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Good soil management can reduce dietary zinc deficiency in Zimbabwe

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Abstract

Background: Dietary zinc (Zn) deficiency is widespread in sub-Saharan Africa (SSA) with adverse impacts on human health. Agronomic biofortification with Zn fertilizers and improved soil fertility management, using mineral and organic nutrient resources, has previously been shown to increase Zn concentration of staple grain crops, including maize. Here, we show the potential of different soil fertility management options on maize crops to reduce dietary Zn deficiency in Zimbabwe using secondary data from a set of surveys and field experiments.

Methods: An *ex-ante* approach was used, informed by published evidence from studies in three contrasting smallholder production systems in Zimbabwe. To estimate current Zn deficiency in Zimbabwe, data on dietary Zn supply from non-maize sources from the Global Expanded Nutrient Supply (GENuS) data set were linked to maize grain Zn composition observed under typical current soil fertility management scenarios.

Results: A baseline dietary Zn deficiency prevalence of 68% was estimated from a reference maize grain Zn composition value of 16.6 mg kg^{-1} and an estimated dietary Zn intake of 9.3 mg capita^{-1} day^{-1} from all food sources. The potential health benefits of reducing Zn deficiency using different soil fertility management scenarios were quantified within a Disability Adjusted Life Years (DALYs) framework. A scenario using optimal mineral NPK fertilizers and locally available organic nutrient resources (i.e. cattle manure and woodland leaf litter), but without additional soil Zn fertilizer applications, is estimated to increase maize grain Zn concentration to 19.3 mg kg^{-1}. This would reduce the estimated prevalence of dietary Zn deficiency to 55%, potentially saving 2238 DALYs year^{-1}. Universal adoption of optimal fertilizers, to include soil Zn applications and locally available organic leaf litter, is estimated to increase maize grain Zn concentration to 32.4 mg kg^{-1} and reduce dietary Zn deficiency to 16.7%, potentially saving 9119 DALYs year^{-1}. Potential monetized yield gains from adopting improved soil fertility management range from 49- to 158-fold larger than the potential reduction in DALYs, if the latter are monetized using standard methods.

Conclusion: Farmers should be incentivized to adopt improved soil fertility management to improve both crop yield and quality.

Keywords: Agro-fortification, Cattle manure, Disability Adjusted Life Years (DALYs), Maize-based cropping systems, Mineral NPK, Soil Zn fertilizers, Woodland leaf litter, Yield: health benefit

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Introduction

Zinc is an essential element required for various metabolic and enzymatic functions in humans (Hotz and Brown 2004). Zinc deficiency causes various physiological disorders including stunting and impaired cognitive development; increased risks of infections (i.e. diarrhoea, malaria and pneumonia) (Bhutta et al. 1999;

Shankar et al. 2000; HarvestPlus 2015; King et al. 2016) and increased risks of mortality and morbidity in children (Roohani et al. 2013). Disability Adjusted Life Years (DALYs), which are the number of healthy life years lost due to premature death, ill-health, or disability (Murray 1994; Stein 2014), can be used to quantify the Zn deficiency burden on a population (Stein et al. 2005; Stein et al. 2006). DALYs can be monetized so that the potential cost-effectiveness of different interventions to reduce Zn deficiency can be compared (Joy et al. 2017). Globally, > 75 million DALYs were lost in 2010 due to micronutrient deficiencies (hidden hunger), with ~25 million DALYs in sub-Saharan Africa (SSA) compared to ~3 million DALYs in Europe and Central Asia (Gödecke et al. 2018). Approximately 9.1 million of the global DALYs lost due to hidden hunger have been attributed to Zn deficiency (Gödecke et al. 2018), although these are not uniformly distributed.

Several studies have estimated the global prevalence of dietary Zn deficiency using food supply data. For example, using food supply data and stunting prevalence, Wessells et al. (2012) estimated a global Zn deficiency prevalence of 17%. Kumssa et al. (2015) estimated global dietary Zn deficiency prevalence of 16%, although noted that dietary Zn deficiency prevalence had decreased between 1992 and 2011. The prevalence of dietary Zn deficiency remains especially high in SSA. This is likely to be due to diets being dominated by cereal grains containing limited bioavailable Zn, compounded by production systems on low Zn soils (Gregory et al. 2017). Joy et al. (2014) estimated a prevalence of dietary Zn deficiency of 40% among 46 countries in Africa, using Food Balance Sheets (FBSs) integrated with food composition data, and similarly Kumssa et al. (2015) estimated a dietary Zn deficiency prevalence of ~40% in Zimbabwe.

Recent studies with smallholder farming communities in Zimbabwe have shown that it is possible to improve grain Zn concentration in staple maize (*Zea mays* L.) and legume grains using improved soil fertility management. This includes the use of inorganic and organic nutrient inputs (manure and leaf litter) and combinations thereof, and agronomic biofortification (agro-fortification) with Zn fertilizers (Manzeke et al. 2012, 2014, 2017, 2019, 2020). Agronomic biofortification is the use of mineral (and/or organic amendments) to increase the concentration of a target mineral in edible portions of crops (Cakmak and Kutman 2018). Recent studies in Ethiopia have also shown that greater soil organic matter content associates with greater Zn concentration in wheat (*Triticum aestivum* L.) grains (Wood et al. 2018). These findings provide intriguing evidence that the consumption of crops grown through the increased use of organic nutrient resources and good soil management can contribute to reducing dietary Zn deficiency, and that such approaches can augment the benefits that could arise from the use of Zn fertilizers alone (Joy et al. 2015, 2017). However, the potential cost-effectiveness of improved soil fertility management in terms of both grain yield and health benefits have not yet been evaluated.

The use of agro-fortification and improved soil fertility management to reduce micronutrient deficiencies can be compared using *ex-ante* methods, including quantifying the likely number of DALYs saved (Lividini et al. 2018). Previously, Joy et al. (2015) noted that enriching granular fertilizers with Zn might be cost-effective, in terms of DALYs saved, in SSA. In Pakistan, Joy et al. (2017) reported that the adoption of widespread (soil and foliar) Zn fertilizer use on wheat in Pakistan could increase dietary Zn intake and halve the prevalence of dietary Zn deficiency. The aim of this paper was to explore the potential of good soil fertility management and agro-fortification with soil Zn for reducing dietary Zn deficiency in Zimbabwe. The following objectives were pursued: (1) to quantify the potential health benefits of alleviating dietary Zn deficiency with soil-applied Zn fertilizer and improved soil fertility management to increase maize grain Zn concentration, using a DALYs framework, and (2) to quantify the potential grain yield benefits from use of soil-applied Zn fertilizer and improved soil fertility management.

Materials and methods

Study sites and rationale

The study uses secondary data, published from our earlier series of field surveys and field experiments conducted in three contrasting natural regions (NRs) in Zimbabwe's smallholder farming communities over an approximately 10-year period. A collection of five published papers was compiled for secondary data analysis (Manzeke et al., 2012, 2014, 2017, 2019, 2020). In these studies, it was shown that improved soil fertility management, including the increased use of mineral NPK fertilizers, organic matter, and agro-fortification with Zn, could potentially increase the grain Zn concentration of maize in Zimbabwe smallholder farming systems. It is within this background that the secondary data analysis was conducted to quantify the potential of good soil fertility management to alleviate dietary Zn deficiency.

Zimbabwe is divided into five NRs (FAO 2006). These regions, also referred to as agro-ecological regions; are defined based on rainfall regime, soil quality, vegetation among other factors (Vincent et al. 1961). Natural region 1 has the best quality of land resource and receives the highest amount of rainfall (> 1000 mm annum^{-1}) which declines as you move towards NR5 (Moyo 1991). Natural region 5 is the driest region of the country

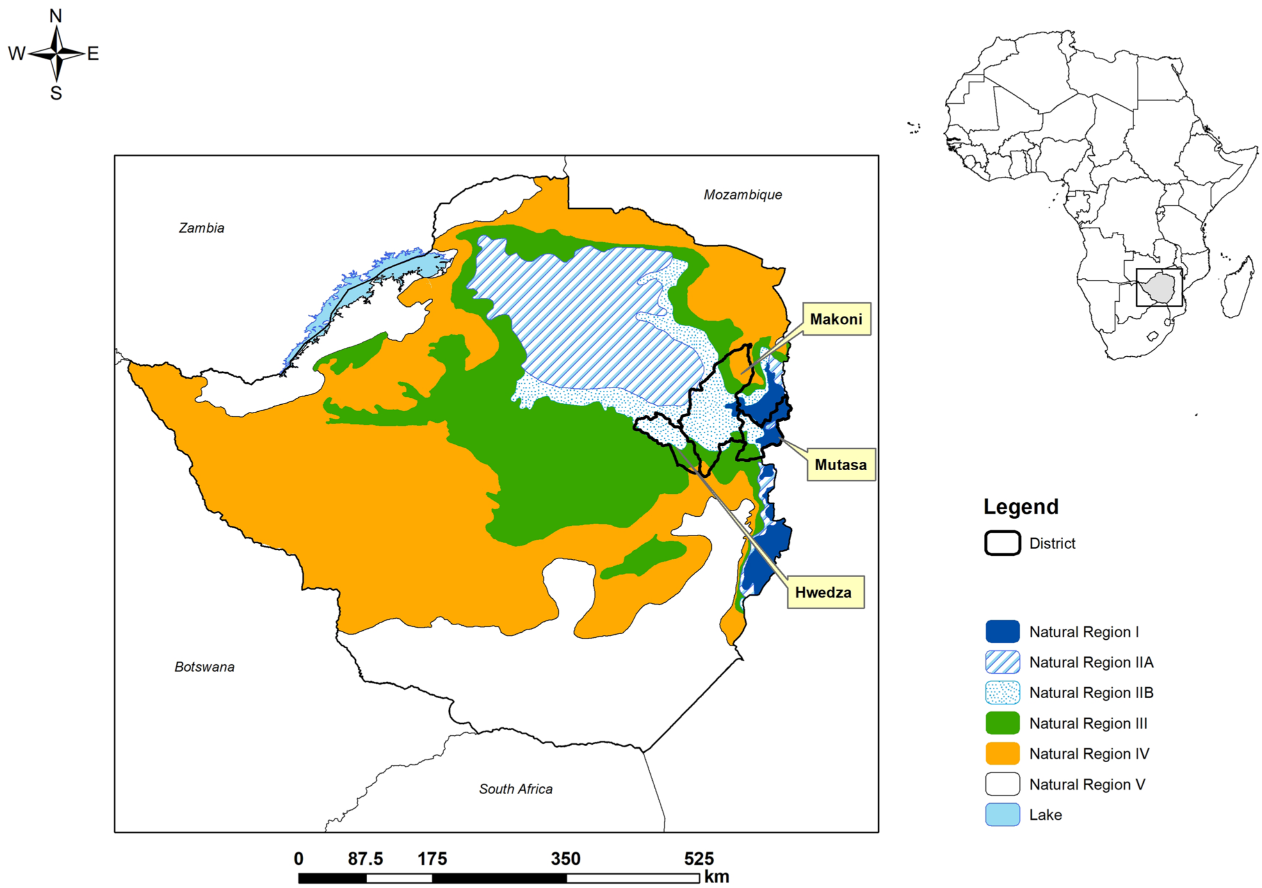

Fig. 1 Location of sites where survey and field experiments were conducted in eastern Zimbabwe between 2009 to 2020

receiving < 450 mm rainfall annum^{-1} (Vincent et al. 1961; Moyo 1991). Studies were conducted in three districts; Hwedza, Makoni, and Mutasa Districts (Fig. 1). Mutasa is in NR 1 of the country (Fig. 1) and Hwedza and Makoni are in the medium to low rainfall areas (NR 2B to 4) of the country receiving between 450 and 800 mm rainfall annum^{-1} (Manzeke et al. 2019).

While the three districts (Hwedza, Makoni and Mutasa) are not nationally representative, they were chosen because they provided contrasting environmental conditions with a high-quality source of data on: (1) baseline Zn concentration in maize grain, (2) current soil fertility management practices among smallholder farmers, (3) experimental data on the responses of maize (yield and grain Zn concentration) to the use of soil fertility management inputs such as organic nutrient resources (which increase organic matter) and agro-fortification with Zn fertilizers. Although data on cowpea (*Vigna unguiculata* [L.] Walp.) grain Zn concentration were also available from these surveys and experiments, only maize data are used in this current study as it is the dominant staple source of dietary energy and Zn intake (FAO 2013, 2015). More than 40% of land area in Zimbabwe is under smallholder (or communal) farming with maize being the dominant crop (ZIMSTAT 2019). Maize provides ~ 39.5% of the total dietary energy intake in Zimbabwe (FAO 2013). Animal source food products provide an additional 8.9% of the dietary energy intake (FAO 2013).

Maize grain zinc concentration and yields from farmers' fields and field experiments

The maize grain Zn concentration and grain yield under different soil fertility management strategies, which are used to conduct this analysis, are shown in Table 1. The maize grain Zn concentrations and yields were generated and reported previously (Manzeke et al. 2012, 2014) in a series of surveys on farmers' fields and field experiments. The surveys, conducted in two contrasting sites (Hwedza and Makoni Districts), encompassed sampling of maize grain grown on farmers' fields on plot sizes measuring 9 m^2 to determine effects of farmer soil fertility management practices on grain yield and Zn concentration. Field experiments were conducted on a typical loamy sandy soil with a low

Table 1 Published maize grain yields and grain Zn concentration in maize grains in Hwedza and Makoni Districts

Soil fertility management option	Maize grain yield ($kg\ ha^{-1}$)	Maize grain Zn concentration ($mg\ kg^{-1}$)	Site	Reference
No form of organic or mineral fertilizer	423	13.5	Farmers' field	Manzeke et al. (2012)
Mineral NPK fertilizer only	990	15.0	Farmers' field	Manzeke et al. (2012)
Mineral NPK + *organic fertilizer	1501	19.3	Farmers' field	Manzeke et al. (2012)
Mineral NPK + ¥soil Zn	2100	25.8	Experimental field	Manzeke et al. (2014)
Cattle manure + mineral NPK + soil Zn	3000	28.0	Experimental field	Manzeke et al. (2014)
Woodland leaf litter + mineral NPK + soil Zn	3400	32.4	Experimental field	Manzeke et al. (2014)

*organic fertilizer was cattle manure or woodland leaf litter or compost. ¥-soil Zn fertilizer was applied at 5 kg elemental Zn ha^{-1} as $ZnSO_4.7H_2O$. Mineral NPK was applied from compound D (7% N:14% P_2O_5:7% K_2O) and ammonium nitrate (AN-34.5% N) to supply optimal rates of N (90 kg ha^{-1}), P (26 kg ha^{-1}) and K (30 kg ha^{-1}) required for maize production (See FAO 2006; Manzeke et al. 2012, 2014; Kurwakumire et al. 2014)

Table 2 Soil fertility management scenarios used in the *ex-ante* analysis

Scenario	Description of scenario and soil fertility management practices	Proportions of farmers using different soil fertility management practices	Weighted average grain Zn $mg\ kg^{-1}$	Weighted average grain yield $kg\ ha^{-1}$
1	Current practice	15:43:42 (0 N:Mineral N:Mineral N + Organic N)	16.6	1119
2	Farmers who were applying no fertilizers start to apply mineral NPK	0:58:42 (0 N:Mineral N:Mineral N + Organic N)	16.8	1204
3	All farmers apply mineral NPK and organic N	0:0:100 (0 N:Mineral N:Mineral N + Organic N)	19.3	1501
4	All farmers apply mineral NPK + *soil Zn	Blanket adoption	25.8	2100
5	All farmers apply cattle manure + mineral NPK + soil Zn	Blanket adoption	28.0	3000
6	All farmers apply woodland leaf litter + mineral NPK + soil Zn	Blanket adoption	32.4	3400

*soil Zn fertilizer was applied at 5 kg elemental Zn ha^{-1} as $ZnSO_4.7H_2O$

plant-available soil Zn concentration of 1.15 mg kg^{-1} (Manzeke et al. 2014). Plant-available soil Zn concentration is the fraction of Zn in the soil which is available for plant uptake (Alloway 2008). Using the ethylenediamine tetra acetic acid (EDTA) method, soils with plant-available Zn < 1.5 mg kg^{-1} are considered low in soil Zn (Dobermann and Fairhurst 2000; Zare et al. 2009). Of the 13 treatments employed on this field site, three treatments which best represented common farmer soil fertility management practices were selected (Table 1). These treatments—although not currently used by farmers—included soil Zn fertilizer applied as $ZnSO_4.7H_2O$. Grain Zn concentration and yield data produced from the surveys and field experiments were then used as secondary data in this paper to calculate weighted average grain Zn concentration and grain yield for six scenarios (Table 2). The six scenarios represent one scenario based on current farmer practices from field surveys (baseline scenario) and five scenarios which represent the wider adoption of improved soil fertility management practices and agrofortification (as informed by field experiments).

Determining Zn supply and deficiency rates in Zimbabwe

Baseline dietary Zn supply from non-maize sources for Zimbabwe was estimated to be 4.7 mg $capita^{-1}$ day^{-1} (Global Expanded Nutrient Supply, GENuS, data set; https://dataverse.harvard.edu). Dietary Zn supply from maize was estimated under six scenarios, as described in the next section.

The prevalence of inadequate dietary Zn intake under each of these six scenarios was calculated using the Estimated Average Requirement (EAR) cut-point method as described by Wessells and Brown (2012), Kumssa et al. (2015) and Joy et al. (2014). The EAR is the intake level which meets the needs of 50% of an age- and sex- specific population group. In the present study, a population-weighted EAR of 10.4 mg $capita^{-1}$ day^{-1} was used, as estimated for Zimbabwe by Kumssa et al. (2015). This is similar to the Zn EAR of 10.2 mg $capita^{-1}$ day^{-1} reported by Allen et al. (2020) for adult women consuming a diet high in phytic acid. Phytic acid binds to Zn (and other cations), making them unavailable for absorption in the human gut.

DALYs currently lost due to ill-health were derived from the Global Health Data Exchange (GBD; http://ghdx.healthdata.org/). The number of DALYs lost under the six scenarios in this study was assumed to be in proportion to the national prevalence of inadequate dietary Zn, as described by Stein et al. (2010).

Defining Zn supply scenarios

Dietary Zn supply from maize for six scenarios was based on published data from surveys and field experiments as described earlier. For the baseline scenario (Scenario 1; Table 2), survey data from 74 sole maize-cropping farms in Hwedza and Makoni Districts (Manzeke et al. 2012) were used to estimate the proportion of smallholder farmers currently using different soil fertility management strategies. Among these farms, 15% of the farmers applied no form of either mineral NPK or organic fertilizer to their maize crop, 43% used mineral NPK fertilizer alone (as compound D; 7% N:14% P_2O_5:7% K_2O and ammonium nitrate-34.5% N), 42% applied mineral NPK and organic nutrient resources in the form of cattle manure, compost and woodland leaf litter from miombo (*Brachystegia, Combretum* and *Julbernadia* spp.) woodlands. No farmers used any form of Zn-supplying fertilizer. A further 46 farmers practiced legume-cereal rotations as a soil fertility management strategy (Manzeke et al. 2012). However, given that the scenarios in this study are based on a single cropping season, potential quality and yield benefits from the legume-cereal rotations were not considered in this study.

Scenario 1 is therefore the baseline scenario which denotes soil fertility management options currently practiced by smallholder farmers. Scenario 2 assumes that farmers who were applying no fertilizers (15%) start to apply mineral NPK fertilizer. This would mean 58% of smallholder farmers apply mineral NPK with 42% of the farmers applying organic N fertilizer (Table 2). In scenario 3, all farmers (100%) start applying mineral NPK and organic N fertilizer. Scenarios 4, 5 and 6 assumes that all farmers adopt use of mineral NPK and soil Zn fertilizer, cattle manure + mineral NPK + soil Zn and woodland leaf litter + mineral NPK + soil Zn, respectively (Table 2). These three scenarios denote universal adoption of improved soil fertility management encompassing soil Zn and organic nutrient resource use.

Assumptions regarding maize grain Zn concentration and grain yields

Grain Zn concentration

Grain Zn concentration under farmers' fields and field experiments ranged from 13.5 to 32.4 mg kg^{-1} (Table 1, Manzeke et al. 2012, 2014). Scenario 1 would give a weighted average maize grain Zn concentration of 16.6 mg kg^{-1} (Table 2). This was calculated by multiplying the weighted average maize grain Zn concentration of 13.5, 15.0 and 19.3 mg kg^{-1} attained under each of the three farmer practices (Table 1) by the proportion of farmers under each practice (%) divided by 100% as shown below:

$$\frac{Maize\,grain\,Zn\,concentration\,x\%\,of\,farmers}{100\%}$$

This weighted average maize grain Zn concentration represents the current grain Zn concentration in maize cropping systems in Zimbabwe as attained by farmers without any agro-fortification intervention.

For Scenario 2, we assumed that all farmers currently applying no fertilizer start to apply mineral NPK only, meaning that 58% of farmers would apply mineral NPK fertilizer only (15 + 43%) and 42% would still be applying mineral NPK and organic fertilizers, leading to a weighted average maize grain Zn concentration of 16.8 mg kg^{-1} (Table 2). For Scenario 3, we assumed that all farmers currently applying no fertilizer, or mineral NPK only, move to applying mineral NPK and organic fertilizers. This would mean that all of the surveyed farmers (15 + 43 + 42%) would start to use mineral NPK and organic fertilizers in their maize crop. This assumption leads to a weighted average maize grain Zn concentration of 19.3 mg kg^{-1} (Table 2).

For Scenarios 4, 5, and 6, we assumed universal practices were adopted, whereby all smallholder farmers start to apply soil Zn fertilizer together with various combinations of mineral NPK and organic fertilizers. Grain Zn concentrations in these scenarios were derived from data for maize grain grown with Zn fertilizer from field experiments conducted over a two-year cropping season (2009–2011) (Manzeke et al. 2014) as described earlier. Assuming that 100% of smallholder farmers adopted soil Zn fertilizers in combination with mineral NPK fertilizers would result in a weighted grain Zn concentration of 25.8 mg kg^{-1} (Scenario 4; Table 2). Soil Zn fertilizers in combination with mineral NPK fertilizers and cattle manure would increase the grain Zn concentration to 28.0 mg kg^{-1} (Scenario 5; Table 2) if all farmers adopt this practice. Soil Zn and mineral NPK fertilizers and woodland leaf litter would result in the largest grain Zn concentration of 32.4 mg kg^{-1} (Scenario 6; Table 2) based on universal adoption by farmers. The mineral NPK fertilizer application used here is based on the combined application of compound D and ammonium nitrate (AN) to supply optimal rates of elemental N (90 kg ha^{-1}), P (26 kg ha^{-1}) and K (30 kg ha^{-1}), as recommended for smallholder maize production (FAO, 2006; Manzeke et al. 2012, 2014; Kurwakumire et al. 2014).

Grain yields

Maize grain yields under farmers' fields and field experiments ranged from 423 to 3400 kg ha^{-1} (Table 1, Manzeke et al. 2012; 2014). These values were used to estimate average maize grain yields for Scenario 1 to Scenario 6 using the same weighted average calculations as used for grain Zn concentration. For Scenario 1, the average maize grain yield under current farmer management practices is 1119 kg ha^{-1} (Table 2). This baseline maize grain yield is comparable to a recently reported average cereal yield of 1266 kg ha^{-1} in SSA but smaller than the global average of 3745 kg ha^{-1} (World Bank 2018; Bonilla Cedrez et al. 2020). For Scenario 2 and Scenario 3, the estimated maize grain yield would increase to 1204 and 1501 kg ha^{-1}, respectively (Table 2). Where universal practices are adopted, whereby all smallholder farmers use a soil Zn fertilizer together with various combinations of mineral NPK and organic fertilizers, the estimated maize grain yields would increase to 2100 kg ha^{-1} (Scenario 4), 3000 kg ha^{-1} (Scenario 5) and 3400 kg ha^{-1} (Scenario 6).

Definitions of technical terms and parameters used for the DALYs analyses

1. **Dietary supply of Zn from maize**
   This is the consumption of Zn in maize grain person^{-1} day^{-1} based on a daily consumption of 278.3 g maize person^{-1} day^{-1} (GENuS maize consumption from grain and corn flour; https://dataverse.harvard.edu), modified according to the grain Zn concentrations for the six scenarios described in Table 2. Dietary Zn supply from maize would differ for each scenario depending on the grain Zn concentration.
2. **Dietary Zn deficiency or inadequate intake**
   This value is calculated as a percentage of the population at risk of Zn deficiency due to inadequate consumption of Zn within a selected scenario or population against the recommended dietary Zn intake. We calculated the prevalence of inadequate dietary Zn intake using methods detailed by Wessells and Brown (2012) and Wessells et al. (2012) as guided by the Institute of Medicine (IOM) EAR cut-point method, with mean consumption estimated from national food supplies and an assumed 25% inter-individual coefficient of variation (CV) of intakes. A population-weighted EAR of 10.4 mg capita^{-1} day^{-1} was used (Kumssa et al. 2015) which is similar to the 10.2 mg capita^{-1} day^{-1} for adult women proposed by Allen et al. (2020). Allen et al. (2020) assumed a phytate intake of 1200 mg capita^{-1} day^{-1} from a largely unrefined diet. The present study does not take into consideration further limitation in Zn bioavailability from phytate or other inhibitors of Zn uptake.
3. **DALYs lost due to Zn deficiency**
   These are defined as the number of DALYs lost due to Zn deficiency within a population. The current number of DALYs lost in Zimbabwe due to Zn deficiency are 12,092 according to the Global Health Data Exchange (2017; http://ghdx.healthdata.org/gbd-results-tool/).
4. **DALYs saved due to adoption of improved soil fertility management**
   These are the number of potential DALYs saved due to consumption of maize grain with increased grain Zn concentration, under the scenarios summarised in Table 2.
5. **DALYs burden value (DALYs lost * GDP)**
   This is the monetary value of DALYs lost, calculated by multiplying the number of DALYs lost due to Zn deficiency by the Gross Domestic Product (GDP) of Zimbabwe. We used a GDP per capita of US$1602 (World Bank, https://data.worldbank.org/) for 2017. The World Health Organization (WHO) defines interventions for which the cost per DALY saved is less than the GDP capita^{-1} as 'very cost-effective', between one and three times GDP capita^{-1} as 'cost-effective', and more than three times GDP capita^{-1} as 'not cost-effective' (WHO 2002; http://www.who.int/choice/cost-effectiveness/en/). In this study, we assumed a conservative value of Zn deficiency burden of 1(DALY) * GDP.
6. **Health benefit of adopting a technology (US$ year^{-1})**
   This is the monetized value of DALYs saved and is derived by calculating the difference between the value of DALYs saved within a scenario and the baseline value of DALYs.
7. **Yield per year (% of baseline)**
   The yield per year compared to baseline was calculated as follows:

$$\frac{\textit{Maize grain yield attained in a selected scenario}}{\textit{Baseline grain yield}}\left(\frac{kg}{ha}\right)x100$$

8. **Value of yield**
   This is the product of the grain yield and the producer price of maize. Producer prices are prices received by farmers for primary crops, live animals and livestock primary products as collected at the point of initial sale. These are prices paid at the farm-gate. The producer price for maize used in this paper is US$390 tonne^{-1} (FAOSTAT 2017). We

Table 3 Potential contribution of different soil fertility management options to improving dietary Zn supply and reducing the number of DALYs lost due to ill-health

Parameter	Scenario 1 (baseline)	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Dietary Zn supply (mg capita^{-1} day^{-1})	9.3	9.4	10.1	11.9	12.5	13.7
Dietary Zn deficiency (%)	67.7	66.7	55.2	30.9	25.1	16.7
DALYs lost due to Zn deficiency	12,092***	11,915	9854	5516	4486	2973
DALYs saved due to adoption of improved soil fertility management	n.a	177	2238	6576	7606	9119
Value of DALYs lost (DALYs lost * GDP[1]) (US$)	19,371,384	19,088,243	15,786,087	8,836,435	7,186,333	4,763,160
Health benefit[2] (US$ year^{-1})	n.a	283,141	3,585,297	10,534,949	12,185,051	14,608,224
Maize yield annum^{-1} (% of baseline)	100	108	134	188	268	304
Value of maize yield (US$ ha^{-1})	436	470	585	819	1170	1326
Value of national maize production (US$ year^{-1})	588,867,073	633,617,969	789,625,750	1,104,960,402	1,578,514,860	1,788,983,508
Yield benefit (US$ year^{-1})	n.a	44,750,896	200,758,677	516,093,329	989,647,787	1,200,116,435
Net benefit from yield changes and DALYs burden (US$ year^{-1})	n.a	45,034,037	204,343,974	526,628,278	1,001,832,838	1,214,724,658
Scale of yield benefit vs health benefit (Ratio)	n.a	158	56	49	81	82

*** Value obtained from the Global Health Data exchange (2017; http://ghdx.healthdata.org/)

[1] GDP is Gross Domestic Product. The GDP per capita used for Zimbabwe is US$1,602 (https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?locations=ZW for 2017)

[2] Health benefit implies reduction in disease burden due to Zn deficiency, calculated by monetizing each DALY saved. n.a = not applicable. Farmers practicing legume-cereal rotations were excluded from these calculations

used a total area of maize in Zimbabwe of 1,349,158 hectares (FAOSTAT 2017).

9. **Value of lives saved + yield (versus baseline)**
   This is referred to as the net benefit from yield changes and reductions in DALY burdens (US$ year^{-1}). The yield change is calculated by subtracting the baseline value of national maize production from the national value of maize produced under each scenario (US$ year^{-1}). This value is then summed with the monetized health benefit of DALYs saved in the same scenario.
10. **Scale of benefit in yield vs benefit in health**
    This is the ratio in monetized yield benefit versus monetized health benefit within a selected scenario. This scale of benefit in yield vs health benefit, presented as a ratio, is calculated as follows:

$$\frac{Maize\,grain\,yield\,benefit}{Health\,benefit}(US\$)$$

Data analysis

Maize grain Zn concentration and grain yield for the six scenarios (including baseline scenario) were extracted from a survey and field experiments published as Manzeke et al. (2012) and Manzeke et al. (2014), respectively (Data set; Additional file 1). Secondary analysis of this data was done in Excel (Microsoft 365). The percentage of farmers practicing each soil fertility management and the weighted average maize grain Zn concentration and grain yield for each scenario were calculated as described in "Grain Zn concentration" section (Data set; Additional file 1). Calculation of the eight parameters used in the DALYs analysis (including dietary Zn supply, dietary Zn deficiency, DALYs lost, cost of DALYs, health and yield benefits) was conducted for each scenario in Excel (Data set, Additional file 1) as described in "Definitions of technical terms and parameters used for the DALYs analyses" section.

Results

Total dietary Zn supply, disability adjusted life years' lost and cost in Zimbabwe

Scenario 1 (baseline)

Based on a maize grain Zn concentration of 16.6 mg kg^{-1} under current soil fertility management scenarios, the estimated total dietary Zn supply for Zimbabwe will be 9.3 mg Zn capita^{-1} day^{-1}, with an estimated baseline dietary Zn deficiency prevalence of 68% (Table 3). If we assume that this deficiency prevalence contributes to the current 12,092 DALYs lost due to Zn deficiency in Zimbabwe, this will result in a DALYs disease burden due to Zn deficiency of ~ US$19.4 M year^{-1}.

Scenario 2

The adoption of mineral NPK fertilizer by farmers who are currently not adding any fertilizers to maize, would potentially increase Zn supply slightly from 9.3 (baseline) to 9.4 mg Zn capita^{-1} day^{-1}. This would reduce dietary Zn deficiency from 68 to 67% (Table 3). Under this scenario, the number of DALYs lost would be reduced by 177. Use of mineral NPK fertilizers by this group of farmers would reduce the cost of DALYs lost from a current baseline of ~ US$19.4 M to US$19.1 M resulting in a health benefit of ~ US$280,000 year^{-1} (Table 3).

Scenario 3

The universal adoption of mineral NPK fertilizer and organic nutrient resources (i.e. cattle manure and woodland leaf litter) is estimated to increase dietary Zn supply from 9.3 (baseline) to 10.1 mg capita^{-1} day^{-1}. This would reduce dietary Zn deficiency from 68 to 55% (Table 3). Universal adoption of mineral NPK and organic fertilizers would reduce the number of DALYs lost due to Zn deficiency from a baseline of 12,092 to 9854 thus saving 2238 DALYs year^{-1}. This would reduce the value of DALYs lost due to Zn deficiency to US$15.8 M, from a baseline of US$19.4 M year^{-1}, resulting in a net health benefit of US$3.6 M year^{-1} (Table 3).

Scenario 4

The universal adoption of mineral NPK and soil Zn fertilizers is estimated to increase dietary Zn supply from 9.3 (baseline) to 11.9 mg Zn capita^{-1} day^{-1}. This would reduce dietary Zn deficiency prevalence from 68 to 31% (Table 3). Under this scenario, the number of DALYs lost due to Zn deficiency would be halved, to 5,516 DALYs lost year^{-1} compared to a baseline of 12,092 or compared to 11,915 DALYs lost year^{-1} when mineral NPK fertilizer use alone is adopted by farmers currently applying nothing to maize (Table 3). This would reduce the value of DALYs lost due to Zn deficiency to US$8.8 M year^{-1}, from a baseline of US$19.4 M year^{-1}, resulting in a net health benefit of US$10.5 M year^{-1} (Table 3).

Scenario 5

The universal adoption of mineral NPK and soil Zn fertilizers, together with cattle manure is estimated to increase Zn supply from 9.3 (baseline) to 12.5 mg capita^{-1} day^{-1} (Table 3). This would reduce dietary Zn deficiency to 25% from a baseline of 68%. Under this scenario, 4486 DALYs will be lost due to Zn deficiency compared to a baseline of 12,092 (Table 3). This would reduce the value of DALYs lost due to Zn deficiency to US$7.2 M year^{-1}, from of a baseline of US$19.4 M year^{-1}, resulting in a net health benefit of US$12.2 M year^{-1} (Table 3).

Scenario 6

The universal adoption of mineral NPK and soil Zn fertilizers, together with locally available organic woodland leaf litter is estimated to increase dietary Zn supply from 9.3 (baseline) to 13.7 mg Zn capita^{-1} day^{-1} (Table 3). This would reduce dietary Zn deficiency to 17% from a baseline of 68%. Under this scenario, 2973 DALYs will be lost due to Zn deficiency compared to a baseline of 12,092 (Table 3). This would reduce the value of DALYs lost due to Zn deficiency to US$4.8 M year^{-1}, from of a baseline of US$19.4 M year^{-1}, resulting in a net health benefit of US$14.6 M year^{-1} (Table 3).

Net benefit from grain yield and DALYs burden changes in different soil fertility management scenarios

Using a farmgate price of US$390 tonne^{-1} of maize, the baseline value of maize under Scenario 1 (yielding 1119 kg ha^{-1}) is US$436 ha^{-1}, which translates to ~ US$590 M year^{-1} under the current maize production land area of 1,349,158 ha.[1] The adoption of mineral NPK fertilizer by farmers who are currently not adding any fertilizers to maize (Scenario 2), would potentially increase the national value of maize production to US$634 M year^{-1} (Table 3), which represents an additional US$44.8 M year^{-1}. The universal adoption of mineral NPK fertilizer and organic nutrient resources (i.e. cattle manure and woodland leaf litter) in Scenario 3 is estimated to increase the national value of maize production to US$789.6 M year^{-1} (Table 3). The universal adoption of mineral NPK and soil Zn fertilizers (Scenario 4) increases the value of national maize production to US$1105 M year^{-1} (Table 3). The universal adoption of mineral NPK and soil Zn fertilizers, together with cattle manure (Scenario 5) is estimated to increase the national value of maize production to US$1578 M year^{-1} (Table 3). The universal adoption of mineral NPK and soil Zn fertilizers, together with locally available organic woodland leaf litter (Scenario 6) is estimated to increase the value of maize production to ~ US$1789 M year^{-1} (Table 3).

The monetized value of DALYs saved combined with improved yields at a national level under the different scenarios, compared to Scenario 1 baseline, ranged from US$45 M to $ 1215 M (Table 3) with a yield:health ratio monetized-benefit ranging from 49:1 to 158:1 (Table 3). Scenario 2 had the largest yield:health benefit ratio where the monetary benefit in yield was more than two orders of magnitude greater than monetized value of DALYs saved. In all scenarios, monetized value of DALYs saved due to greater nutritional quality of grain is substantial but is still much smaller than the monetised yield benefit. For example, scenarios 3–6 had yield:health benefit ratios of 56, 49, 81 and 82:1; respectively (Table 3).

[1] FAOSTAT, 2017.

Discussion

Baseline Zn deficiency in Zimbabwe

The calculated baseline Zn deficiency prevalence of 68% in Zimbabwe is higher than the deficiency of ~ 40% reported by Kumssa et al. (2015) based on food supply data in 2011. In the absence of food supply data and Zn biomarkers, the International Zinc Nutrition Consultative Group (IZiNCG/WHO) recommends two other indicators for assessing Zn status at the population level: (1) percentage of children less than 5 years of age who are stunted (length- or height-for-age less than 2 SD below the age-specific median of the reference population) and; (2) prevalence of iron (Fe) deficiency anaemia (Brown et al. 2004). The latter is suggestive of Zn deficiency since Fe and Zn are found in the same food sources and are affected by the same inhibitors. The current stunting prevalence in Zimbabwe is 26.2% (Food and Nutrition Council/UNICEF/WFP, 2018). The last assessed prevalence of anaemia was 37% in children between 6–59 months, 27% in women and 15% in men between the age of 15–49 years (Zimbabwe National Statistics Agency and ICF International 2016). Findings from this work showed that if farmers who are currently not adding any fertilizer to maize start to apply mineral NPK fertilizer, Zn supply is increased by small margins of 1.1% thus reducing Zn deficiency of 1 person in every 100 people.

Role of different soil fertility management and Zn agro-fortification in reducing Zn deficiency and improving maize grain yields

Findings from our study showed that universal adoption of mineral NPK and organic fertilizers results in increased Zn supply, reduced Zn deficiency and number of DALYs lost due to Zn deficiency in rural households in Zimbabwe. The use of mineral NPK fertilizer, even without Zn fertilizer, has been reported to increase grain Zn concentration under field-grown maize (Manzeke et al. 2014) and in wheat (Kutman et al. 2011a,b) and rice (*Oryza sativa* L.; Jaksomsak et al. 2017) grown under glasshouse conditions. However, effects of universal adoption of mineral NPK and soil Zn fertilizer on increasing Zn supply are small with an increase in Zn supply of 11.9 mg capita^{-1} day^{-1} realized under this scenario from a baseline supply of 9.3 mg capita^{-1} day^{-1}.

While organic nutrient resources applied with mineral NPK fertilizer have potential to supply a small amount of Zn into soil (Manzeke et al. 2012; Manzeke et al. 2019) and potentially reducing Zn deficiency from a baseline prevalence of 68% to 55% (Scenario 3), it is the effect of organic material on rhizosphere processes which is likely to be primarily responsible for increases in plant-available soil Zn concentration through the formation of soluble organic Zn complexes (Alloway 2008). Findings from our recent survey in Mutasa and Hwedza Districts revealed a two-fold greater concentration of plant-available soil Zn on fields receiving organic nutrient resources, which could be attributed to the addition of extra Zn in the organic resources, which translated to larger grain Zn concentration (Manzeke et al. 2019) (also see Manzeke et al. 2012). Grain Zn concentration averaging 25.0 mg kg^{-1} (median 25.3) in maize was attained in most productive fields, which often receive organic inputs, compared with 23.0 mg Zn kg^{-1} (median 23.5) under low productivity fields which usually do not receive organic inputs (Manzeke et al. 2019). The biggest benefits of 47.3% increase in Zn supply and threefold decrease in Zn deficiency from the baseline are realized when Zn fertilizers are included with good soil fertility management (i.e. mineral NPK and organic nutrient resource management).

While good soil fertility management increased grain Zn concentration and potentially reduce dietary Zn deficiency, our findings show that the yield benefits of good soil fertility management far outweigh the monetized value of DALYs saved. Benefits of good soil fertility management in terms of maize productivity have been reported in similar cropping systems (Mtangadura et al. 2017; Mtambanengwe and Mapfumo 2006; Jama et al. 2017). These assumptions about the benefits from grain yields in this current study are sensitive to farm gate price. In 2019, the Government of Zimbabwe was paying ~ US$235 for a tonne of maize, however, even at these lower prices than used in this analysis, the monetary benefits of yield increase will still outweigh the monetized value of DALYs saved. Furthermore, substantial increases in yield from good soil fertility management could result in surplus grain which could widen dietary diversification in rural households. If the surplus grain earns income or is used as small and/or large livestock feed, alternative sources of dietary Zn (i.e. meat and eggs) could also be available.

The cost:benefit analysis of the different scenarios presented in this study can enable further exploration of which soil fertility management scenarios are likely to be most cost effective in terms of yield and quality. However, the different scenarios here cannot always be costed easily due to variation in, for example, fertilizer cost (Bonilla Cedrez et al. 2020), difficulties in costing labour inputs (i.e. woodland leaf litter collection), and uncertainties in the analysis of trade-offs (i.e. quantity vs quality of life) associated with the analysis. A benchmark for interpreting cost of a DALY saved of < US$260 has been defined as being very cost effective by the World Bank (World Bank 1993). Alternatively, according to WHO, if the cost of saving a DALY is < 1*GDP per capita; the intervention is also considered cost-effective (WHO 2003). Stein et al. (2005) considers standardized international values of US$500 and 1000 (Stein et al. 2005) as potential benchmarks for cost-effective interventions.

Possibility of adopting improved soil fertility management in low-input smallholder farming systems

Joy et al. (2017) previously used a DALYs framework to estimate the Zn deficiency-related disease burden in Pakistan, finding that a soil and foliar Zn fertilizer-use of 7.3 kt year^{-1} ($ZnSO_4.7H_2O$ and chelated Zn forms) could potentially increase dietary Zn supply from 12.6 to 14.6 mg capita^{-1} day^{-1}, and almost halve the prevalence of Zn deficiency to 24%. Interestingly, Joy et al. (2017) found that monetized benefits from improved nutritional quality of grain and yield increases were similar, rather than the substantial weighting towards yield benefits in this current study. This is likely to be because N-containing fertilizers (mostly urea) are already widely used by wheat farmers in Pakistan and, therefore, the yield gap is smaller than seen for maize production in Zimbabwe. The present study therefore suggests that efforts to increase adoption of better soil fertility management by smallholder maize farmers in Zimbabwe should focus on yield benefits, with the greater nutritional quality of grain and other co-benefits considered as ancillary benefits.

While a low average N use of 14 kg ha^{-1} has been reported for SSA compared with rates of 175 and 302 kg ha^{-1} in South America and East Asia respectively (Bonilla Cedrez et al. 2020), improved practices; including use of N-containing fertilizers (Cakmak and Kutman 2018) are a potentially useful strategy to reduce Zn deficiencies in maize-based cropping systems in Zimbabwe and more widely in SSA. In recent field experiments, Manzeke et al. (2020) showed that use of mineral NPK fertilizers together with soil and foliar Zn fertilizer increased maize grain Zn concentration by 19–40% compared to use of Zn fertilizer alone. Greater Zn concentration in cereal grains grown on high organic matter soils have also been observed by Wood et al. (2018) in Ethiopia. Although collection of woodland leaf litter is laborious and may only be accessible to farmers close to uncultivated land and mountain ranges, woodland leaf litter has benefits of improving soil moisture retention in addition to its local availability and supplying of Zn to the soil (Manzeke et al. 2012; Wood et al. 2018). To realize potential quality benefits of harvested grain, we propose that smallholder farmers should be supported with NPK fertilizer subsidies by the Government and increase use of locally available organic nutrient resources.

The study is designed to be a framework rather than an exhaustive test of various assumptions. For example, adoption rates, fluctuations in market prices of maize, and national GDP values will have potentially large effects on the cost:benefit analysis reported here. Further studies could use sensitivity analyses to explore further these factors. Whilst the scenarios explored in this study are locally appropriate, i.e. they could feasibly be adopted by some farmers in Zimbabwe, it is unlikely they could be universally adopted due to the cost of inputs being beyond the reach of many farmers. Another limitation of the study is using dietary Zn supply as a proxy measure of Zn intake, which is not the only factor affecting Zn status (King et al. 2016). Other factors including variable individual requirements (IOM, 2000), bioavailability of Zn (Wise 1995; Sandstrom 1997; IOM 2001; Gibson et al. 2015) and food processing techniques e.g. extent of milling (Brown et al. 2004) and fermentation (Gabaza et al. 2016) would need to be taken into consideration. The effectiveness of agro-fortification technologies under diverse farmer field conditions compared with researcher managed field experiments would also need to be taken into account.

Conclusions

Soil fertility management interventions with mineral NPK and organic nutrient inputs and Zn fertilizers can increase dietary Zn supply and promote Zn cycling in cropping systems. Our DALYs analysis shows that complementary interventions can be evaluated to potentially inform agriculture, nutrition, and health policies, where local experiments have been conducted. The monetized benefits of a reduction in Zn deficiency, estimated using standard methodologies, are dwarfed by yield benefit due to large N-related yield gaps. While it would be technically feasible to adopt the scenarios in low-input smallholder settings in Zimbabwe and similar agro-ecologies, universal adoption of improved soil fertility management is unlikely in the short-term due to input costs. For a more comprehensive analysis, geospatial variation in baseline Zn supply, variable individual Zn requirements, Zn bioavailability in humans, and the role of improved access to dietary diversification (including non-plant foods) would need to be considered in more in-depth analyses, together with a formal cost–benefit analysis of input costs.

Abbreviations

DALYs: Disability Adjusted Life Years; EAR: Estimated average requirement; EDTA: Ethylene-diamine tetra acetic acid; FBSs: Food balance sheets; NR: Natural region; SSA: Sub-Saharan Africa; Zn: Zinc.

Supplementary Information

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Additional file 1. Data set used for maize grain yield, dietary Zn supply and Disability Adjusted Life Years quantification.

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Authors' contributions
All authors contributed to the conceptualization of the paper. M.G.M.-K and E.J.M.J. conducted the analyses and wrote the initial draft. All authors contributed to the final draft of the paper. All authors have read and approved the final manuscript.

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Availability of data and materials
Published data used for secondary DALYs analyses are available online in Manzeke et al. 2012, 2014 and other cited sources.

Declarations

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Not applicable.

Consent for publication
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Competing interests
The authors declare that they have no competing interests.

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