Variation in Crop Zinc Concentration Influences Estimates of Dietary Zn Inadequacy

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Abstract

**Background:** Zinc (Zn) deficiency is one of the most common micronutrient deficiencies worldwide. Accurate estimates of Zn intake would facilitate the design and implementation of effective nutritional interventions.

**Objective:** We sought to improve estimates of dietary Zn intake by evaluating staple crop Zn content and dietary Zn consumption by children under the age of 5 in 9 rural districts of Uganda.

**Methods:** We measured the Zn content of 748 crop samples from household farms and markets, and administered food frequency questionnaires to the primary caretakers of 237 children. We estimated Zn consumption using 3 sources of crop Zn content: (i) the HarvestPlus food composition table (FCT) for Uganda, (ii) measurements from household crops, and (iii) measurements from market crops.

**Results:** The Zn content of staple crops varied widely, resulting in significantly different estimates of dietary Zn intake. 41% of children appeared to be at risk when estimates were based on market-sampled crops, 23% appeared at risk when estimates are based on the HarvestPlus FCT, and 16% appeared at risk when estimates are based on samples from household farms.

**Conclusion:** The use of FCTs to calculate Zn intake overestimated the risk of dietary inadequacy for children who primarily consumed food that was produced on household farms, but underestimated the risk for children who primarily consumed food that was purchased at market. More information on the Zn content of staple crops in developing countries could lead to more accurate estimates of dietary intake and associated deficiencies.
1 Introduction

Zinc (Zn) deficiency is widespread and has severe global health implications. Zn deficiency is associated with poor birth outcomes, reduced growth and cognitive development of infants and children, increased diarrhea and acute lower respiratory infections, and compromised immune function [49, 30, 24]. At least 17% of the global population is at risk of Zn deficiency, with the highest burden in Africa and Sub-Saharan Africa [55]. Children are particularly vulnerable: 116,000 child deaths in 2011 were attributed to Zn deficiency [7], and Zn supplementation is one of the most impactful nutrient interventions for reducing child mortality [6].

To design and implement policies that will improve human Zn nutrition, it is necessary to accurately estimate Zn deficiency rates within a given population. Representative samples of individual blood plasma or serum Zn concentrations can be used to estimate population-level Zn deficiency rates. However, the sampling and measurement of blood Zn concentrations at a nationally or regionally representative level is difficult and expensive. Instead, population-level Zn status is often inferred from the prevalence of Zn intake below the estimated average requirement (EAR) [19, 41, 36, 55]. Typically, these estimates are calculated using surveys of a population’s dietary habits or national food balance sheets, and the “average” Zn content of these foods as reported in food composition tables (FCTs) [54].

However, several studies have shown that estimates of population-level Zn deficiency rates based on nationally-representative measurements of blood Zn concentration do not correspond with population-level estimates of inadequate dietary Zn intake. In a study of 20 middle- or low-income countries for which nationally-representative data were available, Zn deficiency rates based on plasma or serum Zn concentrations were poorly correlated with estimates of dietary Zn inadequacy rates, which generally underestimated the number of women and children who were Zn deficient [27]. Similar incongruity has been found in other studies. For instance, of women surveyed throughout Cameroon, those in the north reported the highest Zn intake via 24-hour dietary recall but suffered the lowest Zn status in the country [13]; prevalence of dietary Zn inadequacy in children rose by a factor of 5 between 2002 and 2012 in China, while deficiency rates dropped by a factor of 4 [44]. Similar discrepancies exist in Serbia [38], Australia [29], Bangladesh [50], India [26], and Benin [16]. These discrepancies are partially due to variation in Zn bioavailability, which is dependent on phytate intake and other physiological factors, and is difficult to measure [8, 47, 17].

Here, we postulate that these discrepancies may also be explained by a second factor: a large variation in food Zn concentration that is not captured currently by the FCTs used to estimate dietary Zn intake. Although it is well known that environmental conditions and agricultural practices drive heterogeneity in crop Zn concentrations [2, 1, 4, 9], most FCTs consist of Zn concentrations measured in samples collected in the United States or western Europe, rather than samples representative of the food supply available in the particular country of interest [32, 53, 37]. For instance, almost all of the nutrient concentrations reported in the HarvestPlus FCT for Uganda are based on the values reported in the United States Department of Agriculture’s FCT, despite the fact that recipes used to create the FCT are specific to Uganda. To our knowledge, Ethiopia is the only African country for which there is an FCT based on nutrient contents measured in
crop samples collected from within the country, but Zn concentrations are not reported in this FCT [20].

Thus, there are two major factors that limit accurate predictions of dietary Zn adequacy: 1) unknown variation in Zn consumption due to heterogeneity in crop Zn concentrations and 2) unknown rates of Zn absorption due to variation in Zn bioavailability. While the latter is a well-documented contributor to human Zn status, no published work to date has investigated the effect of crop Zn heterogeneity on estimates of dietary Zn intake. Although some scientists and practitioners recognize that the food nutrient concentrations reported in FCTs may be inaccurate [16, 56], most authors using FCTs to infer nutrient deficiencies do not acknowledge or address this limitation directly. The degree of measurement error introduced by these FCTs has not been previously quantified and the implications of the potential error are unknown.

In this paper, we examine staple crop Zn heterogeneity in rural Uganda and explore how this heterogeneity affects estimates of Zn consumed by individual children and subsequent estimates of the prevalence of inadequate dietary Zn intake at the population level. To this end, we employ a unique dataset that combines household survey data, Zn concentration measured in staple crops collected from 9 rural districts of Uganda, and food intake data for children living in households engaged in subsistence agriculture. Using food frequency questionnaire data to assess patterns of consumption for children under the age of 5, we estimate dietary Zn intake and Zn inadequacy rates based on three different sources of staple crop Zn concentrations: 1) the HarvestPlus FCT created for Uganda, 2) the Zn values measured in 581 food samples that were grown by households engaged in subsistence agriculture in 9 rural districts of Uganda, and 3) the Zn values measured in 167 food samples purchased from 32 local markets throughout the same 9 districts. Finally, we compare the resulting estimates to explore the degree to which Zn intake is accurately estimated by existing FCTs.

2 Methods

Data

Household survey data were collected from 9 districts of the western, northern, eastern and lakes regions of Uganda during the summer of 2013, as mapped in Figure 1 [5]. Households included in the survey were engaged in subsistence agriculture. Crop samples were collected from household farms at the time of survey. Six staple crops were sampled from each household, if present: maize, sorghum, sweet potato, cassava, beans and groundnuts. A total of 581 crop samples were collected from 282 households in the weeks during and after harvest, as mapped in Figure 2. Only crops produced on a household’s land were included in household-level samples; crops purchased from market were never sampled. For grains and legumes, surveyors subsampled crops from ten locations within each plot. Because cassava and sweet potato are less easily divisible, surveyors subsampled these crops from five or six plants within each plot. The total mass of each composite crop sample collected from a plot was equal to one kg or more. This sampling scheme was chosen to obtain a representative sample of the crop Zn content within each plot [46, 45, 36, 11]. Food samples were also collected from the rural markets nearest these households. Maize flour, cassava flour, millet flour, cowpeas, white rice, and matooke
(a cooking banana used as a staple) were collected from markets. In total, 167 samples from 32 markets were collected. Together, the crops collected from both households and markets include all primary staple crops consumed in Uganda.

Prior to nutrient analysis, all samples aside from the flour samples were brushed and washed with distilled water to remove soil and dust particles, air-dried, ground to pass through a 2.0 mm sieve using a stainless steel mill, and homogenized. Subsamples of 0.5 g were digestion in 5.0 ml of nitric acid and 2.0 ml of perchloric acid. The elemental composition of digested subsamples was measured using an axially viewed Spectro Arcos ICP-AES (Spectro Arcos, Kleve, Germany). Blanks and standard reference materials were run throughout in order to ensure consistency and quality of the ICP-AES analysis. For Zn, three positions were monitored, located at 202.613, 206.200, and 213.856 nm. Visual inspection of the signal at each position ensured that measurements were not impeded by interference between elements. Our subsequent analysis is based on the Zn concentrations measured at 206.200 nm because this position is less prone to fluctuations in plasma conditions. Additionally, Yttrium was used as an internal standard, to correct for instrument drift and matrix interferences. The limit of detection for Zn at 206.200 nm was 0.00308 ppm. This is far below the lowest Zn concentration measured among our samples.

A food frequency questionnaire assessing dietary Zn intake was conducted for one child per household. Children selected for the questionnaire were between 6 months and 5 years of age, present at the time of the survey, and not exclusively breastfed. If multiple children in a household fit these criteria, surveyors chose the oldest biological child of the household head. The food frequency questionnaire was designed and validated using 24-hour food recall data gathered in central and eastern Uganda by Harvestplus for children under 5 [31]. The procedure followed a HarvestPlus technical document [18]. Fifty-two commonly consumed plant- and animal-based foods were included in the questionnaire, in order to capture 98% of total Zn intake in the 24-hour recall data. Because the 2013 food frequency questionnaire included districts in western Uganda as well as in central and eastern Uganda, the food list was expanded to contain a few dishes consumed in western Uganda. Portion sizes (small, medium and large) were chosen as the 25th, 50th, and 75th quantile of portion size weight in the food recall data.

The questionnaire was administered to the primary caregivers of 237 children, who were asked to report how many times their child had consumed each food in the preceding week and the average portion size of each food consumed. To assist caregivers in their estimates of portion size, photographs of small, medium, and large portions were provided. The plate depicted in the photograph was brought to each home for scale (see Appendix in the Supplemental Material). In 99 cases, a second food frequency questionnaire was administered within 1-4 weeks of the first, allowing us to assess weekly variation an individual in child’s diet.

**Statistical Analysis**

To examine heterogeneity in crop Zn concentration, we used univariate kernel density estimation to estimate the distribution of Zn concentration for each of the staple crops collected. We performed this analysis in Stata using the *kdensity* command, an Epanechnikov kernel function, and the optimal bandwidth choice to minimize mean squared error.
We compared the distributions of the Zn concentrations measured in cereals, legumes, and tubers sampled from household farms, and tested their equivalence using a Kolmogorov-Smirnov test. We also compared the distributions of the Zn concentrations measured in crops sampled from markets. In cases where comparable crops were sampled at the household and market level, we compared the distributions of household-sampled crops to market-sampled crops, and tested their equivalence: maize grain vs. maize flour, sorghum grain vs. millet flour, and cassava tubers vs. cassava flour. Alongside these distributional assessments, we also examined summary statistics (minimum, maximum, median, mean, and standard deviation) for the Zn concentration of each crop. For each crop, we compared the mean Zn concentrations to the FCT values using a single sample t-test, and the median Zn concentrations to the FCTs value using a single sample Wilcoxon test.

We estimated dietary Zn intake (mg day$^{-1}$) for each child using 3 sources of values for staple crop Zn concentration: (1) those reported in the HarvestPlus FCT, (2) the median concentrations measured in crops sampled at local markets, and (3) the median concentrations measured in crops sampled from household farms. The second estimate, based on Zn values measured in crops from local markets, represents the risk of dietary Zn inadequacy for children who primarily consume staples purchased at market. The third estimate, based on Zn values measured in crops from household farms, represents the risk of dietary Zn inadequacy for children who primarily consume staples produced by households engaged in subsistence agriculture. Since the Zn concentrations of crops sampled from households were quite heterogeneous, we also calculated two additional estimates of Zn intake to represent variation in the potential range of dietary Zn intake from crops produced on household farms. These two additional estimates were calculated using the 25th and 75th percentile of Zn concentrations measured in samples collected from households.

When estimating Zn intake based on crops purchased at market, we replaced the FCT Zn concentrations of maize grain and flour, sorghum/millet grain and flour, cassava tubers and flour, rice, matooke, and cowpeas with the median Zn concentrations measured in maize flour, millet flour, cassava flour, rice, matooke, and cowpea samples collected from local markets. When estimating Zn intake based on crops produced at households, we replaced the FCT Zn concentrations of maize grain and flour, sorghum/millet grain and flour, cassava tubers and flour, beans, groundnuts, and sweet potatoes with the median Zn concentrations measured in maize grain, sorghum grain, cassava tubers, beans, groundnuts, and sweet potatoes collected from households. For both estimates, we used the Zn concentrations reported in the HarvestPlus FCT to calculate Zn intake from all foods that were not sampled in the relevant location. For each estimate we combined the quantity of millet and sorghum consumed and assigned the same Zn concentration to the total quantity consumed of both crops. This was also done in the FCT estimate because the HarvestPlus FCT lists the same Zn concentration for both sorghum and millet. Finger millet—the primary form of millet grown in Uganda—has a very similar Zn content to sorghum [15, 42, 25]. Pooling the two crops for all estimates provides a market-based counterfactual for sorghum consumption (though sorghum was sampled only at households) and a household-based counterfactual for millet consumption (though millet was sampled only at markets). Additionally, the HarvestPlus FCT applies USDA retention codes to account for nutrient loss due to cooking processes. We applied the same retention codes to account for Zn loss from cooked staples in the Zn intake estimates based
on market-purchased and household-produced foods.

Most families in Uganda process their maize grain at local mills prior to consuming it as flour. Because this process likely results in nutrient loss, we adjusted the Zn concentration of household-sampled whole maize grain down by 50% when it was consumed as maize flour. A wide range of Zn loss can occur when whole maize grain is processed into flour: a study in Benin reported an 11% decrease in Zn when maize was ground into flours at local mills [22], 18% of Zn was lost when maize was ground into the course flour product masa [23], while up to 57% of Zn was lost when maize flour was refined in Malawi [33]. FCTs also report variable differentials between the Zn concentration of maize grain and maize flour [39, 32]. We chose to reduce the Zn concentration of maize that was produced on household farms but consumed as flour by 50% because this provides a statistically conservative estimate of dietary Zn intake. We did not reduce the Zn concentration of household-grown millet and sorghum when they were consumed as flour because studies have shown that milling does not result in appreciable Zn loss from these crops [43, 14, 40, 48].

Thirty-nine of 231 children, aged 6.7-53.2 months, were still breastfeeding at the time of interview. Because breastfed children consumed a portion of dietary Zn through breast-milk, we treated breastfeeding status as a nuisance parameter and adjusted Zn intake estimates upwards for breastfeeding status. To do so, we regressed intake on age in months, breastfeeding status (a binary variable), and an interaction between the two, and then adjusted intake up according to the age-specific effect of breastfeeding. Although the average age of children who were breastfeeding was lower than the age of those who were not, there was sufficient overlap to calculate the age-specific effect of breastfeeding. Because a non-linear effect of age did not contribute to a higher R², we retained the linear model.

The food frequency questionnaire was administered a second time to the caregivers of 99 children a few weeks after the first questionnaire. Intra-subject variation was negligible, accounting for only 5% of total variation. This suggests that the food frequency questionnaire successfully captured “usual” Zn intake for children under the age of 5 in the households sampled. However, to gauge the effect of intra-subject variability, we adjusted intake following the simplified Nusser procedure proposed by Hoffmann et al. [28]. The procedure was performed in Stata. The distributions of the usual intake estimates created through this procedure were slightly less variable than the original estimates of Zn intake. For example, the adjusted intake based on Zn values reported in the HarvestPlus FCT had a standard deviation of 17.39, while unadjusted intake had a standard deviation of 18.96. However, the change in distribution was so slight that the Nusser adjustment did not result in a difference in the predicted rate of dietary Zn inadequacy for estimates based on the HarvestPlus FCT or based on crops sampled from market, and resulted in only a 1% difference for the estimate based on crops sampled from households. We therefore used the original Zn intake estimate for our main analysis, averaging the two Zn intake estimates for children from whom the food frequency questionnaire data was collected twice.

We estimated the prevalence of inadequate dietary Zn intake using the cut-point method and the age-specific EAR recommended by International Zinc Nutrition Consultative Group (IZiNCG) for unrefined cereal-based diets [8]. Since we did not measure the quan-
tity of phytates consumed by each child, we were unable to adjust for variation in Zn bioavailability due to phytates. However, because the diets of all children in this study were cereal-based, these EARs were appropriate for the children in this study. We bootstrapped the standard errors around prevalence of inadequate dietary Zn intake predicted from each of the three sources of staple crop Zn concentrations: the values reported in the HarvestPlus FCT for Uganda, the staple crops sampled from local markets, and the staple crops sampled from households engaged in subsistence farming.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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3 Results

Crop Zn Heterogeneity

The Zn concentrations of staple crops grown and consumed within a household Uganda were highly heterogeneous within each crop type. The maximum Zn concentrations measured in sorghum and maize were 16 and 20 times higher than the minimum concentrations measured, respectively (Figure 3 and Table 1). The log-normal distribution of crop Zn concentration suggests that median Zn concentration values are more representative than the average Zn concentration values that are usually reported in FCTs and used to estimate dietary Zn intake. Although the Zn concentration of legumes is thought to be higher than that of cereals [32, 54]), the distributions measured in our samples were similar: median Zn concentrations of sorghum, beans and groundnuts were within half a standard deviation of the median Zn concentration of maize (Table 1). Median Zn concentration in legumes (33.75 ppm) was only slightly higher than median Zn concentration in cereals (31.37 ppm) with only a marginally significant difference (Wilcoxon test \( p = 0.056 \)). Conversely, both the median and the distribution of tuber Zn concentration were significantly different from those of other crops (\( p < 0.001 \) using a Wilcoxon and Kolmogorov-Smirnov test, respectively).

According to a Wilcoxon test, the HarvestPlus FCT for Uganda does not represent the median crop Zn concentrations of 4 of the 6 staple crops sampled from household farms in our study. The median Zn concentration of sweet potatoes produced on household farms was 40% lower than reported by the HarvestPlus FCT. The median Zn concentrations of maize and sorghum produced on household farms were both 60% higher than the values reported in the HarvestPlus FCT. The Zn concentration of cassava reported in the FCT is only 6% lower than the concentration measured in household samples, but this difference
is significant \( p = 0.003 \). For the remaining 2 staple crops collected from households—groundnuts and beans—the Zn concentrations measured in our samples correspond with the values reported in the HarvestPlus FCT.

The Zn concentrations of market-sampled crops were less heterogeneous than those collected from household farms, but the FCT again does not represent the median Zn concentrations of 4 of the 6 crops. The mean Zn concentration measured in our samples (6.6 ppm) is statistically indistinguishable from the mean concentration of 5.6 ppm reported by Tidemann-Andersen et al. [52] for maize flour samples purchased from Ugandan markets \( p = 0.411 \)^1 However, due to the skewed distribution of the Zn concentrations, the median value provides a better representation of the “typical” maize flour found at market than the mean. The median Zn concentration of matooke samples collected from markets was more than twofold higher than the value reported in the HarvestPlus FCT (Table 2). However, the median Zn concentrations of maize flour, cassava flour, and cowpeas samples collected from markets were approximately 50%, 70%, and 66% lower than the values reported in the FCT, respectively (Table 2 and Figure 4). The median Zn concentrations of millet flour and rice measured in our samples correspond with the values reported in the HarvestPlus FCT. It is worth noting that the mean Zn concentration measured in maize flour samples is almost twofold higher than the median, due to the highly skewed distribution (Table 2 and Figure 4).

The Zn concentrations measured in flours sampled from market were significantly lower than the Zn concentrations measured in whole foods sampled from household farms (Figure 5, \( p < 0.001 \) for each pair based on either a two sample t-test of means or a two sample Wilcoxon test of median equivalence). Most notably, the Zn concentration of maize flour sampled from market was only 10% of the median Zn concentration measured in whole maize grain collected from household farms (3.8 and 38.3 ppm Zn, respectively). Between 11-60% of this difference may be due to processing, which removes part or all of the grain germ and pericarp [33, 22, 53]. The remaining difference between Zn concentration in maize grain and in flour samples may be due to an underlying difference in nutrient concentrations of crops grown on household farms and sold at local markets. The Zn concentrations of cassava flour collected from markets was 30% lower than that of cassava tubers collected from household farms. Since the cassava tubers sampled from household farms were peeled and dried in the laboratory, as they would have been prior to being ground into flour for market, processing loss should not be responsible for the observed difference in Zn content. Similarly, the 33% decrease in median Zn concentration of millet flour compared to whole sorghum grain sampled on farms may be due to nutrients lost during milling, but generally such loss is not observed [43, 14, 40, 48]. In all three cases, consumption of the whole crop or of whole-grain flour rather than refined flour would result in higher dietary Zn intake.

**Implications for Child Zn Intake Estimates**

The results of the food frequency questionnaire suggest that the majority of both the caloric intake and Zn intake by children participating in this study are derived from

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1The Zn concentration in ppm Zn per dry material was calculated by the authors. Tidemann-Andersen et al. [52] report sample values as 4.2, 3.6, and 7.0 mg kg\(^{-1}\) wet matter. According to the reported moisture content of maize flour, this is equivalent to 4.77, 4.09, and 7.95 ppm dry matter, resulting in a mean value of 5.6 ppm and a median value of 4.8 ppm.
staple crops. Of the dietary consumption captured by our food frequency questionnaire, cereals alone contributed 38% of estimated total caloric intake and 33% of estimated total Zn intake for the median child in our study, when Zn intake is estimated according to the HarvestPlus FCT. Legumes, nuts, and seeds provided 16% of the calories and 28% of the Zn consumed by the median child. Tubers, generally considered minor contributors to mineral intake, contributed 19% of the calories and 11% of the Zn consumed. The median child in our study consumed 85% of her caloric intake and 84% of her Zn intake through a combination of only cereals, legumes, nuts, seeds, and tubers. Animal-based foods contributed only 4% of observed calorie intake and 9% of Zn intake for the median child, most of which was due to milk and fish consumption.

Due to a diet that is highly dependent on staple crops for total caloric intake, the population of children participating in this study is vulnerable to heterogeneity in staple crop Zn concentration. Estimates of dietary Zn intake varied significantly depending on the values of staple crop Zn content used to calculate the prevalence of inadequate dietary Zn intake (Kolmogorov-Smirnov test $p < 0.001$, Figure 6). Estimates of dietary Zn intake based on the HarvestPlus FCT suggested that median Zn intake was 28 mg week$^{-1}$ and that 23% of children were at risk of inadequate dietary Zn intake. Estimates based on the Zn values measured in samples collected from markets suggested that Zn intake was 21 mg week$^{-1}$ and that 41% of children were at risk of inadequate dietary Zn intake. Estimates based on the Zn values measured in samples collected from households suggested that Zn intake was 35 mg week$^{-1}$ and that 16% of children were at risk of inadequate dietary Zn intake. A prevalence of inadequate dietary Zn intake greater than 25% is considered elevated [10]. Thus, our results suggest that children whose primary dietary intake comes from household-produced staples are not at elevated risk for dietary Zn inadequacy. However, children whose primary dietary intake comes from market-purchased staples do appear to be at elevated risk for dietary Zn inadequacy.

Even within the population of children who primarily consume food crops produced at household farms, the risk of inadequate Zn intake varied considerably due to the wide distribution of crop Zn concentrations measured in samples collected from those households (Kolmogorov-Smirnov test $p < 0.001$, Figure 7). When Zn intake was calculated according to the 25th percentile of Zn concentration in household-sampled crops, 23% of children appeared to be at risk of inadequate intake. However, only 10% appeared to be at risk of inadequate dietary Zn intake when Zn intake was estimated according to the 75th percentile of household-sampled crops. Intake of animal-based foods was correlated with an increase in calorie and Zn intake via the consumption of both animal- and plant-based foods, for all children participating in the study, thereby decreasing the risk of dietary Zn inadequacy.

4 Discussion

Our findings suggest that in rural Ugandan households, where meat and eggs are rarely consumed, 84% of dietary Zn intake in children under the age of 5 is consumed from plants-based foods. Over 75% of Zn intake is derived from only 7 staple crops (maize, sorghum, millet, beans, ground nuts, cassava, and sweet potatoes) and over 40% is derived from maize and beans alone. While our data may not be representative of the entire population of children under the age of 5 in Uganda, our data include households that...
are located in 9 districts of rural Uganda, representing every agro-ecological zone in the country. A similar dependence on plant-based foods is common in much of sub-Saharan Africa and South Asia, often accompanied by low dietary diversity and risk of Zn deficiency [52, 12, 21]. Although the risk of Zn deficiency in populations whose diets consisting primarily of staple crops is well-recognized, the implications of variation in crop Zn concentration for human Zn status have not been documented.

We show that for populations who consume Zn primarily from plant-based foods, an accurate assessment of Zn concentration in local staple crop supplies is necessary in order to predict the prevalence of inadequate dietary Zn intake. Staple crop Zn concentrations reported in the HarvestPlus FCT led to an overestimate of the prevalence of inadequate dietary Zn intake for Ugandan children under the age of 5, but an underestimate of the prevalence of inadequate dietary Zn intake in children who primarily consume staple crops purchased at market. This discrepancy has widespread implications for our understanding of the global burden of Zn deficiency in young children. While under-estimating the risk of Zn deficiency may lead to inaction and continued loss of life, over-estimating the risk of Zn deficiency has the potential to waste considerable resources [44]. Furthermore, the observed difference between Zn concentration in crops produced on household farms and those sampled at markets suggests greater vulnerability to Zn deficiency in urban areas, and in rural areas during the lean season when African smallholder households are most dependent on food purchased at market [51, 34, 3]. These patterns of vulnerability are not reflected in the Zn intake estimates based on existing FCTs.

More accurate information regarding the Zn concentration of staple crops in developing countries would likely lead to more accurate estimates of the prevalence of dietary Zn inadequacy. For instance, if high-yielding hybrid cereals have lower Zn concentrations than local African varieties and are more commonly grown for sale at market than other local varieties, this could drive lower Zn intake in urban areas compared to rural areas. Local maps of soil characteristics and soil Zn availability may also be used to assess regional vulnerability to crop Zn deficiency and subsequent dietary inadequacy [35]. Country-specific or sub-national data on crop Zn concentration, gathered through widespread sampling, might illuminate spatial patterns in crop Zn concentration and human Zn intake. Such data could be used to create country-specific FCTs, similar to the work conducted in Ethiopia [20]. It is likely that the estimated prevalence of Zn inadequacy based on such tables would more closely reflect actual deficiency rates than those based on existing tables. Since current estimates of global human Zn status predict that over 2 billion people are affected by Zn deficiency, this work is relevant for a large portion of the world’s population, and particularly those highly reliant on plant-based foods for their nutrient intake.

**Contributors**

LB designed the food frequency survey and data collection procedures, and was the country coordinator for the data collection and household surveys. LB also conducted the statistical analyses, with critical insight and suggestions from RH. Both authors contributed to the writing of the manuscript and approved the final version of the manuscript.

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References


## Tables

### Table 1: Zn Concentration (ppm dry material) in Household Samples

<table>
<thead>
<tr>
<th>Sample Values</th>
<th>min</th>
<th>median</th>
<th>mean</th>
<th>max</th>
<th>sdev</th>
<th>FCT Value</th>
<th>% &lt; FCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize grain</td>
<td>6.3</td>
<td>38.3***</td>
<td>42.3***</td>
<td>127.5</td>
<td>19.9</td>
<td>23.8</td>
<td>7.1</td>
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<td>Sorghum grain</td>
<td>11.6</td>
<td>28.2***</td>
<td>34.1***</td>
<td>184.6</td>
<td>23.9</td>
<td>17.6</td>
<td>6.5</td>
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<tr>
<td>Sweet potato</td>
<td>4.2</td>
<td>7.7***</td>
<td>10.7*</td>
<td>90.2</td>
<td>11.7</td>
<td>12.9</td>
<td>85.1</td>
</tr>
<tr>
<td>Cassava</td>
<td>3.2</td>
<td>7.9***</td>
<td>10.0***</td>
<td>43.4</td>
<td>6.5</td>
<td>7.4</td>
<td>45.4</td>
</tr>
<tr>
<td>Beans</td>
<td>19.7</td>
<td>33.7</td>
<td>34.5**</td>
<td>74.5</td>
<td>8.3</td>
<td>32.8</td>
<td>42.4</td>
</tr>
<tr>
<td>Groundnuts</td>
<td>21.7</td>
<td>34.0</td>
<td>61.4</td>
<td>427.6</td>
<td>80.8</td>
<td>34.7</td>
<td>50.0</td>
</tr>
</tbody>
</table>

Stars denote T-test of mean and Wilcoxon test of median equality to FCT,

* *** p<0.01, ** p<0.05, * p<0.1

Source for FCT values:
- Maize grain: HP 1001/1004 from USDA-21 20014
- Sorghum grain: HP 1105 from WFDA 1010 (Senegal)
- Sweet potato: HP 3003 from USDA-21 11507
- Cassava: HP 2001 from USDA-21 11134
- Beans: HP 6121 from USDA-21 16027
- Groundnuts: HP 8015 from USDA-21 16087

### Table 2: Zn Concentration (ppm dry material) in Market Samples

<table>
<thead>
<tr>
<th>Sample Values</th>
<th>min</th>
<th>median</th>
<th>mean</th>
<th>max</th>
<th>sdev</th>
<th>FCT Value</th>
<th>% &lt; FCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize flour</td>
<td>1.5</td>
<td>3.8**</td>
<td>6.6</td>
<td>24.4</td>
<td>6.5</td>
<td>7.9</td>
<td>70.0</td>
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<tr>
<td>Millet flour</td>
<td>13.7</td>
<td>18.6</td>
<td>18.7</td>
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<td>2.3</td>
<td>18.8</td>
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<tr>
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<td>2.8</td>
<td>5.3***</td>
<td>5.5***</td>
<td>8.2</td>
<td>1.3</td>
<td>7.7</td>
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<td>Cowpeas</td>
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<td>30.5***</td>
<td>32.0***</td>
<td>39.5</td>
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<td>10.4</td>
<td>15.5***</td>
<td>15.6***</td>
<td>20.9</td>
<td>2.6</td>
<td>13.8</td>
<td>19.4</td>
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<td>Matooke</td>
<td>5.6</td>
<td>6.8***</td>
<td>7.0***</td>
<td>10.6</td>
<td>1.1</td>
<td>2.9</td>
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Stars denote T-test of mean and Wilcoxon test of median equality to FCT,

* *** p<0.01, ** p<0.05, * p<0.1

Source for FCT values:
- Maize flour: HP 1041 from USDA-21 20522
- Millet flour: HP 1104 from USDA-21 20031
- Cassava flour: HP 2020 from WFDA 10120 (Indonesia)
- Cowpeas: HP 6211 from USDA-21 11191
- White rice: HP 1201 from USDA-21 20450
- Matooke: HP 5001 from USDA-21 9277
Figures

**Figure 1:** Interviewed Children

**Figure 2:** Sampled Crops

**Figure 3:** Zn Concentration (ppm dry material) in Household Samples

FCT sources listed under Table 1
**Figure 4:** Zn Concentration (ppm dry material) in Market Samples

![Graph showing Zn Concentration in Market Samples](image)

FCT sources listed under Table 2

**Figure 5:** Zn Concentration (ppm dry material) by Comparable Farm-Market Pairs

![Graph showing Zn Concentration in Farm-Market Pairs](image)

FCT sources listed under Tables 1 and 2
**Figure 6:** Prevalence of Inadequate Dietary Zn Intake by Concentration Source

*Left: Proportion of children with inadequate dietary Zn intake (intake < EAR).*

*Right: Kernel density distributions for estimated weekly Zn intake.*

In both graphics, “Market” denotes staple Zn concentrations based on median Zn concentration in market-based samples, “FCT” denotes staple Zn concentrations from the HarvestPlus food concentration table, and “House” denotes staple Zn concentrations from median Zn concentration in household samples.
Figure 7: Prevalence of Inadequate Dietary Zn Intake by Household Concentration Quantile

Left: Proportion of children with inadequate dietary Zn intake (intake < EAR).
Right: Kernel density distributions for estimated weekly Zn intake.
In both graphics, “25th” denotes staple Zn concentrations based on the 25th percentile Zn concentration in household samples, while “50th” and “75th” denote staple Zn concentrations based on the median and 75th percentile Zn concentration in household samples, respectively.
Online Appendix

**Figure A1:** Portion Size Picture of Mukene (Small Fish)

**Figure A2:** Portion Size Picture of Katogo (Cassava & Beans)
<table>
<thead>
<tr>
<th>Table A1: Food Frequency Questionnaire</th>
<th>How many times eaten in the last week?</th>
<th>Average portion size? (small, medium, large)</th>
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<tbody>
<tr>
<td>Mugoyo/ Amukeke</td>
<td>Sweet potatoes &amp; beans 1</td>
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</tr>
<tr>
<td></td>
<td>Sweet potato only 2</td>
<td></td>
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<tr>
<td>Katogo</td>
<td>Cassava 3</td>
<td></td>
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<tr>
<td></td>
<td>Cassava &amp; beans 4</td>
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</tr>
<tr>
<td></td>
<td>Cassava &amp; gnuts 5</td>
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<tr>
<td></td>
<td>Matooke only 6</td>
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<td></td>
<td>Matoke, gnuts 8</td>
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<tr>
<td>Posho</td>
<td>Posho (maize) 9</td>
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<tr>
<td>Atap</td>
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<tr>
<td></td>
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<td>Porridge</td>
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<td>Mukene, plain 40</td>
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<td>Mangos 52</td>
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