewa while the reverse trend occurred in Gokwe South, indicating the impact of different soil fertility management strategies on spatial soil fertility gradients. In both districts, maize showed deficiency of N and P, implying that these were the most limiting nutrients. It was concluded that besides farmers' access to resources, the direction of soil fertility gradients also depends on agro-ecological conditions which influence resource management strategies.

Keywords Agro-ecology · Nutrient management strategies · Plant nutrient uptake · Resource endowment · Soil fertility variability

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Introduction

Soil fertility status and nutrient management practices are key factors that determine agricultural productivity with implications on food security and livelihoods of rural households (Mapfumo and Giller

2001). Soil fertility variability on farms may be inherent resulting from differences in parent material and catenal position. Farmers deliberately manage their fields differently, depending on inherent production potentials and other socio-economic factors such as availability of nutrient resources, household priorities and production strategies, farm size, and labour resulting in the development of soil fertility gradients. As a result of the many possible combinations of the biophysical and socio-economic factors, the magnitude of the soil fertility gradients will also vary from farm to farm as well as across agro-ecological zones. Farmers typically apply most nutrient resources to fields closest to homesteads and manage these fields better, and this has led to the establishment of gradients of decreasing soil fertility from the homestead to distant fields in some cropping systems (Tittonell et al. 2005). However, gradients of increasing soil fertility from homefields to outfields have also been reported in the Central Highlands of Ethiopia (Haileslassie et al. 2007).

Soil fertility variability between farms on similar soil types is mainly driven by differing access to nutrient resources between farmers of different resource endowment, e.g. through purchase and use of large amounts of fertilisers. Wealthier farmers also own more cattle which import significant quantities of nutrients to their farms during the cropping season from grazing on communal land and during the dry season from grazing of crop residues on other farmers' fields (Swift et al. 1989). Therefore nutrients accumulate on wealthier farms, often at the expense of the poorer farms (Zingore et al. 2007a).

Spatial variability in soil fertility associated with differential nutrient resource management at farm-scale has largely been ignored when designing technological interventions in smallholder farming systems. For example, fertiliser recommendations used in Zimbabwe are blanket in nature and target application of major nutrients (N, P, K, S, Ca and Mg) and only differentiate agro-ecological regions (Nyamangara et al. 2000). In Malawi, the use of blanket fertiliser recommendations only based on N and P resulted in country-wide S deficiency and regional K, Zn and B deficiency. Therefore fertiliser recommendations which do not take into account spatial variability in soil fertility, which also affects nutrient use efficiency, and farmer resource endowment will fail to allocate scarce fertiliser resources efficiently.

The occurrence of soil fertility gradients has been documented mainly for the sub-humid conditions where production is relatively intensive and arable land for expansion limited. The aim of this study was to compare the effects of resource endowment and soil fertility management strategies by farmers on soil fertility variability and plant nutrient uptake in two smallholder areas, one located in subhumid (44.1 persons km^{-2}) and the other in semi-arid (16.3 persons km^{-2}) agro-ecological conditions. It was hypothesized that gradients of decreasing soil fertility from the homestead occur irrespective of agro-ecology and farmer resource endowment.

Materials and methods

Description of study sites

The study was conducted in two smallholder farming areas in Gokwe South (Njelele I and II and Nemangwe II and III wards) and Murewa (Cheuka ward) districts of Zimbabwe (Fig. 1). Gokwe South District (18° and 19° latitude; 28° and 29° longitude) is located in agro-ecological region III and IV where rainfall is erratic and unreliable, while Murewa District (17° and 18° latitude; 31° and 32° longitude) is located in agro-ecological region II and rainfall is relatively well distributed and more reliable (Table 1).

Farmers in both study areas practice mixed crop-livestock farming with livestock providing draft power and manure for soil fertility improvement while crop residues provide supplementary feed for livestock in winter when grazing is scarce and of poor quality. Grazing in both study areas is communal in open-access areas during the rainy season. Fields are individually owned and managed but are communally grazed in winter.

Soils in Gokwe South are mainly sands (Luvic Arenosols—FAO) of Kalahari origin, while in Murewa sandy soils (Haplic Lixisols—FAO) of granitic origin predominate with smaller areas (<1%) covered by more fertile red clay soils (Chromic Luvisols—FAO) derived from dolerite intrusions (Nyamapfene 1991; Zingore et al. 2007a). The sandy soils from both districts are inherently infertile, characterised by low soil organic carbon (SOC) and deficiencies of N, P and S (Grant 1981; Ahmed et al. 1997). In advanced cases of nutrient mining and high rainfall such as in

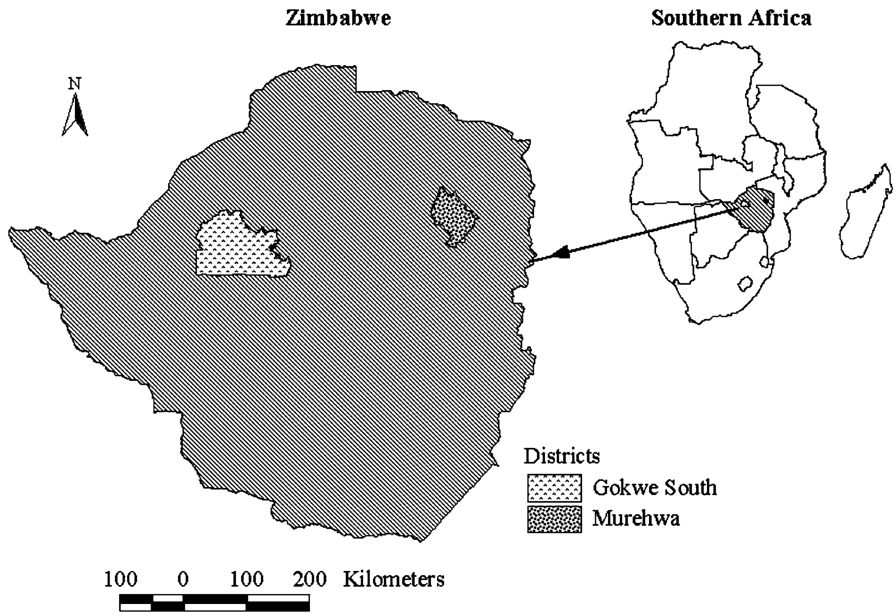


Fig. 1 *Map* showing the location of Murewa and Gokwe South districts in Zimbabwe and the location of Zimbabwe in southern Africa

Table 1 Site characteristics of the study areas in Murewa and Gokwe South districts

	Murewa district (Cheuka ward)	Gokwe South District (Njelele I & II and Nemangwe II & III wards	
		Njelele I & II	Nemangwe II & III
Households sampled	23	19	15
Climate	Subhumid tropical	Semi-arid tropical	Semi-arid tropical
Agroecological natural region	II	III	IV
Rainfall (unimodal) (mm annum^{-1})	750–1,000	650–800	450–650
Soil type	Granitic sands	Kalahari sands	Kalahari sands
Population density[a,b]	44.1	16.3	16.3
Food security crop	Maize	Maize/sorghum	Sorghum/pearl millet
Cash crop	Maize	Maize/sweet potato	Cotton

[a] Statoids (2005), [b] ZIMVAC (2005)

Murewa, nutrient imbalances and extreme acidity have been reported (Nyamangara et al. 2000).

Effect of farmer resource endowment and management on soil fertility and plant nutrient uptake

Twenty-three and 34 farmers were selected in Murewa and Gokwe South districts, respectively, to represent resource-constrained, intermediate and resource-endowed households according to a criteria developed with the participation of farmers shown in Table 2 (Mtambanengwe and Mapfumo 2005; Zingore et al. 2007a). The farmers in the different wealth categories were asked to indicate their most productive and least productive maize fields. The distance of each field from the homestead and cattle pen was measured and the field nearest to the homestead was designated ‘homefield’ and the one furthest ‘outfield’. Cattle pens were located close to homesteads and therefore homefields were also nearest to the cattle pens. A structured questionnaire was used to collect information on soil fertility management practices employed by the selected farmers, including use of mineral fertiliser and the main crops grown.

Table 2 Descriptive criteria for classification of farmers in Gokwe South ($N = 34$) and Murewa ($N = 23$) smallholder farming areas into different wealth classes generated from previous studies[a]

Farmer category	Description
Resource-endowed	≥10 cattle and use own cattle for draught power
(Murewa $n = 6$) (Gokwe $n = 6$)	Field size usually >3 ha
	Own important farming equipment: scotch cart, plough, cultivator, harrow and wheelbarrow and all small implements
	Housing type is usually brick under asbestos/iron roofing
	Afford to hire labour
Intermediate	Own between 4–10 cattle
(Murewa $n = 9$) (Gokwe $n = 12$)	Field sizes 1–3 ha
	Own a plough and an ox-drawn cart
	Housing type usually brick under iron roofing
	Rarely afford to hire labour
Resource-constrained	Own 0–3 cattle
(Murewa $n = 8$) (Gokwe $n = 12$)	Fields <1 ha
	Own small implements such as hoes
	Brick under thatch
	Cannot afford to hire labour

[a] Mtambanengwe and Mapfumo (2005), Zingore et al. (2007a)

At silking stage (ca. 10–12 weeks after emergence) soil (0–20 cm depth) and maize cobleaf samples were taken to assess soil fertility status and plant nutrient uptake. Soil samples were air-dried, passed through a 2-mm sieve and analysed for clay content, pH (0.01 M $CaCl_2$), exchangeable bases, cation exchange capacity (CEC), SOC, total N and P, and available P (Anderson and Ingram 1993; Okalebo et al. 2002). Cobleaf samples were oven dried (65°C), passed through a 2-mm sieve, and analysed for total N, P, Ca, Mg, K, Fe, Mn, Zn and Cu (Okalebo et al. 2002). Plant nutrient contents were assessed using standard methods (Mengel and Kirkby 2001).

Statistical analysis

Questionnaires were analysed and socio-economic factors affecting nutrient management determined using counts and frequencies to separate farmers into different social groups using the statistical package for the social sciences (SPSS). Analysis of variance (ANOVA) tables were generated for soil and plant nutrient status across resources groups and between field types using GENSTAT 7.1 to test for significant differences at $P < 0.05$.

Results

Soil fertility replenishment resources and their management in the field

The average cattle ownership in both study sites was higher (5.4 and 5.6 cattle per household in Murewa and Gokwe, respectively) than the national average (2.8 cattle per household) for smallholder areas (Gambiza and Nyama 2000). There was a significant ($P < 0.05$) relationship between quantity of manure applied and resource-endowment, with wealthy farmers applying more manure (3.5–9 t ha^{-1}) to their fields in Murewa, compared with the intermediate (up to 1.5 t ha^{-1}) and resource-constrained (<1 t ha^{-1}) farmers. Resource-constrained farmers in Murewa applied significantly ($P < 0.05$) less NPKS fertiliser (<100 kg ha^{-1}) compared with resource-endowed (150–200 kg ha^{-1}) and intermediate (up to 175 kg ha^{-1}) farmers. Other nutrient resources used on a limited scale were compost, leaf litter and anthill soil; these were targeted to homefields in Murewa, whilst in Gokwe South very few farmers (6%) used them.

Farmers in Murewa owned small farms (1–3 ha) and continuously cultivated them, while in Gokwe South the farmers owned larger farms (5–10 ha) and frequently fallowed them. Fields in Murewa had been under cultivation for longer periods (~30 years) compared with Gokwe (~15 years). Outfields were generally larger than homefields and the latter constituted about 17 and 32% of the farm area in Murewa and Gokwe South, respectively (Table 3).

Soil fertility status

Soil pH was higher in homefields compared with outfields in Murewa but the difference was only significant for resource-endowed farmers where soil pH was extremely acidic in outfields (Table 4). CEC and all exchangeable bases were also higher in homefields compared with outfields, and were largely similar for resource-endowed and intermediate farmers and much lower for the resource-constrained

Table 3 Characteristics of home- and outfields in Murewa ($n = 23$ farms) and Gokwe South ($n = 34$ farms) districts

	Field type			
	Murewa ($n = 23$)		Gokwe ($n = 34$)	
	Homefield	Outfield	Homefield	Outfield
Average field size (ha)	0.54 ± 0.061[a]	0.63 ± 0.106	1.13 ± 0.160	1.49 ± 0.244
Distance from homestead (m)	29 ± 12.7	159 ± 36.4	51 ± 14.3	763 ± 132.0
Range (m)	5–200	50–700	3–200	30–2,500
Distance from cattle pen (m)	28 ± 12.8	134 ± 38.4	96.1 ± 16.5	431 ± 101.8
Period under cultivation (years)	30 ± 2.7	30 ± 2.7	16 ± 1.9	15 ± 1.9
Main crops grown (frequency %)				
Maize	39.3	46.4	26.5	38.3
Cotton	0	0	35.3	32.4
Groundnuts	31.4	21.4	17.6	8.9
Sorghum	0	0	5.9	2.9
Others	29.3	32.2	14.8	17.8

[a] Values given represent the standard error of the mean

Table 4 Selected soil properties across resource groups on sands of Murewa and Gokwe South Districts

Resource group	Study site	% clay		pH (0.01 $CaCl_2$)		CEC ($cmol_c\ kg^{-1}$)		Exch. Ca ($cmol_c\ kg^{-1}$)		Exch. Mg ($cmol_c\ kg^{-1}$)		Exch. Na ($cmol_c\ kg^{-1}$)		Exch. K ($cmol_c\ kg^{-1}$)	
		HF[2]	OF[3]	HF	OF	HF	OF	HF	OF	HF	OF	HF	OF	HF	OF
1	Murewa	3.5	3.3	6.1	4.4	6.83	5.20	3.10	1.70	0.50	0.30	0.02	0.00	4.00	2.90
2	Murewa	4.7	3.1	5.4	5.1	6.83	4.43	5.53	3.15	1.47	1.06	0.14	0.09	1.98	1.06
3	Murewa	3.0	3.3	5.2	4.8	4.17	2.95	2.95	1.97	0.65	0.17	0.08	0.07	1.10	0.65
	SED	0.63		0.30		0.95		0.98		0.31		0.08		0.98	
1	Gokwe	4.3	4.0	5.7	5.7	15.2	14	16.75	4.2	5.75	1.10	0.02	0.08	1.67	0.51
2	Gokwe	3.3	4.0	5.3	5.0	6.4	10.9	2.70	10.7	1.95	1.85	0.11	0.12	0.22	0.51
3	Gokwe	5	4.0	4.8	5.8	3.4	4.8	4.00	1.95	0.40	0.45	0.05	0.09	0.51	0.56
	SED	0.86		0.22		2.60		3.05		1.04		0.02		0.27	

HF[2]—homefield and OF[3]—outfield

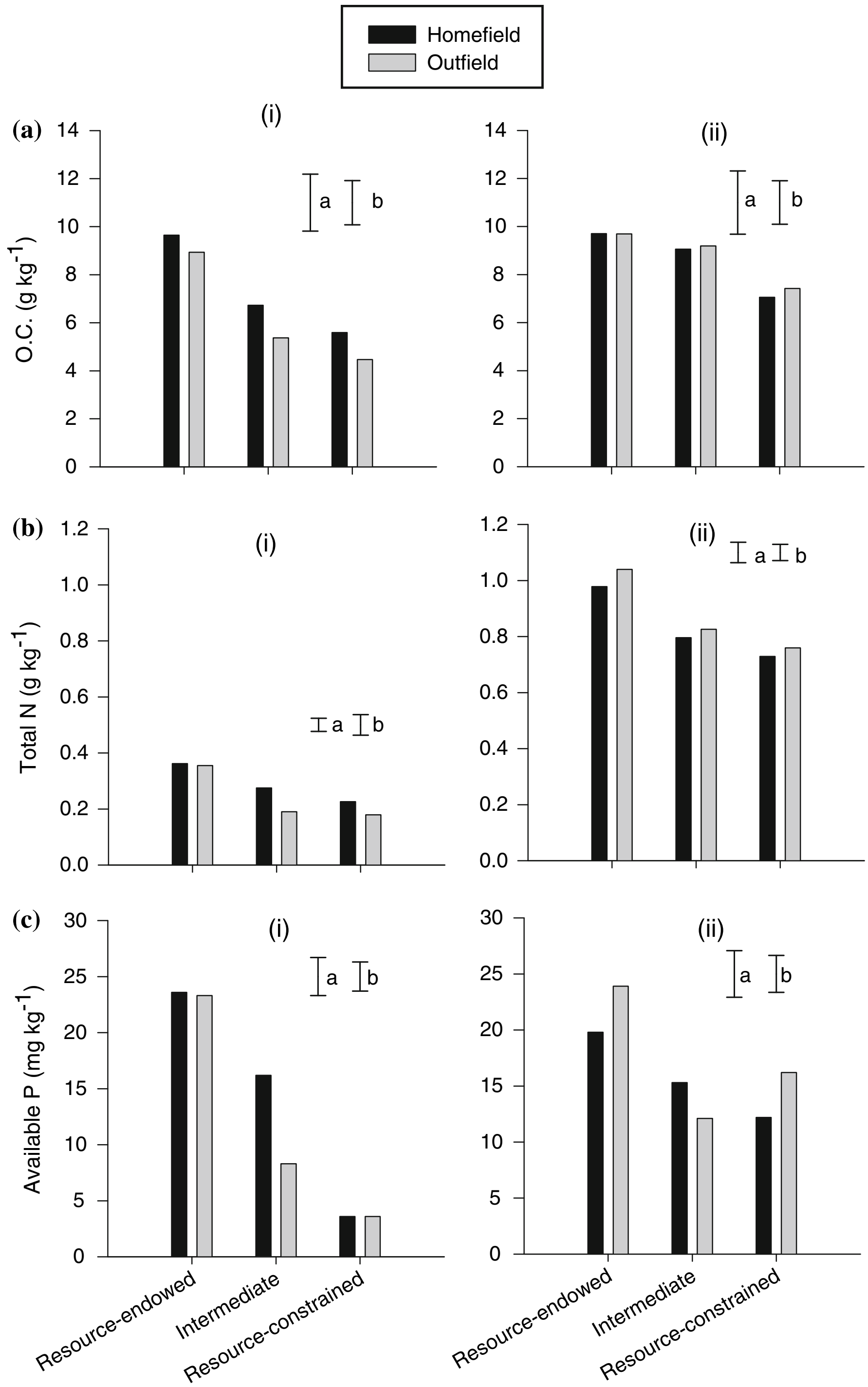
farmers. In Gokwe South soil pH and exchangeable bases, except Mg, showed no specific trend. CEC decreased with decease in resource-endowment in both home and outfields, and the trend was similar for Mg in homefields (Table 4).

There were differences for total soil N and SOC across resource-endowment classes and field types in each wealth category but the differences were not significant (Fig. 2a, b). However, total SOC and N were higher in homefields compared with outfields in Murewa, and the opposite trend was observed in Gokwe South. Available P was particularly responsive to management, decreased sharply from the resource-endowed group (>20 mg kg^{-1}) to less than 5 mg kg^{-1} in resource-constrained group in Murewa (Fig. 2c). In Gokwe South available P was significantly higher in fields of the resource-endowed farmers than the intermediate and resource-constrained farmers (Fig. 2c).

Plant nutrient uptake

Although plant nutrient status varied across wealth classes in both study sites, differences were only significant for N and P in Murewa (Fig. 3) where cobleaf N and P concentration increased with

Fig. 2 Differences in (a) soil organic carbon, (b) total N and (c) soil available P with resource-endowment and field type in (**i**) Murewa and (**ii**) Gokwe Districts. *Bars* represent SEDs for factors (a) resource-endowment group and (b) field type



decreasing resource-endowment. However, in Gokwe the reverse was observed (Fig. 3). The concentration of cobleaf N in resource constrained farmers' fields in Murewa and resource-endowed farmers' fields in Gokwe South were low (2.0–2.5%), while the rest were in the deficient (<2.0%) category according the

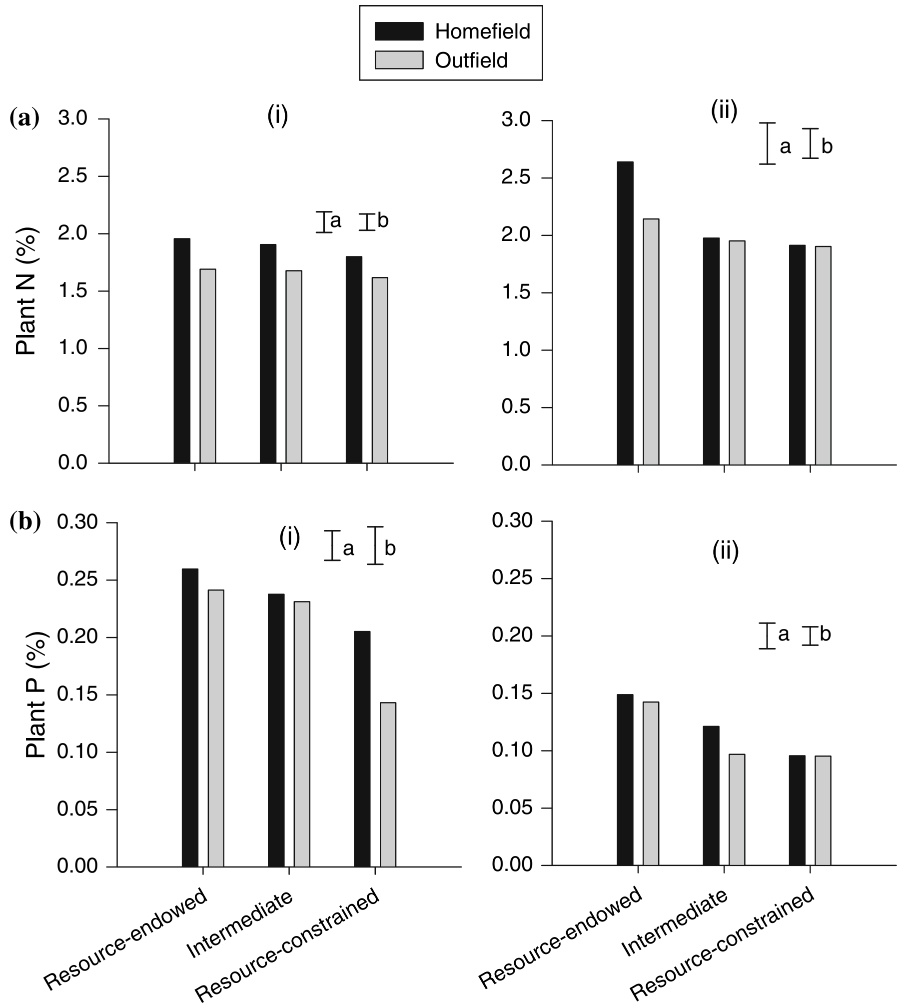


Fig. 3 Plant N and P concentrations of maize cob leaves at silking in **(i)** Murewa and **(ii)** Gokwe South Districts across resource-endowment groups. *Bars* show SEDs for differences in (a) resource endowment and (b) field type

criteria by Mengel and Kirkby (2001). Phosphorus availability was generally higher in Murewa where cobleaf P concentration was adequate (0.20–0.50%) in the resource-endowed and resource-constrained groups (Fig. 3). In Gokwe South, cobleaf P concentration indicated P deficiency (<0.10%) in the resource-endowed group and low P (0.10–0.20%) in the intermediate and resource-constrained groups (Fig. 3). Maize cob leaf K, Mg, Ca and micronutrients (Fe, Cu and Mn) were in the adequate ranges (K 1.5–3.0%, Mg 0.2–1.0%, Ca 0.4–1.0%, Fe 1–400 mg kg^{-1}, Cu >5 mg kg^{-1} and Mn 20–200 mg kg^{-1}) at this growth stage in both study areas and generally tended to decrease with decrease in resource-endowment (Table 5). The only exception was Zn, which was within the adequate range for Gokwe, but was low in most fields in Murewa.

Discussion

Cattle ownership is a form of wealth in smallholder farming systems that can be converted into cash when the need arises (Rufino et al. 2006) justifying the use of cattle ownership to differentiate farmers. Livestock ownership explained the use of higher application rates of manure in farms of resource-endowed farmers in Murewa compared to resource constrained farmers. However, the amount of manure applied to the preferred fields had declined compared with the 1980s where rates up to 80 t ha^{-1} were applied, mainly due to persistent droughts since the early 1990s that have reduced cattle ownership levels per household (Mugwira and Murwira 1997). All the manure available to smallholder farmers in the Murewa and Gokwe South is used for soil fertility

Table 5 Maize cobleaf nutrient contents across farms of different resource-endowments in Murewa and Gokwe South Districts

Resource-endowment group	Study site	% K		% Ca		% Mg		Zn (mg kg^{-1})		Mn (mg kg^{-1})		Fe (mg kg^{-1})		Cu (mg kg^{-1})	
		HF	OF	HF	OF	HF	OF	HF	OF	HF	OF	HF	OF	HF	OF
1	Murewa	1.37	1.31	0.54	0.43	0.13	0.11	21	17	62	49	93	79	7	8
2	Murewa	1.21	1.08	0.55	0.45	0.12	0.12	15	13	69	68	80	79	7	6
3	Murewa	1.41	1.30	0.53	0.43	0.15	0.13	15	14	34	33	125	90	7	7
	SED	0.09		0.04		0.02		1.50		12.0		17.0		0.61	
1	Gokwe	2.35	2.36	0.37	0.31	0.48	0.50	54	57	103	93	390	373	6	7
2	Gokwe	2.31	2.16	0.39	0.38	0.52	0.49	60	54	84	69	422	437	7	6
3	Gokwe	2.11	1.99	0.40	0.39	0.51	0.47	55	51	91	82	399	397	6	5
	SED	0.12		0.05		0.04		11.1		16.1		59.2		1.17	

improvement. The majority of the resource-constrained farmers co-owned the few cattle, e.g. with their sons, and the manure produced had to be spread in all fields hence the low application rates. Farmers in Gokwe applied manure to their fields once every 2–3 years, similar to findings of Ahmed et al. (1997) who reported that smallholder farmers in semi-arid areas of Zimbabwe applied manure once every 3–5 years to their maize crop. Farmers cited the manure scarcity due to low cattle ownership (~6 cattle per household in Gokwe) and large land holdings as the main reason for rotating manure application in their field.

The observed decrease in SOC, total N and available soil P in soils belonging to poorer farmers in sub-humid conditions has been reported elsewhere (Mtambanengwe and Mapfumo 2005; Zingore et al. 2007a) and attributed to differences in the nutrient resources available to the different classes of farmers. As the poorer farmers add little or no fertility amendments to their soils, fertility is likely to decline very rapidly within a few years of continuous cultivation on granitic and Kalahari sands (Zingore et al. 2005). Resource-endowed farmers often have access to livestock manure and financial resources to purchase mineral fertiliser.

A striking decline in soil fertility from homefields to outfields under sub-humid conditions in Murewa was not associated with small landholdings, but with inadequate nutrient resources, resulting in farmers concentrating their nutrient resources in relatively smaller homefields. This trend of variability in soil fertility due to concentration of nutrient resources to homefields has also been reported in the sub-humid and humid zones (Tittonell et al. 2005; Mtambanengwe and Mapfumo 2005; Vanlauwe et al. 2006; Zingore et al. 2007b). A contrasting pattern of resource management resulted in higher soil fertility status in outfields than homefields in semi-arid Gokwe South, implying that the farmers in the contrasting agro-ecological zone used different nutrient management strategies. In Gokwe, where population density is relatively low (16.3 persons per km^2), land for expansion is available (miombo forest) and farmers quickly open up new fields, further way from the homestead once fertility has declined (Mapedza et al. 2003). Soil fertility decline in the Kalahari sands is rapid due to poor physical protection of organic matter. Consequently, soil fertility in Gokwe was higher in the more recently opened outfields compared with the homefields which were continually cultivated for many years (e.g. N and P, Fig 2a–c). Table 3 shows that farmers did not target particular fields for cotton production, and therefore both home- and outfields beneficiated from the relatively higher fertiliser rates applied to cotton compared to other crops. A similar trend of increasing soil fertility from homefields to outfields has also been reported in the East African Highlands in Ethiopia (Haileslassie et al. 2007). Therefore, the influence of population density on resource management and consequent effects on soil fertility variability is important, in addition to farmer resource endowment and socio-economic conditions, in order to understand soil fertility spatial variability in the smallholder areas of sub Saharan Africa.

In ward 5 of Shurugwi smallholder area, located in a semi-arid region in central Zimbabwe but with a much higher population density than Gokwe, a study showed that farmers allocated organic fertiliser (animal manure, compost and leaf litter) to homefields while mineral fertiliser (NPKS) was allocated to outfields, and in all cases maize was grown (Nyagumbo et al. 2007). Since homefields are much smaller compared with outfields, it implies that significant increases in yield output, and hence food security, can only be realised if crop productivity in the outfields is increased.

Plant N and P concentrations were below critical limits (Mengel and Kirkby 2001) at silking implying that nutrient additions even by resource-endowed farmers were also low. Nitrogen is still the most important nutrient limiting crop production in Africa (Sanchez et al. 1997). Plant P was particularly low in Gokwe (<0.15%) implying a higher potential response if the nutrient was applied. Zinc deficiencies are associated with extremely low soil fertility conditions (Grant 1981) and the low Zn contents in maize in Murewa can be attributed to the intensive cultivation in the long-term. In Murewa, Zn was only adequate on the homefields of resource-endowed farms which received large additions of manure in the past. This is most likely due to the supply of Zn in manure applied to the homefield in the past. Due to its relatively high Zn concentration (Lupwayi et al. 2000) manure has been shown to supply significant amounts of Zn to crops (Prasad and Sinha 1982).

Conclusions

Access to resources and farmers' management practices are important determinants of variability in soil fertility within and across farms. In intensive cropping systems in Murewa, fields closest to homesteads were more fertile than fields further away, following gradients of intensity of nutrient resource use. However, in extensive cultivation systems under semi-arid conditions, fields closest to homesteads were less fertile than fields further away, as fields further from homesteads more recently opened for cultivation and were frequently fallowed. Analysis of cob-leaf samples showed that N and P were deficient across all fields in Gokwe and in Murewa, while Zn was also low in outfield in Murewa. This study highlights the influence of population density, in addition to farmer resource endowment and socio-economic conditions, on soil fertility variability and plant nutrient uptake and therefore should be considered when making recommendations for fertilizer use.

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