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Soil and farm management effects on yield and nutrient concentrations of food crops in East Africa

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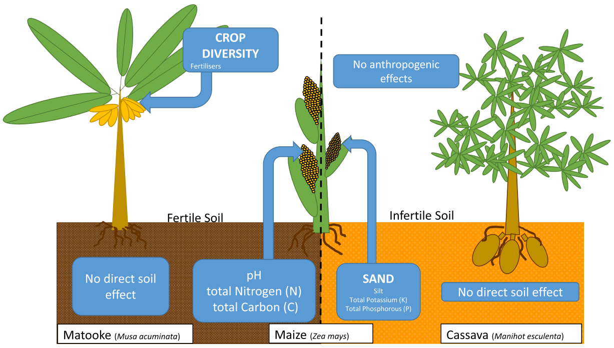
HIGHLIGHTS

- How are soil properties, food nutrient concentrations and yields connected?
- Grain, tubers and fruits were collected on two different soil types.
- Canonical Correspondence Analysis was used to find the most influential variables.
- Annual crops (grains) have a stronger connection to soil than perennial crops.
- Soil organic matter and fertilizer use affected all collected crops on the different soils.

GRAPHICAL ABSTRACT



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ABSTRACT

Crops that grow on soils with higher fertility often have higher yields and higher tissue nutrient concentrations. Whether this is the case for all crops, and which soil and management factors, or combinations mostly affect yields and food nutrient concentrations however, is poorly understood. Here, the main aim was to evaluate effects of soil and management factors on crop yields and food nutrient concentrations in (i) grain, fruit and tuber crops, and (ii) between high and low soil fertility areas.

Total elemental concentrations of Mg, P, S, K, Ca, Fe, Zn, Mn and Cu were measured using a portable X-Ray Fluorescence Spectrometer (pXRF) in maize grain (*Zea mays*; Teso South, Kenya: $n = 31$; Kapchorwa, Uganda $n = 30$), cassava tuber (*Manihot esculenta*; Teso South: $n = 27$), and matooke fruit (*Musa acuminata*; Kapchorwa, $n = 54$). Soil properties measured were eCEC, total N and C, pH, texture, and total elemental content. Farm management variables (fertilisation, distance to household, and crop diversity) were collected. Canonical Correspondence Analyses (CCA) with permutation rank tests identified driving factors of alterations in nutrient concentrations.

Maize grain had higher correlations with soil factors (CCA > 80%), than cassava tuber (76%) or matooke fruit (39%). In contrast, corresponding correlations to management factors were much lower (8–39%). The main soil properties affecting food nutrients were organic matter and texture. Surprisingly, pH did not play an important role. A positive association of crop diversity with nutrient concentration and yield in lower fertility areas was

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observed. Considering, food nutrient composition, apart from yield, as response variables in agronomic trials (e.g. fertilisation or soil improvement strategies), would contribute towards discounting the notion that crops growing on fertile soils always produce healthy and high quality foods.

1. Introduction

Humans largely depend on plants for food and nutrition security. Therefore, nutrients provided by food crops are vital for survival and health. Soils in turn provide crops with most macro- and micronutrients (White and Brown, 2010). Deficiencies in essential nutrients or unavailability in soil can result in a lower quantity and quality of produced foods (Fischer et al., 2019; Joy et al., 2015). In humans, crop nutrient deficiencies can result in a lower intake of vitamins and micronutrients, thereby endangering health and normal human development (Bouis and Saltzman, 2017).

While presence of trace elements in soils plays an important role in plant and human nutrition (about half of the world's soils were reported as being Zn deficient, and 33–50% are deficient in Cu, Mo, and Mn (Knez and Graham, 2013)), crop nutrient availability is vital for crop nutrient uptake. Crop nutrient availability in soils is directly influenced by, parent material (total amount of minerals in the soil), molecule structure and elemental charge, soil chemical and physical properties, as well as the environment. Crop availability of trace elements can result in paradox situations such as with Fe: while only about 3% of all soils are Fe deficient, iron deficiency anaemia is considered a global health problem (Knez and Graham, 2013). Toxicities at the other end of the scale, can occur when the soil has a large amount of readily available elements (either essential elements (e.g. Cu, Zn, Mn, and Fe) or non-essential (e.g. Cd, As, and Pb) (White and Brown, 2010)), taken up by the plant in excessive amounts.

Effects of soil properties on nutrient composition and yields of foods crops are complex. There are many factors involved such as, the availability of nutrients in the soil, plant uptake, partitioning, and translocation within the plant (Baxter, 2010), influenced by the environment and farm management. Environmental effects include soil type, chemical and physical properties, as well as weather (i.e. temperature and precipitation). Fluctuations of the latter two are becoming increasingly significant considering climate change, which can severely affect nutrient concentrations in food crops (Fischer et al., 2019).

Crop diversity has been described as having both positive and negative effects on individual crop performance. The positive effects would include supporting ecosystem services (e.g. nutrient cycling and soil formation), resulting in increased soil fertility (Huang et al., 2015). Adverse effects include an increased resource competition among plants for nutrients, water and light (Huang et al., 2015). Fertilisation, has while increasing the total quantity (yield) of food crops, been postulated to decrease the total quality (nutrient concentration) of foods produced. Current fertilisation regimes focussing on very few macronutrients (mainly N) effectively deplete other nutrients (Riedell, 2010). Excess fertilisation, particularly in the presence of high yielding varieties, has led to a dilution effect defined as “an inverse relationship between growth and mineral concentration” (Riedell, 2010; pg 869). Fertilisation has, however, also been shown to increase the nutrient concentration in crops, for example, through direct fertilisation of micronutrients (fortification), which has been mentioned as a possible solution to counteract nutrient deficiencies both in crops and humans (Bouis and Saltzman, 2017).

Smallholder farmers in rural areas are very dependent on their soils for food and nutrition security. Their health is highly dependent on the produced quantity and quality of foods, and therefore also on factors governing nutrient availability. Soil fertility on farmers' fields in East Africa have been reported to be highly variable (Cobo et al., 2010). Soil fertility has also been related with the distance to the household, revealing an either increasing or decreasing fertility gradient depending on farm type (Tittonell et al., 2016), and therefore potentially impacting the quantity and quality of foods produced on different fields of the same farm.

Although one of the main aims of agriculture is food production, few studies have targeted the actual quality or nutrient composition of the final product. Most research regarding the effect of soil on the nutrient composition in crops focussed on identifying nutrient deficiencies based on specific geographic areas (e.g. the Mediterranean), and regarded deficiencies found in soils and single crop types (Pontieri et al., 2014). Others worked on potential biofortification and enrichment strategies (Bouis and Saltzman, 2017), and compared input and cultivation systems on nutrient concentrations in food (Hattab et al., 2019). Very few studies have compared different soil types and the resulting food nutrient concentrations. Joy et al. (2015), for example showed the effect of calcareous and non-calcareous soils on crop mineral composition. Single interactions between elements/nutrients are known (Baxter, 2010), effects of multiple deficiencies have however, not been studied in detail (Fageria, 2001). Additionally, research on the combined effects of environmental and farm management decisions on food nutrient composition and concentrations is lacking. Thus, improved understanding of soil fertility factors that drive crop productivity are important and needed to develop appropriate soil and nutrient management recommendations. Comparing different food types (grains, tubers, and fruits) is also important as different organs provide different plant functions and should not be expected to react the same way to changes in the environment.

2. Materials and methods

2.1. Research framework

The main aim of this paper was to evaluate the magnitude and impact of soil type and farm management factors on food nutrient concentrations and yields in (i) grain, fruit and tuber crops, and (ii) between high and low soil fertility areas in Eastern Africa.

Two regions with contrasting soil types were selected, one with a relative high fertility (Kapchorwa, with relatively young volcanic soils) and the other with a comparably low fertility (Teso South, with old weathered sandy soils). The subjects of this study were smallholder farmers, whose crop produce is their main food source. As many smallholder farmers in the research areas use low amounts of external inputs such as fertilizers or pesticides, their health and income is directly dependent on their natural resource base.

Crop selection for this study was based on two criteria; the crops had to (i) present a high geographic coverage of the selected regions; (ii) be representative of foods consumed in the area; and (iii) be a major part of the local diet. Staple crops, while not being high in nutrients, do represent foods that are commonly consumed in large amounts by all, and therefore are an integral part of the diet (Yang et al., 2013). The supply of nutrients from local food sources is spatially variable, and according to the research questions of this study, possibly dependent on the variance of soil properties and farm management. Any effective response to nutrient deficiencies must account for this variation through a high geographic coverage.

Farm management methods were selected based on literature findings of the most influential activities on yields and nutrient concentrations in other plant parts such as leaves. The management methods selected for the analysis included fertilisation, crop diversity and distance of the field to the household. Fertilizer application was measured by field and grouped to organic fertilizers (manure and crop residues) and inorganic fertilizers (NPK, DAP, CAN, and Urea) in kg/m^2. Crop diversity per field was measured using crop species richness and crop species diversity. Distance of field to the household, was measured in meters to the household.

In Kapchorwa and Teso South, different crops were cultivated, and different foods consumed, due to different soil types, growth conditions, and possibly society and culture. Using the above mentioned criteria, the most common foods found cultivated and consumed in Kapchorwa were maize (*Zea mays* L.) and matooke (East African Highland Banana (*Musa acuminata* Colla)). In Teso South, the main foods were maize and cassava (*Manihot esculenta* Crantz). The two research areas, therefore, showed maize as a common denominator, thus allowing crop responses to contrasting soil types. Additionally, the chosen different staple crops, allowed the investigation of differences in nutrient compositions between (i) crop organs – fruits (matooke), grains (maize), and tubers (cassava); and (ii) crop growth types – generative annual (maize), generative perennial (matooke), and storage perennial (cassava), in response to soil properties and management factors.

Food production in general follows two main aims, the production of a high amount (yield or quantity) with a high nutrient concentration (quality). In this case, yield (t/ha) was selected as an indicator for productivity of the crops selected. Food quality was analysed as trace elemental concentration. The focus on trace elements was due to their direct uptake from the soil, unlike secondary plant metabolites formed in the plant. The elements selected in this study were Mg, P, S, K, Ca, Fe, Mn, Cu, and Zn, as they are essential for both humans and plants (White and Brown, 2010).

Regarding soil properties, it was expected that specifically pH, eCEC, and texture significantly affected food nutrient concentrations and yields. Grains, generally produced by annual plants were expected to have a stronger connection to soil properties due to their faster rate of growth than perennial species such as fruits and tubers. Considering the different farm management methods, fertilisation was expected to have a positive effect on yield and nutrient concentrations in low fertility areas based on the addition of nutrients, increasing and supporting plant growth and development, and a decreasing effect in high fertility areas based on the dilution effect. Crop diversity was expected to have a positive effect in the higher soil fertility regions, whereas it would have a negative effect in the low soil fertility regions, due to increased competition for a lower amount of nutrients present in the soil. Increased distance from the household was expected to show a decreasing gradient of food nutrient concentrations and yield, following a decreasing gradient of soil fertility.

2.2. Study sites

2.2.1. Teso South, Kenya

Teso South (0.4592722°, 34.10924°; 0.6357222°, 34.27789°) constituency in western Kenya belongs to the larger Busia County. The total surface area of the research area is about 330 km^2 and is divided into two larger wards Amukura and Chakol. The average rainfall ranges from 1420 to 2000 mm/year with two rain seasons (Jaetzold et al., 2009). The altitude ranges from 1200 to 1400 m.a.s.l. with average yearly temperatures from 21 to 22 °C. Orthic acrisols and ferralsols are the main soil types in the region, developed from basement rock (Jaetzold et al., 2009), and are moderately deep and of low fertility.

2.2.2. Kapchorwa, Uganda

Kapchorwa (1.359817°, 34.45045°; 1.450219°, 34.44643°) is situated on the north face of Mt. Elgon. Three adjacent sub-counties that cover the entire altitude gradient of Kapchorwa were chosen for data collection: Kapchesombe, Tegeres, and Kaptanya. The soils are derived mainly from basaltic volcano ash and metamorphic rocks producing clay and nutrient rich nitisols (De Bauw et al., 2016). The altitude gradient covers 1000–3000 m.a.s.l. with a surface area of 297 km^2. The mean yearly rainfall gradient across all Kapchorwa covers 1200–2200 mm/year with a mean yearly temperature range of 1.5–23.5 °C (De Bauw et al., 2016).

2.3. Data collection

2.3.1. Sample collection

The present study was part of the project “Crops for Healthy Diets – Linking Agriculture and Nutrition (HealthyLAND)” (www.healthyland.info). For the sample collection a Probability Proportional to Size (PPS) approach based on the method by Kish (1995), was used for initial household selection, using village population as weights. The PPS was followed by a random selection of households resulting in 72 households selected per research area for this study. A detailed account of the PPS sampling can be found in Fischer et al. (2019).

The household data collection combined a farm visit, farmer interview, and sample collection (Table 1). During the interview, the amounts of fertilizers (both organic and inorganic) applied to each field were recorded. Yields per field of maize and cassava in Teso South, and maize and matooke in Kapchorwa, were converted into t/ha. Crop diversity was calculated per field using the Species Richness Index, defined as the sum of crop species, and the Simpson's (1949) Diversity Index (1-D), ranging between 0 (one crop species in field) and 1 (all crop plants in field are different species).

Plant and soil samples were collected from three fields managed and visited regularly by the selected households (Fig. S1). The three fields selected were the closest field, the mid-distance field, and the farthest field from the household, measured by linear distance in meters from the household. Four soil samples were taken per field, and mixed to form a composite soil sample. Topsoil (0–20 cm) results were selected for use in this paper, as no significant differences in properties or nutrient content could be found to the subsoil (20–60 cm) also collected. Edible parts, in their ripe stage of maize, cassava and matooke were collected on the same fields selected for soil sampling (Table 1). The crops collected were all from land races. Maize grains were shucked from the cob. Cassava and matooke were both peeled and sliced. All plant and soil samples were then sun-dried and stored (Fischer et al., 2019).

2.4. Sample analysis

The dried soil samples were sieved, milled and analysed for total N and C content using a Vario MAX CN-Analyser (Elementar Analysesysteme GmbH, Hanau, Germany). pH was measured in 1 M KCl following the procedure detailed in Lewandowski et al. (1997). The percent texture classes clay (<0.002 mm), silt (0.002–0.05 mm) and sand (0.05–2.0 mm) were measured using the gravimetric method. Exchangeable elements for effective cation exchange capacities (eCEC) were measured using Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES Varian VISTA Pro, the Netherlands). Texture and eCEC were measured using the methods detailed in Pansu and Gautheyrou (2006), at the Core Facility at the University of Hohenheim, Stuttgart, Germany (Fischer et al., 2019).

Table 1
Number of paired plant and soil samples collected from farmers' fields during the harvest time of the long rain season (July-August) in 2016 in both Teso South, Kenya and Kapchorwa, Uganda. The map of collection sites can be seen in the supplementary material – Fig. S1.

Region	Sample type	Sample Number
Teso South, Kenya	Paired maize grain and soil sample	31
	Paired cassava tuber and soil sample	27
Kapchorwa, Uganda	Paired maize grain and soil sample	30
	Paired matooke fruit and soil sample	54

Total elemental analysis of soils and plant samples were done at the Soil Spectral Laboratory of ICRAF – The World Agroforestry Centre in Nairobi, Kenya. Plant and soil samples were milled, and analysed for total trace elemental content of Mg, P, S, K, Ca, Fe, Zn, Mn and Cu, using a portable X-Ray Fluorescent Spectrometer (Tracer 5i pXRF – Bruker Elemental, Kennewick, WA, USA) (see soil results Table 2; maize grain results Table S2; cassava tuber results Table S3; matooke fruit results Table S4).

A previous study by Fischer et al., 2019, investigating the impact of climate change on food quality, in the same research area and using the same samples, showed that Kapchorwa had significantly higher values ($p < 0.05$) of most soil properties (exception of sand) and elements measured (Fischer et al., 2019). The C:N ratio showed no significant differences between the research areas (Table 2). The same study also showed that the maize yield in Kapchorwa at 2.05 t/ha (± 1.20) was significantly ($p = 0.0214$) higher than the maize yield of Teso South at 0.49 t/ha (± 0.36) (Table S2).

Nutrient concentrations in Kapchorwan' maize grain were significantly higher than in Teso South for all nutrients measured (Fig. 1; Table S2). Additionally, the range was greater in Kapchorwa than in Teso South for all maize grain nutrients with the exception of P (Fig. 1). The greatest differences between the two areas was found in Cu, Mn, and Fe, where the differences between means were >70% (Fig. 1; Table S2) (Fischer et al., 2019).

2.5. Statistical analysis

2.5.1. Censored data

The data in this study was observed to be left censored, therefore containing values below the level of detection of the devices used. A maximum likelihood method described by Piepho et al. (2002) was used to estimate left-censored values of variables, if they were < 80% censored. The calculations were done on SAS University Edition 2018, using the method by Piepho et al. (2002) (adapted from Fischer et al., 2019, code in the supplementary materials).

2.5.2. Descriptive analysis

Comparisons on all of the values measured were made between the means of the two different research areas. All comparisons were done using the Surveyreg procedure for sample survey data in the SAS© University Edition 2018 (SAS Institute Inc. USA) (code in the supplementary materials).

Soil values (trace elemental contents and soil properties) were compared to the values of the sentinel soil site African Soil Information Service (AfSIS) (http://africasoils.net/) (Hengl et al., 2015), collected across Sub-Saharan Africa. The comparison was done to determine how representative the collected samples of this study were to Sub-Saharan Africa in general and East Africa in specific. Due to the high standard deviation in the AfSIS dataset, for each variable the percent difference of the medians of the collected values and those of the AfSiS database were calculated. The closer the calculated value to zero, the more similar the compared medians were.

The distribution of the measured total elemental concentrations within the edible part of the three crops were shown using boxplots (Fig. 1), compared to three different nutrient food composition tables. For crops grown in Kenya, the Kenyan Food Composition Table of the FAO (available at: http://www.fao.org/3/I8897EN/i8897en.pdf) was used (maize code: 01018; cassava code: 02007) (FAO and Government of Kenya, 2018), referred to as the Kenyan Food Composition Table. For crops grown in Uganda, the HarvestPlus Food Composition Table for Central and Eastern Uganda (available at: https://www.harvestplus.org/node/562) was used (maize code: 1042; matooke code: 5001) (Hotz et al., 2012), referred to as the Ugandan Food Composition Table. As a global comparison the USDA Nutritional Database (available at: https://ndb.nal.usda.gov/ndb/) was used (maize code: 20314; cassava code: 11134; no matooke) (Nutrient Data Laboratory (U.S.), 1999; USDA, 2018) and will be referred to in this paper as the Global Food Composition Table. Not all nutrients measured were equally represented in all food composition tables (Table S8).

2.5.3. Canonical Correspondence Analysis (CCA)

To understand whether site-specific soil and management factors have an effect on the food nutrient composition, a Canonical

Table 2
Table of top soil (0-20cm) values from samples collected in Teso South, Kenya (n= 157) and Kapchorwa, Uganda (n= 130) during the long rain season (March-August) of 2016. Table adapted from Fischer et al. 2019.

Soil Values	Teso South, Kenya					Kapchorwa, Uganda				
Elements (mg/kg)	Mean	SD	Median	Max	Min	Mean	SD	Median	Max	Min
Na	4.56	2.61	3.52	15.7	2.24	<LOD	<LOD	<LOD	<LOD	<LOD
Mg	105	406	7.55	2478	6.02	4304^{***}	2312	3821	14489	1070
Al	32490	12092	32046	58912	8131	61483^{***}	8835	61217	84238	42985
P	230	118	212	1017	48.5	944^{***}	184	942	1510	424
S	41.7	92.7	10.7	935	1.11	44.6	29.3	36.1	204	10
K	1331	1088	1001	3802	31.6	3448^{***}	2396	2540	10086	201
Ca	587	722	327	3548	20.2	3286^{***}	1896	2770	11161	632
Ti	1862	1348	1475	7267	517	43068^{***}	14472	41934	73861	14023
Cr	43.2	30.7	35.5	350	27.0	253^{***}	224	217	1813	19
Mn	480	239	449	1388	63.0	2864^{***}	757	2800	5266	1180
Fe	23245	10030	21508	63597	9070	154686^{***}	19238	157036	184745	97321
Co	20.1	29.3	7.85	215	6.02	<LOD	<LOD	<LOD	<LOD	<LOD
Ni	13.5	10.2	11.1	52.5	1.42	71.4^{***}	15.2	69.3	104	38.9
Cu	10.8	5.76	10.8	44.5	3.51	<LOD	<LOD	<LOD	<LOD	<LOD
Zn	39.3	6.28	37.8	68.3	30.2	82.8^{***}	10.0	82.5	111	60.7
Se	<LOD	<LOD	<LOD	<LOD	<LOD	0.58	0.17	0.60	0.95	0.20
pH	5.06	0.65	4.94	7.45	4.05	5.67^{***}	0.52	5.65	7.13	4.56
N (%)	0.08	0.12	0.07	1.54	0.02	0.24^{***}	0.11	0.25	0.58	0.01
C (%)	0.86	0.31	0.86	2.02	0.25	3.06^{***}	0.88	3.04	6.07	0.63
C:N	12.1	1.62	12.1	19.3	0.80	13.1	2.27	13.0	18.89	8.76
Sand (%)	55.3^{***}	12.0	55.3	88.4	23.4	20.6	7.30	19.4	39.6	4.5
Silt (%)	20.4	5.09	20.4	35.2	6.35	27.3^{**}	8.41	26	77	17.9
Clay (%)	21.3	7.16	21.3	39.3	0.06	52.8^{***}	8.75	53.3	68.8	18.5
eCEC (mmol/kg)	-0.18	3.42	-0.17	15.4	-11.5	9.93^{***}	6.85	9.46	25.9	-7.66

<LOD stands for less than level of detection and means that the certain value was not detected with the measuring device, in this case the pXRF. Asterisks (*) define level of significance, categorized into $p < 0.05^{*}$; $p < 0.005^{**}$; $p < 0.0005^{***}$. Period (.) signifies a value close to significance $p < 0.10$.

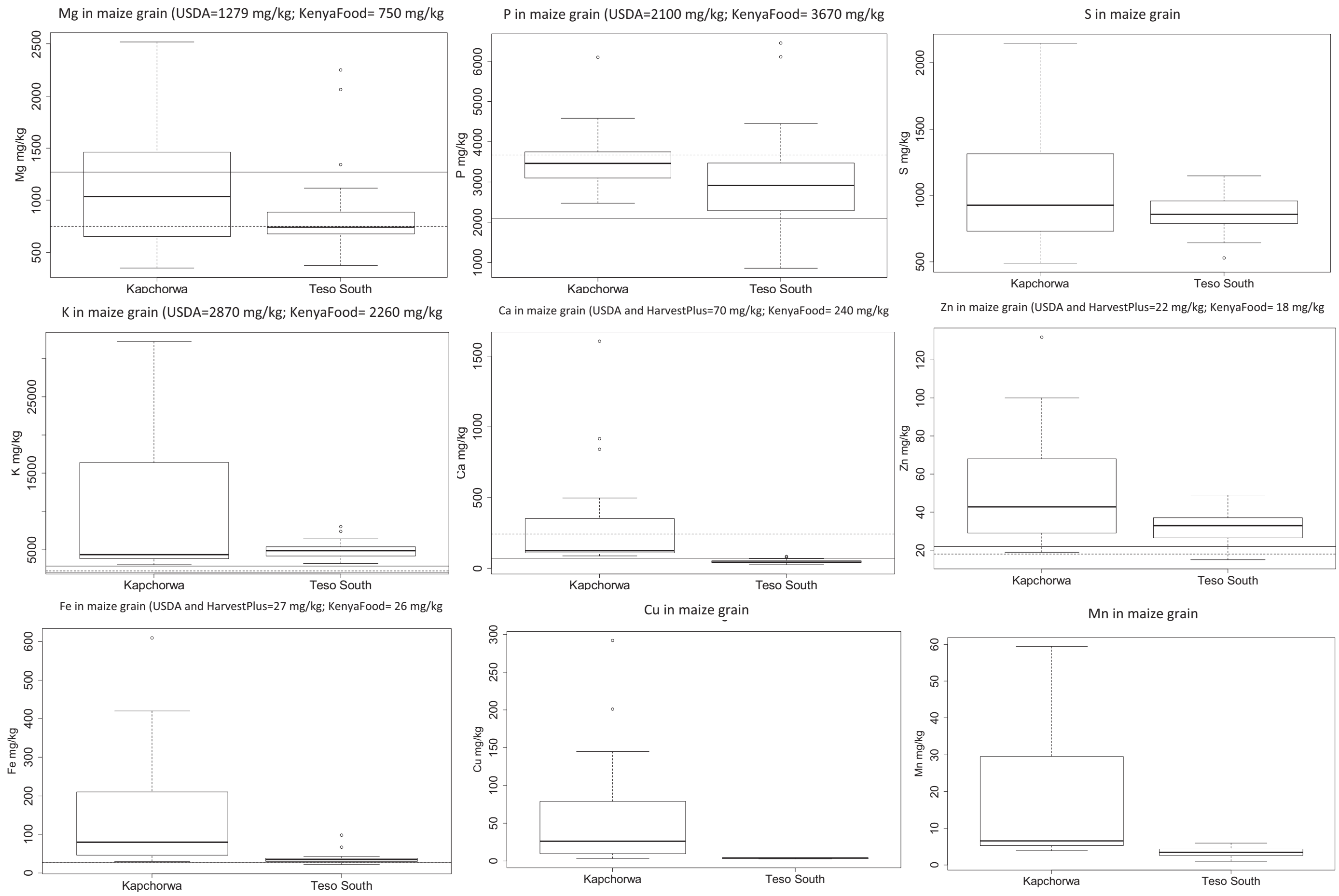

Fig. 1. Boxplots showing the comparison between the nutrient concentrations measured in maize grain collected in Teso South, Kenya and Kapchorwa, Uganda (July–August 2016). The lines indicate the means from nutrient composition databases as comparisons. The dotted line represents the Kenyan Food Composition Table from the FAO (http://www.kilimo.go.ke/wp-content/uploads/2018/10/KENYA-FOOD-COMPOSITION-TABLES-2018.pdf); and the full line represents the mean values of the Global Food Composition Table from the USDA Nutritional Database (https://ndb.nal.usda.gov/ndb/). The full line was also used for the Ugandan Food Composition Table (HarvestPlus: https://www.harvestplus.org/node/562) which for maize were the same values as in the USDA database.

Correspondence Analysis (CCA) was done. The CCA is a multivariate method that uses ordination to find gradients, based on the chi-square distance (Oksanen, 2015). In this study, CCAs were used to establish gradients of soil and management factors affecting food nutrient concentrations. The response variables were food nutrient concentrations (Mg, P, S, K, Ca, Mn, Cu, Fe, and Zn) and yield. The explanatory variables used included soil properties (texture (sand, silt, clay), eCEC, pH, altitude, total Nitrogen (N) and Carbon (C), and Carbon/Nitrogen ratio (CN)), soil elements (Mg, Al, P, S, K, Ca, Ti, Cr, Mn, Fe, Ni, Zn, and Se) and farm management factors (distance to household (Meters), Species Richness (SR), Species Diversity (SD), organic fertilizers (OrganFert), and inorganic fertilizers (InorgFert)) (Table S1). The CCA was calculated using the "cca" function of the packages "vegan" in R Studio Version 1.0.136 (RStudio, USA) (Oksanen, 2015) (see code in supplementary materials). In this study, the variance explained, equalled the cumulative explained variance of the first and second CCA axis. In total seven CCAs were done per food nutrient concentration group (Crop = maize grain from Teso South, or Kapchorwa, cassava tuber from Teso South, or matooke fruit from Kapchorwa), covering the following variants: Crop + All (all variable groups); Crop + Soil Elements (SE) + Soil Properties (SP); Crop + SE + Management Effects (Manag); Crop + SP + Manag; Crop + SP; Crop + SE; Crop + Manag. To clearly distinguish between crop and soil nutrients, a *G*, *T* or *F* will be added as suffix on the crop nutrient names to refer to maize grain, cassava tuber and matooke fruit respectively. Soil will be marked with an *S* (Table S1). The CCAs were analysed by identifying response variable clusters and identifying the most influencing explanatory variables by their vicinity and vector length.

2.5.4. Permutation rank test

A permutation rank test was done on the explanatory variables of the models explaining most variance using the vegan function "anova" (Oksanen, 2015) (please see supplementary materials for codes). The anova permutation test was done for direct (Type I – direct sequential results) and marginal effects (Type III – including both interactions and main effects). The top ten ranks of Type I and III tests were listed according to their p-value. The highest variables in the list thereby having the highest influence on the CCA.

3. Results

3.1. Descriptive analysis

3.1.1. Soil physical and chemical properties

Concerning textural soil properties in comparison to the AfSIS database, Kapchorwan' values showed higher silt and clay values than medians reported for both EA (silt: 42%; clay: 3% higher) and SSA (silt: 7%; clay: 37% higher) in the AfSIS database (Table 2; Fig. S2). Kapchorwan' sand values on the other hand were below medians reported for EA (−8%) and SSA (−49%), as were the pH values (EA: −14%; SSA: −8%). Soil elements in Kapchorwa were higher than medians of EA and SSA with the exception of P, Ni, Fe, and Mg (ranging from −21% to −99% below). In Teso South, silt, clay and pH were below the median values (−15%; −45%; and −19% below SSA, respectively) while sand was above median in both EA (+161%) and SSA (+49%). Concerning soil elements, most were very close to the EA and SSA values and showed only moderate differences (ranging from +42% to −99%) (Fig. S2).

3.1.2. Food nutrient concentrations

In general, the maize grain nutrient concentrations of Teso South were above those of the Global Food Composition Table averages (Fig. 1) with the exception of Mg (global value: 1270 mg/kg). Mg's mean of 861 mg/kg in Teso South was far below the global value, but very close to the Kenyan Food Composition Table mean (Fig. 1). The Global and Ugandan maize grain Composition Table values were below the Kapchorwan values, with the exception of Mg (global value: 1270 mg/kg; Kapchorwa 1071 mg/kg) (Fig. 1).

Zn and Fe maize grain nutrient concentrations in both Kapchorwa and Teso South were slightly above or close to those of the food composition tables means. Macronutrients such as Mg, P, and Ca were, in both regions, often below the food composition table means.

The nutrient concentration within cassava tuber was higher than both Kenyan and Global food Composition Table means, with the exception of Ca where the Teso South mean (327 mg Ca/kg) was similar to the Kenyan Food Composition mean (330 mg Ca/kg) (Fig. S6). For matooke, the only comparison values available were for Fe, Zn and Ca from the Ugandan Food Composition Table. Fe and Ca concentrations were both below the food composition table values, whereas measured matooke Zn agreed with the mean composition table value (Fig. S7).

3.1.3. Distance, biodiversity, and fertilisation

In Teso South, the distances between the house of the farmer to the maize (64 m ± 21) or cassava field (62 m ± 38) was not significantly different. However, in Kapchorwa, the staple crop matooke (255 m ± 499) showed a larger distance between house and fields than maize (104 m ± 128) (Fig. S3).

In Teso South a higher number of cassava fields received organic fertilizers (maize 13% fields; cassava 27% fields), whereas about half of all maize fields received inorganic fertilizers (Table S7). Similarly, in Kapchorwa, more maize fields received inorganic fertilizers (27%) than matooke fields (17%), while more matooke fields received organic fertilizers (45% matooke fields; maize in Kapchorwa 20%). The amounts of fertilizers used in all cases were very low. The maximum used amounts were organic fertilizers in cassava fields (0.09 kg/m^2 ± 0.29). Inorganic fertilizers showed the highest amounts used in matooke fields (0.04 kg/m^2 ± 0.06).

Both species richness and species diversity were not significantly different between matooke and maize field in Kapchorwa (matooke: richness 2.7 ± 1; diversity 0.36 ± 0.24 and maize: richness 2.3 ± 1.6; diversity 0.28 ± 0.24), and maize and cassava fields in Teso South (maize: richness 2.4 ± 1.5; diversity 0.31 ± 0.26 and cassava richness 1.8 ± 1.3; diversity 0.17 ± 0.25) (Fig. S4).

3.2. Multivariate analysis – Canonical Correspondence Analysis (CCA)

The full CCA model (Crop + Soil Properties + Soil Elements + Management Factors) explained most variance for nutrient concentration in all food crops analysed, ranging from 85% for maize in Teso South, to 39% for matooke in Kapchorwa (Fig. 2). Management factors had the lowest effect in all models, and were at their highest in maize grain in Kapchorwa (Crop + Manag) at 19% explained variance, and lowest in matooke fruit at 11% explained variance (Fig. 2). The variance of nutrient concentration in maize grain was determined mostly by soil properties in both Teso South and Kapchorwa. In contrast, the nutrient variance in both cassava and matooke strongly related to presence of soil elements.

The full models were used in the rank test to identify the main factors exhibiting most influence on food nutrient concentration. In Teso South, the two main factors (significant according to Type I test) affecting the nutrient concentrations in maize grain, included sand and silt (Table 3). These were followed by non-significant yet still high ranking properties such as eCEC, soil P, and species richness. Significant marginal effects (Type III tests), on the other hand, listed (in descending order) were clay, sand, soil K and eCEC (Table 3). The CCA from Teso South features a main grain nutrient concentrations cluster (with exceptions of grain Mg and P) (Fig. 3A). The nutrient cluster was most positively affected by the vector of soil C (not listed in the permutation rank test), inorganic fertilizers, species richness, sand, and species diversity. The strongest negative associations with the main grain nutrient cluster and yield were silt, eCEC, and soil P (Fig. 3A). Soil elements (with the exception of total soil P and Ca) had positive associations with the main nutrient cluster. Yield was located within the nutrient cluster and therefore shared its associations. Grain Mg was positively associated with altitude, but negatively associated with all other explanatory variables of the permutation rank test. Grain P was positively associated with organic fertilizers (not in top ten permutation rank test) and eCEC, and negatively associated with species richness, sand and species diversity.

In Kapchorwan' maize grain the main influencers (Type I tests) of nutrient concentrations and yield were pH, soil N, species richness, soil Ca, and soil C (Table 4). Non-significant but still high ranking variables included species diversity, organic fertilizers and inorganic fertilizers (Table 4). Significant marginal effects (Type III) included soil C and species diversity. A main grain nutrient cluster was found very close to the origin, with little scatter, while grain Mn, grain Cu, and yield were separate (Fig. 3B). The main grain nutrient cluster was positively affected by species richness, soil Mg, species diversity and soil Ca. Grain Mn and Cu were positively associated with soil N and C, and negatively associated with pH, sand and CN. Yield (located on the soil Mn vector) was positively associated with variables on the right side of the vertical axis, particularly organic fertilizers, as well as other variables such as soil Mn and Zn (not in the permutation rank) (Fig. 3B). As yield and the main nutrient cluster were situated on opposite sides of the CCA (Fig. 3B), the variables positively associated with grain nutrient concentrations in the cluster were negatively associated with yield, and vice-versa.

Neither cassava nor matooke showed any significant results in the ranking process of the full models (Tables S5 and S6). Matooke was marginally affected ($p = 0.073$) by inorganic fertilizers in Soil Elements + Management (Table S6). In the CCA, the main matooke fruit nutrient cluster was found slightly below and very close to the origin, with very little scatter. One negative association with fruit nutrient concentrations was with inorganic fertilizers. Two exceptions to the nutrient cluster were fruit Ca and S, located near the eCEC vector and the soil K vector respectively. Fruit Ca was positively associated with inorganic fertilizers, as well as eCEC and CN. Fruit S showed a positive association with soil K, soil Al, species diversity and clay. The yield was difficult to identify in the main nutrient cluster (Fig. 4A), and was therefore shown as an explanatory variable in an additional CCA, where its vector is pointing away from the main nutrient cluster (Fig. S5). Yield, located exactly opposite the main fruit nutrient cluster was therefore positively associated with soil Ca, Mg, Mn and Zn.

For cassava significant results were found in the permutation Crop + Soil Properties + Management Factors with altitude and organic fertilizers (both Type I and III), and in the permutation Crop + Soil Elements + Management Factors with altitude (both Type I and III) (Table S5). Other rankings of cassava show repeated Type I and III significance of altitude, organic fertilizers, and distance to household. Similar to the other crops, cassava tuber showed a main nutrient cluster in the CCA, with the exceptions of tuber S, P, Mn, and Ca. The main positive associations with the tuber nutrient cluster were distance to household and altitude. Negative associations included species richness, sand, organic fertilizers, and pH and silt (not in the permutation rank test) (Fig. 4B). Tuber S

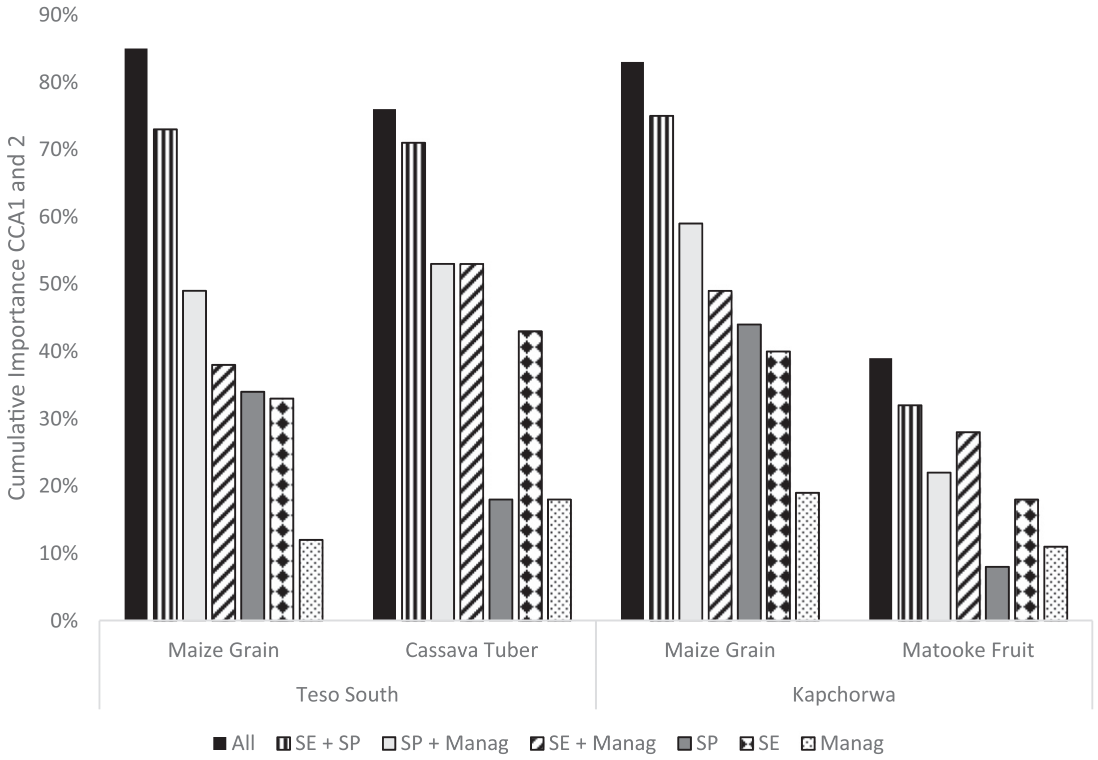

Fig. 2. Comparison of the Canonical Correspondence Analysis (CCA) combinations measured with the cumulative importance of the first two CCA's. The cumulative importance describes the data fit. Per crop nutrient content (concentrations of Mg, P, S, K, Ca, Fe, Mn, Cu, and Zn) 6 different variable permutations are shown (SE: Soil Elements (14 variables); SP: Soil Properties (8 variables); Manag: management factors (5 variables)). For details on the variables used see Table S1.

was above the main nutrient cluster and was not directly positively associated with any variable. Negative associations however included organic fertilizers and silt (not in the permutation rank test). Tuber P and Mn showed positive associations with organic fertilizers, species richness, soil Mg, and silt (not in the permutation rank test). Tuber Ca was the farthest nutrient away from the main tuber nutrient cluster. It was positively associated with distance to the household. It was also positively associated with soil Zn and inorganic fertilizers, although they were not significant in the permutation rank test. Yield was located above the tuber nutrient cluster, and was negatively associated with organic fertilizers and species richness (Fig. 4B). Yield was positively associated with soil Fe and soil C (not in the permutation rank test).

Table 3
Results of the anova permutation rank test done in R using the package vegan. The test ranked the effect of the explanatory variables (soil properties and elements (pH, texture, eCEC, total N and C, and various total elemental contents) and management variables (Organic and Inorganic fertilizer, species richness and diversity, altitude and distance to household) on the nutrient concentration (Mg, P, S, K, Ca, Fe, Mn, Cu and Zn) and yield of maize grain collected in Teso South, Kenya. The tables shows the Type I (direct) and Type III (marginal) effects of the highest ranked 10 variables.

Maize Grain - Teso South, Kenya Anova - Type I terms - 500 permutations

	Variable	DF	ChiSquare	F - value	Pr(>F)
1	Sand	1	0.0051523	9.415	0.006^{**}
2	Silt	1	0.0045156	8.2515	0.009^{**}
3	eCEC	1	0.0018012	3.2914	0.087.
4	PS	1	0.0018185	3.3231	0.087.
5	Species Richness	1	0.0015688	2.8667	0.094.
6	FeS	1	0.0015638	2.8576	0.134
7	Altitude	1	0.0012501	2.2844	0.147
8	pH	1	0.0012488	2.2819	0.159
9	Inorganic Fertilizer	1	0.0009296	1.6986	0.206
10	CN	1	0.0007863	1.4368	0.269

Maize Grain - Teso South, Kenya Anova - Type III marginal - 500 permutations

	Variable	DF	ChiSquare	F - value	Pr(>F)
1	Clay	1	0.007769	14.1965	0.004^{**}
2	Sand	1	0.0061949	11.3201	0.006^{**}
3	KS	1	0.0042017	7.6779	0.012^{*}
4	eCEC	1	0.0033707	6.1594	0.022^{*}
5	Species Richness	1	0.0018012	3.2914	0.073.
6	Species Diversity	1	0.0014691	2.6846	0.114
7	Silt	1	0.0011115	2.0374	0.186
8	FeS	1	0.0010017	1.8305	0.199
9	MnS	1	0.0009474	1.7313	0.223
10	PS	1	0.0007289	1.3319	0.311

Asterisks (*) define level of significance, categorized into $p < 0.05^{*}$; $p < 0.005^{**}$; $p < 0.0005^{***}$. Period (.) signifies a value close to significance $p < 0.10$. For definitions of variables see Methods of this paper and table S2.

4. Discussion

4.1. Representativeness of soils and foods

Soil fertility in total was higher in Kapchorwa than in Teso South based on the significantly higher values of almost all variables measured in soils (Fischer et al., 2019). The comparison of the measured soil values of Teso South and the AfSIS soil database showed that Teso South was largely representative of relatively poor soils of both East Africa (EA) and Sub-Saharan Africa (SSA). Kapchorwa on the other hand, was more representative of higher fertility areas compared to EA and SSA.

Areas with higher levels of soil fertility (Kapchorwa) produced crops with significantly higher yields and nutrient concentrations then areas of lower fertility (Teso South) (Fischer et al., 2019). Macronutrients had a higher likelihood of depletion in foods in both lower and higher fertility soils than micronutrients (although lower fertility areas had a higher magnitude of deficiency), most likely due to the higher amount needed by the crops, and the low amount of fertilizers used in both areas. These findings were corroborated by other researchers who have identified large nutrient imbalances in agricultural fields across SSA (Cobo et al., 2010).

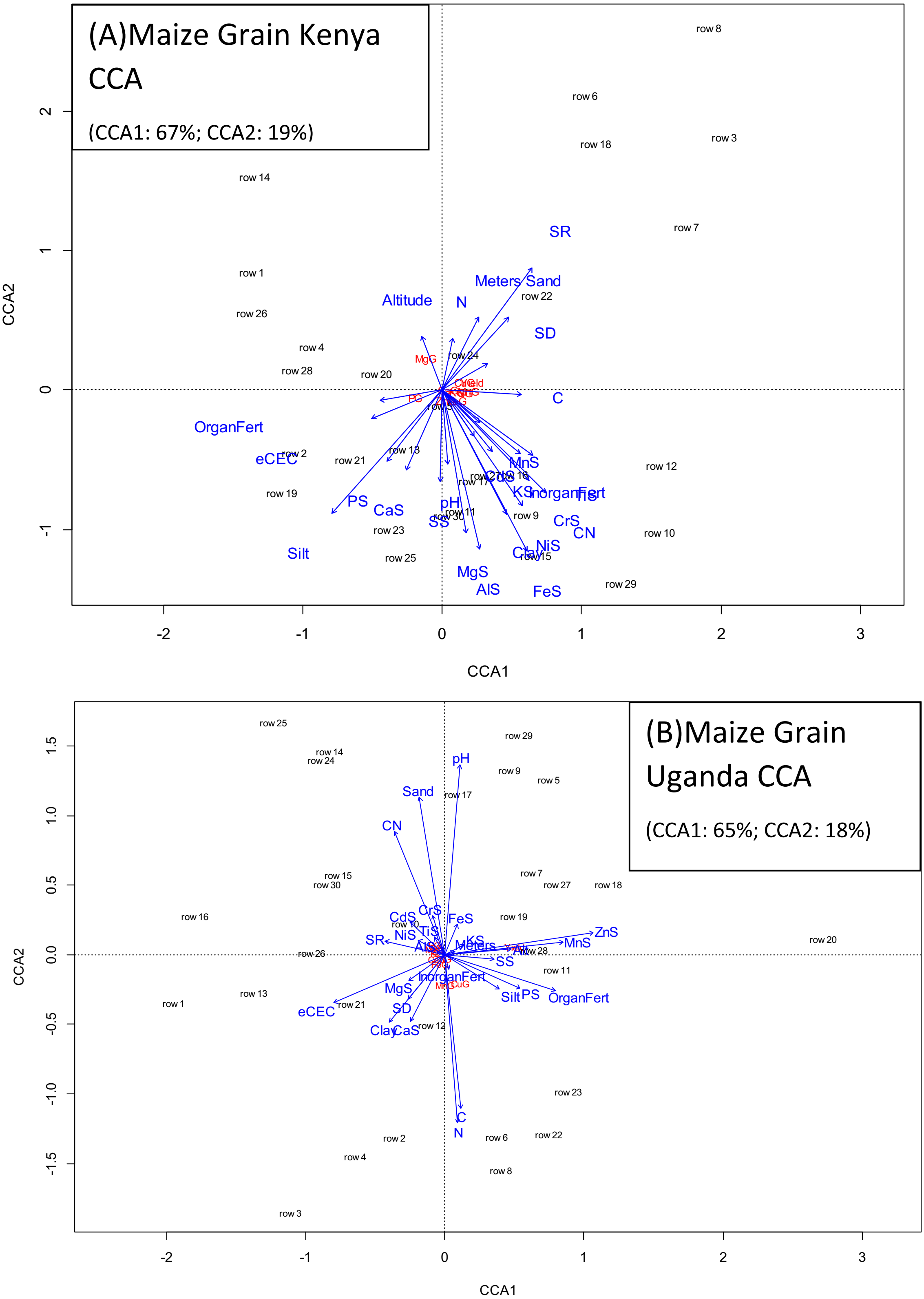

Fig. 3. Panels A and B represent the Canonical Correspondence Analysis (CCA) biplot diagrams that show each crop (A) maize grain in Teso South, Kenya; (B) maize grain in Kapchorwa, Uganda. The plot shows the response variables in red (nutrient concentrations in food parts Mg, P, S, K, Ca, Fe, Mn, Cu and Zn), plotted against the explanatory variables in blue showing farm management variables (OrganFert, InorgFert, species richness and diversity, altitude and distance to household), and soil properties and elements (pH, texture, eCEC, total N and C, and various total elemental contents). The vectors represent the explanatory variables. Rows signify each crop nutrient concentration sample in the CCA.

Table 4
Results of the anova permutation rank test done in R using the package vegan. The test ranked the effect of the explanatory variables (soil properties and elements (pH, texture, eCEC, total N and C, and various total elemental contents) and management variables (Organic and Inorganic fertilizer, species richness and diversity, altitude and distance to household) on the nutrient concentration (Mg, P, S, K, Ca, Fe, Mn, Cu and Zn) and yield of maize grain collected in Kapchorwa, Uganda. The tables show the Type I (direct) and Type III (marginal) effects of the highest ranked 10 variables.

Maize Grain – Kapchorwa, Uganda Anova - Type I terms - 500 permutations

	Variable	DF	ChiSquare	F - value	Pr(>F)
1	pH	1	0.0290975	13.636	0.002**
2	N	1	0.0141599	6.6358	0.005**
3	Species Richness	1	0.008969	4.2032	0.020*
4	CaS	1	0.0081372	3.8133	0.024*
5	C	1	0.0048919	2.2925	0.049*
6	Species Diversity	1	0.0051116	2.3955	0.062.
7	Organic Fertilizer	1	0.0049798	2.3337	0.067.
8	Inorganic Fertilizer	1	0.0040194	1.8836	0.096.
9	ZnS	1	0.0038876	1.8219	0.102
10	Clay	1	0.0034529	1.6181	0.133

Maize Grain – Kapchorwa, Uganda Anova - Type III marginal - 500 permutations

	Variable	DF	ChiSquare	F -value	Pr(>F)
1	C	1	0.0097006	4.546	0.008**
2	Species Diversity	1	0.0068224	3.1972	0.032*
3	N	1	0.005031	2.3577	0.053.
4	MgS	1	0.0051372	2.4075	0.076.
5	AlS	1	0.0034573	1.6202	0.113
6	CrS	1	0.0032093	1.504	0.143
7	FeS	1	0.0026473	1.2406	0.168
8	Altitude	1	0.0025924	1.2149	0.19
9	Clay	1	0.0022432	1.0512	0.202
10	pH	1	0.001977	0.9265	0.243

Asterisks (*) define level of significance, categorized into $p < 0.05$*; $p < 0.005$**; $p < 0.0005$***. Period (.) signifies a value close to significance $p < 0.10$. For definitions of variables see Methods of this paper and table S2.

While the food composition table values were compatible with the values measured in maize grain, they were lower than observed in both cassava tuber and matooke fruit. This could indicate that the samples collected for the food composition tables were either cultivated on different soils, had a low sample size, or measurement differences. Food composition tables are used frequently as a basis for comparison, formulating guidelines, and as means. However, as our results for matooke and cassava indicate, their values should be regarded with caution (Vila-Real et al., 2018).

4.2. Annual vs. perennial growth cycles effect on food nutrient concentrations

Whether a crop was annual or perennial had a significant effect on relationships between food nutrient concentrations and soil properties or farm management variables. The variance of nutrient concentrations in maize grain was governed strongly by soil properties in both Teso South and Kapchorwa, therefore being dependent on processes that make nutrients more available. In contrast, the nutrient variance in both cassava and matooke was more related to presence of soil elements. Since no variable number effect (higher variable number, higher variance explained) was observed in the CCAs, the results were deemed valid.

The variance of nutrient concentrations in matooke was not well described by the tested explanatory variables. However, its stronger connection to soil elements compared to soil properties could be due to matooke as a perennial plant not being immediately dependent on available nutrients, but rather able to mobilise sufficient nutrients from a given pool over time. A similar temporary uncoupling of nutrient uptake during growth and development stages has been observed in trees (Rennenberg and Schmidt, 2010).

As well as being either annual or perennial, the type and function of the crop organ consumed as food was important for the final nutrient concentrations. Although, much variance in cassava tuber of Teso South was described by soil chemical and physical properties and management variables, almost no variables were actually significantly important for the nutrient concentrations in tubers. This could be due to cassava tubers being storage organs, instead of generative organs (e.g. grain and fruit) as the other plant parts in this study were. Generative organs are usually sink limited, whereas storage organs (such as tubers) are source limited (Engels et al., 2011), and therefore more likely to be affected by plant processes rather than direct soil uptake.

4.3. Environmental effects on food nutrient concentrations

4.3.1. Permutation rank tests

The main variables that significantly affected the CCA distribution differed between countries and crops. This meant that different crops grown in the same location and soil, or in different locations and soils (i.e. fertile vs. infertile) did not share the same significant influencing factors affecting their yields or nutrient concentrations.

Maize nutrient concentrations in Teso South, showed texture as their most important variable significantly affecting the distribution of the CCA. Texture is important as it affects water storing capacity and with that nutrient losses through leaching. Particularly soils with a high sand content such as in Teso South are more likely to show high nutrient leaching and a low water holding capacity (Blume et al., 2010). Nutrient concentrations of maize in Kapchorwa (higher fertility), on the other hand, had a higher effect of pH, and N and C content. Organic matter related variables (such as N and C content) (Wood and Baudron, 2018), as well as pH, eCEC, and soil structure, have been found to be important for nutrient concentrations in plants (Frossard et al., 2000; Wood and Baudron, 2018). Soil organic matter and pH are directly related to the availability of soil nutrients either through mineralisation or pH dependent complexation affecting the release of nutrients (Blume et al., 2010). The lack of a similar importance of N and C content in Teso South was most likely due to the comparably low amount of soil organic matter present in the soil, as well as the lower variance present in the collected samples, compared to Kapchorwa. Particularly surprising was that pH did not play a more important role in affecting the nutrient concentrations in Teso South, as its mean pH was significantly lower than in Kapchorwa. In Kapchorwa on the other hand, an elevated pH favoured a higher nutrient availability (6–7 pH, ideal for nutrient bioavailability (McGrath et al., 2014)) and hence, food nutrient concentrations.

4.3.2. Canonical Correspondence Analysis

The main maize grain nutrient cluster in the CCA of Teso South (also including yield), was positively associated with soil C, although it was not significant in the permutation rank test. The lack of significance was most likely due to the low presence in the Teso soil. The negative association of the main nutrient cluster and yield with eCEC and organic fertilizers was unexpected, as increased organic fertilizers can increase eCEC, as well as yields and nutrient availability of maize (Adediran et al., 2004). It is however understandable when considering the very low level of eCEC and low level of fertilizer use, as well as their low variability in Teso South. The positive association of crop diversity with nutrient concentrations and yield in lower fertility areas is corroborated by literature, where positive effects have been seen in low resource areas with higher diversity (Zhang and Zhang, 2006). Grain Mg and P were negatively correlated with the main grain nutrients and yield. P deficient rice plants have been observed to negatively affect the accumulation of other nutrients within the grain (Rose et al., 2016). In the case of maize in Teso South, the negative correlation of both grain P and soil P to the main nutrient cluster could be due to low P availability or deficiency limiting the uptake of other nutrients as seen in rice. Mg

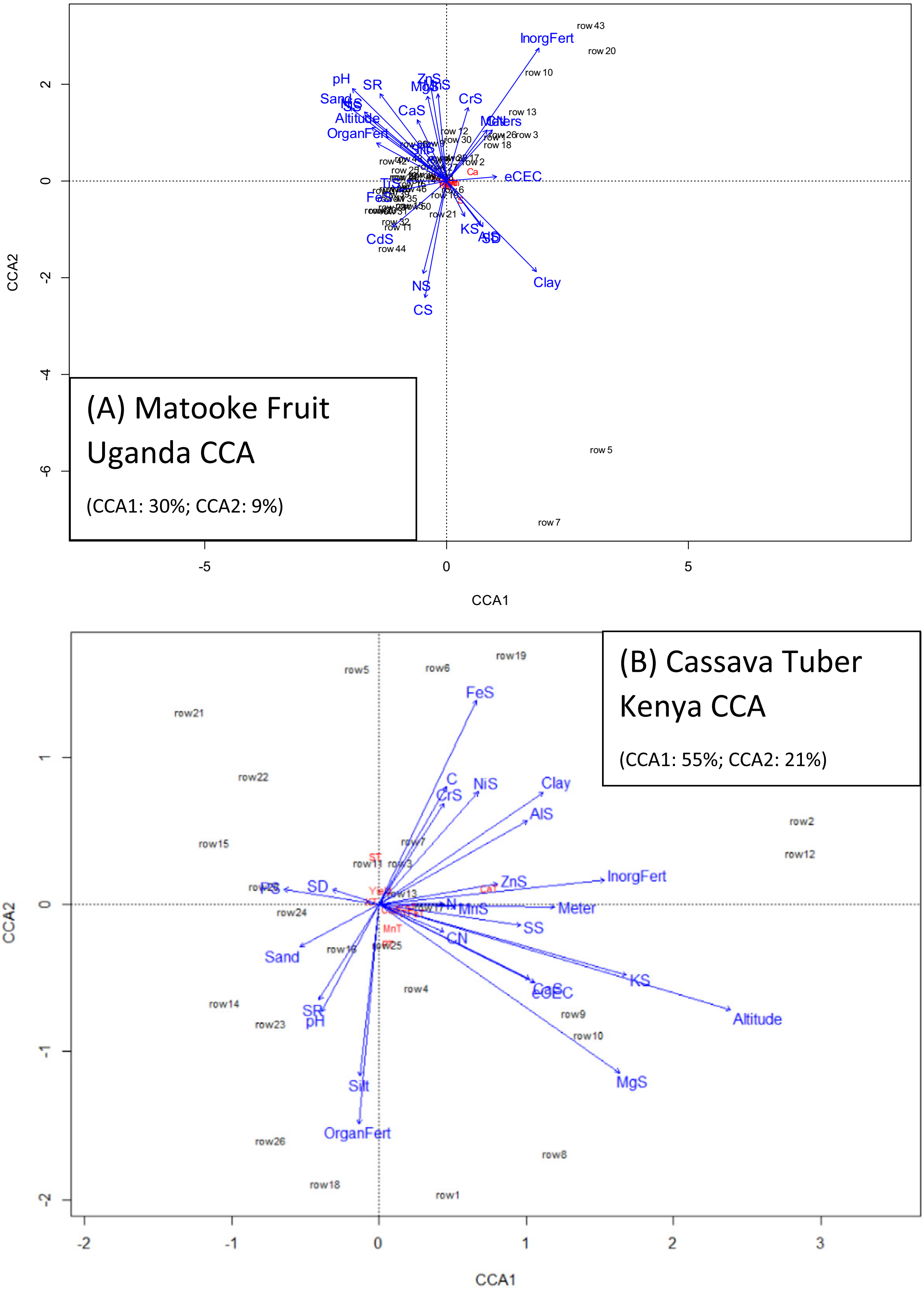

Fig. 4. Panels A and B represent the Canonical Correspondence Analysis (CCA) biplot diagrams that show each crop (A) matooke fruit in Kapchorwa, Uganda; (B) Cassava tuber in Teso South, Kenya. The plot shows the response variables in red (nutrient concentrations in food parts Mg, P, S, K, Ca, Fe, Mn, Cu and Zn), plotted against the explanatory variables in blue showing farm management variables (OrganFert, InorgFert, species richness and diversity, altitude and distance to household), and soil properties and elements (pH, texture, eCEC, total N and C, and various total elemental contents). The vectors represent the explanatory variables. Rows signify each crop nutrient concentration sample in the CCA.

deficiency has been identified as an increasing worldwide problem, as there has been a sharp decline of Mg contents in plants over time (Guo et al., 2016). The opposing position of soil Mg to grain Mg in the CCA suggested a low plant availability. This can occur in acidic soils with low eCEC as was the case in the soil of Teso South (Verbruggen and Hermans, 2013).

The main nutrient cluster of maize grain in Kapchorwa was very close to the origin with little scatter. Therefore, most of the explained variance pertains to yield, grain Mn, and grain Cu rather than the other nutrients. Yield of maize grain in Kapchorwa, unlike maize in Teso South, was not located near the main grain nutrient cluster, and was therefore associated with different variables, indicating a potential dilution effect (Riedell, 2010). Although organic fertilizers were observed as a significant factor in the CCA, it was difficult to form any robust conclusions on their influence and importance, due to the low amounts used and the lack of variance in amounts applied. Also interesting were the results of species richness and diversity, which showed a slightly positive effect on the nutrient concentrations, while having a negative effect on yield. This could be a result of lower yield per hectare as less plants per species were cultivated in intercropped systems (sparing effect), or due to light or water competition, thereby decreasing total yield (Huang et al., 2015). Soil pH, C, and N seemed to affect the nutrient concentrations cluster and yield equally. In maize grain grown in Kapchorwa, Mn, Cu and yield were negatively associated with the other grain nutrients. Other researchers have identified low pH and low organic matter content, as increasing plant available Mn (Fageria, 2001). Soil pH had a negative correlation with grain Mn, therefore corroborating the literature evidence of a higher pH decreasing available Mn (Fageria, 2001). Grain Cu followed the same pattern as grain Mn concerning pH and organic matter content (Miotto et al., 2014).

The main matooke fruit nutrient cluster showed a similar situation to the maize grain nutrient cluster in Kapchorwa in that there was very little scatter, and therefore the variance explained mainly yield, fruit Ca and fruit S. Similar to Kapchorwan' maize, the fruit yield in matooke was away from the nutrient cluster, therefore also indicative of a nutrient dilution effect. Yield was more positively associated with soil elements including Mg, Ca, Mn, and Zn. Yield was also positively associated with organic and inorganic fertilizers. Fertilizer addition has been found to strongly increase matooke yield (Wairegi and van Asten, 2010). The potential consequences on fruit nutrient concentrations have however not been investigated so far. Fruit Ca and S were negatively correlated with the main matooke nutrient cluster. A study based on Mt. Elgon, De Bauw et al. (2016), found crop available S and Ca to have a high spatial variance, therefore confirming possible low nutrient availability of matooke.

Cassavas main nutrient cluster also contained yield. Although some nutrients were farther away from the main nutrient cluster, all were located in the same area and therefore influenced by similar variables (except tuber S). Sand content had a negative association with nutrient concentrations and yield possibly due to higher nutrient leaching in coarse soils and reduced water availability (Tahir and Marschner, 2017). Surprisingly, the very low amount of inorganic fertilizers added to cassava fields showed a positive effect for both nutrient concentrations and yield. Inorganic fertilizers, particularly containing N (and P and K depending on the responsiveness of the soil), have been shown to increase cassava yields (Senkoro et al., 2018). The negative association of soil P with nutrient concentrations (particularly with tuber P and inorganic fertilizers) and yield seen in the CCA is worrying as it could be a sign of very low P availability, low P fertilisation, and/or potential soil unresponsiveness. Cassava was the only crop to show a (positive) significant association between distance to the household with nutrient concentrations and yield. This was surprising as similar studies had found significant decreasing levels of soil fertility with increasing distance in similar areas to our research areas (Tittonell et al., 2016). A reason for the positive association could be that fields farther away were infrequently cultivated and show a lower level of degradation, than fields closer to the household.

4.4. Implications for food and nutrition security

Regarding the presence of the dilution effects found in soils of moderate to good soil fertility (Kapchorwa) and not being able to attribute it to the use of high yielding varieties, increased fertilisation may increase the dilution effect and therefore, decrease the nutrient concentrations within foods (Römheld, 2012). Since a dilution effect was observed in two different crop types, it may be observed in food nutrient concentrations in other food crops cultivated on the same soil. It is vital to keep the dilution effect in mind when planning fertilizer recommendation strategies as this effect may be exacerbated (Riedell, 2010), and may impact human nutrition.

The nutrient interactions and particularly the diversity of nutrient interactions in different crop and soil types are important for food and nutrition security. The results of maize grain in Teso South and in matooke fruit in Kapchorwa, showed macronutrients (grain Mg and P and fruit Ca and S) negatively associated with the remaining food nutrient concentrations. Macronutrients, are required by the plant in larger amounts than micronutrients and therefore, their deficiencies require more resources to rectify. Due to the present negative associations, increasing macronutrient concentrations through fertilisation may negatively affect concentrations of other food nutrients, such as Fe and Zn. The diversity of nutrient interactions should be subject to more research to understand what situations cause negative nutrient interactions (Baxter, 2010), to avoid a negative impact on human health.

4.5. Recommendations

The results have shown that different crops on different soil types vary in their response to yields and nutrient concentrations. Two particular aspects were found to affect all three crops sampled in both regions. Both soil C and soil N where either found to be significant in the permutation rank test or otherwise important for nutrient concentrations and yield on both soil types. Maintaining and building up a good level of soil organic matter can improve soil fertility as well as improve nutrient concentrations and yields (Wood and Baudron, 2018). The second most relevant aspect was the use of fertilizers. While fertilizers in the area showed a very low level of usage, they affected nutrient concentrations and yield. Inorganic fertilizers had a strongly positive impact on crops from Teso South, and an indeterminate but significant effect on those in Kapchorwa. Organic fertilizers on the other hand were not significantly positively associated with nutrient concentrations and yields in all crops. Organic fertilizers in the area constituted mainly fresh crop residues from the field (no compost, no mixing, very little manure) and were available only in low quantities, potentially affecting crop nutrient availability (Palm et al., 2001). Increasing the diversity crop types in the residues is recommendable, as well as using composting methods to avoid microbial nutrient immobilisation induced by poor quality residue (Handayanto et al., 1997). Alternatively, higher quality and increased amounts of organic fertilizers could also be achieved through improved crop-livestock interactions and by enhancing livestock holding. This would facilitate recycling of crop residues through the animal and improve soil organic matter, hence soil fertility, through enhanced manure conditions.

All crops are dependent on soil for nutrient acquisition, and therefore the main aim should always be to improve and/or maintain soil fertility and nutrient availability. It is however important to keep in mind that while annual generative food organs would show results (positive or negative) to soil amendments relatively quickly, perennial generative and perennial storage food organs are likely to show changes after a period of time. Additionally, soils with a lower level of fertility are expected to show effects in food crops sooner than food crops cultivated on soils with higher fertility.

5. Conclusion

The authors found a strong connection between agriculture and nutrition, going beyond producing yields, but focusing on nutrient concentration and its effect on food and nutrition security. Due to the representative nature of the soils found in this study covering both lower and higher fertility areas in Sub-Saharan Africa, the results are transferable to other similar regions. Importantly, crop organ type and life-span of the plant will affect the magnitude of direct environmental effects on food nutrient concentrations. Generative annual food organs (grain) had higher correlations to environmental factors, than storage perennial (tubers) or generative perennial organs (fruits). Generative annual foods would therefore show a more immediate effect to changes made to the soil, compared to storage perennial or generative perennial crops.

Soil organic matter has been identified as one of the most important factors positively influencing nutrient concentrations and yields of foods, even when present in very small amounts. Fertilisation, particularly inorganic fertilisation showed a positive effect on nutrient concentrations and yields. The lack of importance seen from organic fertilisation may be more due to the low quality of organic fertilizers used in this area specifically, rather than a conclusion on organic fertilizers in general. Increasing knowledge on, and investing in both inorganic and organic fertilisation plans for smallholder farmers could increase both yield and food quality. The observed dilution effect should be kept in mind when formulating soil improvement strategies on medium to higher fertility soils, as it could inadvertently affect food nutrient concentrations. Nutrient interactions were shown to be highly diverse, and require more research to understand, particularly focussing on the negative feedback loops. Considering food composition as a response variable in agronomic trials (such as fertilisation and soil improvement strategies) in addition to yields, would work towards discounting the notion that only healthy and high quality foods can be cultivated on fertile soils.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.137078.

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