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Zinc fertilization influence on maize productivity and grain nutritional quality under integrated soil fertility management in Zimbabwe

Grace M. Manzeke[a,b], Florence Mtambanengwe[a,b], Hatirarami Nezomba[a,b], Paul Mapfumo[a,b,*]

[a] Department of Soil Science and Agricultural Engineering, University of Zimbabwe, P.O. Box MP 167, Mount Pleasant, Harare, Zimbabwe
[b] Soil Fertility Consortium for Southern Africa (SOFECSA), University of Zimbabwe, P.O. Box MP 167, Mount Pleasant, Harare, Zimbabwe

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ABSTRACT

Current efforts to promote integrated soil fertility management (ISFM) for improved productivity of staple cereal crops in sub-Saharan Africa have paid little attention to soil micronutrient deficiencies under smallholder farming. This has not only compromised yields, but also undermined the nutritional quality of harvested grains. To address this knowledge gap, a study was carried out over two cropping seasons in Hwedza district in eastern Zimbabwe to assess the added grain yield and nutritional benefits of zinc (Zn) fertilizer application to maize (*Zea mays* L.) under different ISFM options. In all cases, Zn application resulted in added maize grain and quality benefits. Application of Zn (11 kg ha^{-1}) in combination with organic nutrient resources (5 t ha^{-1}), and mineral fertilizers (90 kg N ha^{-1} and 26 kg P ha^{-1}) gave the highest maize grain yields of up to 3.9 t ha^{-1}; which translated to 1.3 times more yield than under sole mineral NPK fertilizers. In the subsequent season, there were significantly higher residual effects (2 t ha^{-1}) from organic *x*Zn combinations compared with sole mineral fertilizer treatments. Organic nutrient resources and Zn application significantly ($P < 0.05$) influenced maize grain P and Zn concentration, with cattle manure consistently producing the highest grain P concentrations of 0.44%. Maize grain under combinations of mineral NPK, Zn and leaf litter gave the highest grain Zn concentration of up to 35 mg kg^{-1}. The Zn-based treatments increased grain Zn concentration and yield by 67 and 29%, respectively, indicating that there was much more benefit in grain quality than just yield after external Zn application. Combined organic resource and Zn fertilization also resulted in a significant build up of plant available soil P and ethylenediaminetetraacetic acid (EDTA) extractable Zn. Concentrations of 7.4 mg P kg^{-1} and 5.5 mg Zn kg^{-1} were measured after application of organics, compared with initial values of 5.2 mg kg^{-1} and 1.15 mg kg^{-1}, respectively. It was concluded that benefits of ISFM options currently promoted in smallholder farming systems in Zimbabwe are constrained by soil Zn deficiencies. Combining these ISFM options with Zn fertilizer formulations increased yields and grain quality of the staple maize, enhancing scope for agronomic fortification of maize to enhance human nutrition.

1. Introduction

Apart from inadequate soil N and P, soil zinc (Zn) deficiencies also pose a serious threat to global crop production and food nutrition (Cakmak, 2002; Nube and Voortman, 2006), with 50% of cereal grown areas exhibiting deficiencies (Graham and Welch, 1996; Grant, 1981). This results in insufficient amounts of Zn in cereal grains to meet human nutritional needs, particularly for the majority of poor people in developing countries whose diets are dominated by maize, rice and wheat (Cakmak, 2008; World Bank, 2008). Globally, 162 million children under the age of five years are stunted due to malnutrition with 36% of this population found in Africa (WHO, 2012). Grain Zn concentrations as low as 5–12 mg Zn kg^{-1} in wheat (Erdal et al., 2002) and 13–23 mg Zn kg^{-1} in maize (Manzeke et al., 2012) have been measured in cereal crops produced in Zn-deficient soils. This is against the recommended 40–60 mg Zn kg^{-1} necessary to meet human requirements (Pfeiffer and McClafferty, 2007). For example, during early 2000s, 6.4% of the children in Zimbabwe were said to

* Corresponding author at: University of Zimbabwe, Soil Science & Agricultural Engineering, Soil Fertility Consortium for Southern Africa, University of Zimbabwe, Harare, Zimbabwe. Tel.: +263 712 803 971; fax: +263 4 307 304.
E-mail addresses: gmanzeke@agric.uz.ac.zw (G.M. Manzeke), fmtamba@agri.uz.ac.zw (F. Mtambanengwe), hatienez@yahoo.co.uk (H. Nezomba), pmapfumo@agric.uz.ac.zw, paulmapfumo@gmail.com (P. Mapfumo).

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be undernourished with a significant proportion of the rural population experiencing acute malnutrition (FAO/WFP, 2002).

More than 300 enzymes involved in the key metabolic processes (e.g. carbohydrate and protein metabolism) in humans contain Zn (FAO/WHO, 1996; Cakmak et al., 1999). This emphasises the need for adequate grain Zn in cereal-based human diets. Recommended intake of dietary Zn ranges from 1.1 to 11.2 mg day^{-1} in children and 3.0–19.0 mg day^{-1} in adults (FAO/WHO, 1996; Imtiaz et al., 2010). However, in poor communities, intake in food is often inadequate (Nube and Voortman, 2006). About two-thirds of all global deaths in children are associated with micronutrient nutritional deficiencies, and sub-optimal growth and mortality are some of the severe symptoms associated with Zn deficiency (Welch, 2002). In pregnant women, Zn deficiency symptoms may include high rates of infectious diseases and complications during pregnancy or at birth (Ruel and Bouis, 1998; Welch, 2002).

In plants, the physiological functions of Zn include carbohydrate and protein metabolism, membrane integrity, auxin metabolism and reproduction (Alloway, 2008). Concentrations in soil range from 10 to 300 mg kg^{-1} (Kiekens, 1995) depending on parent rock responsible for soil formation. Low concentrations of ~48 mg kg^{-1} have often been measured in granitic parent rocks (Krauskopf, 1967; Wedepohl, 1978), which account for ~70% of cropped lands by smallholders in Zimbabwe (Thompson and Purves, 1978). Maize grown on such soils is therefore often deficient in Zn and other essential micronutrients. This paper therefore focuses on how application of Zn-containing mineral fertilizers to staple cereal crops may contribute towards improved yields and grain quality as a pathway to enhancing nutrition of smallholder communities in maize-based farming systems. Agronomic fortification could be a cost-effective strategy to enhance nutrition in these communities given that the majority of farmers often do not have the financial capacity to purchase other Zn-rich foods including meat (FAO/WHO, 1996).

In Zimbabwe and other parts of sub-Saharan Africa, there are widespread deficiencies of common macro- and micronutrients on granite derived sandy soils (Tagwira, 1991). This has prompted a search for deeper understanding of the roles of different nutrient resources in soil fertility management (Mapfumo et al., 2013). Use of external mineral fertilizers by most farmers has often been constrained by their high costs. Consequently, most resource-constrained farmers have often resorted to combined use of locally available organic nutrient resources and the limited mineral fertilizer they can afford (World Bank, 1995; Mapfumo and Giller, 2001). Several studies have evaluated the importance of such organic nutrient resources including woodland litter, livestock manure and green manure crops in improving crop productivity on a sustainable basis (Zingore, 2006; Mtambanengwe and Mapfumo, 2009). However, few studies have explicitly examined the value of these local organics as sources of micronutrients such as Zn, and their potential interactions with Zn-containing mineral fertilizers. The limited empirical studies available suggest that, Zn supplied in locally-available organic nutrient resources in Zimbabwe is insufficient to sustain the required levels of cereal grain yields and nutrient concentrations without external mineral fertilization (Manzeke et al., 2012). This paper therefore aims to investigate and quantify the added benefits of Zn fertilization as a pathway to agronomic fortification of staple maize under combined use of organic and mineral NPK fertilizers as currently promoted among smallholder farmers in the context of ISFM. The specific objectives of the study were to: (i) evaluate the potential role of cattle manure and woodland litter, as sources of Zn and P in maize production, (ii) assess the added grain yield and quality benefits of Zn following combined use of organic nutrient resources and mineral NPK fertilizers.

2. Materials and methods

2.1. Study site

The study was conducted between 2009 and 2011 in Goto ward in Hwedza smallholder farming area (18°41′S, 31°42′E) in eastern Zimbabwe, under the auspices of the Soil Fertility Consortium for Southern Africa (SOFECSA). The SOFECSA work focused on promoting co-learning approaches with farmers and diverse service providers in eastern Zimbabwe. Hwedza is ~150 km south-east of Harare, and in agro-ecological region (NR) II which receives about 750 mm of annual rainfall (Vincent and Thomas, 1961; Department of Surveyor-General, 1984). According to the World Reference Base (2006), soils dominant in Hwedza can be classified as Arenosols and Lixisols. The major limiting nutrients for crop production for these soils are N, P, S and Zn (Grant, 1981; Mapfumo and Giller, 2001).

Hwedza has been under smallholder settlement for over 80 years with farm holdings ranging from 1 ha to 5 ha. Farming in Hwedza is predominantly based on mixed crop-livestock systems, with maize (*Zea mays* L.) production dominating. Legumes such as groundnut (*Arachis hypogaea* L.), cowpea (*Vigna unguiculata* L.) and common beans (*Phaseolus vulgaris* L.) are also grown but on a relatively small scale. Cattle are the dominant livestock and important for provision of manure, draught power and meat but are owned by a few farmers.

2.2. Preliminary assessment of soil Zn status in farmers' fields

A preliminary field study was conducted during the dry months of August–September 2009, to investigate soil Zn status of different smallholder farms. Working with farmers and local national agricultural extension workers (AEWs), 15 farms were randomly selected and soil samples collected at 10 random points within each farmer's field from a depth of 0 to 20 cm using an auger. Samples were then placed in well-labelled polythene bags, air-dried and sieved through a 2 mm sieve. A sub-sample from each of the prepared soil sample was used to analyse for extractable Zn using the ethylenediaminetetraacetic acid (EDTA) method (IITA Manual, 1981; Norvell, 1989). Soil extractable Zn was then measured by atomic absorption spectroscopy using a Varian SpectrAA 50 spectrophotometer. Soil texture was determined using the hydrometer method (Gee and Bauder, 1986). Results from this diagnostic exercise were used to inform selection of the field site for experimentation. Consequently, a field at Nhika farm that had a Zn concentration of 1.15 mg kg^{-1} was selected for experimentation. Field soils with values below 1.5 mg Zn kg^{-1} are normally considered as indicating deficiencies in cropping systems (Dobermann and Fairhurst, 2000; Zare et al., 2009). The selected field had a loamy sand soil with a pH of 4.9 (0.01 M $CaCl_2$). Available N and P, organic carbon (C) and exchangeable base values are presented in Table 1.

2.3. Field experimentation

The field experiment was established with the first effective rains in November 2009. The selected field was prepared by conventional ploughing and following treatments were effected on experimental plots measuring 4.5 m × 5 m in gross area:

1. 90 kg N ha^{-1} + 26 kg P ha^{-1}.
2. 90 kg N ha^{-1} + 26 kg P ha^{-1} + Zn.
3. 30 kg N ha^{-1} + 14 kg P ha^{-1}.
4. 30 kg N ha^{-1} + 14 kg P ha^{-1} + Zn.
5. 90 kg N ha^{-1} + 14 kg P ha^{-1}.
6. 90 kg N ha^{-1} + 14 kg P ha^{-1} + Zn.