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REGULAR ARTICLE

Soil fertility management effects on maize productivity and grain zinc content in smallholder farming systems of Zimbabwe

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Abstract
Background and aims Low soil zinc (Zn) threatens crop production and food nutrition in most cereal-based cropping systems in Africa. Agronomic management options that include farmers' locally available organic nutrient resources need to be evaluated in the context of Zn nutrition in staple cereals. A three-year study (2008–11) was conducted in two smallholder farming areas of eastern Zimbabwe to evaluate the influence of farmers' diverse soil fertility management practices on soil Zn status and effect on uptake patterns and nutritional value in maize (*Zea mays* L.).
Methods Participatory research approaches and formal surveys enabled identification of farmers' diverse soil fertility management practices, which were then classified into five main domains: manure or woodland litter + mineral fertilizer; sole mineral fertilizer; legume – maize rotation; and a non-fertilized control. Over 60 randomly selected farms in each study area were then surveyed for influence of identified practices on soil Zn status across the domains. Maize growth, yield and Zn uptake patterns were monitored on a sub-sample of 20 farms covering the five management domains in each study area.
Results Ethylenediaminetetraacetic acid (EDTA) extractable soil Zn ranged from 0.50 to 2.43 mg kg^{-1}. Different farmer management practices significantly influenced Zn uptake ($p<0.01$). Combined use of organic and inorganic fertilizer yielded >2.1 tha^{-1} maize grain, against <0.8 tha^{-1} in the non-fertilized control. Maize grain Zn concentrations increased by 46–64 % over the control. Regardless of management practice, resultant phytic acid to Zn (PA: Zn) ratios were above the critical value of 15 suggesting inadequacies in current farmer management options.
Conclusions We conclude that the current farmer soil fertility management regimes are insufficient to influence Zn nutrition in maize grown without external Zn fertilization on Zimbabwean sandy soils.

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Introduction

Nearly 50 % of cereal growing areas in the world have soils with low plant available Zn (Graham and Welch 1996; Cakmak 2002), resulting in Zn concentrations in cereal grains of as little as 5–12 mg kg^{-1} against a requirement of 40–60 mg kg^{-1} (www.harvestplus.org; Pfeiffer and McClafferty 2007). Since the introduction of the Green Revolution in Asia, cultivation of high yielding genotypes, improved agricultural mechanization and production of macronutrient fertilizers with low impurities of trace elements has resulted in higher crop production per unit area and with greater depletion of plant available micronutrients (Cakmak 2008; Khoshgoftarmanesh et al. 2009). Besides the inherent deficiency of micronutrients on sandy to sandy loam soils which characterize much of the cereal growing areas of Southern Africa including Zimbabwe (Grant 1981), most micronutrient deficiency problems are exacerbated by the cultivation of high yielding crop cultivars that quickly deplete the limited soil nutrients (Cakmak et al. 1996; Martens and Lindsay 1990). Use of mineral fertilizers in most countries in sub-Saharan Africa has remained <10 kg ha^{-1} year^{-1} (Jama and Pizarro 2008), and most of the fertilizers in use do not contain Zn. This presents a further challenge on pathways for addressing Zn deficiency in cereal based cropping systems.

Zinc is required for structural and functional integrity of about 2,800 proteins, contributes to protein biosynthesis and is a key defence factor in detoxification of highly toxic oxygen free radicals (Cakmak 2000; Broadley et al. 2007). Therefore Zn deficiency in cultivated soils, as documented at global level (Alloway 2004), poses a serious threat to crop production and human nutrition. Cereal-based diets are the major source of nutrients for the majority of the world's population, but over the past two to three decades, concentrations of essential minerals such as Zn have been found to be on a downward trend, far below the required 25–50 mg Zn kg^{-1} (FAO 1996). Although meat is known to have a high Zn concentration, it is not readily available to many resource-constrained households who often constitute >60 % of the population in developing countries (Paul et al. 1998; Cakmak et al. 1999). Zinc deficiency in humans was rated by WHO (2002) as the fifth of the ten leading causes of illness and disease especially in children and women in low income countries. Health problems associated with Zn deficiency include pregnancy complications, low birth weight, impairments in brain development and function, and growth faltering in infants and children (Gibson 1994).

In Southern Africa, the most prevalent diets for many households are a combination of grains from both cereals (maize or sorghum/millets) and legumes. However, most of these grains store phosphorus (P) in form of myo-inositol hexaphosphate, also known as phytic acid (PA), which happens to be one of the main inhibitors of Zn uptake in humans (O'Dell et al. 1972; Gibson 2006; Ryan et al. 2008). In addition to their capacity to store PA, both cereal and legume grains respond to P-enhancing crop management practices such as P fertilizer application by further increasing their PA concentrations. This practice may render Zn stored in these grains largely unavailable to humans. The PA- to- Zn molar ratio is a widely used criterion to estimate bioavailability of Zn in humans. The critical value of the ratio is taken as <15. At ratios >15, Zn bioavailability may be limited by PA (Morris and Ellis 1989; Gibson 2006). Bioavailability of a mineral nutrient refers to the amount of a nutrient that can be potentially absorbed by humans after a meal and consequently be utilized for various metabolic processes in the body (Welch 2002). There is evidence that calcium (Ca) may accentuate the effect of PA on Zn bioavailability and thus the molar ratio of (Ca x PA): Zn has also been suggested as an indicator of Zn bioavailability in humans. Ellis et al. (1987) suggested that the (Ca x PA): Zn ratio >200 indicates poor Zn bioavailability.

Approaches for improving the nutritional wellbeing of humans such as food diversification, supplementation with capsules or syrups, molecular biology and industrial food fortification still require much investment and social acceptance (Ruel and Bouis 1998; White and Broadley 2005). Conventionally, use of inorganic Zn fertilizers and synthetic chelates provide avenues to alleviate Zn deficiency related problems both in human nutrition and crop production. However, these are not commonly used by resource-constrained smallholder farmers in developing countries due to either high costs or inaccessibility. For example in Zimbabwe and most of Southern Africa, farmers continue to struggle to access basic nitrogen (N), P, potassium (K) fertilizer formulations (e.g. Abuja Summit 2006), with a resultant negative feedback on fertilizer manufacturing. This has negative implications on inclusion of micronutrients such as Zn in these formulations as this normally attracts an extra cost. Despite a national policy that mandates fertilizer manufacturers in Zimbabwe to include Zn in some basal compound fertilizers, uptake of such fertilizers by smallholder farmers has remained negligible. Farmers have tended to rely on organic resources as alternative nutrient sources (Carter and Murwira 1995; Mapfumo and Giller 2001). These include livestock manure, woodland/leaf litter, termitarium/anthill soil (derived from termite mounds), rotations involving N_2-fixing legumes, crop residues and fallowing (Nyathi and Campbell 1993; Mtambanengwe and Mapfumo 2008). Though not yet commonly used by farmers, indigenous legumes such as *Crotalaria pallida* (L.) (Nezomba et al. 2008), and green manure species which include velvet bean (*Mucuna pruriens*) and sunnhemp (*Crotalaria juncea*) (Muza 2003) have been grown for their soil fertility benefits. However, the influence of these alternative nutrient sources on soil Zn availability in maize- and other cereal-based cropping systems that predominate in Southern Africa is not well known.

To date, studies that have been conducted in Zimbabwe have concentrated on general Zn distribution in soils (Tagwira 1991), effects of Zn on maize productivity under controlled conditions (Zingore 2006), with little attention on farmers' production circumstances and management practices. This paper focuses on how different soil fertility management practices by smallholder farmers in Zimbabwe influenced soil Zn status and subsequently uptake of the nutrient by staple maize, particularly into the grains. Implications of the emerging patterns on current crop fertilization strategies and human nutrition are discussed.

Materials and methods

Study sites

The study was conducted in Makoni (18° 13′S, 32° 22′E) and Wedza (18° 41′S, 31° 42′ E) Districts of eastern Zimbabwe between 2008 and 2011, under the auspices of the Soil Fertility Consortium for Southern Africa (SOFECSA) (www.sofecsa.org). Wedza, an old communal area with >80 years of smallholder settlement, is in Natural Region (NR) II receiving rainfall between 750 and 800 mm annum^{-1}, while Makoni is a post-independence resettlement area in NR III which receives 650–750 mm annum^{-1}. Agro-zonation in Zimbabwe is defined in terms of mean annual rainfall during a unimodal season that occurs between November and March, with NR 1 receiving the highest annual rainfall of >1,000 mm annum^{-1} and NR V receiving ≤450 mm annum^{-1} (Vincent and Thomas 1961; Department of Surveyor-General 1984). Wedza is approximately 150 km southeast of Harare and average farm holdings range from 1 ha to 3 ha per household. Makoni District is approximately 250 km east of Harare. Formerly a large scale commercial farming area, Makoni resettlement area was opened for smallholder agriculture by the Government of Zimbabwe during the first phase of decongestion of communal areas between 1982 and 1983. Households have an average landholding of 6 ha, with maize (*Zea mays* L.) cropping being the dominant enterprise, although there is a strong crop-livestock interaction with average cattle ownership of at least five cattle household^{-1} (Chisora 2006). Grain legumes, mainly groundnuts (*Arachis hypogaea* L.) and cowpea (*Vigna unguiculata* [L.] Walp), are produced at a comparatively low scale. The soils in both areas range from coarse sands to sandy clay loams classified as Arenosols and Lixisols (WRB 1998) with <10 % clay, low in N and P, and organic carbon contents <0.65 %. The areas were selected for their known problems of widespread Zn deficiency (Tagwira 1991) and baseline studies confirmed the known deficiencies in Zn in these soils. The natural vegetation in both study areas is dominated by tropical savannah woodland (miombo) trees of the genera *Brachystegia*, *Julbernadia, Combretum* and *Terminalia*.

Identification and characterization of farmers' common soil fertility management practices

Farmers' common soil fertility management practices and associated major nutrient resources were identified using key informant interviews and focus group discussions. The key informants comprised local extension workers, village heads and leaders of farmers' groups as well as local representatives of farmer associations. Focus group discussions were held during meetings organised by SOFECSA local committees in collaboration with extension workers. A check list was used to guide the focus group discussions, resulting in three major outcomes:

i. Determination of Zn content in the range of nutrient resources available within and around the farm and commonly applied to maize: These included cattle manure, compost from household waste and crop residues, woodland litter and ash. Prior to the onset of the 2008/09 cropping season, a preliminary study was conducted to make an appraisal of inherent Zn concentrations in these organic nutrient resources in the forms that they were used by farmers. The rationale was that if these materials showed varied Zn concentrations, then the patterns of their use by farmers would influence plant available soil Zn status. At least 20 replicated samples for each of the identified nutrient resources were collected from across randomly selected farms in each study area.
ii. Identification of major soil fertility management practices influencing maize production in the two study areas: These management practices were then used to define domains within which farmers could be classified. The resultant management domains included use of cattle manure or woodland litter in combination with mineral fertilizer, rotations involving mainly N_2-fixing grain legumes and maize, and sole application of NPK basal and N top dressing fertilizers (Table 1). The practices apparently reflected integrated soil fertility management (ISFM) options that farmers were prioritizing in the recent years based on their participation in SOFECSA initiatives aimed at improving soil productivity for household food security. However, farmers also emphasized that a high number of their fields did not receive any external nutrient inputs, and such fields were used as controls. We therefore evaluated these domains for plant available soil Zn status.
iii. Defining the criteria to categorize farmers according to identified management domains: Basing on their experience, farmers were able to define different levels of management required to influence crop yields under each of the identified domains. Apart from farmer criteria, we also drew on literature from previous studies in the same area to determine optimum frequencies and rates for organic resource use on sandy soils (e.g. Mtambanengwe and Mapfumo 2008). For example, a farmer was only considered to be a cattle manure user if they used application rates of at least 5 $t ha^{-1}$ within a period of 3 years on a given field (Table 1). Such quantities were estimated on the basis of number of scotchcart loads per given area versus influence on yield as observed by farmers. To ensure application of 5 $t ha^{-1}$, farmers applied an equivalent of 14 loads ha^{-1} using their standard scotchcart with a capacity of ~350 kg manure $load^{-1}$. With respect to legume-based crop rotations, farmers considered the attainment of at least 1.0 $t ha^{-1}$ grain yield by a selected legume in the preceding season as a precondition for effective rotational benefits (Table 1; also see Kanonge et al. 2009). Selected fields constituting the sole mineral fertilizer treatment were those that received the recommended mineral fertilizer application rate of 300 kg ha^{-1} Compound D ($7N:14P_2O_5:7K_2O$) and 200 kg ha^{-1} ammonium nitrate (34.5 %N) to supply 90 kg N ha^{-1} and 18 kg P ha^{-1} (AGRITEX 1985; Mapfumo and Mtambanengwe 2004).

Table 1 Common soil fertility management practices as recognised by smallholder farmers in Wedza and Makoni districts of Zimbabwe

Management practice	Characteristics
1. Non-fertilized control	Comprised fields that had been consecutively cropped to maize in the previous three seasons, but with no fertilization
2. Maize after legume	Land size under maize was supposed to be the same as land size under legume in the previous season.
	Field was considered to have effective rotational benefits if legume grain yields of at least 1 $t ha^{-1}$ were obtained.
3. Cattle manure + mineral NPK	Organic fertilizer application rate of at least 5 $t ha^{-1}$
4. Leaf litter + mineral NPK	Organic fertilizer application rate of at least 5 $t ha^{-1}$
5. Mineral NPK only	Farmer applied a rate of about 90 kg N ha^{-1}

Assessment of soil Zn status as influenced by soil fertility management practices

To determine the distribution of the identified soil fertility management practices among farmers, and assess their relative influence on plant available soil Zn status, a questionnaire survey was designed and implemented during the dry period prior to the 2009/10 cropping season. Building on findings from the focus group discussions and key informants, 120 households were randomly sampled from across the study areas using village lists provided by extension and local councillors. The survey emphasised on how farmers used named ISFM options in their fields over the past three consecutive seasons (years), and with a particular focus on maize. The proportions of farmers commonly using different management practices were then established. This enabled categorization of farmers into the management domains within which field sites were selected for evaluation of soil Zn status and crop monitoring. Soil samples were collected from at least 20 specific field sites representative of each management domain and analyzed for plant available Zn. The soil samples (0–20 cm depth) were collected from ten random points per target field using an auger.

Sample preparation and analyses

The samples were air–dried and sieved through a 2-mm sieve, before sub-sampling for extractable Zn using the ethylenediaminetetraacetic acid (EDTA) method (IITA 1981; Norvell 1989). The EDTA extractable soil Zn was used as a proxy for plant available Zn consistent with previous studies revealing a strong correlation between the two parameters (Coffman and Miller 1973; Madziva 1981). Soil having less than 1.5 mg kg^{-1} EDTA extractable Zn is believed to be deficient in plant available Zn (Dobermann and Fairhurst 2000).

Soil pH was determined using the 0.01*M* $CaCl_2$ method and read on a Jenway 3510 pH meter. Nitrogen (N) and P were measured using the micro–Kjeldahl digestion method, and organic carbon (C) measured by the Walkley Black method (Anderson and Ingram 1993). Exchangeable bases (magnesium (Mg^{2+}) and calcium (Ca^{2+})) were determined using the acidified ammonium acetate method. Concentrations of EDTA extractable Zn, Ca and Mg were then determined by atomic absorption spectroscopy using a Varian SpectrAA 50 while C, N and P were determined colorimetrically (Anderson and Ingram 1993) using a BUCK Scientific 100 VIS spectrophotometer.

Determination of maize yield and Zn uptake patterns

At the start of the 2009/10 cropping season, farmers were provided with maize seed, SC 513, a local early-to-medium maturity cultivar that takes about 140 days to physiological maturity. With the help of local extension, farmers planted and managed the maize using general agronomic recommendations for each agro-ecological zone (AGRITEX 1985).

Maize grain yields were quantified at physiological maturity from three replicate net plots measuring 9 m^2. Harvested maize was air-dried, shelled and grain yield determined at 12.5 % moisture content. Subsamples of maize grain were ground in a stainless steel Thomas – Wiley Model 4 Laboratory mill (Thomas Scientific, USA) and analyzed for total Zn, N, P, Ca, Mg and K following digestion with nitric acid (HNO_3) and 50 % hydrogen peroxide (H_2O_2) (Anderson and Ingram 1993). Total Zn uptake (g Zn ha^{-1}) was calculated by multiplying grain Zn concentrations with the respective yield (Shivay et al. 2008).

Data analyses

The effect of farmer soil fertility management practices on grain yield, grain nutritional value and soil physico-chemical properties was examined using analyses of variance (ANOVA) with GENSTAT version 13 statistical package (Lawes Agricultural Trust, Rothamsted Experimental Station, U.K). Farmers were used as replicate blocks while the least significant difference (LSD) at P=0.05 was used to differentiate between statistically different means. Relationship between grain Zn concentration and extractable soil Zn was explored with simple regressions using Sigma Plot version 10.0 (SPSS Chicago IL. USA).

Results

Distribution of soil fertility management practices among farmers

Grain legume – cereal rotations was the predominant soil fertility management domain employed by most farmers in the two study areas (Fig. 1). The results indicated that at least 41 % of the households in Wedza and 35 % in Makoni used legume-cereal rotations in a relatively systematic way. It was apparent that most smallholder farmers across the study areas understood the principles of legume – cereal rotations from their participation in SOFECSA learning alliances, hence the relatively high proportion of farmers using this

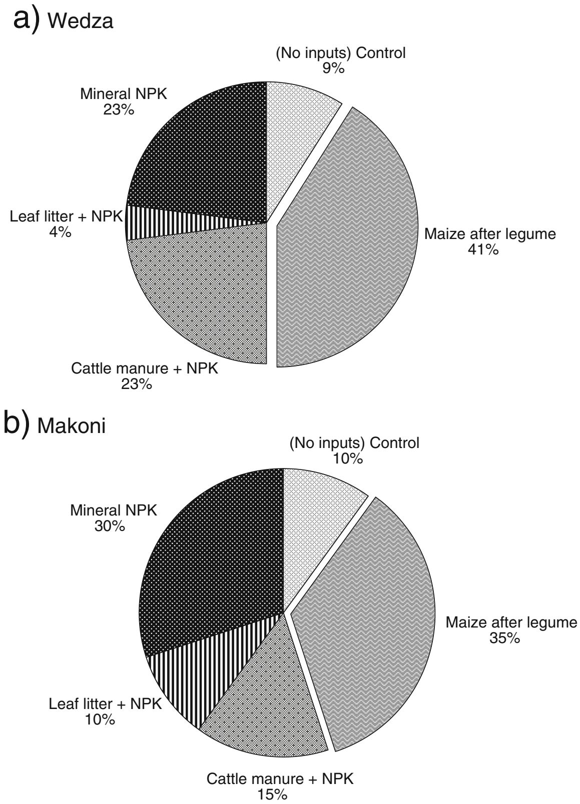

Fig. 1 Common soil fertility management practices by farmers after conducting a household survey in Wedza and Makoni

practice. In Makoni, about 30 % of the farmers used mineral fertilizers (NPK), making this management domain the second most important after the legume – cereal rotations. In Wedza, about 23 % of the farmers applied some form of mineral fertilizer while between 15 and 23 % of the farmers in both study areas combined cattle manure with NPK mineral fertilizer. Use of cattle manure in combination with mineral fertilizers was apparently common among resource endowed farmers who owned relatively large herds of cattle. Approximately 10 % of the farmers did not apply any external nutrient inputs to their maize crop (Fig. 1). Woodland litter appeared to be the smallest domain, accounting for only 4 % in Wedza and 10 % in Makoni.

Chemical characterization of the organic resources available to farmers showed that they contained significantly high concentrations of Zn. Woodland litter contained 86 mg Zn kg^{-1}, almost four times more than cattle manure (Table 2), suggesting its potential as a source of Zn for crops under farmers' current crop production circumstances. Compost and household ash, both commonly applied by farmers around homesteads, also exhibited high concentrations of 56 and 236 mg Zn kg^{-1}, respectively. It was therefore apparent that systematic application of these organic resources would most likely influence availability of Zn to plants growing in these poor soils.

Effect of farmer soil fertility management practices on plant available soil Zn status

The different soil fertility management practices used by farmers only exhibited significant ($P<0.05$) effects on available soil Zn, P and Ca, with no influence on all other measured soil chemical parameters (Table 3). Plant available soil Zn concentration ranged from 0.5 to 0.7 mg kg^{-1} on fields receiving no fertilization to 2.4 mg kg^{-1} on soils amended with woodland leaf litter. Consistently, soils collected from unfertilized fields and those receiving only mineral NPK fertilizers had the lowest Zn concentrations of <1.0 mg kg^{-1}. On the other hand, available soil P was consistently low, ranging from 3.5 mg kg^{-1} in unfertilized fields to 9.1 mg kg^{-1} for fields receiving combinations of cattle manure and mineral fertilizer (Table 3). The management domain involving grain legume-maize rotations consistently gave comparable soil chemical properties to organic-resource based treatments and apparently exhibited relatively high concentrations of Ca and Mg. For example, legume – maize rotational treatments had the highest Ca concentrations of 1.7–1.9 $cmol_c kg^{-1}$ compared to unfertilized treatments which only had between 0.7 and 0.9 $cmol_c kg^{-1}$.

Soil fertility management effects on maize grain yield

Maize grain yields varied significantly under the different soil fertility management domains ($P<0.05$). The highest maize yields were achieved when cattle manure was used in combination with mineral fertilizer, outyielding the control by between 189 and 350 % across the study areas (Fig. 2). Application of woodland litter produced 1.6–1.9 tha^{-1} of maize grain yield and was comparable to cattle manure. Grain legume – based rotations in combination with mineral fertilizer more than doubled maize grain yields to about 1.6 tha^{-1} with respect to the control but did not differ significantly from the sole mineral fertilizer domain. The non – fertilized treatment domain consistently produced the lowest yields of between 0.5 and 0.8 tha^{-1} (Fig. 2).

Table 2 Zinc concentration and general chemical characteristics of organic nutrient sources locally available for use by smallholder farmers in Zimbabwe

Amendment	Total Zn[a] mg kg^{-1}	Total N[b] %	Total P[c] %	Total Ca[a] %	Total K %	Organic C[d] %	C:N ratio
Cattle manure	22.5 (113)	0.8	0.26	1.37	0.11	22.0	29.6
Charcoal	90.5 (453)	Trace	0.16	nd	0.12	55.8	nd
Compost	56.0 (280)	1.0	0.02	nd	0.88	12.8	12.4
Leaf litter	86.0 (430)	0.9	0.03	1.63	0.26	40.7	40.5
Unamended soil	<1.5	0.02	3.5	0.7	0.20	0.3	15.0
Wood - ash	236 (1180)	Trace	0.54	nd	0.03	>90	nd

Procedures by: [a] Aqua Regia, [b] Kjeldahl procedure, [c] Molybdate – vanadophosphoric acid method, [d] Walkely and Black method; nd – not determined; na – not applicable. Figures in parentheses denote potential Zn added (g) through application of 5 tha^{-1} organic material

Soil fertility management effects on maize grain Zn concentration and uptake

Maize grain Zn concentration was significantly ($P < 0.05$) influenced by farmer soil fertility management practices in Wedza (Table 4). However, no such significant differences were observed in Makoni. Highest Zn concentrations of 19 to 23 mg kg^{-1} obtained in Wedza were from the management domain involving combined application of leaf litter and mineral fertilizer. Combined use of cattle manure and mineral fertilizer produced Zn concentrations of between 17 and 21 mg kg^{-1}, and this was not significantly different from the treatment domain involving grain legume-

Table 3 Effect of different management practices on soil chemical properties in Wedza and Makoni

Treatment	Extractable Zn mg kg^{-1}	Extractable P mg kg^{-1}	Ca cmol $_c$ kg^{-1}	Mg cmol $_c$ kg^{-1}	Total N %	Organic C %	pH $CaCl_2$
Wedza							
Unfertilized maize	0.7^{a} (0.5–0.8)	4.0^{a}	0.7^{a}	0.5	0.02	0.30	4.2
Maize after legume	2.1^{bc} (1.8–2.9)	9.0^{c}	1.9^{c}	0.9	0.05	0.40	4.7
Cattle manure + NPK	1.5^{b} (1.3–1.8)	9.0^{c}	1.3^{b}	1.1	0.05	0.50	5.1
Leaf litter + NPK	2.4^{c} (2.4–2.6)	8.0^{c}	1.7^{bc}	0.8	0.03	0.60	4.9
Mineral NPK only	0.9^{ab} (0.8–1.4)	6.0^{b}	1.1^{a}	0.7	0.04	0.39	4.4
Mean	1.55	7.1	1.3	0.8	0.04	0.43	4.6
SED	0.3	0.9	0.2	0.2	0.01	0.1	0.4
F test	***	***	***	ns	ns	ns	ns
Makoni							
Unfertilized maize	0.5^{a} (0.2–0.8)	3.0^{a}	0.9^{a}	0.6	0.02	0.28	4.1
Maize after legume	1.6^{b} (1.1–2.0)	9.0^{bc}	2.1^{d}	1.2	0.03	0.53	4.8
Cattle manure + NPK	1.5^{b} (1.1–1.8)	10.0^{c}	1.6^{c}	1.3	0.05	0.61	5.2
Leaf litter + NPK	2.3^{b}(1.1–3.0)	9.0^{bc}	1.9^{d}	0.9	0.02	0.53	4.8
Mineral NPK only	0.9^{ab} (0.7–1.3)	8.0^{b}	1.3^{b}	0.9	0.03	0.35	4.6
Mean	1.36	7.6	1.6	1.0	0.03	0.46	4.7
SED	0.4	0.8	0.1	0.2	0.01	0.1	0.4
Ftest	***	***	***	ns	ns	ns	ns

Extractable Zn and P were considered to be directly correlated to plant availability. *** means treatment means significantly different at $P<0.05$; *ns* not significantly different at $P<0.05$; Figures in parentheses denote ranges

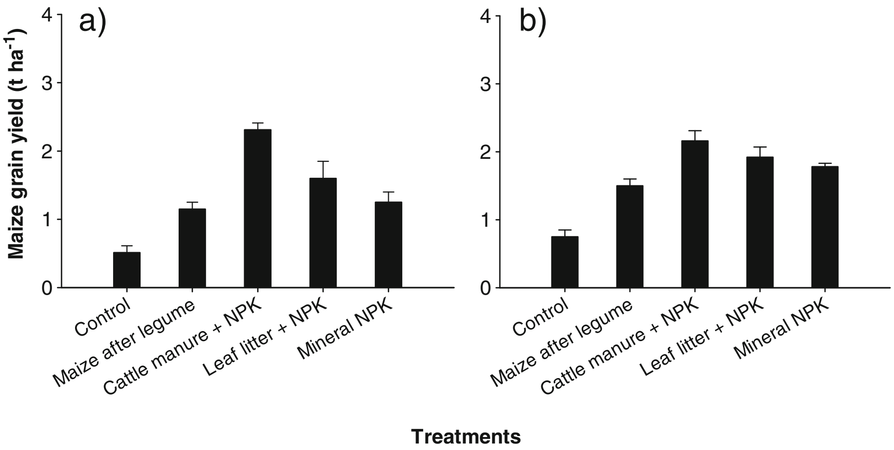

Fig. 2 Maize grain yields (12.5% moisture content) obtained from farmers' fields during the 2009/10 growing season in **a** Wedza and **b** Makoni. *Bars* represent SE

maize rotations. Both these treatment domains consistently out-performed the sole mineral fertilizer and control domains across the study areas (Table 4). The unfertilized treatment domain had the lowest maize grain Zn concentration of between 13 and 14 mg kg^{-1}. In both study areas, there was a significant linear relationship between EDTA extractable soil Zn and maize grain Zn concentrations (R^2>0.80), with maize grain Zn concentration increasing with an increase in soil Zn (Fig. 3). Overall, maize grain Zn uptake in Wedza ranged between 7.1 and 48.5 g Zn ha^{-1}, while a narrower range of 9.8 to 36.9 g Zn ha^{-1} was obtained in Makoni (Table 4). Maize under combined use of cattle manure and inorganic fertilizers had the highest Zn uptake in both study areas, yielding up to six times the amount taken up under the unfertilized control treatment domain (Table 4).

The different management domains also exhibited significant (P<0.05) differences in maize grain P concentration, with the legume-cereal rotation giving the highest concentration of 3.5 g P kg^{-1} in Wedza (Table 4). However, cattle manure, woodland litter and sole mineral fertilizer management domains showed no significant differences. In Makoni, maize obtained from the sole mineral fertilizer treatment had the highest grain P concentration, superseding the unfertilized maize by up to 24 %. Apart from the unfertilized control which exhibited the lowest P concentration, the rest of the management domains did not show significant differences in this study area (Table 4). The management domain involving grain legume-cereal rotations exhibited relatively high Ca concentrations which ranged from 49.2 to 76.1 mg kg^{-1}.

Effect of soil fertility management domains on indicators of Zn bioavailability

An analysis of phytic acid to zinc (PA: Zn) molar ratio showed significant (P<0.05) effects of the different management regimes (Table 5). The PA: Zn molar ratio

Table 4 Zinc, Ca and P concentration in maize grain and Zn uptake as influenced by farmer management practices in Wedza and Makoni smallholder farming areas in Zimbabwe

Treatments	Wedza				Makoni			
	Zn (mg kg^{-1})	Ca	P (g kg^{-1})	Zn uptake (g ha^{-1})	Zn (mg kg^{-1})	Ca	P (g kg^{-1})	Zn uptake (g ha^{-1})
Unfertilized maize	14^a	37.0	2.7^a	7^a	13	50.1	2.6^a	10
Maize after legume	19^b	49.2	3.5^c	22^a	15	76.1	3.0^b	23
Cattle manure + NPK	21^b	42.9	3.4^c	49^b	17	58.2	3.0^b	37
Leaf litter + NPK	23^c	44.4	3.4^c	37^b	19	60.6	2.9^b	37
Mineral NPK only	16^a	40.6	3.2^b	20^a	14	57.4	3.4^c	25
Mean	18.5	42.8	3.2	27	15.4	60.5	3.0	26
SED	1.7	9.3	0.1	8	2.2	18.4	0.1	9.5
F test	***	ns	***	***	ns	ns	***	ns

ns treatments not significantly different. Means followed by same letters within the column did not differ significantly at P<0.05

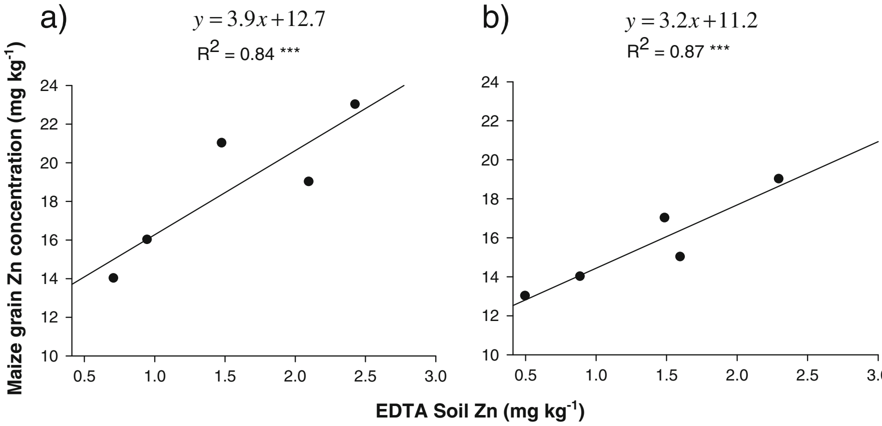

Fig. 3 Relationship between maize grain Zn concentration and EDTA extractable Zn in **a** Wedza, **b** Makoni. *** means significantly related at $P<0.05$

ranged from 96 to 158 and this substantially exceeded the known critical value of <15. Maize under sole mineral fertilizer exhibited relatively higher PA: Zn molar ratios of 130–158 compared to unfertilized treatment which gave a range of between 125 and 130 (Table 5). Combined application of mineral fertilizer with either cattle manure or woodland litter resulted in the lowest PA: Zn molar ratio, but even these still exceeded the critical value of <15. There were, however, no significant treatment effects on (Ca x PA): Zn molar ratio, another commonly used indicator for Zn bioavailability (Table 5). The Ca x PA: Zn molar ratio ranged from 4 266 to 9 893 and was extremely high relative to the known critical values. The observed trends were however similar to those shown for the PA: Zn molar ratio, with combined use of organic and inorganic fertilizers resulting in the lowest Ca x PA: Zn molar ratio across study areas.

Discussion

Nutrient resources defining soil fertility management domains

Major soil fertility management domains differentiating crop production by the smallholder farmers were defined by N_2-fixing grain legumes, livestock manure, woodland litter and mineral fertilizers. The proportion of farmers applying sole mineral fertilizer to maize was relatively high across the agro-ecological zones, possibly due to availability of fertilizers under an input loan scheme promoted by government in the study areas. Innovations that involved selling of surplus maize by farmers to the national Grain Marketing Board (GMB), in exchange for mineral fertilizer, could also have contributed to the high number of farmers in this domain. Grain legumes showed potential to benefit the

Table 5 Effect of fertility treatments on indicators of Zn bioavailability: PA, PA: Zn and Ca x PA: Zn

Treatment	Wedza			Makoni		
	§PA (mg kg^{-1})	PA : Zn	Ca x PA : Zn	§PA (mg kg^{-1})	PA : Zn	Ca x PA : Zn
Unfertilized maize	1 755^{a}	125^{b}	4 638	1 690^{a}	130^{b}	6 513
Maize after legume	2 275^{c}	119^{b}	5 891	1 950^{b}	130^{b}	9 893
Cattle manure + NPK	2 210^{b}	105^{a}	4 515	1 950^{b}	115^{a}	6 675
Leaf litter + NPK	2 210^{b}	96^{a}	4 266	1 885^{a}	99^{a}	6 012
Mineral NPK	2080^{b}	130^{b}	5 278	2 210^{c}	158^{c}	9 061
Mean	2 106	115.3	4 918	1 937	126.4	7 631
SED	93.5	6.4	610	128	8.1	861
F test	***	***	ns	***	***	ns

PA phytic acid; PA was assumed at 65 % of P in the grain; *** means significant treatment differences at $p<0.05$; means accompanied by same letter within a column are not significantly different; *ns* no significant differences at $P<0.05$

different resource categories of farmers. The importance of this domain was most likely amplified by the strengthening of partnerships between farmers and private seed companies under a SOFECSA-mediated contract scheme for production of cowpea and soyabean (Kanonge et al. 2009). A combination of mineral fertilizers with cattle manure was mainly used by resource-endowed farmers, a group defined by their high (>10) cattle ownership and capacity to access credit for purchase of crop inputs (Mtambanengwe and Mapfumo 2005). Only a small proportion of farmers used woodland litter, mainly those living in close proximity to mountains and common natural woodlands, as well as those who had draught power and labour to collect the litter. Resource-constrained farmers who neither owned livestock nor had the capacity to purchase mineral fertilizers accounted for the majority of poor fields that yielded <0.2 tha^{-1} of maize grain.

Organic nutrient resource management effects on plant available soil Zn and P status

The quality of organic nutrient resources at incorporation apparently had a strong influence on available soil Zn, P and Ca. For instance woodland leaf litter, which contained about six times the amount of Zn measured in cattle manure, had the strongest influence on plant available soil Zn. This suggests that dominant miombo tree species have high capacity to mobilize soil nutrients in their growth environments and accumulate high levels of Zn in leaves. The tropical savanna woodland (miombo) tree species are known for their potential to scavenge for nutrients from deeper soil horizons (Muller–Samann and Kotschi 1994; Ryan et al. 2011) and to tightly recycle major macronutrients including N (Mtambanengwe and Mapfumo 1999). Upon senescence, their leaves decompose and form humic substances that are important both in the retention of micronutrients in the soil and transportation in soil solution (Geering and Hodgson 1969).

Use of legume-cereal rotations proved a possible avenue for improving plant available soil Zn as indicated by high levels of EDTA-extractable Zn. This may be due to the high capacity of legumes to scavenge nutrients from the soil and release back to the soil through dropping of leaves (Cakmak 2002; Zuo and Zhang 2009). However, the EDTA-extractable soil Zn values for most of the treatments measured in this study were still below the critical value of 1.5 mg kg^{-1} (Dobermann and Fairhurst 2000) suggesting the soil Zn stocks were inherently too low to support any meaningful accumulation of the nutrient for cropping purposes. These findings strongly highlight the inadequacies of available organic materials to meet cropping demands for soil Zn uptake, calling for measures which promote increased use of Zn-containing mineral fertilizers. Another other option would be for farmers to use high input rates of organic nutrient resources but this is unlikely against a background of inherently low soil Zn stocks and general scarcity of organic resources as the natural pools decline.

Differential impact of soil fertility management practices on available soil Zn, P and Ca imply that the three nutrient elements could be among factors critically limiting maize performance and compromising grain quality in the farming systems. Both P and Zn are known to be inherently low in granitic parent materials of Zimbabwe (Grant 1981; Tagwira 1991), and results from this study suggest that farmer management practices have a further and strong influence on distribution of these nutrient elements across field and temporal scales. Combined application of organic and inorganic fertilizers, and legume-maize rotations significantly improved availability of Ca, Zn and P. High Ca concentrations in legume-cereal rotations treatments and cattle manure treatments could be attributed to external application of Ca containing fertilizers to legumes and potential supply of secondary nutrients by cattle manure. Leguminous plants have been particularly found to improve mobilization, recycling and subsequently availability of nutrients including Ca under poor fertile soils (Palm et al. 1997; Cakmak 2002; Mapfumo and Mtambanengwe 2004). However, results from this study indicate that the building of stocks of these soils may be insufficient in meeting the demands of cereals, making mineral fertilization an important consideration.

Maize grain yield under different soil fertility management domains

Maize grain yields following combined application of organic and mineral fertilizers were about two-fold higher than other soil fertility management domains regardless of type of organic material. This could be attributed to improved nutrient use efficiencies often associated with positive interactions derived from combinations of organic and mineral nutrient resources (Palm et al. 1997; Chikowo et al. 2010). Organic materials do not only improve a range of soil biological and physical properties, but also directly contribute to SOM build up and supply of secondary- (Mg and Ca) and micro-nutrients such as Zn (Mtambanengwe and Mapfumo 2009; Masvaya et al. 2010). This positively influences plant uptake and use of macro-nutrients such as N and P. Some studies conducted in tropical regions also realized yield benefits of legume-cereal rotations (Giller 2001; Zuo and Zhang 2009). However, in some cases the influence of micronutrient deficiencies is not readily expressed in crop yield reduction. For example, in the current study, there were significant differences in plant available soil Zn, P and Ca, but Zn availability did not significantly influence grain yields. Zinc availability was unlikely to have an overriding effect in soils inherently deficient in N and P. Availability of P from organic nutrient resources, mainly woodland leaf litter could therefore have been the possible reason for the observed differences in grain yields. In several studies evaluating legume-cereal rotations under smallholder farming systems, cereal yields have often been more than doubled (Waddington and Karigwindi 2001; Adjei-Nsiah et al. 2008), but in many cases, there has been failure to explain such yield benefits solely in terms of N contributions by the legume(s). The influence of micronutrient supply patterns on the yields of subsequent cereals under such rotational studies has remained largely unexplored.

Soil fertility management practice influence maize grain Zn uptake and subsequent bioavailability

Overall, maize Zn uptake could be differentiated according to farmers' different management domains. A combination of woodland litter and mineral fertilizers gave the highest grain Zn quality, suggesting that the Zn contained in the organic materials is readily available within a single cropping season. This finding implies that organic nutrient resources could also be used as a complementary source of Zn in maize production. This may explain why several studies have recorded benefits in cereal Zn concentrations following combined use of organic resources and Zn fertilizers (Singh et al. 1983; Rupa et al. 2003). Apart from increasing Zn stocks, organic matter in soils can also influence both solubility and mobility of the nutrient (Marschner 1993). Maize grown after legumes had higher maize grain Zn concentrations than that grown under continuous mineral fertilizer application. In this study, Zn concentration measured in grain legumes were 22 mg kg^{-1} in cowpea and 25 mg kg^{-1} in soybean (data not shown), and these values were higher than those measured in maize. These findings highlight a need for improved Zn fertilization to maintain soil stocks in legume-cereal systems. Plant organic materials can act as majors stores for available Zn, however management practices favouring the exportation of such resources may lead to rapid mining of the nutrient.

The PA: Zn ratios reported in this study exceed the critical value of 15 (Morris and Ellis 1989; Hambidge et al. 2008), implying that maize produced under current farmer soil fertility management practices has poor Zn bioavailability. The Ca x PA: Zn molar ratios measured were also above the critical ratio of 200 which further implied poor bioavailability of Zn in human diets. The nutritional adequacy of dietary Zn depends on both its amount in staple grains and bioavailability in the diet. Based on this study, fertilization of staple maize with Zn-containing fertilizers, coupled to appropriate use of available organic nutrient resources, provides a potential avenue for improving the Zn nutritive value of maize in smallholder farming systems.

Conclusions

The study revealed that the current soil fertility management practices employed by smallholder farmers have a differential impact on plant available soil Zn and P, even if they may not obviously influence crop yields and other soil chemical properties such as SOM in the short term. Combined use of organic nutrient resources, such as cattle manure and woodland leaf litter, with mineral fertilizer, as well as legume-based rotations, significantly increased plant available soil Zn status. Although these nutrient resources can lead to high yields of staple maize under farmers' current soil fertility management regimes, they remain inadequate to meet the Zn uptake levels required to eliminate threats of human nutritional deficiencies in the smallholder sector in Zimbabwe. While farmers' current management practices have shown a significant influence on plant available soil Zn, the overall problem is in inherently low stocks of Zn and P in soils. Current fertilizer formulations used on maize tend to further reduce Zn bioavailability due to the resultant high P and Ca concentrations in the grain. It is therefore imperative that options such as use of Zn-containing mineral fertilizers should be systematically used to recapitalize Zn and enhance the potential role of current soil fertility management efforts by resource-poor communities in addressing Zn malnutrition.

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