



# Widespread heterogeneity in staple crop mineral concentration in Uganda partially driven by soil characteristics

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**Abstract** Calcium (Ca), iron (Fe), selenium (Se), and zinc (Zn) deficiencies are widespread in sub-Saharan Africa, with severe implications for human health. In Uganda, where the predominant diet depends heavily on plant-based staples, crop mineral concentration is an important component of dietary mineral intake. Studies assessing the risk of nutrient deficiency or the effectiveness of nutrient-focused interventions often estimate dietary mineral intake using food composition tables that are based on crops grown in developed countries. However, little is known about the actual nutritional content of crops grown in Uganda. Here, we document the Ca, Fe, Se, and Zn concentration of staple crops collected from Ugandan household farms. While median mineral concentrations were similar to those reported previously, variation in crop mineral concentration was high, particularly for Fe and Se. An ordinary least squares regression showed that some soil characteristics were correlated with crop mineral concentrations. Of these, soil pH was often positively associated with crop mineral concentration, while sand and organic

carbon concentrations were negatively associated with several crop mineral concentrations. However, much of the variation in crop mineral content was not associated with the soil characteristics measured. Overall, our results suggest that extensive heterogeneity in staple crop mineral concentration in Uganda is likely due to a combination of edaphic characteristics and other variables. Because staple foods constitute a large portion of dietary mineral intake in Uganda and other developing countries, these results have implications for estimates of dietary mineral intake and the development of effective intervention strategies in such regions.

**Keywords** Micronutrient · Deficiency · Calcium · Selenium · Iron · Zinc · Soil · Staple crops

## Introduction

Mineral micronutrient deficiencies affect over 2 billion people worldwide and take a serious toll on human health (De Benoist et al. 2008; Horton et al. 2009; FAO et al. 2015). Of these deficiencies, calcium (Ca), iron (Fe), selenium (Se), and zinc (Zn) deficiencies are the most common in Africa (Kennedy et al. 2003; Joy et al. 2014), and the associated burden of disease is large, particularly for mothers and children. Both Fe and Zn deficiency impede childhood cognitive development and physical growth, impair the

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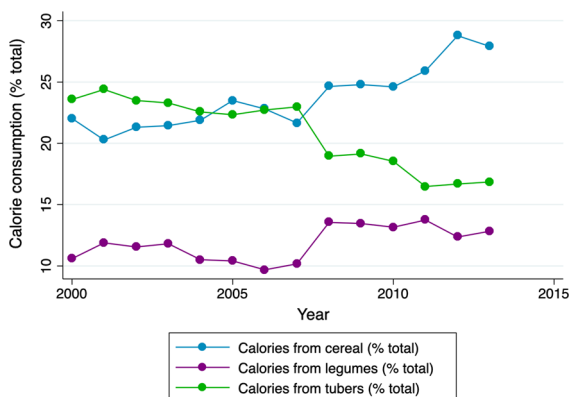
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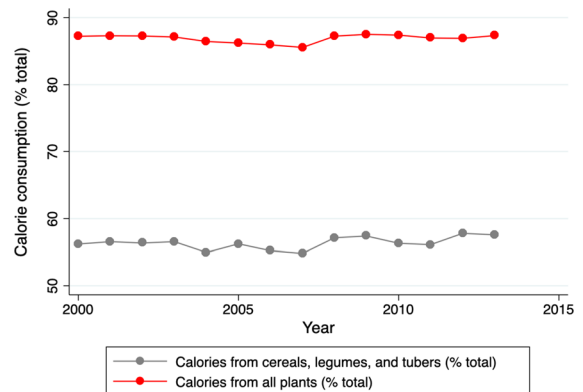
immune system, increase morbidity from infections, and increase risk of infant and maternal mortality (Prasad 2003; Wessells and Brown, 2012; Black et al. 2013; Haase and Rink 2014). Zinc deficiency alone is responsible for up to 1.7% of child deaths per year (Black et al. 2013). Calcium and Se deficiencies are also associated with impaired development and immune function, and both increase the risk of preeclampsia, the second-highest cause of maternal death (Mistry et al. 2012; Bhutta et al. 2013; Black et al. 2013).

Estimated human mineral deficiency rates in East Africa are 75%, 69%, 52%, and 14% for Ca, Zn, Se, and Fe, respectively (Joy et al. 2014). The predominant diets in these regions consist largely of plant-based staple foods (Ecker et al. 2010). According to FAO food balance sheets, 90% of calories consumed in Uganda come from plant-based sources (Laroche et al. 2016). Recent FAO data show that 25% of the calories consumed in Uganda come from cereals, 18% from tubers, and 15% from legumes (Fig. 1). Together, these three categories constitute almost 60% of total caloric intake, and together, all plant-based foods contribute almost 90% of total caloric intake (Fig. 2). Therefore, the mineral concentration of cereal, tuber, and legume crops has a large influence on dietary mineral intake in Uganda.

Risk of mineral deficiency in a population and the effectiveness of nutrient-focused interventions are often inferred from surveys that assess dietary mineral intake. In Uganda, for instance, the 2008 USDA-funded Uganda Food Consumption Survey assessed mineral and vitamin intake in three areas of Uganda



**Fig. 1** Proportional consumption of staple crops



**Fig. 2** Dietary reliance on plant-based foods

via 24-h food recall methods. Data collected in this survey informed Uganda's National Nutrition Policy and food fortification programs (Harvey et al. 2010; Kyamuhangire et al. 2013). A HarvestPlus food composition table was used to calculate intake for all vitamins and minerals. This food composition table—based almost solely on published food nutrient content values from the USDA (USDA 2008; Hotz et al. 2012a)—was created to gauge vitamin A intake in Central and Eastern Uganda and to evaluate the effectiveness of a program introducing orange-fleshed sweet potato to Uganda (Hotz et al. 2012b).

However, because the mineral and vitamin concentrations of foods vary depending on crop variety, environmental conditions, crop production and storage practices, and other factors, the USDA values used in the HarvestPlus food composition table may not be representative of the foods available in Uganda or other developing countries. In Malawi, for example, Ferguson et al. (1988) reported that the Ca and Zn concentrations of edible leaves were substantially higher than the concentration values reported in the 1984 USDA food composition table. Tidemann-Andersen et al. (2011) found that Fe and Zn concentrations measured in a variety of crops and meats in Uganda differed from those listed in food composition tables for Kenya or Mali. Joy et al. (2017) compared median mineral concentration in Malawian rice to values reported in other countries. They found that magnesium concentration in Malawian rice was almost twice as high as that reported in a study of Tanzanian rice and that Se concentration in Malawian rice was four and eight times higher than values

reported in Egypt and Nigeria, respectively, but only 15% of values reported in the USA. Cereal Se concentrations measured in different locations may vary by orders of magnitude, from 0.39 to 37.2 mg kg<sup>-1</sup> in China to 13–670 mg kg<sup>-1</sup> India (dos Reis et al. 2017).

Wide heterogeneity in crop mineral concentration has also been noted within a single country and has been linked to variation in soil characteristics. For instance, crops grown on calcareous soils in Malawi are higher in Se, Ca, and Zn than crops grown on non-calcareous soils, and the difference is large enough to result in substantial differences in human Se status (Joy et al. 2015a, b; Phiri et al. 2019). In India, where soil Zn deficiency is widespread, wheat grain Zn concentration doubles across locations ranging from low to high Zn availability (Joshi et al. 2010), and Zn fertilization is associated with increased cereal Zn concentrations (Shivay et al. 2008a, b; Sahrawat et al. 2008). Soil characteristics can influence crop mineral concentration through their effects on total soil mineral content, mineral bioavailability, and plant function (Alloway 2009; Wood et al. 2018; Ngigi et al. 2019). Relationships between soil characteristics and crop mineral concentration are also mediated by climate, crop variety, and agricultural practices (Karami et al. 2009; Bouis and Saltzman 2017; Manzeke et al. 2019), rendering it difficult to identify key mechanisms driving crop mineral concentrations. However, since plants derive mineral nutrients from soil, variation in soil characteristics is likely linked to variation in crop mineral content. Recent studies show that sub-Saharan soil mineral deficiencies are widespread, but heterogeneous, suggesting that crop mineral concentrations may also vary widely across this region (Hengl et al. 2017; Kihara et al. 2020).

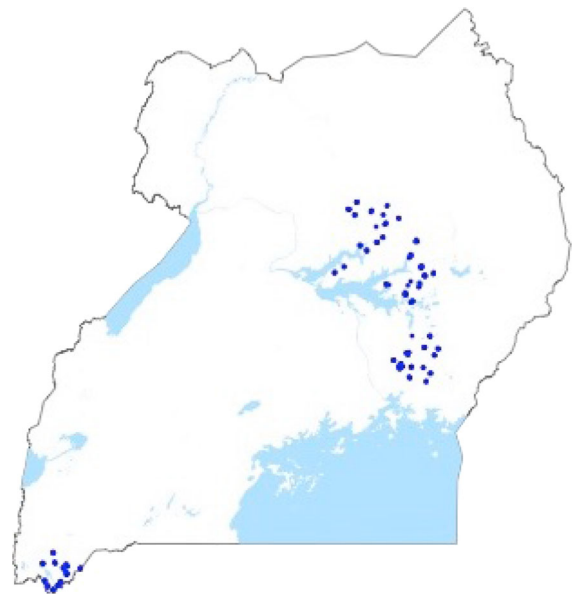
Because there is extensive variation in crop mineral concentration within and across countries, it is useful to document country-specific food nutrient composition (Bevis and Hestrin 2020; van Heerden and Schönfeldt 2004). More accurate assessments of country-specific food and crop mineral composition can help gauge national risk for mineral deficiencies (Chilimba et al. 2011; Joy et al. 2015a, b). This information can also facilitate the implementation of food guidelines, nutrition interventions and nutrition education programs (van Heerden and Schönfeldt 2004). Additionally, it is useful to examine drivers of crop nutrient concentration, since understanding these

relationships may help to predict the locations or sub-populations that are particularly at risk for mineral deficiencies (Joy et al. 2015a, b). We therefore seek to address these needs in Uganda, by first examining heterogeneity in the mineral concentration of six staple crops collected from household farms, and then examining the relationships between soil characteristics and crop mineral concentrations.

## Methods

### Crop and soil sample collection

Crop and soil samples were collected from households in 9 districts of Uganda spread across four agro-ecological zones during the summer of 2013 (Bevis et al. 2017). The location of these samples is shown in Fig. 3. Households included in the study practiced semi-subsistence farming, growing crops primarily for home consumption but also for sale. 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 taken from 282 households in the weeks during or directly after harvest. Crops were sampled directly from the field unless harvest had already occurred, in which case they were sampled from household storage. Thus, only



**Fig. 3** Map of crop and soil samples

mature crops that were grown by the household were included in the study; crops purchased from market were never sampled. For grains and legumes harvested from the field, surveyors subsampled crops from 10 locations within each plot. Because cassava and sweet potato are less easily divisible, surveyors subsampled these crops from up to 6 plants within each plot. The total mass of each composite crop sample collected from a plot was equal to 1 kg or more. This sampling scheme was chosen to obtain a representative sample of the crop nutrient content within each plot (Maziya-Dixon et al. 2000; Manzeke et al. 2012; Joy et al. 2015a, b; De Moura et al. 2015). A minimum of 12 soil subsamples were collected from a depth of 0–20 cm in locations evenly distributed within each plot in which crop samples were grown. Soil subsamples were mixed thoroughly, and a 500 g composite soil subsample from each plot was stored for subsequent analysis.

#### Crop and soil sample analysis

Prior to nutrient analysis, all crop 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 digested 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). The instrument detection limits were 0.113 ppm for Ca, 0.004 ppm for Fe, and 0.001 ppm for Zn. Blanks, standard reference materials, and calibration standards prepared from NIST-traceable standard solutions were run throughout in order to ensure consistency and quality of the ICP-AES analysis (High-Purity Standards, North Charleston, SC). Recovery rates for certified reference materials are provided in Table 7. For Zn, three positions were monitored, located at 202.613, 206.200, and 213.856 nm. For Ca and Fe, two positions were monitored (211.276 and 317.933 nm for Ca, 259.941 and 275.573 nm for Fe). 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, Fe, and Ca concentrations measured at 206.200, 259.941, and 211.276 nm, respectively, because these positions were less prone

to fluctuations in plasma conditions at the concentration levels examined. Additionally, Yttrium was used as an internal standard to correct for instrument drift and matrix interferences. Selenium concentration was measured using a mass spectrometer (Agilent ICP-MS 750, USA).

Soil samples were air-dried, ground to pass through a 2.0-mm sieve using a stainless-steel mill, and homogenized. A modified Morgan extraction was used to assess plant-available soil nutrients. The modified Morgan extractant is a well-buffered weak acidic solution that is used to extract a wide range of soil elements, including micro- and macronutrients. This extractant was developed as a “universal” extractant that would—to the extent possible—mimic the conditions in the rhizosphere in order to assess nutrients available to plants grown in acidic soils (Morgan 1941; McIntosh 1969). Like all soil extractants, the modified Morgan solution does not perfectly mimic a rhizosphere soil solution and extracts some nutrients more efficiently than others. We chose the modified Morgan extract for our experiment because it was developed for a wide range of nutrients and for acidic soils, which were predominant at our sample sites in Uganda. Subsamples of  $5.0 \text{ g} \pm 0.5 \text{ g}$  soil were extracted with 20 mL of modified Morgan solution (0.62 N  $\text{NH}_4\text{OH}$  and 1.25 N  $\text{CH}_3\text{COOH}$  adjusted to pH 4.8). This slurry was mixed for 15 min on a platform shaker and extracted through a Whatman 2 V filter. The elemental composition of each extract was measured using an axially viewed Spectro Arcos ICP-AES, as described above for crop nutrient analysis (Spectro Arcos, Kleve, Germany). Selenium concentration was not measured in the soil samples due to methodological difficulties. Soil pH was determined in a 2.5:1 water-to-soil suspension following a 30-min equilibration time (Okalebo et al. 2002). Soil organic carbon was determined with the Walkley–Black method (Walkley and Black 1934). Soil texture was determined with a hydrometer following oxidation of organic matter with hydrogen peroxide and dispersion with sodium hexametaphosphate (Bouyoucos 1936; Okalebo et al. 2002).

## Data analysis

### *Analysis of central tendencies and heterogeneity in crop mineral concentration*

All statistical analyses were conducted using Stata. We examined heterogeneity in crop mineral concentration ( $\text{mg kg}^{-1}$  dry mass) by plotting the estimated probability distributions of log-transformed mineral concentration and documenting mineral concentration statistics and percentiles. We estimated the Epanechnikov kernel density distribution of log-transformed mineral concentration because almost every distribution is highly right-skewed, whereas the distribution of log-transformed mineral concentrations is close to Gaussian. The optimal kernel bandwidth for each distribution was specified as that which would minimize the mean integrated squared error if the data were Gaussian and a Gaussian kernel were used. This is the default bandwidth chosen by Stata. A comparison of the distribution of log-transformed mineral concentrations across crops for each mineral illustrates the relative degree of dispersion for each crop mineral combination.

For each crop mineral combination, we also calculated the mean and median mineral concentration as well as the minimum and maximum, the 10th, 25th, 75th, and 90th percentiles, the standard deviation, and the inter-quartile range (IQR). The IQR measures the difference between the 75th and 25th percentiles of a distribution. Because the distributions of Ca, Fe, Se, and Zn concentrations are highly right-skewed, median values provide a better representation of each crop's mineral concentration than do the mean values. For the same reason, IQR is a more representative measure of variation than the standard deviation.

To contextualize the mineral concentrations of crops sampled from Ugandan households, we compared the mineral concentrations measured in our samples to those reported in other studies conducted in sub-Saharan Africa. Most studies list either mean or median crop nutrient concentration, often alongside the standard deviation or the IQR. For studies that listed the nutrient concentrations of wet food matter, we used the reported dry matter content of each food to calculate the mineral concentration in each food's dry matter equivalent in  $\text{mg kg}^{-1}$ . For studies that did not report dry matter content, we used an analogous value reported in a similar study to calculate the nutrient

concentration for the dry matter equivalent. Because Joy et al. (2015a, b) published a comprehensive dataset, we calculated the median nutrient concentration and IQR for crops sampled from both calcareous and non-calcareous soils in Malawi and compared the Epanechnikov kernel density distribution for each log-transformed mineral concentration of maize to that measured in our maize samples. Although a comparison with more crop types sampled from different countries would have been informative, this was only possible with maize collected by Joy et al. (2015a, b) due to the limited size of our sample set and the lack of available datasets.

### *Analysis of relationship between soil characteristics and crop mineral concentration*

To further investigate the relationship between soil characteristics and crop mineral concentrations, we modeled crop nutrient concentration as a function of soil characteristics through an ordinary least squares (OLS) regression. Because OLS standard errors are only valid for normally distributed outcomes, we used log-transformed crop mineral concentrations in the regression (Joy et al. 2015a). Each regression included fixed effects for each staple crop in order to allow mean shifts in the mineral concentration of each crop. The regressions also included a dummy variable indicating whether the crop was sampled directly from the field or sampled from storage. Soil pH, organic carbon, and sand content were included in the regressions because these are soil characteristics that have been shown to influence crop mineral uptake (Alloway 2009; Manzeke et al. 2019). Extractable soil Ca, Fe, and Zn were also included when examining relationships between soil characteristics and crop Ca, Fe, and Zn concentration, respectively. Extractable soil Se was not available.

Because the relationship between soil characteristics and crop mineral concentration may vary by crop, we also ran the OLS regressions separately for each crop. While these crop-nutrient-specific regressions demonstrate heterogeneity in the relationship between soil characteristics and crop mineral concentrations, the sample sizes for each crop are small, and so the resulting regression coefficients should be interpreted with caution.

Because pH can influence soil mineral availability, we also conducted the same crop-nutrient-specific

OLS regressions with an interaction term between soil pH and the extractable soil mineral concentration of interest. In the cases for which the  $p$  value on this interaction coefficient was less than 0.100, we plotted the marginal effect of extractable soil mineral concentration across the pH distribution. This plot was created using Stata's margins command.

### Interpretation of $p$ values

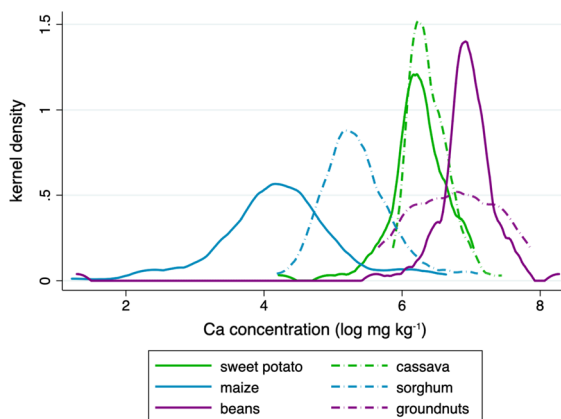
While we recognize that in many disciplines it is common to discuss only those regression coefficients for which a  $p$  value is below 0.05, statisticians have long pointed out the arbitrary nature of this cut-off. In 2016, the American Statistical Association published a document that attempts to address misperception and misuse of the  $p$  value in the broader scientific research community (Wasserstein and Lazar 2016). Among the principles laid out is a caution against using mechanical bright-line rules such as " $p < 0.05$ " and a recommendation to consider several contextual factors when making scientific inferences.

We therefore interpret the results of our regression analyses with the understanding that  $p$  values for any given regression coefficient depend on the magnitude of the underlying relationship, heterogeneity, and sample size. We consider a coefficient to be significant if  $p < 0.05$ , and marginally significant if  $p < 0.10$ . However, we also consider coefficient magnitude and trends across multiple specifications of the same regression. While this approach may not yet be widely accepted within all scientific disciplines, we believe that it enhances our understanding of the complex relationships between soil characteristics and crop mineral nutrient concentrations.

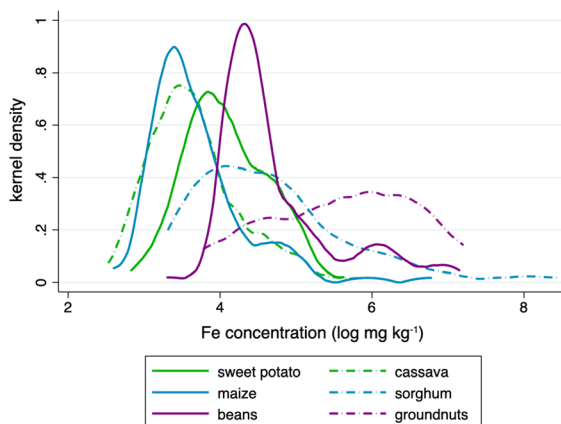
## Results and discussion

### Crop mineral concentrations

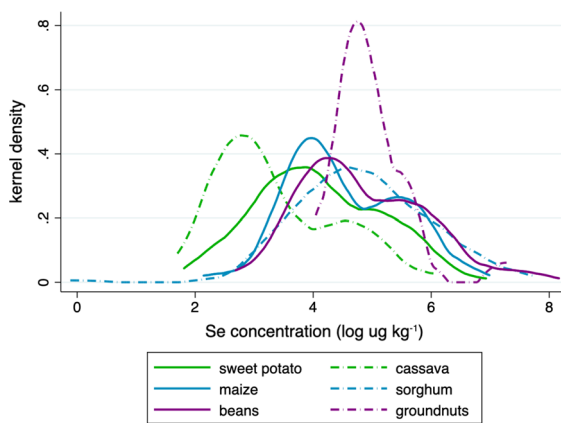
Overall, patterns in the median nutrient concentrations of different crops matched the patterns reported in existing food composition tables (USDA 2013; Hotz et al. 2012a; Figs. 4, 5, 6, 7 and Tables 1, 2, 3, 4). Legumes contained higher Ca, Fe, Se, and Zn concentrations compared to most grains and tubers.



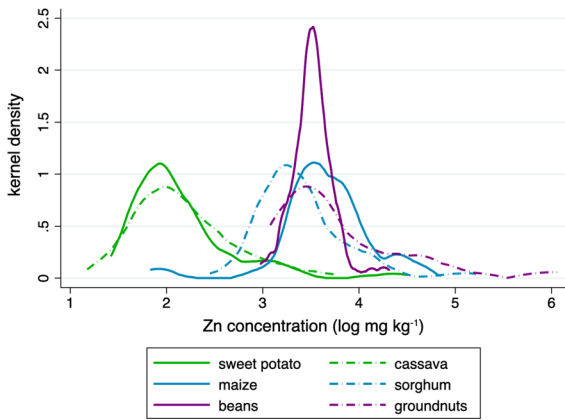
**Fig. 4** Crop Ca concentration



**Fig. 5** Crop Fe concentration



**Fig. 6** Crop Se concentration



**Fig. 7** Crop Zn concentration

*Calcium in staple crops*

Median Ca concentrations ranged from 68 to 1017 mg kg<sup>-1</sup> (Fig. 4 and Tables 1, 2, 3, 4). Maize,

sorghum, and groundnuts contained similar Ca levels compared to crops previously sampled in Malawi, while beans, cassava, and sweet potatoes contained less Ca (Ferguson et al. 1988; Joy et al. 2015a, b).

*Iron in staple crops*

Median Fe concentrations ranged from 34 to 341 mg kg<sup>-1</sup> (Fig. 5 and Tables 1, 2, 3, 4). For most crops, Fe concentrations were similar to those measured in Malawi (Joy et al. 2015a, b), but lower than those previously measured in Uganda (Tidemann-Andersen et al. 2011). However, sweet potatoes and groundnuts contained substantially higher Fe compared to crops previously sampled in Uganda and Malawi.

**Table 1** Crop Ca concentration

	<i>N</i>	Median	Mean	Min	p10	p25	p75	p90	Max	SD	IQR	IQR/median
Maize	112	67.50	100.61	0.00	22.59	41.95	106.52	158.88	761.82	120.22	64.57	0.96
Sorghum	155	195.94	250.61	65.72	119.03	151.17	278.97	390.08	1207.34	186.46	127.80	0.65
Sweet potato	87	498.06	554.02	67.54	304.89	434.89	670.96	889.18	1135.34	215.72	236.06	0.47
Cassava	108	563.01	621.16	353.04	441.42	488.95	718.10	877.17	1709.60	206.07	229.14	0.41
Beans	92	1017.11	1102.77	3.63	661.39	879.23	1238.34	1647.95	3915.61	483.01	359.11	0.35
Groundnuts	25	741.29	1017.61	285.92	349.51	543.14	1414.30	1930.96	2592.02	617.65	871.16	1.18

*N* denotes number of observations; min and max denote minimum and maximum values; p10, p25, p75, and p90 denote the 10th, 25th, 75th, and 90th percentiles; sd and IQR denote standard deviation and inter-quartile range (75th–25th percentiles). Crop Ca concentration is given in mg kg<sup>-1</sup> dry mass

**Table 2** Crop Fe concentration

	<i>N</i>	Median	Mean	Min	p10	p25	p75	p90	Max	SD	IQR	IQR/median
Maize	112	34.14	55.10	13.48	23.19	25.85	50.46	97.89	878.45	89.88	24.61	0.72
Sorghum	155	93.84	232.65	27.45	38.95	47.76	165.68	396.97	4708.32	555.68	117.92	1.26
Sweet potato	87	53.65	69.07	16.92	31.00	39.66	84.24	126.37	277.20	42.36	44.58	0.83
Cassava	108	36.31	48.30	12.54	19.73	25.25	51.45	90.55	350.49	44.02	26.20	0.72
Beans	92	80.50	170.35	27.29	62.14	71.63	146.05	431.97	1273.24	222.04	74.42	0.92
Groundnuts	25	340.52	384.37	43.60	53.99	116.45	628.66	857.54	1341.71	326.19	512.21	1.50

*N* denotes number of observations; min and max denote minimum and maximum values; p10, p25, p75, and p90 denote the 10th, 25th, 75th, and 90th percentiles; SD and IQR denote standard deviation and inter-quartile range (75th–25th percentiles). Crop Fe concentration is given in mg kg<sup>-1</sup> dry mass

**Table 3** Crop Se concentration

	<i>N</i>	Median	Mean	Min	p10	p25	p75	p90	Max	SD	IQR	IQR/median
Maize	112	72.80	148.82	8.53	32.96	44.77	227.63	322.96	1082.28	167.90	182.86	2.51
Sorghum	155	120.56	233.57	0.89	33.44	60.53	278.41	578.74	2355.74	334.17	217.87	1.81
Sweet potato	87	49.21	105.90	6.12	14.14	29.15	136.41	267.62	1021.26	140.92	107.26	2.18
Cassava	108	21.65	51.94	5.47	9.69	13.84	61.62	132.72	431.13	71.99	47.78	2.21
Beans	92	101.63	251.51	14.68	41.30	57.88	306.84	469.93	3512.91	450.88	248.96	2.45
Groundnuts	25	126.40	195.99	57.09	68.50	105.41	197.09	257.53	1446.49	269.39	91.68	0.73

*N* denotes number of observations; min and max denote minimum and maximum values; p10, p25, p75, and p90 denote the 10th, 25th, 75th, and 90th percentiles; SD and IQR denote standard deviation and inter-quartile range (75th–25th percentiles). Crop Se concentration is given in  $\mu\text{g kg}^{-1}$  dry mass

**Table 4** Crop Zn concentration

	<i>N</i>	Median	Mean	Min	p10	p25	p75	p90	Max	SD	IQR	IQR/median
Maize	112	38.31	42.31	6.29	26.60	30.32	48.82	69.13	127.55	19.88	18.50	0.48
Sorghum	155	28.20	34.12	11.59	18.66	21.78	36.82	53.45	184.62	23.86	15.05	0.53
Sweet potato	87	7.71	10.66	4.16	5.33	5.94	10.05	18.26	90.22	11.70	4.11	0.53
Cassava	108	7.92	10.04	3.24	4.65	6.14	11.47	19.18	43.37	6.52	5.33	0.67
Beans	92	33.75	34.52	19.69	26.22	30.19	37.42	42.39	74.54	8.33	7.23	0.21
Groundnuts	25	35.09	62.78	21.73	24.64	28.49	55.33	107.16	427.60	82.20	26.84	0.76

*N* denotes number of observations; min and max denote minimum and maximum values; p10, p25, p75, and p90 denote the 10th, 25th, 75th, and 90th percentiles; SD and IQR denote standard deviation and inter-quartile range (75th–25th percentiles). Crop Zn concentration is given in  $\text{mg kg}^{-1}$  dry mass

### Selenium in staple crops

Median Se concentrations ranged from 22 to 126  $\mu\text{g kg}^{-1}$  (Fig. 6 and Tables 1, 2, 3, 4). These values were higher for beans, cassava, and maize compared to samples collected across different soil types in Malawi (Donovan et al. 1992; Chilimba et al. 2011; Joy et al. 2015a, b). However, median Se concentrations for groundnuts, sorghum, and sweet potatoes were lower than those measured in Malawian crops grown on calcareous soils and higher than those measured in Malawian crops grown on non-calcareous soils.

### Zinc in staple crops

Median Zn concentrations ranged from 8 to 38  $\text{mg kg}^{-1}$  (Fig. 7 and Tables 1, 2, 3, 4) and were similar to those previously measured in crops

collected in Uganda and Malawi (Ferguson et al. 1988; Tidemann-Andersen et al. 2011; Joy et al. 2015a, b). The median Zn concentration measured in cassava was slightly lower than previously reported, while sorghum Zn concentration was slightly higher.

### Dispersion of crop mineral concentrations

Although the median crop mineral concentrations primarily followed expected patterns, the variation in mineral concentrations measured within each crop type was surprisingly high, particularly for Fe and Se (Figs. 5 and 6 and Tables 1, 2, 3, 4). The average IQR/median ratio across crops was 0.67, 0.99, 1.95, and 0.53 for Ca, Fe, Se, and Zn concentration, respectively. This suggests that median mineral concentrations of Fe and Se in particular are not representative of the actual concentrations of a large portion of the crops sampled. Conversely, the Ca and Zn



concentrations of a large portion of crops are relatively well represented by the median values measured, with the exception of the Ca concentration in groundnuts. Interestingly, while the crop-average IQR-to-median ratio varies substantially by nutrient, the nutrient-average IQR-to-median ratio does not vary much across crops. It is difficult to compare crop nutrient concentration dispersion in our samples to dispersion documented in previous studies because most authors do not report IQR or other metrics of dispersion.

The observed variation in staple crop mineral concentration has important implications for estimates of dietary mineral supplies and population-level dietary intake in Uganda and in other regions where staple crops play an important role in mineral intake. Although the relatively low variation in crop Zn concentrations suggests that the median Zn values may provide a representative value for the purpose of dietary estimates, substantial variation in the Ca, Fe and particularly Se concentrations indicates that estimates of dietary Ca, Fe, and Se intake based on one mean or median value per crop may misrepresent actual dietary intake of a large portion of the population.

To illustrate the importance of this variance, we estimated potential differences in dietary requirements met by the consumption of maize porridge, a common staple for Ugandan children.<sup>1</sup> If the maize contains 41.95 mg kg<sup>-1</sup> Ca (representing the 25th percentile of maize Ca concentration per dry mass), a child 1–3 years old would consume less than 1% of the Recommended Dietary Allowance (RDA) for Ca (700 mg day<sup>-1</sup>) through three “medium” sized portions of maize porridge per day. The same child would consume approximately 2% of the RDA if maize Ca concentration is 106.52 mg kg<sup>-1</sup> dry mass (75th percentile). If the maize contains 25.85 mg kg<sup>-1</sup> Fe dry mass (25th percentile), the child would consume 43% of the RDA for Fe (7 mg day<sup>-1</sup>), but 83% of the RDA if maize Fe concentration is 50.46 mg kg<sup>-1</sup> dry mass (75th percentile). The child would consume only 26% of the RDA for Se (20 mcg day<sup>-1</sup>) if the maize Se

concentration is 44.77 mg kg<sup>-1</sup> dry mass (25th percentile), but would exceed the RDA by 31% if maize Se concentration is 227.63 mg kg<sup>-1</sup> dry mass (75th percentile). The child would exceed the RDA for Zn (3 mg day<sup>-1</sup>) by 16% if maize Zn concentration is 30.32 mg kg<sup>-1</sup> dry mass (25th percentile), but exceed it by 88% if maize Zn concentration is 48.82 mg kg<sup>-1</sup> dry mass (75th percentile). Because dispersion is greatest in crop Fe and Se concentration, the uncertainty regarding dietary intake of these two nutrients is also largest.

This variation may also influence our understanding of the relative nutritional value of different staple crops, which is difficult to establish when a crop's nutrient concentration varies widely. For instance, sorghum Se concentrations are generally higher than Se concentrations in maize or sweet potatoes. Despite this, low-Se sorghum samples (60.52 µg kg<sup>-1</sup> at the 25th percentile) had lower Se concentration than either high-Se sweet potato samples (136.41 µg kg<sup>-1</sup> at the 75th percentile), or high-Se maize samples (227.63 µg kg<sup>-1</sup> at the 75th percentile). Similarly, while the median Se concentration in beans was fivefold, the median Se concentration in cassava, low-Se bean samples (at the 25th percentile) and high-Se cassava samples (at the 75th percentile) had approximately similar Se concentrations (57.88 and 61.62 µg kg<sup>-1</sup>, respectively).

While comparing the median, standard deviation, and IQR of mineral concentrations in different contexts is informative, a comparison of the entire probability distribution of mineral concentrations enables a more complete assessment of the similarities and differences between mineral concentrations measured in different sample sets. With the data collected from sub-Saharan Africa and available to us, this comparison is only possible for maize samples gathered in our study and maize samples gathered by Joy et al. (2015a, b) from calcareous and non-calcareous soils in Malawi. The distribution of mineral concentrations in Ugandan maize is often quite different than the distribution in Malawian maize (Figs. 8, 9, 10, 11). For every mineral measured, the concentration in Ugandan maize grown on non-calcareous soils (Foster 1981) is more similar to the mineral concentration of Malawian maize grown on calcareous soils than on non-calcareous soils. This suggests that both the total mineral content and heterogeneity in mineral concentrations vary significantly within and between

<sup>1</sup> Based on food frequency data collected in Uganda (Bevis and Hestrin 2020), the median quantity of maize porridge consumed daily by young children is estimated to be 314 g. Maize porridge contains approximately 12% raw maize flour by weight, providing 38.47 g of maize flour per meal, or 115.42 g per day (Hotz et al. 2012a).

**Table 5** Soil characteristics

	Median	Mean	Min	p10	p25	p75	p90	Max	SD	IQR
Organic carbon (%)	1.65	1.56	– 0.73	0.65	1.16	2.02	2.31	3.00	0.64	0.86
Sand content (%)	56.26	52.86	7.12	27.12	41.12	64.40	71.84	89.12	16.72	23.28
pH	6.00	5.97	4.00	5.30	5.70	6.30	6.60	7.50	0.54	0.60
Ca (mg kg <sup>-1</sup> )	934.16	1061.03	120.04	420.24	669.89	1297.41	1831.45	7523.48	671.77	627.52
Fe (mg kg <sup>-1</sup> )	1.46	5.45	0.25	0.59	0.84	5.01	15.64	95.63	11.11	4.17
Zn (mg kg <sup>-1</sup> )	0.27	0.47	0.03	0.10	0.16	0.55	0.98	12.75	0.74	0.39

Extractable soil Ca, Fe, and Zn are shown in mg kg<sup>-1</sup>; min and max denote minimum and maximum values, respectively; p10, p25, p75, and p90 denote the 10th, 25th, 75th, and 90th percentiles, respectively; SD and IQR denote standard deviation and inter-quartile range (75th–25th percentiles), respectively

countries in sub-Saharan Africa. It also indicates that broad categorical classifications—such as calcareous and non-calcareous—may not be sufficient to represent the heterogeneity in crop mineral concentrations and their relationship with soil characteristics or other drivers across a large geographic region (Table 5).

#### Relationship between soil characteristics and staple crop mineral concentrations

The crops that we collected from household farms in Uganda were grown on non-calcareous soils with a median soil pH of 6.00 (IQR 0.60), median organic carbon content of 1.65% (IQR 0.86), and median sand content of 56.26% (IQR 23.28). The median extractable Ca, Fe, and Zn concentrations were 934.16 mg kg<sup>-1</sup> (IQR 627.52), 1.46 mg kg<sup>-1</sup> (IQR 4.17), and 0.27 mg kg<sup>-1</sup> (IQR 0.39), respectively. While the median soil pH, organic carbon, and sand contents are within ranges not expected to severely limit soil nutrient availability and plant nutrient uptake, the mineral concentrations are low (Weil and Brady 2017). In particular, the extractable soil Zn concentrations are below the threshold considered necessary for optimal plant growth (Alloway 2009). This corresponds to findings by Kihara et al. (2020) that Zn deficiency is one of the most widespread soil micronutrient deficiencies in sub-Saharan Africa and likely limits crop productivity and nutrition. When interpreting the soil nutrient concentrations, it is important to note that although the modified Morgan solution is considered a universal extractant, it extracts some elements more efficiently than others. Comparisons to soil mineral concentrations measured in other studies are difficult due to a lack of studies

investigating soil minerals in Uganda and differences in soil extraction and analysis methods. However, most of the ranges reported here are similar to those reported by other authors working in Uganda (Gray 2011; Hengl et al. 2017).

To investigate drivers of the wide variation observed in staple crop mineral content, we examined the relationships between soil characteristics and crop mineral concentrations (Table 6). Regression analysis pooled across all crops revealed an inconsistent relationship between the extractable soil mineral concentrations and crop mineral concentrations: extractable soil Ca concentration was negatively associated with crop Ca concentration ( $p < 0.01$ ), extractable soil Fe concentration was positively associated with crop Fe concentration ( $p < 0.05$ ), and there was no statistically significant relationship between extractable soil Zn and crop Zn concentration (Columns 1, 2, and 4 of Table 6). We expected to find a positive association between soil mineral concentration and crop mineral concentration (Joshi et al. 2010; Joy et al. 2015a, b; Ligowe et al. 2020). We attribute our equivocal findings to the observational nature of our study. The size and characteristics of our sample set many have been insufficient to disentangle the complex relationships between environmental conditions, agronomic practices, and crop nutrient content. Additionally, the household farms that we sampled from did not utilize mineral fertilizers. Therefore, our work does not indicate that mineral amendments would not facilitate higher crop mineral concentrations at these locations. Soil pH was positively associated with crop Ca and Se concentration ( $p < 0.05$  and  $p < 0.10$ , respectively). This corresponds with previous observations of mineral

**Table 6** OLS regression of crop mineral concentration and soil characteristics

	Ca (log mg kg <sup>-1</sup> )	Fe (log mg kg <sup>-1</sup> )	Se (log µg kg <sup>-1</sup> )	Zn (log mg kg <sup>-1</sup> )
Extractable soil Ca (log mg kg <sup>-1</sup> )	- 0.112*** (0.0423)			
Extractable soil Fe (log mg kg <sup>-1</sup> )		0.0695** (0.0339)		
Extractable soil Zn (log mg kg <sup>-1</sup> )				0.00282 (0.0216)
Soil pH (pH)	0.111** (0.0438)	0.0628 (0.0636)	0.326*** (0.0905)	- 0.0167 (0.0373)
Soil organic carbon (%)	- 0.0447 (0.0389)	- 0.203*** (0.0736)	- 0.378*** (0.0911)	0.0148 (0.0341)
Soil sand content (%)	- 0.00117 (0.00161)	- 0.000653 (0.00280)	- 0.0135*** (0.00387)	- 0.00340** (0.00167)
Observations	573	574	574	574
R <sup>2</sup>	0.732	0.368	0.269	0.704

Crop fixed effects are included, and a dummy variable for collection of crops directly from the field rather than storage

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

availability in moderately acidic soils (Fordyce 2005; Weil and Brady 2017). Although soil Fe and Zn availability generally decreases in alkaline soils, the pH of the majority of our soil samples was within a range that does not limit the availability of these elements. Soil sand and organic carbon content were generally negatively associated with crop mineral concentration, although these relationships were only significant for some minerals (Table 6). Soil organic carbon content was negatively associated with crop Fe and Se concentration (*p* < 0.01). This may be due to the formation of organo-mineral complexes which can remove Fe and Se from the soil solution (Chen et al. 2014; Supriatin et al. 2015). Soil sand concentration was negatively associated with crop Se and Zn concentration (*p* < 0.01), but the effect was small. Soil texture can influence many other edaphic properties that are important for plant growth and nutrition, such as water holding capacity and nutrient retention, which are particularly important in rain-fed, low-input agricultural systems such as those common in rural Uganda (Alloway 2009). It is possible that through these mechanisms, sandier soils were less conducive to crop nutrient uptake compared to soils with a larger clay or silt fraction.

Because relationships between soil characteristics and crop nutrient concentrations may be crop-specific, we also disaggregated regression results by crop

(Tables 8, 9, 10, 11, 12, 13). While these results should be interpreted with caution due to their small sample sizes, they highlight a few notable patterns that were obscured by the pooled regression analysis. First, extractable soil Ca concentration was negatively associated with Ca concentration in maize and sorghum (*p* < 0.05 and *p* < 0.10, respectively), but not other crops (i.e., these two relationships drove the negative association observed in Column 1 of Table 6). Second, of all crops examined, groundnuts appeared to be most responsive to soil pH (Table 9). A one unit increase in soil pH was associated with an average 91%, 157%, and 48% increase in groundnut Ca, Fe, and Se concentration, respectively (*p* < 0.01 for each nutrient). Previous work has shown that groundnuts are particularly sensitive to low pH and suffer from reduced germination, growth, and survival below pH 6.0 (Murata et al. 2003). Our work suggests that soil acidity may substantially inhibit groundnut mineral concentrations in Uganda. Third, of the minerals measured, crop Se concentration was most consistently associated with higher soil pH (Tables 8, 9, 10, 11, 12, 13). This corresponds with trends observed in Malawi and Kenya (Chilimba et al. 2011; Ngigi et al. 2019) and suggests in moderately acidic sub-Saharan soils, Se uptake by a wide variety of crops is highly responsive to soil pH. Also, crop-specific regressions including an interaction term to account

for the relationship between soil pH and extractable soil mineral concentrations show that an increase in soil pH strengthens the positive relationship between extractable soil mineral concentration and crop mineral concentration (Figs. 12, 13, 14 and Tables 14, 15, 16, 17, 18, and 19). This was most apparent for cassava Ca concentration, maize Zn concentration, and sweet potato Fe concentration, suggesting that these specific soil–crop mineral relationships are particularly pH-dependent. Taken together, these results show that edaphic characteristics are associated with crop mineral content and that many relationships are nutrient- and crop-specific. However, much of the heterogeneity in mineral crop concentrations observed here could not be explained by the soil characteristics measured in our study. As noted above, it is possible that the observational nature of this study and the relatively small sample size may also have limited our ability to identify potential causal relationships between edaphic conditions and crop mineral concentrations.

## Conclusion

Here, we show that the Ca, Fe, Se, and Zn concentrations of staple crops produced on Ugandan household farms are highly variable and in some cases differ from values reported in the food composition tables commonly used to predict human mineral intake. In most cases, this variation exceeded that observed in similar crops collected in Malawi, particularly for Fe and Se (Joy et al. 2015a, b; Joy et al. 2017). Although we observed some significant relationships between soil characteristics and crop mineral concentrations, soil characteristics did not appear to be the main drivers of heterogeneity in crop mineral concentrations. This suggests that among the household farms surveyed, non-edaphic factors such as crop variety, climate, and agricultural practices may have been more dominant drivers of crop mineral concentration than soil characteristics at the time of sampling. However, our samples are neither nationally representative, nor do they represent a wide range of soil types and agricultural management practices. It is possible that a larger sample representing more diverse geographic regions, edaphic characteristics, and agricultural practices (such as the application of micronutrient fertilizers or cultivation of biofortified

crop varieties) would uncover a stronger relationship between soil conditions and crop mineral concentrations.

Understanding the drivers of crop mineral concentration is important for nutrition policy development. Dietary mineral intake can be increased through multiple intervention points within the food system: crop biofortification through breeding, foliar sprays, use of mineral-enriched irrigation water or fertilizer or nutrient-rich organic amendments, fortification of processed foods, and direct dietary supplementation (Delong et al. 1997; Cakmak 2002; Fiedler and Afidra 2010; Chilimba et al. 2012; Manzeke et al. 2012, 2014; Barrett and Bevis 2015; Kupka et al. 2016; Bouis and Saltzman 2017). Biofortified crops such as Fe-rich beans and Zn-enriched maize have been introduced in Uganda and may provide a promising intervention strategy if adopted widely. Fortified foods such as enriched oils or grain flour may also be effective if they are made available and adopted in both urban and rural areas.

Taken together, these data suggest that more work is necessary to understand regional variability in crop mineral concentrations and the drivers responsible for such variability. Larger sampling and measurement efforts would improve estimates of mineral supplies available in sub-Saharan Africa. Because the relationships between edaphic conditions and crop mineral content are complex, a much larger sampling effort is necessary to establish robust relationships between the two. Additionally, information about crop varieties, climate, and agricultural practices would help determine the key drivers of crop mineral concentrations and identify causal relationships between soil and crop characteristics. Combined with an understanding of the socioeconomic elements of food systems, this information may help predict which regions are most susceptible to particular mineral deficiencies and guide more targeted nutritional interventions.

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**Compliance with ethical standards**

**Conflicts of interest** The authors have declared that no competing interests exist.

**Availability of data and material** Raw data are available upon request.

**Appendix**

See Tables 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, and 19.

**Table 7** Recovery rates of NIST certified reference materials and an internal standard for ICP-AES analyses run at the Cornell Nutrient Analysis Laboratory (CNAL)

		Fe (ppm)	Ca (%)	Zn (ppm)
NIST Orchard Leaves 1571	CNAL	216	2.14	27
	NIST value	270 ± 20	2.09 ± .03	25 ± 3
NIST Tomato Leaves 1573a	CNAL		5.09	31
	NIST value		5.05 ± 0.09	30.9 ± 0.7
NIST Tomato Leaves 1573	CNAL	505	3.1	66.7
	NIST value	690 ± 25	3.0 ± 0.03	62 ± 6
		Fe (ppm)	Ca (ppm)	Zn (ppm)
NIST Bovine Liver 1577	CNAL	269	139	143
	NIST value	268 ± 8	124 ± 6	130 ± 13
Internal CNAL Standard 2	CNAL	4.939	198.750	1.019
	calibrated value	5	200	1

**Table 8** Bean mineral concentration and soil characteristics

	(1) Ca	(2) Fe	(3) Se	(4) Zn
Extractable soil Ca (log mg kg <sup>-1</sup> )	0.0477 (0.138)			
Extractable soil Fe (log mg kg <sup>-1</sup> )		– 0.110* (0.0562)		
Extractable soil Zn (log mg kg <sup>-1</sup> )				– 0.00989 (0.0267)
Soil pH (pH)	0.0667 (0.0697)	– 0.375*** (0.142)	0.452* (0.238)	– 0.0242 (0.0349)
Soil organic carbon (%)	0.0529 (0.0801)	– 0.178 (0.165)	– 0.179 (0.191)	0.0610 (0.0425)
Soil sand content (%)	0.000289 (0.00279)	0.00837 (0.00554)	– 0.0284** (0.0112)	– 0.000669 (0.00206)
Observations	92	92	92	92
R <sup>2</sup>	0.012	0.248	0.113	0.068

Crop fixed effects are included, and a dummy variable for collection of crops directly from the field rather than storage

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

**Table 9** Groundnut mineral concentration and soil characteristics

	(1) Ca	(2) Fe	(3) Se	(4) Zn
Extractable soil Ca (log mg kg <sup>-1</sup> )	0.0716 (0.236)			
Extractable soil Fe (log mg kg <sup>-1</sup> )		0.124 (0.198)		
Extractable soil Zn (log mg kg <sup>-1</sup> )				– 0.144 (0.180)
Soil pH (pH)	0.914*** (0.106)	1.576*** (0.246)	0.484*** (0.161)	– 0.133 (0.281)
Soil organic carbon (%)	– 0.264 (0.194)	– 0.869*** (0.268)	0.122 (0.255)	0.160 (0.241)
Soil sand content (%)	– 0.0102 (0.00763)	– 0.0238 (0.0169)	0.00206 (0.00718)	– 0.00398 (0.0150)
Observations	25	25	25	25
R <sup>2</sup>	0.654	0.741	0.173	0.254

Crop fixed effects are included, and a dummy variable for collection of crops directly from the field rather than storage

\* $p < 0.1$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$

**Table 10** Maize mineral concentration and soil characteristics

	(1) Ca	(2) Fe	(3) Se	(4) Zn
Extractable soil Ca (log mg kg <sup>-1</sup> )	– 0.384** (0.185)			
Extractable soil Fe (log mg kg <sup>-1</sup> )		0.160** (0.0645)		
Extractable soil Zn (log mg kg <sup>-1</sup> )				0.0146 (0.0464)
Soil pH (pH)	0.239 (0.162)	0.0915 (0.130)	0.135 (0.251)	– 0.206** (0.0903)
Soil organic carbon (%)	– 0.343** (0.158)	– 0.504*** (0.184)	– 0.366 (0.234)	– 0.138 (0.103)
Soil sand content (%)	– 0.0198*** (0.00705)	– 0.0127 (0.00774)	– 0.0161 (0.0104)	– 0.000955 (0.00484)
Observations	106	107	107	107
R <sup>2</sup>	0.091	0.137	0.036	0.071

Crop fixed effects are included, and a dummy variable for collection of crops directly from the field rather than storage

\* $p < 0.1$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$

**Table 11** Sorghum mineral concentration and soil characteristics

	(1) Ca	(2) Fe	(3) Se	(4) Zn
Extractable soil Ca (log mg kg <sup>-1</sup> )	- 0.131* (0.0707)			
Extractable soil Fe (log mg kg <sup>-1</sup> )		0.0334 (0.0726)		
Extractable soil Zn (log mg kg <sup>-1</sup> )				0.0117 (0.0453)
Soil pH (pH)	- 0.0338 (0.0673)	- 0.0970 (0.122)	0.399** (0.168)	0.0556 (0.0728)
Soil organic carbon (%)	- 0.0308 (0.0679)	- 0.218 (0.150)	- 0.265 (0.170)	- 0.0101 (0.0562)
Soil sand content (%)	0.00497* (0.00257)	0.00944* (0.00493)	- 0.0116* (0.00596)	- 0.00447 (0.00288)
Observations	155	155	155	155
R <sup>2</sup>	0.080	0.173	0.056	0.081

Crop fixed effects are included, and a dummy variable for collection of crops directly from the field rather than storage

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

**Table 12** Sweet potato mineral concentration and soil characteristics

	(1) Ca	(2) Fe	(3) Se	(4) Zn
Extractable soil Ca (log mg kg <sup>-1</sup> )	- 0.0518 (0.0615)			
Extractable soil Fe (log mg kg <sup>-1</sup> )		0.0190 (0.0489)		
Extractable soil Zn (log mg kg <sup>-1</sup> )				- 0.0186 (0.0855)
Soil pH (pH)	0.00262 (0.103)	- 0.103 (0.126)	0.389* (0.220)	- 0.127 (0.103)
Soil organic carbon (%)	0.0508 (0.0811)	0.0637 (0.120)	- 0.622*** (0.198)	- 0.0329 (0.0877)
Soil sand content (%)	- 0.000034 (0.0033)	- 0.0074** (0.0037)	- 0.0141* (0.0084)	- 0.0065 (0.0040)
Observations	87	87	87	87
R <sup>2</sup>	0.055	0.180	0.148	0.105

Crop fixed effects are included, and a dummy variable for collection of crops directly from the field rather than storage

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

**Table 13** Cassava mineral concentration and soil characteristics

	(1) Ca	(2) Fe	(3) Se	(4) Zn
Extractable soil Ca (log mg kg <sup>-1</sup> )	0.0316 (0.0634)			
Extractable soil Fe (log mg kg <sup>-1</sup> )		0.178* (0.104)		
Extractable soil Zn (log mg kg <sup>-1</sup> )				0.0887* (0.0518)
Soil pH (pH)	0.0374 (0.0738)	0.310** (0.131)	0.288 (0.261)	0.142 (0.123)
Soil organic carbon (%)	- 0.0840 (0.0704)	- 0.123 (0.142)	- 0.440 (0.282)	0.132 (0.109)
Soil sand content (%)	- 0.000681 (0.00466)	- 0.00889 (0.00917)	0.00394 (0.0150)	- 0.00301 (0.00574)
Observations	108	108	108	108
R <sup>2</sup>	0.030	0.093	0.076	0.098

Crop fixed effects are included, and a dummy variable for collection of crops directly from the field rather than storage

\* $p < 0.1$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$

**Table 14** Bean mineral concentration and soil characteristics, with pH interaction

	(1) Ca	(2) Fe	(3) Se	(4) Zn
Extractable soil Ca (log mg kg <sup>-1</sup> )	0.227 (0.591)			
Extractable soil Fe (log mg kg <sup>-1</sup> )		- 0.226 (0.381)		
Extractable soil Zn (log mg kg <sup>-1</sup> )				- 0.125 (0.167)
Extractable soil Ca × Soil pH	- 0.0309 (0.108)			
Extractable soil Fe × Soil pH		0.0201 (0.0646)		
Extractable soil Zn × Soil pH				0.0196 (0.0295)
Soil pH (pH)	0.276 (0.739)	- 0.408** (0.183)	0.452* (0.238)	- 0.0120 (0.0325)
Soil organic carbon (%)	0.0535 (0.0814)	- 0.179 (0.166)	- 0.179 (0.191)	0.0599 (0.0421)
Soil sand content (%)	0.000393 (0.00285)	0.00854 (0.00568)	- 0.0284** (0.0112)	- 0.000705 (0.00207)
Observations	92	92	92	92
R <sup>2</sup>	0.012	0.249	0.113	0.072

Crop fixed effects are included, and a dummy variable for collection of crops directly from the field rather than storage

\* $p < 0.1$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$



**Table 15** Groundnut mineral concentration and soil characteristics, with pH interaction

	(1) Ca	(2) Fe	(3) Se	(4) Zn
Extractable soil Ca (log mg kg <sup>-1</sup> )	0.140 (2.753)			
Extractable soil Fe (log mg kg <sup>-1</sup> )		2.244 (3.453)		
Extractable soil Zn (log mg kg <sup>-1</sup> )				0.607 (2.578)
Extractable soil Ca × Soil pH	- 0.0117 (0.476)			
Extractable soil Fe × Soil pH		- 0.353 (0.568)		
Extractable soil Zn × Soil pH				- 0.123 (0.404)
Soil pH (pH)	0.993 (3.265)	1.657*** (0.318)	0.484*** (0.161)	- 0.358 (0.828)
Soil organic carbon (%)	- 0.261 (0.183)	- 0.874*** (0.272)	0.122 (0.255)	0.155 (0.247)
Soil sand content (%)	- 0.0101 (0.00726)	- 0.0260 (0.0179)	0.00206 (0.00718)	- 0.00461 (0.0146)
Observations	25	25	25	25
R <sup>2</sup>	0.654	0.745	0.173	0.257

Crop fixed effects are included, and a dummy variable for collection of crops directly from the field rather than storage

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

**Table 16** Maize mineral concentration and soil characteristics, with pH interaction

	(1) Ca	(2) Fe	(3) Se	(4) Zn
Extractable soil Ca (log mg kg <sup>-1</sup> )	0.868 (2.024)			
Extractable soil Fe (log mg kg <sup>-1</sup> )		0.289 (0.454)		
Extractable soil Zn (log mg kg <sup>-1</sup> )				- 1.828** (0.703)
Extractable soil Ca × Soil pH	- 0.211 (0.352)			
Extractable soil Fe × Soil pH		- 0.0199 (0.0763)		
Extractable soil Zn × Soil pH				0.306*** (0.114)
Soil pH (pH)	1.684 (2.374)	0.102 (0.149)	0.135 (0.251)	0.217 (0.177)
Soil organic carbon (%)	- 0.335** (0.152)	- 0.495*** (0.187)	- 0.366 (0.234)	- 0.153 (0.102)

**Table 16** continued

	(1) Ca	(2) Fe	(3) Se	(4) Zn
Soil sand content (%)	– 0.0202*** (0.00724)	– 0.0119 (0.00808)	– 0.0161 (0.0104)	– 0.00250 (0.00482)
Observations	106	107	107	107
$R^2$	0.095	0.143	0.036	0.120

Crop fixed effects are included, and a dummy variable for collection of crops directly from the field rather than storage

\* $p < 0.1$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$

**Table 17** Sorghum mineral concentration and soil characteristics, with pH interaction

	(1) Ca	(2) Fe	(3) Se	(4) Zn
Extractable soil Ca (log mg kg <sup>-1</sup> )	0.491 (0.662)			
Extractable soil Fe (log mg kg <sup>-1</sup> )		– 0.700 (0.526)		
Extractable soil Zn (log mg kg <sup>-1</sup> )				0.435 (0.427)
Extractable soil Ca × Soil pH	– 0.110 (0.114)			
Extractable soil Fe × Soil pH		0.127 (0.0918)		
Extractable soil Zn × Soil pH				– 0.0732 (0.0753)
Soil pH (pH)	0.703 (0.785)	– 0.296* (0.177)	0.399** (0.168)	– 0.0101 (0.0997)
Soil organic carbon (%)	– 0.0243 (0.0665)	– 0.223 (0.148)	– 0.265 (0.170)	– 0.00967 (0.0566)
Soil sand content (%)	0.00460* (0.00261)	0.0102** (0.00490)	– 0.0116* (0.00596)	– 0.00470 (0.00285)
Observations	155	155	155	155
$R^2$	0.084	0.181	0.056	0.086

Crop fixed effects are included, and a dummy variable for collection of crops directly from the field rather than storage

\* $p < 0.1$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$

**Table 18** Sweet potato mineral concentration and soil characteristics, with pH interaction

	(1) Ca	(2) Fe	(3) Se	(4) Zn
Extractable soil Ca (log mg kg <sup>-1</sup> )	- 0.326 (0.724)			
Extractable soil Fe (log mg kg <sup>-1</sup> )		- 0.633 (0.391)		
Extractable soil Ca × Soil pH	0.0470 (0.126)			
Extractable soil Fe × Soil pH		0.113* (0.0671)		
Extractable soil Zn × Soil pH				0.229 (0.145)
Soil pH (pH)	- 0.309 (0.826)	- 0.309 (0.186)	0.389* (0.220)	0.117 (0.212)
Soil organic carbon (%)	0.0442 (0.0794)	0.0348 (0.122)	- 0.622*** (0.198)	- 0.0451 (0.0901)
Soil sand content (%)	- 0.000180 (0.00331)	- 0.00853** (0.00384)	- 0.0141* (0.00836)	- 0.00688* (0.00400)
Observations	87	87	87	87
R <sup>2</sup>	0.056	0.204	0.148	0.129

Crop fixed effects are included, and a dummy variable for collection of crops directly from the field rather than storage

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

**Table 19** Cassava mineral concentration and soil characteristics, with pH interaction

	(1) Ca	(2) Fe	(3) Se	(4) Zn
Extractable soil Ca (log mg kg <sup>-1</sup> )	- 1.411*** (0.490)			
Extractable soil Fe (log mg kg <sup>-1</sup> )		0.123 (1.119)		
Extractable soil Zn (log mg kg <sup>-1</sup> )				- 1.158 (0.786)
Extractable soil Ca × Soil pH	0.233*** (0.0790)			
Extractable soil Fe × Soil pH		0.00849 (0.185)		
Extractable soil Zn × Soil pH				0.206 (0.130)
Soil pH (pH)	- 1.602*** (0.573)	0.309** (0.142)	0.288 (0.261)	0.419** (0.170)
Soil organic carbon (%)	- 0.0901 (0.0734)	- 0.122 (0.142)	- 0.440 (0.282)	0.125 (0.109)

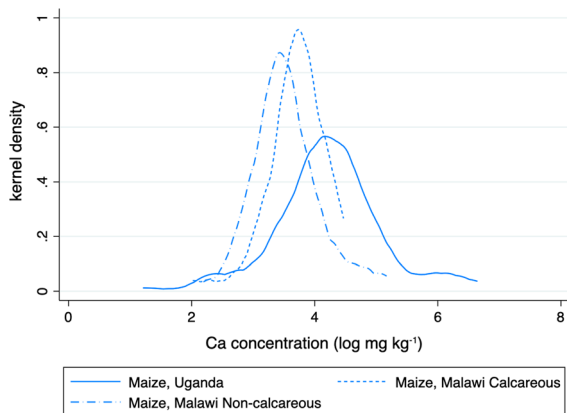
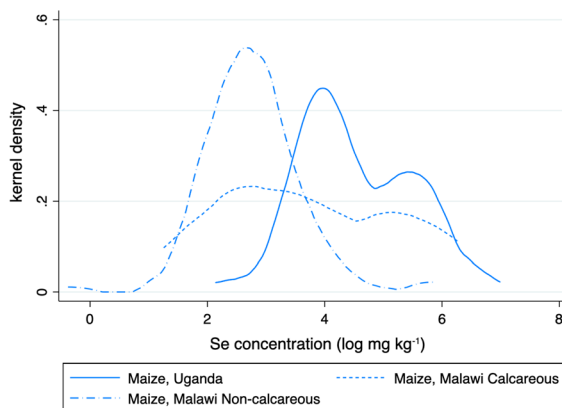
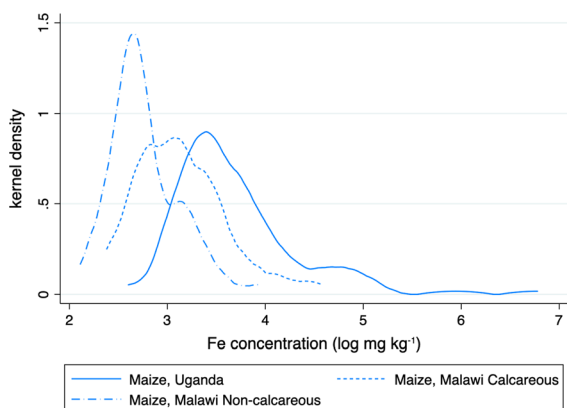
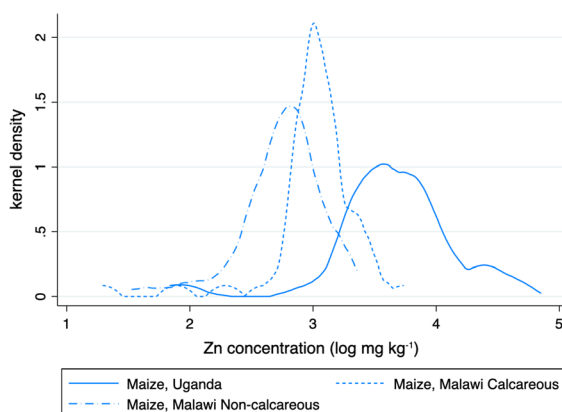
**Table 19** continued

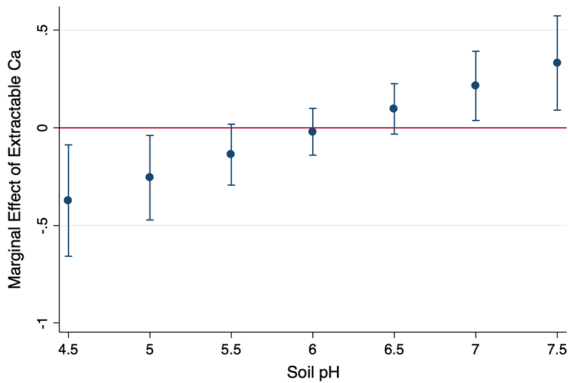
	(1) Ca	(2) Fe	(3) Se	(4) Zn
Soil sand content (%)	– 0.00158 (0.00446)	– 0.00890 (0.00926)	0.00394 (0.0150)	– 0.00174 (0.00592)
Observations	108	108	108	108
$R^2$	0.078	0.092	0.076	0.113

Crop fixed effects are included, and a dummy variable for collection of crops directly from the field rather than storage

\* $p < 0.1$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$

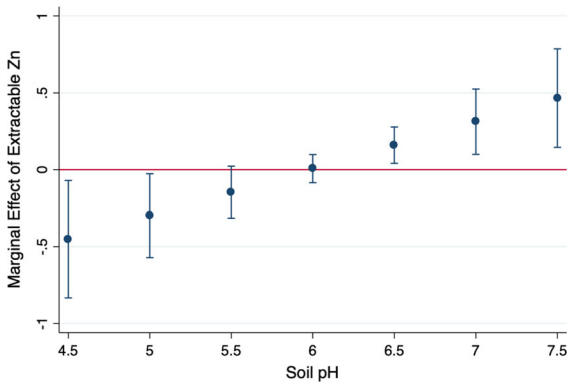
See Figs. 8, 9, 10, 11, 12, 13, and 14.

**Fig. 8** Maize Ca concentration in Uganda and Malawi**Fig. 10** Maize Se concentration in Uganda and Malawi**Fig. 9** Maize Fe concentration in Uganda and Malawi**Fig. 11** Maize Zn concentration in Uganda and Malawi



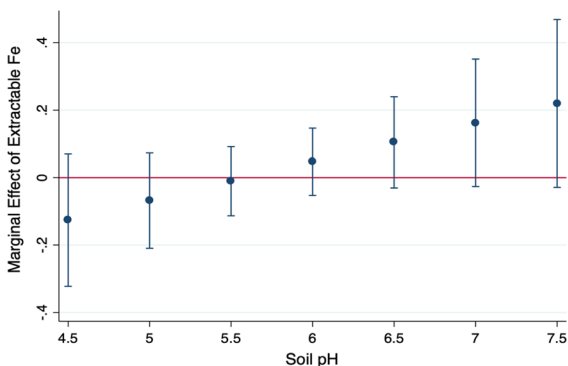
Interaction coefficient shown in Table A12 Column 1.

**Fig. 12** Marginal effect of extractable soil Ca on Cassava Ca concentration, across pH range



Interaction coefficient shown in Table A9 Column 4.

**Fig. 13** Marginal effect of extractable soil Zn on maize Zn concentration, across pH range



Interaction coefficient shown in Table A11 Column 2.

**Fig. 14** Marginal effect of extractable soil Fe on sweet potato Fe concentration across pH

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