Field Crops Research 213 (2017) 231–244

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Zinc fertilization increases productivity and grain nutritional quality of cowpea (*Vigna unguiculata* [L.] Walp.) under integrated soil fertility management

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ARTICLE INFO

Keywords:
Agronomic biofortification
Dietary Zn supply
Grain legumes
Organic nutrient resources
P-Zn interaction

ABSTRACT

Cowpea (*Vigna unguiculata* [L.] Walp.) is an important but under-studied grain legume which can potentially contribute to improved dietary zinc (Zn) intake in sub-Saharan Africa. In this study, surveys were conducted on smallholder farms in Zimbabwe during 2014/15 to determine the influence of diverse soil fertility management options on cowpea grain productivity and nutrition quality. Guided by the surveys, field experiments were conducted to investigate the influence of Zn fertilizer on the productivity and quality of cowpea under integrated soil fertility management (ISFM). Experiments were conducted on two soil-types, namely, sandy (6% clay) and red clay (57% clay) in 2014/15 and 2015/16 where cowpea was grown in rotation with staple maize (*Zea mays* L.) and fertilized with combinations of Zn, nitrogen (N), phosphorus (P) and two organic nutrient resources, cattle manure and woodland leaf litter. Cowpea grain yields on surveyed farms ranged from 0.3 to 0.9 t ha^{-1}, with grain Zn concentration ranging from 23.9 to 30.1 mg kg^{-1}. The highest grain Zn concentration was on fields where organic nutrient resources were applied in combination with mineral N and P fertilizers. Within the field experiments, mean grain yields of cowpea increased by between 12 and 18% on both soil types when Zn fertilizer was applied, from a baseline of 1.6 and 1.1 t ha^{-1} on red clay and sandy soils, respectively. When Zn fertilizer was co-applied with organic nutrient resources, grain Zn concentrations of cowpea reached 42.1 mg kg^{-1} (red clay) and 44.7 mg kg^{-1} (sandy) against grain Zn concentrations of 35.9 mg kg^{-1} and 31.1 mg kg^{-1} measured in cowpea grown with no Zn fertilizer on red clay and sandy soils, respectively. Agronomic biofortification of legumes is feasible and has the potential to contribute significantly towards increasing dietary Zn intake by humans. A greater increase in grain Zn of cowpea grown on sandy than red clay soils under Zn fertilization illustrates the influence of soil type on Zn uptake, which should be explored further in agronomic biofortification programs.

1. Introduction

Zinc (Zn) is an essential micronutrient in both food crops and humans (FAO/IAEA/WHO, 2002). Despite current increases in global food and energy supplies, Zn deficiency remains prevalent in most developing countries (Cakmak et al., 2017) largely because the food systems in these countries fail to supply adequate micronutrients (Gregory et al., 2017; Joy et al., 2014; Kumssa et al., 2015; Manzeke et al., 2016). Symptoms of Zn deficiency in humans include impaired growth, immuno-incompetence, pregnancy complications in child-bearing mothers, acute malnutrition and otherwise curable diarrheal incidences in children under five years of age. These problems continue to impose an economic burden in developing countries (FAO/WFP, 2002; Wessells and Brown, 2012). Dietary Zn deficiency affects ∼17% (1.1 billion people) of the global population (de Valença et al., 2017; Kumssa et al., 2015; WHO, 2016). In sub-Saharan Africa (SSA) alone, > 25% of the population is at risk of inadequate dietary Zn intake compared with 9.6% in Central and Eastern Europe (Wessells and Brown, 2012). The risk of Zn deficiency in Zimbabwe has been estimated to be ∼26%, based on food system supplies, but is likely to be greater among some groups (Joy et al., 2015a; Kumssa et al., 2015).

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http://dx.doi.org/10.1016/j.fcr.2017.08.010
Received 25 April 2017; Received in revised form 7 August 2017; Accepted 10 August 2017
0378-4290/

Previous studies have shown that Zn-based fertilizers can improve dietary Zn supply in cereals (Cakmak, 2008; Joy et al., 2015a, 2017; Wang et al., 2016; White and Broadley, 2009) by increasing grain Zn concentration whilst simultaneously improving crop yields (Cakmak et al., 2010; Welch and Graham, 2004; Zou et al., 2012). For example, Zn-based fertilizers have been reported to increase productivity and nutritional composition of wheat (*Triticum aestivum* L.) (Cakmak et al., 1999; Joy et al., 2017; Ram et al., 2016; Zou et al., 2012), maize (*Zea mays* L.) (Harris et al., 2007; Manzeke et al., 2014, 2016) and rice (*Oryza sativa* L.) (Ram et al., 2016; Shivay et al., 2015) grown on Zn-deficient soils. However, most studies on Zn fertilizer use have largely focused on staple cereals with fewer such studies on grain legumes.

Grain legume crops support the livelihoods of poor households in SSA through contributing to their dietary energy, protein and mineral intake (Messina, 1999; Mtambanengwe and Mapfumo, 2009; Rusinamhodzi et al., 2017). The average *per capita* consumption of grain legumes in southern Africa is ~4.5 kg *capita*$^{-1}$ year^{-1} (http://www.fao.org/faostat/en/#data/FBS). Grain legumes have been reported to provide approximately 12% of dietary Zn supply (Joy et al., 2014), although there is considerable variation between countries. In Zimbabwe, of the 10 mg Zn *capita*$^{-1}$ day^{-1} supplied by major foods, grain legumes provide only 10% (1.0 mg Zn *capita*$^{-1}$ day^{-1}) compared to a supply of up to 8.7 mg Zn *capita*$^{-1}$ day^{-1} in West Africa (Joy et al., 2014). An example of an important drought tolerant grain legume under smallholder cropping in SSA is cowpea (*Vigna unguiculata* [L.] Walp). Despite its exceptional biological nitrogen fixation (BNF) potential on nutrient-depleted soils and a relatively high protein content of up to 25% (IITA, 2015; Rusinamhodzi et al., 2006), the productivity of cowpea has increasingly declined in part, due to lack of nitrogen (N) and phosphorus (P) fertilization (Giller, 2001; Kanonge et al., 2015; Zingore et al., 2008).

Research on Zn fertilizer use in grain legumes production has mostly been done under greenhouse conditions (Brennan et al., 2001; Poblaciones and Rengel, 2016; Valenciano et al., 2010), with limited studies at field and farm levels (e.g. Johnson et al., 2005; Khan et al., 2000). To date we are not aware of studies exploring the optimal use of Zn fertilizers in the context of the integrated soil fertility management (ISFM) approaches, which encompass organic nutrient resource use and appropriate rotations in grain legume production, yet this is how farmers are encouraged to grow crops on nutrient-depleted sandy soils of southern Africa (Giller, 2001; Kanonge et al., 2015; Mapfumo et al., 2001; Mpepereki et al., 2000; Mtambanengwe and Mapfumo, 2009). The legume-cereal rotations help build soil fertility, diversify household diets and break crop pests and disease cycles.

Application of N fertilizers promotes uptake and translocation of Zn and other micronutrients (Aciksoz et al., 2011) in wheat (Kutman et al., 2010, 2011) and rice (Jaksomsak et al., 2017), whereas P fertilizer application decreases Zn uptake in dwarf bean (*Phaseolus vulgaris* L., cv. Borlotto nano) due to a dilution effect (Alloway, 2008; Gianquinto et al., 2000; Prasad et al., 2016; Zhu et al., 2001). However, N x Zn, and P x Zn interaction effects on nutrition of field-grown grain legumes have not been reported previously. The objectives of this study were: i) to determine grain yield and grain Zn nutritional quality of cowpea grown on smallholder farms under diverse soil fertility management options used by farmers; ii) to determine the productivity and grain quality of cowpea fertilized with combinations of Zn-, N- and P-based fertilizers and locally available organic nutrient resources grown under a cowpea-maize rotational sequence; iii) to evaluate the potential contribution of Zn-fertilized cowpea towards dietary Zn supplies for households reliant on legume-cereal rotational systems.

2. Materials and methods

The study was conducted in Hwedza District (18° 41′ S, 31° 42′ E) in Eastern Zimbabwe. It comprised a survey of 60 farmers in 2014/15, and field experiments at two sites in 2014/15 and 2015/16 cropping seasons. The study builds on the Soil Fertility Consortium for Southern Africa (SOFECSA)'s work on legume production in smallholder farming communities under diverse ISFM techniques that included systematic legume-cereal rotations, crop diversification and combined use of mineral and organic nutrient resources. SOFECSA had been working with smallholder farmers in Hwedza since 2005. Hwedza encompasses three of Zimbabwe's agro-ecological region/natural regions (NR) IIb to IV, receiving 450–800 mm year^{-1} between November and March. Soils in this community are broadly classified as Lixisols (FAO/ISRIC/ISSS, 2006). Maize is the dominant crop under a mixed crop-livestock farming system (Mtambanengwe and Mapfumo, 2009). Legumes such as groundnut (*Arachis hypogea* L.), cowpea and common bean (*Phaseolus vulgaris* L.) are typically grown on smaller patches of land compared with the staple maize (Rusinamhodzi et al., 2006), often with minimal or zero fertilization (Kanonge et al., 2015) resulting in inefficient legume-cereal rotational systems. Cattle are the dominant livestock mainly kept for manure and draught power provision. In the absence of cattle manure, farmers often collect woodland leaf litter from the tropical savanna woodlands for soil fertility management. Rainfall in Hwedza is often unevenly distributed (Rurinda et al., 2013), for example, the district received > 800 mm annum^{-1} in the 2014/15 cropping season, with 314 mm obtained within the month of December 2014 alone (Fig. 1).

2.1. Survey

A survey was conducted in Dendenyore (agro-ecological zone IIb) and Ushe (agro-ecological zone III–IV) Wards in Hwedza to determine the range of soil fertility management options employed under cowpea production and to quantify grain yields and Zn nutritional composition. The survey targeted households working with SOFECSA on cowpea production, and other grain legumes, under its ISFM initiatives. Farmers (n = 60) were selected randomly from a total of 150 farmers under the SOFECSA cowpea production initiative with the help of local Agricultural Extension Workers (AEWs). Under the SOFECSA program, one main variety of cowpea, CBC2, which is a high-yielding, semi-bushy, short season (60–90 days to maturity) cultivar, has been promoted to eliminate genotypic variation. The farmers planted and managed the cowpea using agronomic recommendations appropriate within their agro-ecological zones (AGRITEX, 1985), with technical support from AEWs and SOFECSA researchers. Appropriate agronomic recommendations included plant spacing of 0.45 m × 0.075 m and application of agro-chemicals to control aphid manifestation during the hot and dry periods of the cropping season. Research approval for this study was obtained from the Department of Agricultural Technical and Extension Services (AGRITEX) of The Government of Zimbabwe's Ministry of Agriculture, Mechanization and Irrigation Development.

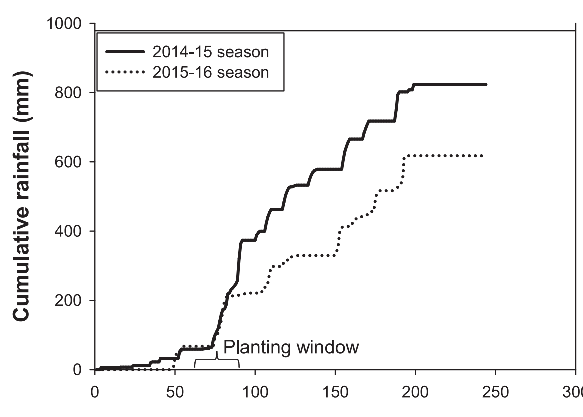

Fig. 1. Cumulative rainfall received in Hwedza, Zimbabwe during the 2014–15 and 2015–16 cropping seasons.