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Environmental and Farm Management Effects on Food Nutrient Concentrations and Yields of East African Staple Food Crops

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"Ich lebte mit den Pflanzen; ich legte das Ohr an den Boden, und es schien mir, als wären die Pflanzen froh, etwas über die Geheimnisse ihres Wachstums erzählen zu können"

(I lived with the plants; I laid my ear on the ground and it seemed as though the plants were happy to tell me about their secrets of growth)

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Contents

List of Abbreviations

AfSIS	African Soil Information Service
C	Carbon
Ca	Calcium
CCA	Canonical Correspondence Analysis
Cu	Copper
EA	East Africa
eCEC	effective Cation Exchange Capacity
ENSO	El Niño Southern Oscillation
FAOSTAT	Statistics Division, Food and Agriculture Organisation of the United Nations
Fe	Iron
FGS	First Growing Season
K	Potassium
Mg	Magnesium
Mn	Manganese
N	Nitrogen
P	Phosphorus
PPS	Probability Proportional to Size
pXRF	portable X-Ray Fluorescence Spectrometer
REML	Restricted Maximum Likelihood
S	Sulfur
SDG	Sustainable Development Goals
SE	Soil Elements
SGS	Second Growing Season
SOM	Soil Organic Matter

SP	Soil Properties
SPI	Standard Precipitation Index
SSA	Sub-Saharan Africa
TAMSAT	Tropical Applications of Meteorology using SATellite and ground-based observations
USDA	United States Department of Agriculture
Zn	Zinc

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1 General Introduction

"Goal 2: Zero Hunger" of the Sustainable Development Goals (SDG) aims to end hunger, achieve food security, improve nutrition and promote sustainable agriculture by 2030 (SDG, 2019). This goal links agriculture and nutrition to the common aim of sustainably producing and distributing high quantity (yields) and quality (nutrient composition and concentrations) foods. Humans rely strongly on plants to fulfil their food and nutrition security, and gain their dietary nutrients including carbohydrates, proteins, fats, fibres, essential elements, and vitamins (amongst others) mainly from plant sources. Plants in turn, gain their nourishment through the soil, water and air. Essential plant elements such as Nitrogen (N), Carbon (C), Oxygen (O), Magnesium (Mg), Phosphorus (P), Potassium (K), Calcium (Ca), Sulfur (S), Silicon (Si), Iron (Fe), Zinc (Zn), Manganese (Mn), Molybdenum (Mo), Sodium (Na), Boron (B), and Copper (Cu) are mainly taken up from the soil in a variety of ionic states and assimilates (Kirkby, 2012). They are used directly in the plant unlike, for example, vitamins, that are synthesized by the plant. Plants and humans require the essential nutrients, N, C, O, Mg, P, S, K, Ca, Mn, Cu, Fe, and Zn (White and Brown, 2010). Human survival and well-being are, therefore, strongly influenced by the plant's ability to attain nutrients from the soil, as well as the plants' nutrient partitioning into the edible part.

Much research has gone into understanding nutrient uptake and nutrient partitioning in plants. However, to date, not much is known about environmental or farm management effects on the nutrient composition of produced foods. Information is also lacking concerning the cumulative effects of environment and farm management on food nutrient composition and yields, as well as the implications of these effects for food and nutrition security.

1.1 The importance of dietary diversity and selected essential elements for human nutrition

Food can provide humans with the nutrients required for their survival and well-being (Table 1.1). However, not all people in the world have the same access to and availability of food, causing food and nutrition insecurity. In the worst cases, food and nutrition insecurity can lead to malnourishment (insufficient calorie/energy intake) and hidden hunger (micronutrient deficiencies). Hidden hunger can lead to clinical underdevelopment and serious chronic diseases (Von Grebmer et al., 2014), and mainly affects pregnant women, pre-school children, and children within the 1000 days window[1] (Yang et al., 2013). It can be measured in young children using the proxys indicator stunting (low height for age). Worldwide, 150.8 million (22.2%) children under age five are stunted. The prevalence of hidden hunger is particularly high in Africa with stunting rates at 58.7 million (30.3%) (The Global Nutrition Report, 2018).

1.1.1 The importance of, and difficulties in, achieving dietary diversity

Consuming a diverse diet increases dietary quality (Timler et al., 2020), as diverse foods (different food groups) contain different types and amounts of nutrients. Maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.), for example, are considered staple crops, and are mainly energy (carbohydrate) carriers, whereas green leafy vegetables, such as chard (*Beta vulgaris* L.), are considered to be nutrient-dense. Bioavailability of nutrients differs between nutrients, food sources, and preparation techniques. The differences in bioavailability are largely due to the type of food matrix – meaning the type, structure, and size of the molecule the nutrient is bound to (Capuano and Pellegrini, 2019), and therefore defines the ability of the body to take up the nutrient in question. For example, animal-source iron (heme iron) has a higher bioavailability and absorption than plant-source iron (non-heme iron). The difference in absorption is due to heme

[1] The 1000 days window of opportunity refers to the first 1000 days between pregnancy and the child's second birthday. During this time a childs brain developes, therefore, the nourishment of women and child has a very strong effect on a childs later life (Source: https://thousanddays.org/why-1000-days/; Accessed 15.09.2020)

iron being taken up directly by the human body, whereas non-heme iron is dependent on different factors, such as the balance between absorption inhibitors (anti-nutrients such as phytates) and enhancers, and the individuals current iron status (Hurrell and Egli, 2010). Another example of differences of bioavailability is calcium. Calcium is less bioavailable when coming from oxalate-rich foods such as spinach (*Spinacia oleracea* L.) (White and Broadley, 2009). During human development even timing of nutrient uptake is important, as different nutrients are required in different amounts during different ages, life stages (e.g. teenager years), or events (such as pregnancy) (Biesalski and Tinz, 2018).

Due to global differences in access and availability of foods, consuming a diverse diet is not always possible for every person (Oliver and Gregory, 2015). In developing countries staple crops are often the main source of nutrients consumed due to the low amount of other foods available (Knez and Graham, 2013), but cannot fulfil all dietary requirements. The focus on staple crops is often due to the mind-set of filling the belly (as well as market factors), and their production frequently subsidized by national governments (Jassogne et al., 2013). Coupled with increased research and improved varieties of staple crops (maize, wheat and rice), production of other types of foods has decreased (Timler et al., 2020). The effects of decreased agrobiodiversity can be seen in health and diet as areas with a high cereal and staple crop production and consumption often coincide with regions of high malnutrition rates (Knez and Graham, 2013). Increasing dietary diversity - one of the main methods suggested to combat malnutrition – is also the most popular method, as it uses locally available resources (low cost), increases agrobiodiversity, and therefore benefits the environment. Other options to combat malnutrition, however, also exist such as supplementation, and increasing mineral and ß-carotene concentrations in edible crops (biofortification) (White and Broadley, 2009). While consuming a high diversity of foods is important, understanding how nutrients from the soil are taken up by the plants, and how in turn, food quality and quantity is affected is also vital. An understanding of these mechanisms could help in preparing for shocks (for example, droughts or floods) and preventing a decline in population health, particularly when studying events affecting soil nutrient availability.

1.1.2 The importance of essential elements for human nutrition

In the human body most nutrients can become both deficient and toxic. Toxicity of most essential elements is more often linked with environmental pollution than related to diets (excessively consuming certain foods) (Elmadfa and Leitzmann, 2015). In this thesis, emphasis will be placed on essential element deficiencies, as they currently present a larger global problem. The most prevalent global human micronutrient deficiencies are vitamin A, Fe, Iodine (I), Zn and folate (Bailey et al., 2015). The focus of this thesis is on essential elements, for both humans and plants, and therefore only these will be discussed in detail here, e.g. Fe and Zn (while I is not plant essential). Globally, it is estimated that about two billion people are Zn deficient (Kabata-Pendias and Szteke, 2015). In 2016 the WHO estimated 32.8% of women and 41.7% of children under age five worldwide to be anaemic (it is estimated that about 50% anemia is caused by Fe-deficiency). In Africa, the WHO estimated 39% of women and 59.3% of children under the age of five to be anaemic (WHO, 2017). The frequency of Fe and Zn deficiency comes from the relative low bioavailability in plant source foods and the associated lower availability of animal source foods. Other trace elemental deficiencies are also present, although not as prevalent as Fe and Zn. Ca deficiency is diet related and worldwide most often deficient in adolescents, the elderly, and people with a restricted diet or no access to diverse foods, particularly dairy products (Beto, 2015). Worldwide estimations state that countries in Africa and South America show the lowest levels of Ca intake (Balk et al., 2017), with approximately 54% of the population in Africa at risk of Ca deficiency (Joy et al., 2014). Human Mg deficiency is very difficult to assess, as serum values (usual method of assessing Mg in the body) do not give any indication on intracellular Mg, thereby not giving a clear indication of Mg levels in the human body (DiNicolantonio et al., 2018). While some sources suggest that the risk of Mg deficiency (based on dietary intake) is very low (Joy et al., 2014), others suggest that subclinical Mg deficiency is rampant, a leading cause of chronic disease and early mortality, and should be considered a public health crisis (DiNicolantonio et al., 2018). P and K deficiencies are rarely diet related, unless there is an underlying physiological condition (Kovesdy, 2016). Human S deficiency is not well researched with only few studies assuming larger than expected diet related deficiencies, particularly in the elderly (Nimni et al., 2007). Cu deficiency is rarely diet related, but can occur as a by-product of various diseases (Prohaska, 2014).

Mn deficiency is highly unusual and has so far only been found in humans with a very restricted diet (Mehri, 2020).

1.2 Long-distance transport of essential elements in the plant and its effect on food

Elements taken up by plants, and essential to both plants and humans, can be divided into macronutrients (Mg, P, S, K, and Ca) and micronutrients (Fe, Zn, Mn, and Cu) (Kirkby, 2012) (Table 1.1). This division into macro- and micronutrients using the plant nutrition definition will be used throughout this thesis. Nutrients are predominantly taken up through the root system of the plant as ions. They are then transported through the vascular system into the different plant parts. Root ion uptake is characterized by (i) selectivity, where some elements are taken up preferentially to others; (ii) accumulation, plant elemental concentration can be higher than in the soil; and (iii) genotype, different species have different uptake affinities. Different types of nutrients have different uptake mechanisms depending on their size, charge, and abundance required by the plant (White, 2012a). A full description of nutrient uptake through the roots can be found in White (2012a).

The xylem and phloem are the two main parts of the plants vascular system, responsible for long distance nutrient transport, and therefore nutrient distribution throughout the plant (White, 2012b). The non-living xylem usually features the root to shoot transport of solutes, powered by gradients of water potential through root pressure, a gradient in water potential, and the leaf transpirational pull (White, 2012b). This mass flow driven by transpiration can be so strong that it has been shown to have the potential to accumulate large amounts of nutrients (Etienne et al., 2018). The xylem's dependence on transpiration can affect its nutrient transport efficiency. Transpiration can be decreased in certain plant growth stages, such as during the spring bud growth, or in annual plants during the reproductive stage. The xylem mass flow is susceptible to environmental conditions that close the stomata (for example, to conserve water in the plant) thereby interrupting the transpiration pull. Drought for example can disrupt xylem mass flow, even causing embolisms (air bubbles inside the xylem), disrupting water flow and potentially destroying the xylem (Sevanto, 2014).

The living phloem cells (sieve tubes) transport organic compounds through its sap from source to sink tissues, powered by osmotic gradients produced by differences in phloem sucrose concentrations of different plant parts (White, 2012b). The phloem, while not showing the same limitations as the xylem, is otherwise limited in its transport capabilities. Some macronutrients (Mg, P, S, and K) are stated to being highly phloem-mobile (Etienne et al., 2018; Maillard et al., 2015). Micronutrients (Fe, Cu, and Zn) have an intermediate to low phloem mobility (highly dependent on crop type), and the macronutrient Ca and micronutrient Mn are considered phloem-immobile (Etienne et al., 2018). Reliable data on micronutrient contents of phloem sap is, however, lacking (White, 2012b), and the observations measured therefore, are dependent on crop type. Ca, for example, is phloem-immobile and is transported through the apoplast with water. The reason for this form of transportation may be due to Ca's function in plant water regulation. Additionally, Ca active sites and uptake mechanisms can be substituted by other nutrients such as K and Mg. Therefore, separating the transportation forms (xylem and phloem), may be a way to reduce possible nutrient competition, for example between K, Mg and Ca. Ca^{2+} also promotes callose formation and swelling, which is a highly hydrated polysaccharide found in the phloem and when swollen can block the sieve tubes. Since even low concentrations of Ca^{2+} elicit callose swelling, Ca is not transported in the phloem (White, 2012b). The form in which nutrients are transported (e.g. as an ion) differs for each nutrient. The phloem or xylem loading concentration also differs between nutrients, genotypes, and nutrient concentrations already present in the plant (White, 2012b). The final nutrient concentration in the given plant part could therefore, depend on environmental factors, and the type of nutrient in question. The strength of this effect on edible part nutrient concentration is, however, still unknown.

Focussing on the long-distance transport of the plant, the final nutrient presence in plant tissue differs depending on (i) the type (species, variety, genotype, etc.) of crop in question; (ii) the transport of the nutrient to the tissue; and (iii) the type and function of the tissue. Crop type (such as annual or perennial, woody or bushy, etc.) plays an important role in food nutrient concentration, as different crops require different amounts of nutrients. Nutrient accumulator plants for example, are able to take up more nutrients such as heavy metals than others (Stein et al., 2017). Perennial crops in comparison differ from annual crops in their internal nutrient management, as they maintain normal plant functions during their reproductive cycle (concurrent vegetative and reproductive cycles) (Srivastava and Malhotra, 2017), whereas annual crops end their life with the reproductive cycle. The type and function of plant tissue could also be important, as predominantly phloem fed tissues (for example fruits) are not a good source for Fe, Zn, Cu or I, whereas green leafy vegetables (leaves) contain higher amounts of these nutrients (White and Broadley, 2009).

1.3 Crop nutrient deficiencies and toxicities

Agricultural systems differ from natural systems in many ways. The types of crops, and field crop compositions are selected by the farmer. Oftentimes, the selected crop species are not endemic, and despite breeding to increase the level of adaption, are often more susceptible to environmental changes (Shelef et al., 2017). The higher susceptibility of non-endemic species and agricultural systems as a whole, occurs mainly due to the lack of ecosystem services (such as nutrient cycling and regulation of natural hazards; further discussed in section 1.4) compared to natural systems (Kopittke et al., 2019). Plants are sessile organisms and are, therefore, highly dependent on, and susceptible to, changes in their environment. Although plants do have an arsenal of possibilities to maintain their inner balance of nutrients (or homeostasis), they are susceptible to nutrient deficiencies and toxicities. Similar to humans, plants are also susceptible to "hidden hunger" (Laekemariam et al., 2016), and often only show signs of nutrient deficiency when the deficiency is severe, making chemical analysis necessary to sustain yields and remedy deficiencies (Alloway, 2008).

Crop production is nutrient extractive. Whenever crops are harvested nutrients are removed from the soil by removing the crop, or parts of crops. Soil nutrients are also lost through other mechanisms such as leaching and erosion. This thesis will focus on the soil nutrients lost through extraction by crops, therefore specifically nutrients taken up by plants from the soil, that have been bound in the plant's biomass. Farmers use different methods (e.g. fertilisation, composting, mulching) to provide plant available nutrients in the soil and maintain production levels. Crop nutrient deficiencies and toxicities can be defined by critical levels of nutrient concentrations in plant tissue (often represented by the leaf), in a range above or below the amount needed to attain maximum yield

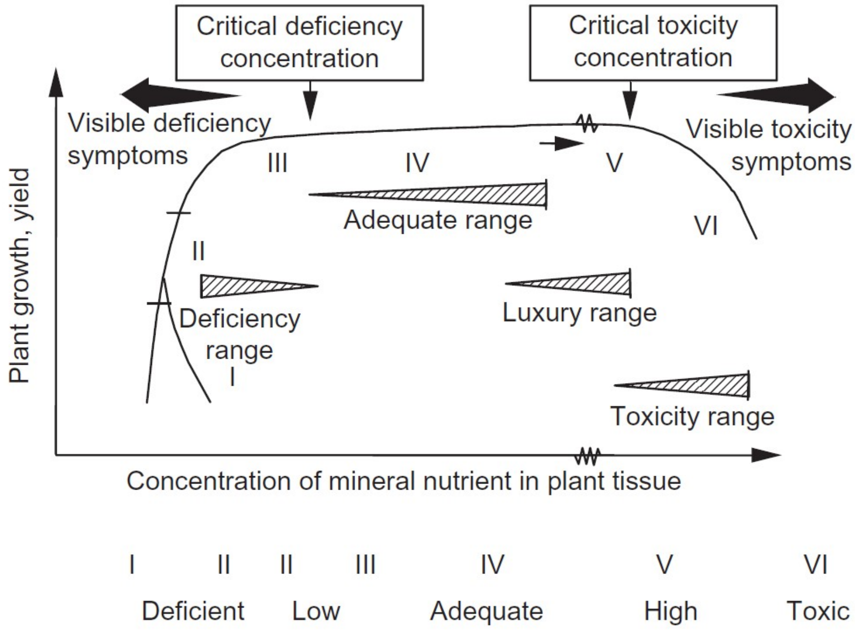

Figure 1.1: The effects of nutrient concentrations in plant tissues on yield, categorized into different sufficiency levels and ranges, and defining critical concentration values. Figure from Römheld (2012), pg.303.

(Reuters and Robinson, 1997; Römheld, 2012). There are two categories of critical nutrient levels: the critical deficiency, and the critical toxicity level. Nutrient ranges around the critical levels are defined as deficiency, adequacy, luxury and toxicity range (Figure 1.1). For example, when leaf nutrients are measured as deficient or below the critical level, fertilisers can be added to correct the deficiency before the yield is affected.

Table 1.1: Description of the function of each nutrient within plants and humans. The nutrient functions in plants were summarized from Hawkesford et al. (2012) and Broadley et al. (2012). The nutrient functions in humans were summarized from Elmadfa and Leitzmann (2015) (Mg, K, P, S, and Ca based on table 4.3 on pg. 258; Fe, Zn, Cu and Mn based on table 4.5 on pg. 261). Further sources used were mentioned in the table. Nutrient amounts for humans based on 70 kg body weight (Elmadfa and Leitzmann, 2015).

Nutrient	Plants	Humans
Magnesium (Mg)	1.5-3.5 g/kg dry weight required. Mg is the central atom in chlorophyll. Additionally, it plays an important role in enzyme activation and phosphorylation.	About 0.03% of the body. Mg is found in bones and teeth, and as a coenzyme. It is also important for storage and release of hormones and affects blood clotting.
Potassium (K)	20-50 g/kg dry weight required, and after N the nutrient required in the highest amount. K is important for enzyme activation, protein synthesis, photosynthesis, osmoregulation, phloem transport, energy transfer, cation-anion balance, and stress resistance.	About 0.2% of the body. K is important in intracellular liquid, neuromuscular impulses, hormone secretion, enzyme activation, glycogen formation and protein synthesis.
Phosphorus (P)	3-5 mg/g dry weight required. P is a component of nucleic acids, phospholipids, phosphate esters, adenosine tri-phosphate (ATP), and phytates. It plays an important role in starch and protein synthesis, carbohydrate transport, and cell structure.	About 0.8% of the body. P is important for transforming, storing and utilizing energy from phosphorus compounds. It is important in energy compounds (ATP), a building block of nucleic acids, and part of the inorganic bone structure.

Sulphur (S)	Required is 0.1-0.5% dry weight. Constituent of the amino acids' cysteine and methionine, and therefore proteins. Sulphur is also an important component of glutathione, which functions to maintain redox potential within the plant, detoxification and cell signalling (Rouhier et al., 2008).	About 0.2% of the body. S is an essential part of cell proteins and S-containing energy rich bonds (such as acetyl coenzyme A). S also activates enzymes, and plays a part in detoxification processes.
Calcium (Ca)	1-50 g/kg depending on the growing conditions, plant species, and plant organ. Ca is important for cell wall stabilisation, cell extension, membrane stabilisation, cation-anion balance, osmoregulation, and as a secondary messenger.	About 1.4% of the body. Ca is important in bone and teeth formation, blood clotting, muscle contraction, heart function, cell membrane permeability, activation and secretion of enzymes, and secretion of hormones and neurotransmitters.
Iron (Fe)	50-150 mg/kg critical deficiency concentration in the leaves. Fe is required for heme proteins (e.g. cytochromes), enzyme activity, chloroplast development, and photosynthesis.	About 4-5 g of the body. Fe is a vital part of haemoglobin and therefore oxygen transport, cellular oxidation, synthesis of steroid hormones, bile acid, neurotransmitters, and plays a part in detoxification.

Zinc (Zn)	The critical deficiency in Zn is variable and plant species dependent. At least 2800 proteins are dependent on Zn. It plays a role in DNA replication and gene expression, and contributes to plant tolerance to stress factors.	About 1.5-2.5 g of the body. Zn is an important part for many enzymes, important for chromatin structure, gene expression, hormone metabolism, the immune system, and its antioxidant functions.
Manganese (Mn)	The critical deficiency concentration of Mn is variable and plant species dependent. Mn is a vital part of many enzymes (e.g. superoxide dismutase (MnSOD), protecting from reactive oxygen species) and acts as a cofactor in the activation of other enzymes.	About 0.01-0.04 g of the body. Mn activates reactions for urea formation, protein metabolism, glucose oxidation, fatty acid synthesis, and is part of the superoxide dismutase (MnSOD).
Copper (Cu)	1-5 μg/g dry weight in vegetative plant parts. Cu is important for photosynthesis, respiration, C and N metabolism, and protects against oxidative stress.	About 0.1g of the body. Cu is important for iron mobilisation, anti-oxidative action, collagen bonds, myelin sheath structure, and melanin formation.

1.4 Soil nutrients and factors affecting their availability

1.4.1 Soil formation and mineral nutrients

Soils used for agricultural production, constitute one of the most important resources in food and agricultural commodity production. Focussing on food production, soils are the basis of almost the entire food system (with exception of water-based foods), as they constitute a growth medium containing almost all nutrients for plant growth, thereby providing nourishment for humans as well as animals (Kopittke et al., 2019). Essential elements found in soils can have many different origins, for example, they can originate from the lithosphere (parent material) (lithogenic), from the parent material but changed through soil forming processes (pedogenic), and elements deposited by humans (anthropogenic) (Kabata-Pendias and Mukherjee, 2007). Parent material, soil processes, chemical and physical properties (Table 1.2), as well as anthropogenic effects strongly affect the element/nutrient concentration in the soil, as well as its phyto-availability (plant availability). Minerals from lithogenic origin usually come from bedrock and parent material. The minerals are made available to plants through physical, chemical, and biological weathering processes. Physical weathering occurs mainly through pressure release, and temperature ice and salt bursts, root pressure, and/or osmotic swelling. The mechanical friction of rocks against each other due to ice, water and wind movement contribute to soil formation. The impact of chemical weathering depends on molecule size and is greater with smaller grain size. The main processes include hydration, hydrolysis, oxidation, and protolysis. The biota tends to increase the weathering process by breaking down larger molecules using either physical or chemical methods (Blume et al., 2016). While most soils depend largely on their parent material, minerals of mature soils often have pedogenic origins (Blume et al., 2016). A pedogenic origin also implies an origin from lithogenic sources, but altered due to soil forming processes (Kabata-Pendias and Mukherjee, 2007). Pedogenic processes control the formation, distribution, and behaviour of different species of trace elements (Kabata-Pendias and Mukherjee, 2007).

Mineral elements from anthropogenic origin can result from a variety of sources, including agricultural practice (i.e. fertiliser) but also through emissions from industry, transport, and power generation. These minerals usually have a higher phyto-availability than minerals of litho- or pedo-origin (Kabata-Pendias and Mukherjee, 2007).

Soils are highly variable in their mineral nutrient content, depending on the parent material, age, and development. Soils provide many functions such as element cycling, decomposition, water and organic matter cycling, and habitat provision (Blume et al., 2016). While all soil functions mentioned above are important for defining soil types and for soil formation, this thesis will focus mainly on functions affecting plant nutrient availability and therefore, soil fertility and agricultural productivity, as well as quality of production (Table 1.2).

1.4.2 Soil fertility

The concept and definition of soil fertility was first written for the German word "Bodenfruchtbarkeit" and describes the capacity of the soil to produce crop yields (Bünemann et al., 2018). The FAO defines soil fertility as "Soil fertility is the ability of a soil to sustain plant growth by providing essential plant nutrients and favorable chemical, physical, and biological characteristics as a habitat for plant growth." (FAO and Partnership, 2021). Elemental content in the soil is analysed by measuring the total elemental concentration (measuring all nutrients in the soil), or the plant available elements (elements in solution, and unbound from soil matrix). While elements can be present in the soil (as measured by their total concentration), and therefore show the total potential of nutrient content of the soil (as in theory they can become unbound from the soil matrix), oftentimes measurements consider only available nutrients, which can result in a much lower concentration compared to the total amount. Soil mineralogy (total elemental concentration) is a determinant of many soil properties, and reflects the mineralogy of the parent material, with variations caused by weathering and land use (Towett et al., 2015b). Available nutrients are measured in solution (Pansu and Gautheyrou, 2006), and represent the nutrients that are potentially plant available, and usually only constitute a very small part of the total elemental concentration (Blume et al., 2016). Plant available nutrients can be measured in two ways: (i) measuring the soil available nutrients by measuring the nutrients soluble in water and (ii) measuring the nutrients taken up by the plant (Reuters and Robinson, 1997). The methods selected largely depend on the research question and will be further explained in section 1.7.5 Methods.

Soil nutrient availability is affected and defined by soil chemical and physical properties. The soil chemical and physical properties covering the most important factors found in literature to affect soil nutrient phyto-availability will be analysed and discussed in this thesis (Table 1.2).

Table 1.2: Description of the soil chemical and physical properties selected to be used in this thesis for evaluation of soil fertility and resulting nutrient phytoavailability (Definitions summarized from (Fageria et al. (2011)) and supplemented by other sources mentioned in the table).

Soil Chemical and Physical Properties	Definition
Texture (sand, silt and clay)	Soil texture is defined by the relative proportions of different soil particle sizes such as sand (0.05-2 mm), silt (0.002-0.05 mm), and clay ($<$0.002 mm) (FAO, 2006). Soil texture can affect the water holding capacity, aeration, and temperature of soils. It can also affect the cation exchange capacity (see below).
Soil organic matter (measured here in total N and C content)	Soil organic matter (SOM) (i.e. total N and C stocks as a proxy measurement (Bai et al., 2017)), refers to all materials of plant, microbial, or animal origin formed in or added to soils. This includes the highly decomposed and colloidal hummus, as well as residues that have not lost their structure. SOM is a manageable soil property and can affect others such as the eCEC (Wood and Baudron, 2018).
pH	pH measures the acidity or alkalinity of the given soil. Neutrality is at pH 7, anything below is acidic and anything above is alkaline. Nutrients vary in availability at different pH levels (Figure 1.2) also dependent on the plant species in question. The pH is also a manageable property (Wood and Baudron, 2018).
effective Cation Exchange Capacity (eCEC)	The sum of exchangeable cations retained in the soil at soil pH. It is a reversible chemical reaction and corresponds to the negative charge of the soil. Factors that strongly affect eCEC include texture, SOM, and pH.
Total elemental content	The total elemental content of the soil gives an indication on the type of soil present, as well as potential toxicities and deficiencies.

Soil texture can give an indication on the water holding capacity, bulk density, aeration, and soil structure. Loamy soils for example are often associated with a higher fertility as they provide a higher water holding capacity, lower leaching rate, a higher potential eCEC, and therefore, better conditions for nutrient uptake. Sandy soils, are more often associated with low fertility, as they have a low water holding capacity, a high leaching rate, a lower potential eCEC and therefore, worse conditions for nutrient uptake. Different crops, however, have different requirements (some grow well on very salty or very acidic soils) and are adapted to different situations, therefore a perfect agricultural soil does not exist (Blume et al., 2016; Helliwell et al., 2019). Soil pH has been described as the most important variable in nutrient phyto-availability (McGrath et al., 2014), as it has an impact on the precipitation and dissolution of nutrients, the magnitude of Cation Exchange Capacity (CEC) and Anion Exchange Capacity (AEC) on variable charge nutrients, the degree of ion-exchange and chemisorption reactions, microbial activity, and solubility of Al. The degree to which pH affects nutrient phytoavailability does however, depend on the soil mineralogy and nutrient in question (Figure 1.2) (McGrath et al., 2014). The eCEC is highly dependent on the pH (Fageria et al., 2011). The eCEC is, however, also dependent on the clay content of the soil, humified organic substances, and the type of clay minerals. The exchange of cations in the soil is reversible and balanced. Cations are limited to movement from the adsorbed site into the soil solution by diffusion. The attachment affinity of elements is defined by their size and charge, the larger the size and the ionic radius, the higher the affinity (Blume et al., 2016).

Soil organic matter (SOM) mainly consists of plant and animal residues in different stages of decay. SOM is important for soil structure, is a sorbent for organic and inorganic substances, has a high carbon content, provides an energy source for soil microbes, and nutrients for plant growth (Blume et al., 2016). SOM is highly dynamic, as new material is added, other materials already in the soil are continuously decomposing. The main drivers of SOM dynamics include temperature, soil type, and land use management. Through the drivers the quality and quantity of inputs, the composition of inputs, as well as SOM rates of mineralization, leaching and erosion are regulated (Feller and Beare, 1997). The soil biota, particularly microorganisms such as bacteria and fungi are very important for SOM as they play an important role in decomposition, nitrogen fixation, and improve nutrient phyto-availability of for example, P, K, Zn and Fe (Ahmad et al.,

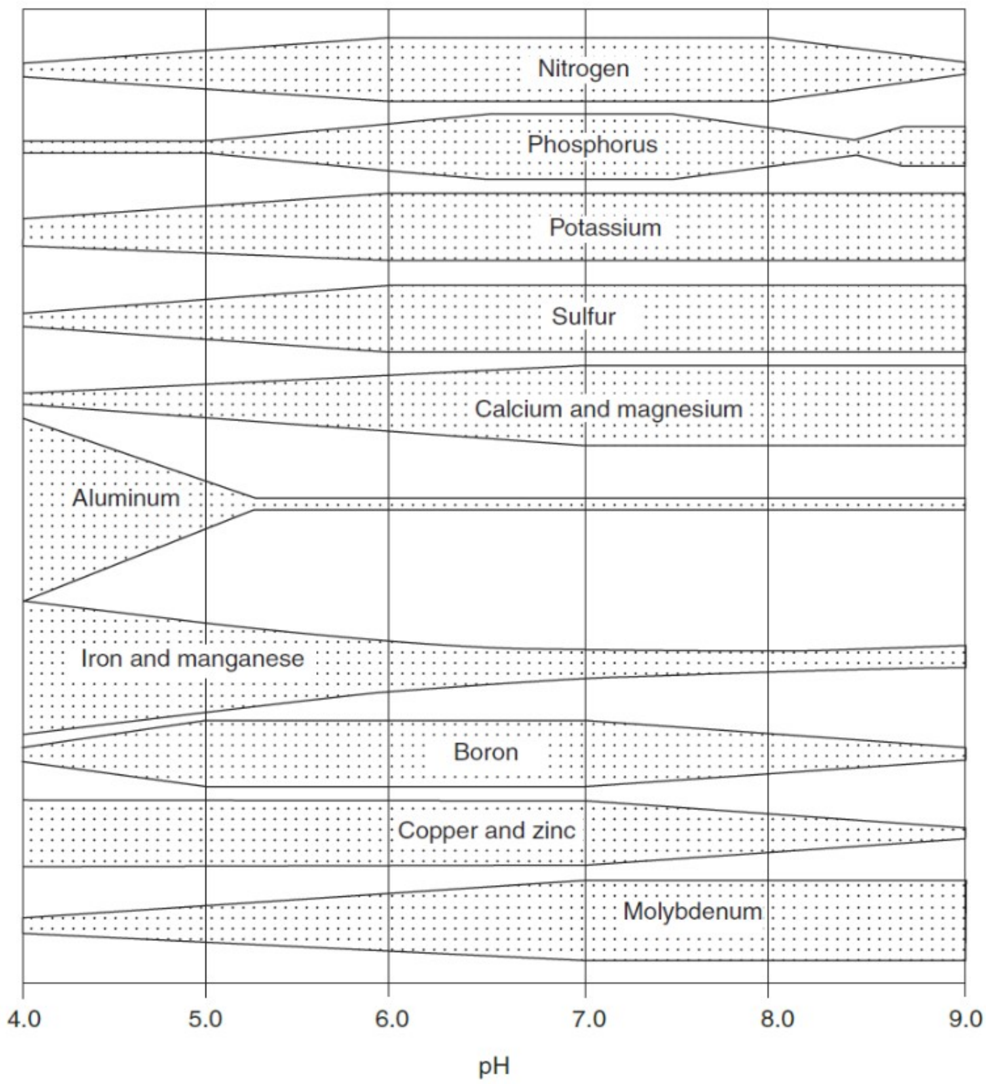

Figure 1.2: Plant availability of the essential plant nutrients varies with pH. In this classical illustration, the width of the bar indicated relative nutrient availability; as bar width increases, the nutrient availability increases as well. Adapted from Truog (1947). Figure and figure description from McGrath et al. (2014); pg. 176.

2018). The quality of SOM is also very important for nutrient phyto-availability, and defines the variety of microbes present. Most inputs include leaves and litters, green and farmyard manures, and the stover and roots from crop residues. Building up and maintaining SOM levels in the soil are important to maintain soil fertility. Some authors even stipulate that SOM is the most important factor for crop nutrient concentration (Wood and Baudron, 2018).

The most available materials to increase SOM tend to be biomass (plant or animal residues), often originating from own production. Much of the most available material however, mainly plant litter compounds (such as lignin), do not contribute a great deal to SOM persistence in the soil (FAO and ITPS, 2015). Producing own organic inputs leads to a cycle of nutrients being removed from the soil by the plant biomass and then replaced by adding the plant residues back to the soil. If the soil has low nutrient availability, few nutrients are taken up by the plants used to improve SOM, and often fewer nutrients and biomass are returned to the soil, due to a lower biomass yield caused by a low soil fertility (Giller et al., 2009). Crop production is, usually nutrient extractive due to the main outflow of harvested products and crop residue removal (Cobo et al., 2010b). By constantly cropping the same area, without access to, or use of, mineral fertilizers, and dependence on own grown organic materials leading to soil nutrient depletion, many farmers now face organic materials that are low in quantity and quality (Palm et al., 2001). Increasing SOM in a soil with low fertility does have positive consequences, such as increasing water holding capacity, lowered soil temperatures, and in the long run better soil structure and less erosion (Giller et al., 2009).

Not only do plants need to take up sufficient nutrients for their own survival, in the case of crops, humans also rely on sufficient nutrients present in the edible part for their survival and well-being. Nutrient phyto-availability is a very complex matter, and is different for every soil type, every nutrient, and every crop. Although plants can, to a certain extent, control their nutrient uptake based on their needs through homeostasis, the control capabilities are limited. Oftentimes nutrient concentrations in plants are positively correlated to nutrient concentrations in the growth medium (such as soils), creating consequences, particularly on low fertility soils, not only for the plants but also for animals and humans (Kabata-Pendias and Mukherjee, 2007).

1.4.3 The state of agricultural soils

Soils used for crop production in particular, are subject to anthropogenic influence, such as mineral fertilisation, pesticide and herbicide application, and nutrient uptake and removal, causing issues for the environment and human health (Kabata-Pendias and Mukherjee, 2007). Feeding an increasing human population (projected to 10 billion by 2050) is pressuring agriculture to produce increasing amounts of food (Ramankutty et al., 2018). In addition to demographic pressure, climate change and an increasing competition for land and water resources are degrading natural resources (for example, soils and water), particularly in Asia and Africa (FAO, 2011) where farmers are highly dependent on these resources.

Measurements of the state of soil fertility in the world are generally focussed on the available macronutrient content, a focus stemming largely from the green revolution. The green revolution encompassed a period from the 1960s to roughly the 1980s, and was located mainly in Asia and Latin America. While only located in some parts of the world, the technologies such as high yielding varieties and associated fertilizers were widely distributed. Macronutrients, particularly N, P, and K, were required in large amounts by the high yielding varieties to maintain and increase agricultural production (Jones et al., 2013b). The focus on just a few macronutrients coupled with a continuous crop production has, however, led to the neglect and in some cases deficiency of other essential elements (Khoshgoftarmanesh et al., 2010). The green revolution did in fact manage to hinder starvation through decreased food prices and increased access to foods (Welch, 2002). In the current times, however, it also caused variable farm income and poor human nutrition through its focus on few crops (Ramankutty et al., 2018).

Sillanpää (1990), in the first global study covering micronutrient phytoavailability, found half of the world's major agricultural soils to be Zn-deficient, and a third to be B-deficient. Cu, Mo and Mn deficiencies were each found in 10-15% of soils, and all three deficiencies together affected about 40% of the world's soils (Knez and Graham, 2013). Although macronutrients in total have received more attention than micronutrients, they are often not added in the required amounts to maintain yields, due in part to a high variance of fertilizer production, and availability and access to fertilizers (FAO, 2011). Additionally, the access, availability and use of fertilizers containing nutrients other than N, P and K, is highly variable in many areas of the world (Sheahan and Barrett, 2017).

Soil acidity (affecting about 30% total ice free land (FAO and ITPS, 2015)), often occurs on older weathered soils. Soil acidity is, however, increasing due to industrial activities, causing acid rain, as well as the use of ammonia-based fertilizers (Bleam, 2012). Soil acidity can strongly affect the presence and phytoavailability of Ca, Mn, Mg, and K (Figure 1.2). Faced with an increasing degradation, coupled with a dependence to maintain food production, soil should be treated as a fragile, scarce and irreplaceable resource that is mandatory for life and should be conserved (Bindraban et al., 2012).

Agricultural soils in Sub-Saharan Africa (SSA), in particular, are often considered to be old, weathered, nutrient poor, and in general of low fertility. This notion stems from constant cropping in a low input and low resource environment (Stewart et al., 2020). However, not all soils in SSA are nutrient poor, and some are even considered nutrient rich. Activities of Volcanism, associated with positively affecting soil fertility by depositing large amounts of Soil Organic Carbon (SOC) (Fiantis et al., 2019), for example in the great rift valley of East Africa, has strongly affected the soils of the region (Davies, 2008). While many agriculturally used soils in SSA do have a low level of SOM and a low level of inputs in general, not all fields have a negative nutrient balance, some even featuring positive ones, as a result of smallholders using highly heterogeneous management systems (Vanlauwe and Giller, 2006).

1.5 Effects of climate and farm management on crop production

1.5.1 Climate effects

The level of dependence on natural resources defines the level of influence of many abiotic and biotic factors. Using precipitation as an example, if irrigation is used for production, the water supplied by precipitation and any associated variance in supply (early or late rain onset) looses importance for production. Abiotic factors mainly refer to topography, soil and climate factors, while biotic factors include all living organisms affecting crop production, such as soil microorganisms or weeds. Biotic factors have received a constant amount of attention (for example, weed ecology, and symbiosis through bacteria). Effects of abiotic factors, on the other hand, have gained in interest in the face of climate change. With climate change, erratic weather occurrences are increasing, severely affecting agricultural productivity. Various reports have shown that increasing temperatures, CO_2 and ozone concentrations, and drought incidences have affected yields and crop nutrient concentrations. As a result, abiotic factors could potentially affect food nutrient concentrations and production amounts, and therefore negatively impact food and nutrition security (Soares et al., 2019). Climate change effects can be divided into long-term constant changes and short-term shocks. Long-term changes such as constant increases of CO_2, ozone, and temperatures cause slow changes in food and nutrition concentrations (Soares et al., 2019). Short-term changes such as erratic weather, causing sudden changes in rainfall and temperature, are immediate recurring problems severely affecting food and nutrition security and human health, through for example the increasing occurrence of famines (Qu et al., 2019).

Precipitation contributes about 65% of the water used in global crop production (Rosa et al., 2020). Although climate change affects the entire world, the African continent has been disproportionally hard hit, due to its high vulnerability, low capacity for adaption, and high population (Thomas and Nigam, 2018). Additionally, Africa is highly dependent on agriculture with an 80% dependence on agriculture to secure livelihoods (Adamtey et al., 2016). The high vulnerability and low capacity for adaption, of course, vary from country to country, and are a composite measure of factors, such as access to services, health, education, and access to improved water facilities on a household level, and governance and risk of political violence on a country level (Busby et al., 2014). SSA already has a high climate variability, is reliant on climate sensitive activities such as agriculture, and has limited institutional and economic capacity to cope with increasing temperatures and rainfall unpredictability (Perez et al., 2015). Droughts are projected to occur more frequently in many parts of the world, particularly in SSA (Naumann et al., 2018). The "long rains" (March-May) in East Africa, for example, have been affected by a series of severe droughts, despite the prediction of increased rainfall due to climate change – this phenomenon is known as the "East African Paradox" (Rowell et al., 2015). Climate change affects food production through gradual changes in crop productivity (Belesova et al., 2019) and through changes to usually predictable rain patterns (or seasons). Droughts can affect food and nutrition security by decreasing available foods (yields), income, and food access particularly in regions dependent on rain-fed agriculture (95% of African agricultural production is dependent on rainfall (Belayneh et al., 2014)). While droughts cause a yield decrease, the effects of drought stress on food nutrient concentrations are currently unclear, and will therefore be focussed on in this thesis. These effects are important to understand as changes to nutrient concentrations and therefore, food quality could add a whole new dimension to climate change effects, by directly impacting human health through food.

1.5.2 Management effects

Farm or even field management can strongly affect crop food production. Agrobiodiversity, for example, can have diverse effects on both yields and food nutrient concentrations. An increasing diversity could increase ecosystem services. Ecosystem services are services provided to humans from ecosystems, and can be divided into four main groups, i.e., provisioning, regulating, cultural, and supporting services. While all services are important for agricultural production (provisioning as the main output (food and materials), regulating as the basic parameters for production, and cultural services influencing the level of care-taking), supporting services provide the most direct connection to food production (DeClerk, 2013). Supporting services comprise soil formation, nutrient cycling and primary productivity, thereby also regulating soil fertility and providing the basis for soil nutrient phyto-availability (DeClerk, 2013). Increasing agrobiodiversity can also have negative effects, if species are incompatible and compete for resources such as light, nutrients, and water (Huang et al., 2015). Badly managed agrobiodiversity (for example when harvesting entire plants and not leaving any crop residues) can also be very nutrient extractive. More agrobiodiversity can, however, also boost household dietary diversity. A higher crop diversity increases (i) the probability of consuming different types of nutrients and therefore, increasing dietary quality; and (ii) resilience, as the production of different kinds of crops raises the probability of having a crop that is resistant to a shock (such as a pest or drought), thereby securing production (Lachat et al., 2018).

Other management options controlled by farmers include the addition of nutrients, such as fertilizers. Fertilisation with essential macro- and micronutrients, can increase the uptake of the nutrients in question by the crops and therefore, improves their yield (Reuters and Robinson, 1997). Access to fertilizers is uneven across the world. In SSA, for example, access to fertilizers is limited particularly for smallholder farmers (Jindo et al., 2020), as they are often poor or live in remote rural areas. In the case of biofortification, fertilisation has also been used to increase the concentration of specific nutrients in the edible part (Bouis and Saltzman, 2017). There are three main delivery methods for fertilisation: (i) fertilising the soil; (ii) fertigation; and (iii) leaf spraying. Fertilising the soil directly is well known and represents the most common fertilisation practise. Fertigation uses irrigation water as a delivery system. Both direct fertilisation and fertigation, however, pass through the soil, thereby potentially also losing some nutrients through soil binding and leaching. Leaf spraying on the other hand bypasses the soil and is, therefore, highly available for the plant (Fageria et al., 2011). The technologies used for leaf spraying nutrients are, however, not always available (for example for smallholder farmers in SSA).

Fertilisation, often in connection to high yielding varieties, can also show a dilution effect. The dilution effect is defined, as an increased crop yield without a proportional increase in nutrient concentration (Marles, 2017), and can lead to lower crop nutrient concentrations with higher yields. As crop nutrient deficiency and sufficiency are analysed via the leaf nutrient concentrations and the resulting yields, the effects of fertilisation on food nutrient concentrations (with the exception of biofortification) is largely unknown, as the edible plant parts are usually not measured. Therefore, to understand the implications of fertilisers on food nutrient composition, this thesis will focus on the knowledge gap of the effects of smallholder fertilisation systems, on food nutrient composition and yields.

Agricultural operations come in different sizes, from large industrial scale to smallholder production. There are about 570 million smallholder farms in the world with less than two hectares of land. About 83% smallholder farmers are in SSA and Asia, and provide the population with about 70% of their calories (Fanzo, 2017). Smallholder farmers, particularly in Africa and Asia, are often very resource poor and depend largely on their natural resource base and local climate for survival and production. Soil fertility on smallholder farmer's fields is highly variable (Cobo et al., 2010b), and therefore, could affect both yields and nutrient concentrations within crops. For example, Tittonell et al. (2013) and Wood and Baudron (2018) found that depending on the type of smallholder field management system, gradients can form, mainly focussed around the distance to the household. These gradients are influenced by both natural soil fertility as well as nutrient input by the farmer and the type of cropping system selected (including fallows etc.). Distance from the homestead was found to be a significant factor in the availability of nutrients (focussing on N, P, and K). Although different farm types form different gradients (Tittonell et al., 2016), the most common gradient found was a decrease of soil fertility with an increasing distance from the household. The gradient was mainly due to low fertilizer availability, and potentially also transport difficulties for distribution (Tittonell et al., 2016). Since distance has such a detectable effect on nutrient availability, it is highly likely that it would also have an effect on nutrient concentrations within foods. This, however, has not yet been tested, and will be focussed on in this thesis.

Farm management, encompassing decisions made on the crops cultivated, as well as what fertilizers to select and use are very often market driven, and strongly affected by socio-economic factors. Markets and socio-economy, however, move beyond the scope of this thesis and associated research questions. Therefore, while the importance of these factors are recognised, they will not be specifically discussed.

1.6 Current understanding of environmental effects on food quality

Research on the connection between soil fertility, crop production, and human nutrition is not new. Albrecht (1945) published his paper "Food is fabricated soil fertility" and Sillanpää (1990) and Sillanpää (1982), published his micronutrient assessment of the world's soils, strongly alluding to the effects of varying soil fertility on food and nutrition security. After all, "food is a product of the environment" (Burdock and Crawford, 2015; pg.1) and therefore, the effects of the environment on food should be studied. Current unsustainable and extractive (focus on few crops and nutrients) production systems need to be changed to avoid the continuous depletion of nutrient stocks and stop a potential "nutrient poverty" (Jones et al., 2013b), potentially decreasing both the quantity and quality of foods produced as well as increasing nutrient deficiency related diseases.

Research on soil fertility effects on crop nutrient concentration has shifted from only looking at N, P, and K to also including other nutrients. The research done, focussed on soil and plant micronutrients related to specific geographic regions (for example, Mediterranean (Pontieri et al., 2014), SSA (Riikka et al., 2019; Towett et al., 2015a)), finding the most limiting nutrient (De Bauw et al., 2016), and comparing different cultivation systems (Hattab et al., 2019; Li et al., 2007; Wierzbowska et al., 2018). Most of these studies have focussed on measuring plant health through analysis of the leaf nutrient composition. Although leaves can also occasionally be used as food, very few studies have considered looking at non-leaf foods (e.g. fruits, grains, tubers) such as Joy et al. (2015), who compared food composition on calcareous and non-calcareous soils.

Direct connections between soil and human health have been established for single nutrients. For example, human iodine (I) deficiency, often visible through the formation of a goitre was found to be highly correlated with the I content in the soil (Ubom, 1991). A case study in Finland found a deficiency of Selenium (Se) in soils, grains, animal meat, and humans. A country-wide Se fertilisation scheme managed to increase the amounts of Se from soils to humans (Alfthan et al., 2015). The elements I and Se are explicit examples that can easily be traced since neither nutrient is essential for plants and therefore, its uptake is not regulated to the extent of other essential elements. Essential elements for both plants and humans have also shown the above trend. Soil Zn for example, was shown to have a positive relationship with serum Zn in children in Ethiopia (Tessema et al., 2019). Further and more in-depth research of the effects of soils and edible part nutrient concentrations on human health are lacking. This thesis will attempt to broaden the knowledge base on these effects, as soils could have a very strong effect on human health that has so far not been considered. If soils do have a strong effect on human health, then it could be assumed that the origin and living place of a person, if the food chain is local, could be a defining factor of a persons health.

Breeding has been explored as a method of increasing nutrient concentrations of certain nutrients in the edible parts of crops. For example, iron-fortified beans (Fe-beans) consumed in Rwanda showed an increase of iron status in the test population (Haas et al., 2016). Iron fortified pearl millet improved the Fe status of school children in India (Finkelstein et al., 2015). Breeding has, however, mainly focussed on one nutrient at a time, and is therefore, not the best option for solving hidden hunger, as often more than one nutrient is deficient.

To increase the diversity of foods in the household, and therefore boost the consumption of a diversity of nutrients, research has also attempted to find the connections between an increased agrobiodiversity and household dietary diversity (DeClerck et al., 2011), as a more sustainable and accessible way to improve food and nutrition security. Results on increased biodiversity effects on dietary diversity are, however, varied (Termote et al., 2012), and although usually not negative, also not clearly positive. The reason for this ambiguity could be the involvment of many different socio-economic and behavioural factors, also affecting the choice of foods used in the household.

1.7 Knowledge gaps on environmental effects on food quantity and quality

Scientists in both agronomy and nutrition work towards a common goal of providing enough foods with a high nutrient content. The research approaches in the two disciplines are, however, quite different and often incompatible. While nutritionists measure the edible part of the crop and disregard the environment, agronomists measure different plant tissues and the environment, but often disregard the edible part. This is problematic as the edible part (although sometimes being the leaf) is usually an entirely different plant part, provides a different function to the plant, and therefore potentially has a different nutrient concentration. Leaf nutrient concentrations and yields do show some correlations, which can be seen through yield improvement due to leaf nutrient concentration increase (Fageria et al., 2011). A similar connection has not been investigated for edible part nutrient concentrations, and would also be more difficult to analyse as edible parts fulfil a wider array of plant functions (reproductive, storage, transport), than leaves (photosynthesis). Clearly, there seems to be a knowledge and coordination gap between nutritionists and agronomists, that needs to be urgently addressed if more nutrient dense and high yielding crops should be produced.

Most research related to plant-environment interactions has used either non-food plants (i.e. *Arabidopsis halleri* L. (Stein et al., 2017)), or when focussed on crops, usually looked at leaf or stem tissue nutrient concentrations (De Bauw et al., 2016). Soils around the world show a very high variance in their composition (Stein et al., 2017). Leaf nutrient composition also shows a high variance, often traceable to the variance in soil composition (De Bauw et al., 2016; Hattab et al., 2019). Foods also show a high variance in their composition and can affect human health, observable in food composition tables. When looking for example at maize grain nutrient composition from different countries, an often high variance can be identified (Elmadfa and Meyer, 2010). So far, the reason for the variance in food composition is unclear, although the main assumption is that differing environments, particularly soils, and possibly differences in management, are responsible. This thesis will be looking at two different soil types, and will analyse whether variances in soil composition affects the variance of food nutrient composition of different edible parts of crops.

The effects of some management factors on the nutrient concentrations of the edible part have been tested (Hattab et al., 2019; Tarozzi et al., 2006). However, most management effects, such as fertilizer trials or distance to the household (Tittonell et al., 2013), as well as soil gradients´ effects on nutrient composition (De Bauw et al., 2016), do not relate to nutrient compositions of edible parts, but to nutrient compositions of the leaves and yields, leaving the final food quality as a question mark. This thesis will analyse whether there are any connections between nutrient concentrations in leaves, edible parts, and yields, to understand whether agricultural interventions could also affect the nutrient concentrations of the edible parts, and whether this could have an effect on food and nutrition security.

1.8 Methods

1.8.1 HealthyLAND Project

This thesis was embedded in the German Federal Office for Agriculture and Food (BLE) funded project "Crops for healthy diets – Linking agriculture and nutrition" (HealthyLAND). The HealthyLAND project was based in Teso South, Kenya, and Kapchorwa, Uganda (Figure 1.3). The main research question of the HealthyLAND project was "Can an increased agricultural diversity increase food and nutrition security of households?". HealthyLAND contained three different work packages (WP): WP1 "Nutrition and Dietary Diversity", WP2 "Agricultural practices, income generation strategies, and diversity in farming", and WP3 "Farming System Innovation". This thesis

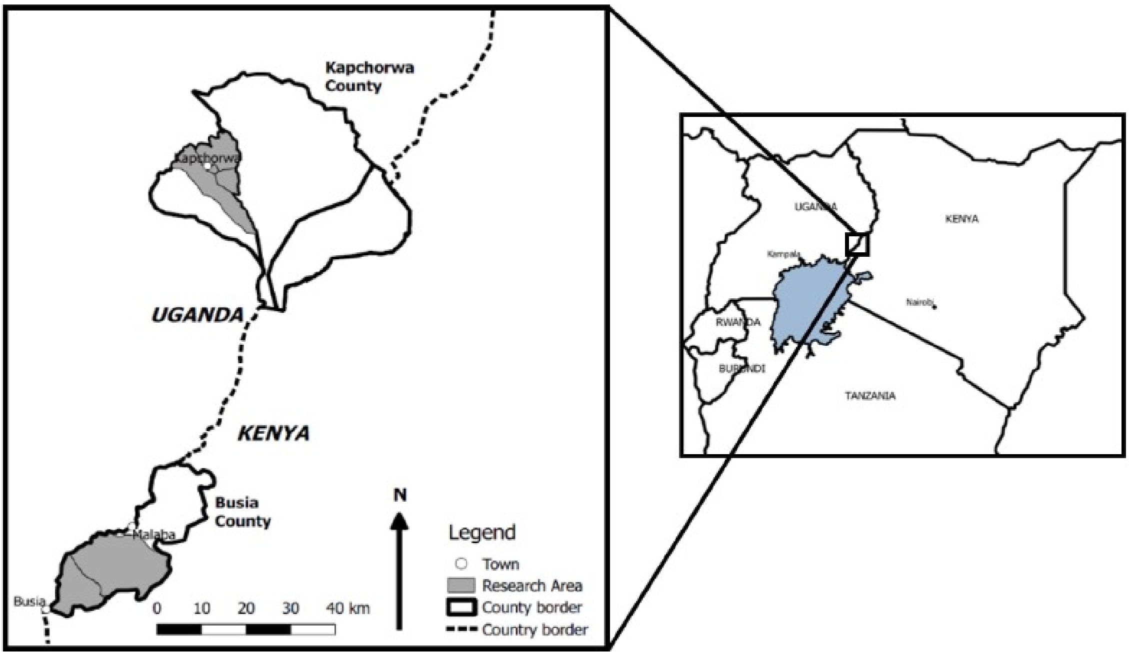

Figure 1.3: Map of the research areas. Research areas Teso South, Kenya and Kapchorwa, Uganda, are in grey. The remaining county is presented in white. The overview map was taken from: https://mapscompany.com/collections/east-africa (Accessed 06.01.2020). The map was made using QGIS 2.8.

was part of WP2 and WP3, and was well integrated into the project, as it attempts to link agriculture and nutrition in the common goal of producing high quality and quantity foods.

1.8.2 Research Areas

Sub-Saharan Africa (SSA) was selected as a suitable region for this thesis, as it (i) has a high variance in soil fertility; (ii) the level of malnutrition is very high; (iii) a majority of the population depends on agriculture for food and income (Timler et al., 2020). East Africa (EA) shows extreme differences in soil due to variations in parent material stemming from high volcanic activity of the Great Rift Valley making nutrient rich soils (Davies, 2008), to older more weathered soils, frequently found across SSA (Stewart et al., 2020). To understand the environment-plants-humans nutrients nexus, a region where people are highly dependent on their local environment and resources was chosen. Rural areas with low infrastructure in particular, very often feature a more localized food system. Resource poor smallholder farmers produce, sell, buy and consume foods produced on and with their natural resources. Therefore, their food and nutrition security should be a function of their environment, with minimal outside influence.

The two research areas Kapchorwa, Uganda and Teso South, Kenya were selected from the project regions due to their contrasting environments (Figure 1.3). Kapchorwa, Uganda is located on the northern slope of Mt. Elgon, the largest and oldest extinct shield volcano from the Pliocene Epoch of the Great Rift Valley (Jiang et al., 2014; Knapen et al., 2006). Due to its volcanic background, the soils have been described as nutrient rich Nitisols (Jiang et al., 2014; Knapen et al., 2006). The research area in Kapchorwa covers an altitude from 1000-3000 m a.s.l.. Teso South in Busia County, Kenya is located on high plains, occasionally broken up by hilly landscapes (Figure 1.3). The soils are mainly described as old, weathered, nutrient poor orthic acrisols and othric Ferralsols (Jaetzold et al., 2009). The research area covers an altitude of 1200-1400 m a.s.l.

1.8.3 How to measure environmental effects on human health

Examining the effects of the environment on human health, particularly when considering essential elements, has been done by measuring the essential elemental content in the environment (such as in the soil or in the water), and then in humans. This direct effect from soil to human is, however, more easily identified with toxic elements, such as Arsenic or Mercury, as they are not usually present in the human body (Steffan et al., 2018). Nutrients that are essential, can have various forms and storage locations in the human body, and can therefore lead to difficulties in measurement, as mentioned for Mg in section 1.1.2.

For essential elements, the best method was, therefore, to measure the yields and nutrient concentrations of foods, to calculate the potential nutrient production per field and household. Smallholder farmers are most often semi-subsistent (up to 60-80% in Kenya (Cobo et al., 2010b)), and therefore consume a considerable part of their own produce. Measuring the produced crops in conjunction with soils, can give an indication on the nutrient availability in the soils, and the amount and quality of the final produce available to the household. The method gauges the potentially available nutrients, as not all produce will be consumed (some yield sold, given away, or lost), and the human bioavailability of nutrients differs depending on the type of food and the preparation technique (Capuano and Pellegrini, 2019). This method also captures (i) the effects of soil chemical and physical properties on food nutrient concentrations, while also allowing for the effects of plant homeostasis – which would be lost by only measuring soil available nutrients; and (ii) the comparison between nutrients produced on different soil types, and their potential effect on food and nutrition security, through comparisons to database values.

In the presented work, the total soil elemental concentration was measured instead of the plant available (water soluble elements of the soil) elemental concentration. The total elemental concentration is indicative of the total soil potential. Since different crops have different uptake affinities and methods, the interest of this thesis lay mainly in the final product available, which are the nutrient concentrations and yields of foods. Measuring total essential elements allowed the use of the portable X-ray Fluorescent Spectrometer (pXRF - Tracer 5i, Bruker) and, therefore, allowed a low cost and labour, but high precision scanning of a large number of samples for a large number of essential elements (Rouillon and Taylor, 2016). Nutrient availability in the soil is a function of the total essential elemental concentration and the different soil biological, chemical and physical properties making these available, as well as the parent material and weathering stage. Since an aim of this thesis is to understand, what soil properties show the highest importance for food nutrient concentrations in the plant, the soil properties were of particular interest. As another aim was to interpret the effects of different soil types, total elemental concentrations were preferred, as they are a representation of the soils parent materials, and give a clear indication of the type of soil used (Towett et al., 2015a).

Other methods that have been used to measure the effects of the environment on human health were for example, taking blood tests and directly measuring the nutrient concentration of the blood, or using food composition tables to measure the quality of food intake. This can, however, be misleading as (i) a deficiency in the blood does not prove causality of the environment as there may be an underlying physical condition (such as HIV/AIDS, which was high in our research area (Kothari and Elliott, 2016)). Blood tests are not adequate for all nutrients that were measured in this thesis. For example, serum Mg is not indicative of the total Mg levels of the human body (DiNicolantonio et al., 2018). Using food composition tables could also be misleading as oftentimes these tables do not contain enough data sources to encompass the variance present due to environmental or varietal effects (Vila-Real et al., 2018). Since foods can also be acquired off farm, the origin of all foods consumed in the household may also be unclear, and not directly related to the immediate environment, and therefore dilute results and potential causalities.

1.8.4 Database usage

Databases covering climate, soil chemical and physical properties, leaf and edible part nutrient concentrations, and yields were used. The values from the databases were used to contextualize the results from the thesis, and to understand the adaptability of the results to other areas. As mentioned above, SSA is highly susceptible to climate change effects (Maidment et al., 2017). It is, however, difficult to come by reliable historic, and current climate data. Precipitation is a factor of climate that is highly relevant for SSA, and particularly in EA as (i) precipitation is split into rain seasons, thereby dictating the timing of food production and (ii) most of the agriculture in SSA and EA is rainfed. A few precipitation databases are available for SSA. The most precise one found was the Tropical Applications of Meteorology using SATellite and ground-based observations (TAMSAT), as it uses both satellite and rain gauge data (Dinku, 2019; Maidment et al., 2017; Tarnavsky et al., 2014). Additionally, TAMSAT had the highest resolution of the different databases, making it very suitable for the research areas.

The African Soil Information Service (AfSIS) was one of the main efforts to create a soil map of Sub-Saharan Africa in a high resolution (Hengl et al., 2015). Other soil maps of SSA found included the Harmonized World Soil Database (HWSD) that had brought together numerous other soil maps to form one, based on the World Reference Base for Soil Resource classification System (WRB) (Dewitte et al., 2013). However, while the HWSD had, for some areas of the map, a better resolution than AfSIS, AfSIS provided more information, such as soil properties measured using infrared spectroscopy and interpolated using geo-statistics, as well as providing total trace elemental concentrations (Towett et al., 2015b).

Availability of databases containing nutrient concentrations depend strongly on the plant part of interest. Leaf nutrient concentrations are generally found in resources focussing on agronomy. For maize four main sources were found (Broadley et al., 2012; Fageria et al., 2011; Hawkesford et al., 2012; Reuters and Robinson, 1997). The sources used were selected as they had a good coverage of the nutrients analysed in this thesis, and showed the number and origin of the samples. Due possibly to the lower level of production, less data sources were available for both cassava and matooke. For cassava leaf nutrient concentrations were used from Reuters and Robinson (1997). Matooke leaf nutrient concentrations had no data available, and therefore values for banana were used (Reuters and Robinson, 1997).

The nutrient concentrations of the edible parts were found in food composition tables. Food composition tables can be found to be country specific for Kenya and Uganda (FAO and Government of Kenya, 2018; Hotz et al., 2012) and global (Nutrient Data Laboratory (U.S.) et al., 1999). Unfortunately, no food composition table could be found for Uganda that contained all nutrients measured in this thesis, and only contained values for Ca, Fe, and Zn (Hotz et al., 2012). Country data using FAOSTAT (Food and Agricultural Organization to the United Nations (FAO), 2018) was used for yields as local yield values were not available, and FAOSTAT provided both current and historical data.

1.8.5 Methods and crop selection

Staple crops maize (*Zea mays* L.) and cassava (*Manihot esculenta* Crantz) were selected in Teso South, Kenya, and maize and matooke (East African Highland Banana, *Musa acuminata* Colla) in Kapchorwa, Uganda, for analysis in this thesis. While staple crops are definitely not known for their high nutrient concentration, they were selected as they are (i) the basis of the food system in both regions, in terms of human consumption; (ii) the food consumed and accessible to most population members; (iii) the most widely cultivated food, therefore providing the best spatial coverage of the research areas; and (iv) represent three contrasting food types (grain, tuber and fruit).

The leaves and the edible parts of the crops were sampled and the trace elemental content measured using a portable X-Ray Fluorescence Spectrometer (pXRF). The use of the pXRF allowed for the measurement and analysis of the multiple nutrients (Rouillon and Taylor, 2016). Other possibilities for scanning samples for total elemental concentration included the Total X-Ray Fluorescence Spectrometer (TXRF), the Atomic Absorption Spectroscopy (AAS), and Inductively Coupled Plasma - Optical Emission Spectrometry/Mass Spectronomy (ICP-OES/MS). The TXRF, AAS, and ICP all had complex and work intensive preparation steps, occasionally even including acid digestions. The pXRF had shown to have high correlations with the ICP when measuring both plant and soils samples, and was therefore deemed accurate (Towett et al., 2015a). The pXRF was the most labour and cost effective method to scan a large number of trace elements in a high diversity of materials, and was therefore selected for this thesis.

The HealthyLAND Project used a Probability Proportional to Size (PPS) sampling method (Kish, 1995) to select the initial group of 400 households per research area. Out of these 400 households, 72 were randomly selected per region for this thesis. The PPS was used as it allows for an even selection of households under consideration of their "clusters" (in this case village population) size. The method was important as differences in cluster size could be linked to, for example, market access, wealth, farm size, or availability of farm inputs, and therefore reduced the selection bias.

Since the three different chapters discussed different research questions, different statistical methods were used for different variable groups. While most chapters used more than one statistical method, each chapter had one main method. The methods are explained in detail within each chapter. The main unifying factor all methods used in the separate chapters, was the inclusion of the sampling strategy used, using the weights calculated for the PPS, followed by the random selection of first village, then households, finally followed by the field selection based on the distance criteria. The methods selected considered each element separately, with the exception of the method used in Chapter 3 (Canonical Correspondence Analysis) using a multivariate analysis.

1.9 Research Questions and Hypotheses

The main aim of this exploratory thesis was to identify and attempt to close the knowledge gaps between quantity and quality of agriculturally produced foods and human nutritional needs. To address the aim, this thesis analysed the effects of soil, farm management, and abiotic factors on the quantity (yield) and quality (food nutrient concentration specifically concentrations of Mg, P, S, K, Ca, Fe, Zn, Mn, and Cu) of the edible part of popular food crops (Maize (*Zea mays* L.), Cassava (*Manihot esculenta* Crantz), and Matooke (East African Highland Banana (*Musa acuminata* Colla))), and the implications for food and nutrition security. The research questions and associated hypotheses are summarized with the associated chapter they are analysed in (Table 1.3).

Table 1.3: Summary of research questions and associated hypotheses covered in the doctorate thesis "Environmental and farm management effects on food nutrient concentrations and yields of east African food crops". The chapters in which, the specific research questions and hypotheses are discussed are marked.

Research Question	Hypothesis	Chapter
1. Does soil fertility affect the nutrient concentration of the edible part and the yield?	The soil is the main source of nutrients for plants, and therefore a soil with a higher fertility and consequently more available nutrients would produce a significantly higher yield with significantly higher nutrient concentrations in edible parts than on a soil with lower fertility.	2 and 3
2. How do abiotic effects such as drought affect the nutrient concentrations of the edible part and the yield?	Drought brings about water stress, therefore inhibiting nutrient uptake and nutrient transport. Yields and edible part nutrient concentrations will be significantly lower during drought than in a season with normal rainfall.	2

3. Does long-distance nutrient transport in the crop affect the edible part nutrient concentration?	Nutrients are transported differently through the plant, some are transported predominantly in the xylem, whereas others are also able to be transported in the phloem. The type of edible part, and whether it is predominantly xylem or phloem fed will affect the nutient concentration. The phloem and xylem also react differently to stress, xylem being particularly sensitive to water stress, therefore nutrients transported predominantly in the xylem (Ca, Mn, Fe and Cu) would be most affected in the edible part during water stress.	2 and 4
4. What soil properties affect yield and edible nutrient concentrations the most?	pH is expected to be the most important soil property affecting plant nutrient availability as it affects nutrient precipitation and dissolution, affects the eCEC, and the degree of ion-exchange. It is expected to have an increasing negative effect on food nutrient concentration with increasing acidity (alkalinity not being relevant in the research areas).	3

5. What farm management options (fertilizers, distance to household, and crop diversity) affect yields and/or edible part nutrient concentrations?	The most common fertilizers used involve N, P, and K and therefore, no significant effect is expected in the concentrations of other nutrients measured, although yield is expected to increase, under fertilizer use. Distance to household is expected to show a decreasing gradient in soil fertility, yield and nutrient concentrations as distance increases, due to the longer travel time to deliver inputs to farther fields. Crop diversity is assumed to increase edible part nutrient concentrations through higher nutrient availability as a result of increased ecosystem services.	3

6. Do varying crop types (annual or perennial) and varying food types (grain, tuber, and fruit) show differences in the connections between edible nutrient concentrations and environmental effects?	Perennial and annual crops are expected to show significant differences in their response to environmental factors as perennial crops have a higher buffer capacity, due often to a higher biomass and therefore, nutrient storage possibilities, to deal with stress caused by environmental factors than annual crops. Varying food types provide different plant functions, and therefore are expected to react differently to stress. It is expected that the nutrient concentrations in grains and fruits (both generative) will react similarly, whereas the nutrient concentrations in tubers (storage) will react differently to stress.	2, 3, and 4
7. Do nutrient concentrations in different crop parts correlate and show similar correlations to yield?	The nutrient concentrations in different plant parts are expected to correlate strongly as they are all part of the same organism, and affected by the same environment and management. They are also expected to correlate strongly with yield.	4

8. What environmental factors most impact yield and food nutrient concentrations to the point of potentially affecting food and nutrition security?	Any water related environmental stressor will affect both yields and food nutrient concentrations, as water is the main medium used for nutrient uptake. Whether the impact is strong enough to affect food and nutrition security depends on the length of time and intensity of the stressor.	2, 3, and 4

1.10 Outline of the Thesis

This thesis is conceived as a cumulative thesis, where each chapter represents a journal article with the exception of the general introduction and discussion. Chapter 2 investigates the effects of drought on the nutrient concentrations of the edible parts of different food crops of East Africa. Chapter 3 examines soil and farm management effects on nutrient concentrations in the edible part of different food crops of East Africa. Chapter 4 analyses correlations between leaf and edible part nutrient concentrations, as well as correlating yield to leaf and edible part nutrient concentrations of the same three East African food crops. The general discussion revisits the research questions, combines the findings of all chapters, critically discusses the results, and makes recommendations based on the findings.

2 Do we need more drought for better nutrition? The effect of precipitation on nutrient concentration in East African food crops

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Abstract

Soil, inputs, and environmental factors such as weather control plant nutrient availability and nutrient content in food. Drought periods affect nutrient bioavailability. Nutrient transport within the plant and allocation of nutrients within organs of the plant is water dependent and therefore drought susceptible. This study compared Kapchorwa, Uganda and Teso South, Kenya that experienced drought during the second season in 2016. The main research questions were: (i) do droughts have an impact on the nutrient composition of food; (ii) is there a difference in nutrient concentrations in food based on their xylem or phloem mobility? Maize (*Zea mays*) grain (n=62) and matooke (*[Musa acuminata*) fruit samples (n=90) in Kapchorwa, and maize grain (n=61) and cassava (*Manihot esculenta*) tuber (n=64) in Teso South were collected during a normal season (March- July) and drought season (October-December) in 2016. Crop samples were analysed using a pXRF for P, K, Ca, Mg, S, Fe, Mn, Cu, and Zn. The Standardized Precipitation Index (SPI) was calculated using TAMSAT database to compare drought intensities. The drought in Kapchorwa (SPI: -1.14 to -0.32) was severer and began two months prior to Teso South (SPI: 0.09 to 0.55). Nutrient concentration in Kapchorwa decreased significantly from normal to drought in both crops. In contrast, during the moderate drought in Teso South, nutrient concentrations increased significantly. Lacking nutrient phloem mobility is suggested to play a vital role in mobilisation of micronutrients (Fe, Mn, and Cu) as shown by their decreased concentration under severe drought in the yield. Total nutrients assimilated in crop samples were significantly higher in the normal than the drought for almost all samples. Micronutrients and yields during drought were strongly affected, leading to a "double-burden" for consumers through affected quantity and quality. Future research considerations should particularly include the focus on potential nutrient increases during mild drought.

2.1 Introduction

Food and nutrition security of many East African countries is heavily dependent on rain-fed agriculture (Belayneh et al., 2014; Thompson et al., 2010). Fluctuations of rainfall intensity and erratic distribution are increasingly becoming a larger problem all around the world for agriculture, as a direct effect of climate change. Increasing frequency of El Niño Southern Oscillation (ENSO) events is a recent example of a climate change effect (Cai et al., 2014). ENSO events, generally occur every 2 to 7 years, (Wara et al., 2005), and cause extreme events such as floods or droughts. An El Niño event is often (but not always) followed by a La Niña event – essentially the cold phase of El Niño. La Niña reduces the amount of rainfall and can induce drought in East Africa (Fer et al., 2017). La Niña combined with a strong Indian Ocean Dipole (IOD) caused a severe drought during the second growing season of 2016 in East Africa (Lim and Hendon, 2017).

Due to reduced crop productivity, drought has been known to cause famines (Masih et al., 2014). Further risks to food security through drought are more serious in areas already subject to malnutrition. In 2014, 26% in Kenya and 33% in Uganda of children below age 5 were stunted (low height for age), and 4% in Kenya and Uganda were wasted (low weight for age) (Akombi et al., 2017; FAO and Government of Kenya, 2018). One important cause of stunting and wasting is an insufficient dietary intake in terms of quantity and quality of mineral nutrients (i.e. P, S, K, Mg, Ca, Fe, Zn, Cu, Mn). Due to plants being the predominant part of the human diet, particularly in many areas of Sub-Saharan Africa (Yang et al., 2013), the main human mineral nutrients source is plant based food.

Soil moisture is a key factor in plant nutrient acquisition, as it provides the medium through which plants take up nutrients from the soil (Marschner and Rengel, 2011). Additionally, soil moisture also provides the plant with necessary water for different functions including nutrient transport. The ability to transport nutrients through the xylem and phloem is vital under normal conditions as well as under stress, as the plant can reallocate the required nutrients between organs (Etienne et al., 2018; Savage et al., 2016; Sevanto, 2018). Reallocation within the plant mainly occurs via the phloem. As not all nutrients are equally phloem mobile due to differences in size, charge, and transportation methods, some nutrients such as Fe and Mn are more dependent on xylem transport, and therefore plant organs are more dependent on direct xylem filling (Etienne et al., 2018). Xylem transport, however, is more affected by drought than phloem transport, partially due to its role in stomatal closure and the increased possibility of embolism (Sevanto, 2014), thereby potentially limiting the amount of nutrients reallocated to the food parts of crops.

A drought effect has been observed to affect, for example, the protein, mineral and antinutrient composi-tion of wheat grains (Singh et al., 2012). The effect of different drought severities on mineral food composition of crops, however, has to our knowledge not been researched intensively so far, par-ticularly concerning food grown in farmer fields under field conditions. From a plant nutrition perspective, measuring the edible part of the crop also holds interest as it often represents a storage or reproductive organ (for example, fruits, grains, tubers). As these represent plant organs with different underlying functions (storage, reproduction, assimilation), they may have different reactions and nutrient compositions than the rest of the plant during drought stress.

This paper considers a drought episode caused by the 2016 La Niña effect in East Africa (Lim and Hendon, 2017) to explain the effect of different drought severities on food composition, using data collected on farmers' fields. The study took place in Teso South, Kenya and Kapchorwa, Uganda, representing two areas with different topographies and varying levels of soil fertility. The main question addressed in this paper is to what extent drought can change or affect the concentrations and total amounts of nutrients in the edible parts of most popular food crops of the two areas. Specifically, this question encompassed the following other research questions: (i) does drought affect the mineral nutrient concentrations and total nutrient amounts assimilated of food crops; and (ii) does the effect of drought on mineral nutrient concentrations of crops differ with (a) soil fertility and (b) topography? The drought in both research areas differed very strongly in intensity, thereby making it impossible to analyse the second research question based on the effect of soil fertility and topography. In light of this, another research question was added: (b) does nutrient mobility affect nutrient concentrations within the edible part of the plant? We hypothesized that during a drought, the amount of mineral nutrients being plant available, taken up, and translocated by the crop is limited. Therefore, the amount of mineral nutrients present in the produced food is significantly lower than in a season with normal rainfall. The concentration of various nutrients in the edible part of cultivated plants would differ strongly based on their phloem mobility within the plant, as xylem nutrient transport is very quickly affected by drought. In particular, the elements, which are not phloem mobile will be more likely to be deficient in the edible part of plants, rather than elements that are phloem mobile.

2.2 Material and Methods

2.2.1 Study Sites

Teso South, Kenya

Teso South is located in western Kenya and belongs to the larger Busia county (0.4592722°, 34.10924°; 0.6357222°, 34.27789°) (Figure 1.3). The research area in total has a surface area of 330 km^2, and includes the two sub-counties Chakol and Amukura. In total, the altitude ranges from 1200 to 1400 m.a.s.l., with average yearly temperatures from 21 – 22.2°C. The yearly average rainfall ranges from 1420-2000 mm/year and is bimodal, covering a long rainy season during March-May and a short rainy season from September-November (Jaetzold et al., 2009). The soils of Teso South are moderately deep and have a low fertility (Mbuvi, 1975). They mainly comprise orthic acrisols and orthic ferralsols developed from basement rock (Jaetzold et al., 2009). The growing period for cere-als lasts about 170 days during the first growing season (FGS), from March-July, and 105-150 days during the second growing season (SGS), from September-December.

Kapchorwa, Uganda

Kapchorwa is a county in Uganda, situated on the northern face of Mt. Elgon (1.359817°, 34.45045°; 1.450219°, 34.44643°) (Figure 1.3). Mt. Elgon is the largest and oldest extinct shield volcano from the early Pliocene Epoch in East Africa and is part of the Great Rift Valley System (Jiang et al., 2014; Knapen et al., 2006). In the county of Kapchorwa, three sub-constituencies were selected for data collection, i.e. Kapchesombe, Tegeres, and Kaptanya. The selected sub-counties are adjacent and cover the entire altitude gradient from the bottom of Kapchorwa to the edge of the natural park. The soils in Kapchorwa derived mainly from basaltic volcano ash with soils developed from meta-morphic rocks and mixed volcanic-metamorphic rocks, producing clay and nutrient-rich nitisols (Jiang et al., 2014; Knapen et al., 2006; Mugagga et al., 2012). The altitude of the research area var-ies from 1000-3000 m m.a.s.l., and covers an area of 297 km^2. Annual mean temperatures range from 1.5 - 23.5°C, and the gradient of rainfall ranges from 1200 – 2200 mm/year (De Bauw et al., 2016). While the lower areas feature a bimodal rainfall with peaks in April/May and October, the higher reaches have one long rainy season from April – October with a peak in April/May (Kapchorwa District Production and Environment Planning Commitee, 2004). Temperature and rain-fall can both vary strongly due to the altitude gradient (Musau et al., 2015). Kapchorwa, similar to Teso South, also has two growing seasons, the first from March-August and the second from Sep-tember-December. Again, due to the altitude, the dates vary slightly.

2.2.2 Data Collection

Climate and Precipitation

Data on precipitation in both research areas was provided by existing government managed rain gauges within the two research areas of Teso South (n=4) and Kapchorwa (n=1), for the years 2015, 2016, and the first three months of 2017 (Figure A.1). The rain gauge data was summed up per month and the average taken for the different rain gauge locations per research area.

Tropical Applications of Meteorology using Satellite and ground-based observations (TAMSAT) data was used for historic rain data. TAMSAT uses satellite data geostationary Meteostat thermal infra-red cold cloud duration combined with rain gauge data wherever available, making it one of the most precise datasets for precipitation for Africa (Black et al., 2016; Dembélé and Zwart, 2016; Kimani et al., 2017; Maidment et al., 2014; Tarnavsky et al., 2014). TAMSAT data was downloaded from the website: https://www.tamsat.org.uk/data/archive. The data was extracted using GPS coordinates of both research sites, amounting to 48 data points in Teso South, and 20 in Kapchorwa (Figure A.2).

The Standardized Precipitation Index (SPI) was used to measure the intensity and severity of drought. It is a meteorological drought index that is based only on precipitation data (Belayneh et al., 2014; McKee et al., 1993). The SPI requires at least 30-50 years of historical precipitation data, and can be adapted to time-spans of 1, 3 or 24 months (Vicente-Serrano et al., 2010). It is a measure of the deviation of precipitation from average conditions over time. SPI has been accepted as a universal meteorological drought index allowing comparisons across climatic regions, and has been used for the evaluation of the severity of agricultural droughts (Feng et al., 2018; Shahabfar and Eitzinger, 2013; Shin et al., 2018; Shrivastava et al., 2018; Spinoni et al., 2018; Hazbavi et al., 2018). The SPI was calculated by fitting a gamma distribution to the frequency distribution of precipitation and then transforming the gamma distribution into a standard normal distribution, using an equal probability transformation. The mean SPI is, therefore, zero and for any given drought, the SPI score shows by how many standard deviations the cumulative precipitation deficit or excess deviates from the normalised average (Zargar et al., 2011). Drought is then classified as mild (0 < SPI < -0.99), moderate (-1.0 < SPI < -1.49), severe (-1.5 < SPI < -1.99), and extreme drought (< -2.00) (McKee et al., 1993). The SPI was calculated using the TAMSAT data per month from 1983-2017, using the R-package "SPI" on RStudio Desktop (Version 1.1.435).

The TAMSAT monthly precipitation values from 2015 and 2016 were compared to the self-collected rain gauge mean monthly precipitation values of both years per research area, using Pearson correlation in RStudio.

WorldClim annual temperature (°C) data from the years 1970-2000 was used and extracted using the GPS points of the sampling sites (WorldClim, 2018). The temperature as well as the precipitation from TAMSAT were both regressed onto altitude using a simple linear regression (lm) in RStudio.

Soil Sample Collection

This study is embedded in the project "Crops for Healthy Diets – Linking Agriculture and Nutrition" (HealthyLAND) (www.healthyland.info) and used the project selection criteria. Villages were selected in both research areas using Probability Proportional to Size (PPS) sampling (Kish, 1995). Both research areas were stratified into their regions. Within each region, the villages were used as clusters and weighted using the villages' population size. Subsequently, twelve households were selected in each village for the project baseline survey (total: 396 households per research area). A subsample survey was conducted with 72 households per region. The 72 households were selected by first randomly selecting 18 out of the previously selected 33 villages, and then randomly selecting four out of the previously selected twelve households per village. The households were visited and samples collected during July-August 2016 for the FGS, and in January-February 2017 for the SGS.

In the subsample household survey, three fields were selected per household for plant and soil samples. Four soil samples were taken per field at 0-20 cm and mixed to form composite samples. In total, three soil samples were taken from every household. The soil samples were each paired with collected crop samples (originating from the same fields). The plant samples collected were maize cobs mainly from land races and cassava tubers in Teso South, and maize cobs and matooke fruits in Kapchorwa, in their ripe and edible stages. The mentioned species were collected as they (i) were found most frequently in both areas and (ii) are the most consumed staple foods in the region, thus providing the nutritional base of rural households. As not all farmers planted the same crops on the sampled fields during both seasons, only the sample fields where the same crop could be collected during both seasons were used in this

Table 2.1: Sample size of all samples collected compared to the sample size of the longitudinal samples, collected from the same fields in both seasons, in Teso South, Kenya and Kapchorwa, Uganda for both plant types collecte per region.

Region	Crop part collected	First Growing Season (FGS) 2016 (no.)	Longitudinal Study FGS 2016 Sample (no.)	Second Growing Season (SGS) 2016 (no.)	Longitudinal Study SGS 2016 Sample (no.)
Teso South	Maize grain	31	15	30	15
	Cassava tuber	27	14	37	14
Kapchorwa	Maize grain	30	15	32	15
	Matooke Fruit	54	19	36	19

paper for a longitudinal analysis (Table 2.1; Figure A.1). Similar to the soil samples, at least three plant samples were collected per field and combined to form a composite sample per field. The maize grains were shucked from the cob, whereas cassava roots and matooke fruits were both peeled and either air and sun dried or dried in a desiccator.

Interviews were done per household for information regarding yields of the collected samples, as well as information on planting and harvest dates. Data on fertilisation was collected but due to its low and infrequent application was considered negligible in this study.

Sample Analysis

The dried soil samples were sieved and milled. The samples were analysed for N and C content using a Vario MAX CN-analyser (Elementar Analysesysteme GmbH, Hanau, Germany) (Naumann and Bassler, 2012). Additionally, pH was measured in 1M KCl (Lewandowski et al., 1997). Texture was measured using the gravimetric method and divided into percentages of clay ($<$ 0.002 mm), silt (0.002-0.05 mm) and sand (0.05-2 mm) (FAO, 2006). Both texture and the effective Cation Exchange Capacity (eCEC) were measured using the methods described in Pansu and Gautheyrou, 2006 at the Core Facility of the University Hohenheim. The exchangeable elements for eCEC were meas-ured using Inductively Coupled Plasma, Optical Emission Spectrometry (ICP-OES Varian VISTA Pro from EVISA, France).

All samples were sent to the Soil Spectral Laboratory of the World Agroforestry Centre, where they were re-dried, milled to µm particle size, and analysed for the total trace elemental content of P, K, Ca, Mg, S, Mn, Fe, Cu, and Zn using a portable X-Ray Fluorescence Spectrometer (Tracer 5i pXRF – Bruker Corporation, Billerica, Massachusetts). The elements measured were selected as they are essential for both plants and humans alike (White and Brown, 2010).

As is commonly observed in measured environmental datasets, the present data contained values below the level of detection (LOD). LODs occur when the machines used to measure the samples still detect the presence of the elements but cannot quantify them (Helsel, 2012). LODs often complicate the evaluation of environmental datasets, and ignoring them can lead to biased results (Helsel, 2012; Piepho et al., 2002). Here, a maximum likelihood method described by Piepho et al. (2002), was used to estimate the censored values. The calculations were done on SAS University Edition 2018, using the code provided by Piepho et al. (2002).

Mineral nutrient concentrations (mg/kg) were then tested for normality, log transformed, and used for statistical analysis. Soil fertility was evaluated using the different measured soil properties: texture, eCEC, pH, and N and C content. Potential associations with altitude were also tested, as the altitude gradient particularly in Kapchorwa, is very large, and was assumed to affect some variables. Associations were tested using Pearson correlation in SAS University Edition 2018.

The term "nutrients" will be used throughout this paper and will signify the measured plant macro- (P, K, Ca, Mg, and S) and micronutrients (Mn, Fe, Cu, and Zn) (Marschner, 2012). Nutrient concentration is expressed as mg/kg dry weight throughout this paper. To calculate the nutrient amounts assimilated per unit of produced crop yield, the production amount (t/ha) was multiplied by the nutrient concentration (mg/kg) converted into grams per hectare (g/ha).

δ13C Isotope measurements were done to measure the level of water stress that the plants expe-rienced during the SGS. The method is well known and accepted as a proxy measurement for water stress in both C3 and C4 plants (Clay et al., 2001; Hussain et al., 2015; Pansak et al., 2007; Schmitter et al., 2011). Presence of water stress was analysed by comparing the normal season (FGS) δ13C of both crops per research area to the corresponding drought season (SGS) δ13C using a randomly selected subsample (n=8 per crop) of the collected plant samples. As nutrient uptake can also influence the δ13C content of plants, δ15N levels were also analysed. Samples were measured at the University of Hohenheim using a Euro EA Elemental Analyzer (Euro Vector) coupled to a Finnigan Delta IRMS (Thermofinnigan, U.S.A).

Yield gaps for maize were calculated using the average t/ha produced per household, as assessed from the farmer interviews. These were then compared to average country yields using FAOSTAT data from 2016. The country average maize yield for Kenya was 1.43 t/ha and the country average maize yield for Uganda was 2.32 t/ha. For cassava the Kenyan country average was 12.3 t/ha in 2016, and in Uganda the average yield of matooke was 4.39 t/ha (FAO and Government of Kenya, 2018).

The statistical analysis was done in four steps, all using the SURVEYREG and SURVEYMEANS packages available from SAS University Edition 2018 for sample survey data. These analyses took into account the sampling probabilities, which were varied according to the probability-proportional-to-size (PPS) sampling scheme. (1) The nutrient concentration of maize grain was compared between Teso South and Kapchorwa during a normal rainy season, and therefore only used data from the FGS in both countries. A t-test was done to identify whether any country had a significantly higher amount of nutrients than the other. (2) The nutrient concentration between different seasons were compared to determine if the change in season (from normal season to drought season) had any statistically significant effect on the nutrient concentration. Specifically, each nutrient concentration of each collected crop per country was compared. (3) Maize grain data was used to compare the effect of the two critical stages on final maize nutrient concentration and yield. Critical stages are moments in the development of maize when drought has the strongest reducing effect on yield. In this paper, flowering and initial grain filling, defined as 61-90 days after sowing, was used as "critical stage 1" (SPI1). "Critical stage 2" (SPI2) was grain filling and drying and was defined as 91-120 days after sowing (Barron et al., 2003) (Table A.1). The time periods representing the critical stages were calculated from the planting dates supplied by the farmers in both research areas. The SPI was calculated for the months representing the critical stages, and subsequently compared to the nutrient concentration within each country. (4) The nutrient amount accumulated (g/ha) was calculated for all plant samples collected and was compared between the FGS and the SGS to evaluate the impact of the previously analysed changes to nutrient concentration and yield due to the drought. Here, nutrient amounts assimilated were compared between seasons within each country using the same methods as described above. All codes used for the statistical analysis can be found in the supplementary material.

2.3 Results

2.3.1 Climate and Precipitation

The rain gauge data of both countries (Figure 2.1) showed a much lower rainfall (Teso South: -49%; Kapchorwa: -59%) than expected during the SGS of 2016 when compared to the one of 2015 (September-December). Lower precipitation was observed from rain gauge data in Teso

South beginning from September 2016 to December 2016, while in Kapchorwa, the onset of precipitation deficiency appeared to be end of September 2016 (Figure 2.1). In Teso South the precipitation decreased but then levelled out, whereas in Kapchorwa the precipitation decreased sharply until it ceased completely.

As a preliminary step, the rain gauge data and TAMSAT data of the monitored period were compared to each other, to identify whether TAMSAT was comparable to the actual measured precipi-tation data of the rain gauges in the study regions. The two datasets correlated strongly (Teso South R^2=0.80*** (Figure A.3); Kapchorwa R^2=0.82*** (Figure A.3)). Therefore, TAMSAT data was used for the remainder of this paper as it provided more data points (Teso South n=48; Kapchorwa n=17) than the rain gauges (Teso South n=4; Kapchorwa n=1). The SPI showed an increasing trend over time (Figures A.4) in both countries from 1983-2017. The total yearly precipitation when regressed over the same time showed a significant positive relationship (Teso South (R^2=0.55; $p<0.05$*), and Kapchorwa (R^2=0.49; $p<0.05$*)) (Figure A.5).

During the FGS 2016 in Teso South, SPI appeared to be similar to previous years (2010-2015) and was even noted as above average with strong positive values with an SPI ranging from 1.5 to 2, despite the negative value in March, presenting the late onset of rains (Figure 2.2). During the SGS de-creased levels in SPI were identifiable beginning October with levels far below the previous years, particularly December, showing a severe drought at SPI -2.0 (Figure 2.2).

In Kapchorwa, the SPI values of the FGS during 2016 showed strongly positive values when compared to the previous years (Figure 2.3).The SPI values from 2016 of the SGS, however, with the exception of a high SPI in September (SPI 2.2) featured values below zero (Oct= -0.1, Nov=-0.6, Dec=-1.5). The values indicated a mild to severe drought developing during the season.

2.3.2 Plant Analysis

All nutrient concentration means and yields of maize (with the exception of Mg and S), were signifi-cantly higher in Kapchorwa than in Teso South during the FGS (Table A.9). Additionally, Kapchorwan maize grain had a very large variance in nutrient concentrations, whereas Teso South maize grain, in comparison, was more homogenous with the exception of P, where Teso and Kapchorwa had simi-lar distributions (Table A.9). When comparing maize yields between research areas, Kapchorwa produced a higher average yield of 2.05 t/ha (yield gap 33%), whereas Teso South had a mean yield of 0.49 t/ha (yield gap 64%) during the FGS (Table

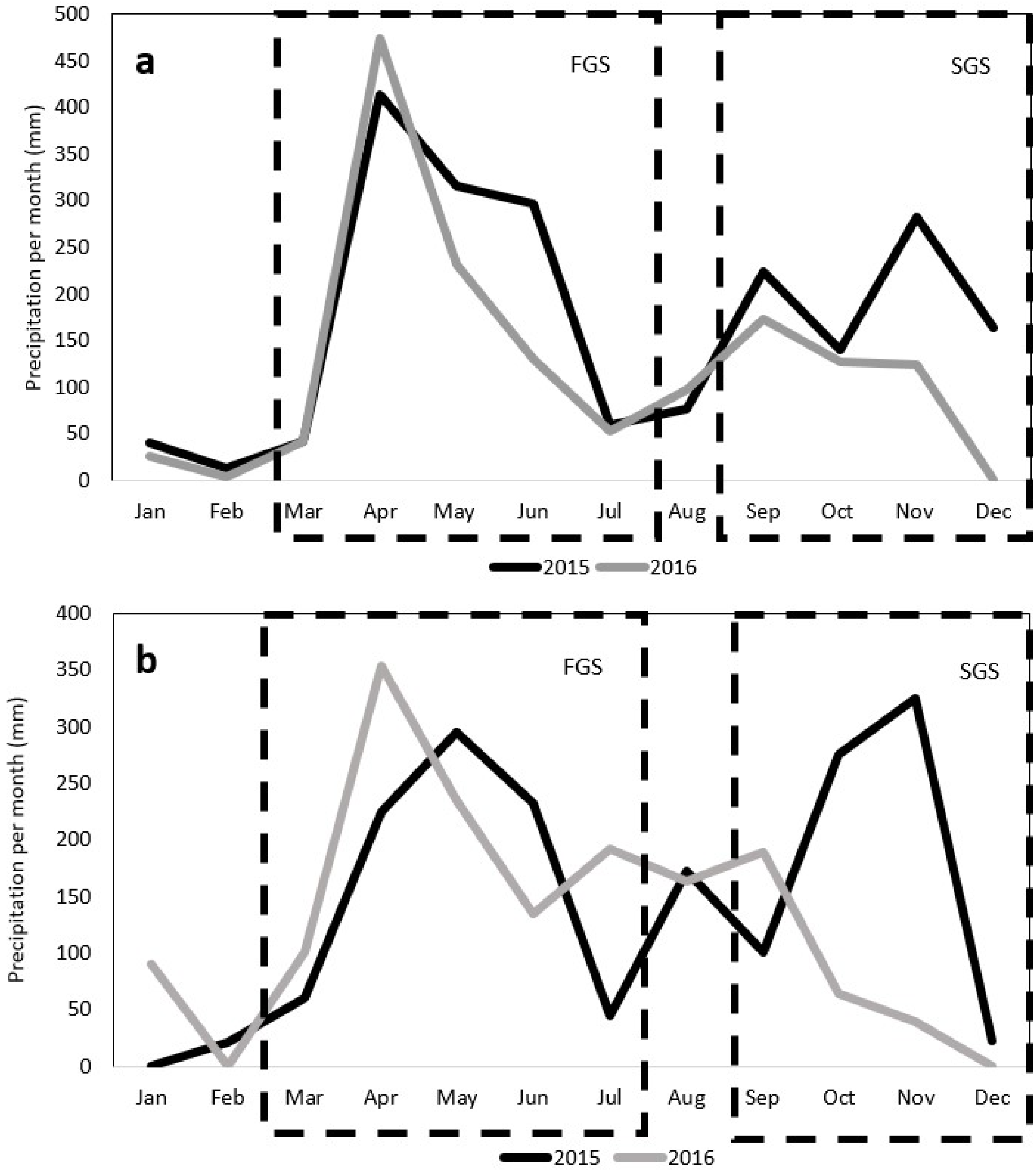

Figure 2.1: Sum of precipitation per month, averaged from the four rain gauges located in Teso South, Kenya (a) from 2015 and 2016. (b) Sum of precipitation per month from the rain gauge located in Kapchorwa Town in Kapchorwa, Uganda from 2015 and 2016, highlighted are the first (FGS) and second growing seasons (SGS). For the locations of the rain gauges, see maps Figure A.1. Note difference in y-axis scale.

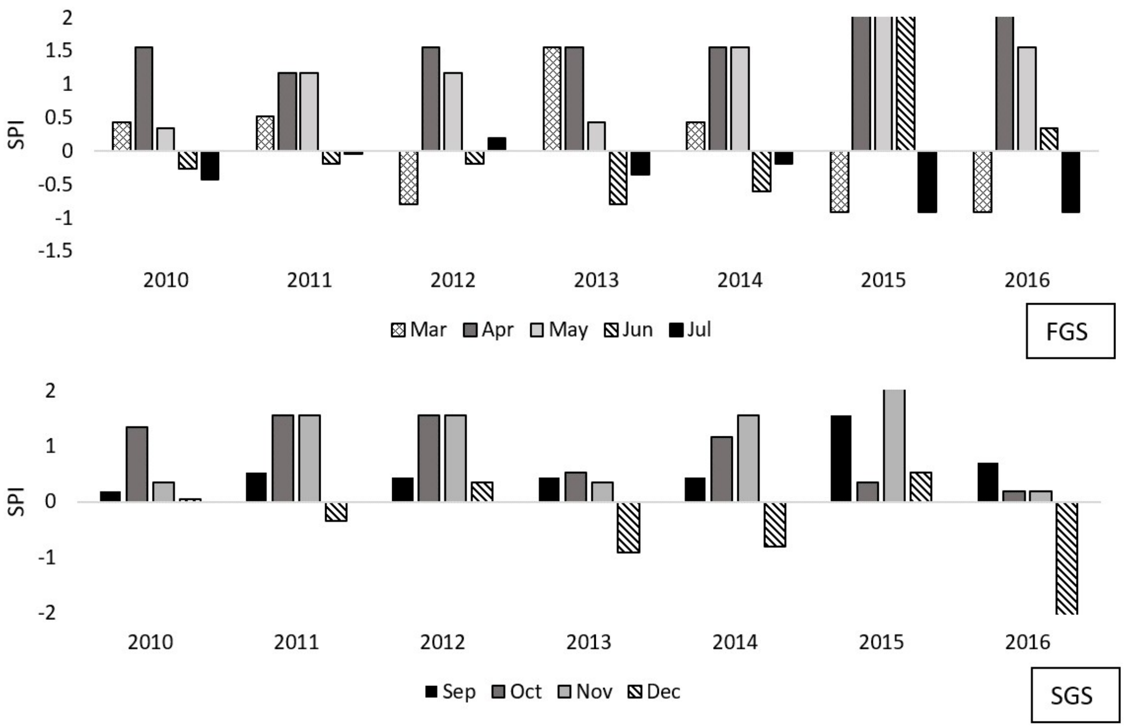

Figure 2.2: Comparison of monthly Standardized Precipitation Index (SPI) values in Teso South calculated from the TAMSAT data (source: https://www.tamsat.org.uk/data/archive), of the first (FGS) (March - July) and second growing seasons (SGS) (September - December). Shown are the years 2010-2016. Drought is then measured by: mild drought (0 < SPI < -0.99), moderate drought (-1.0 < SPI < -1.49), severe drought (-1.5 < SPI < -1.99), and extreme drought (< -2.00).

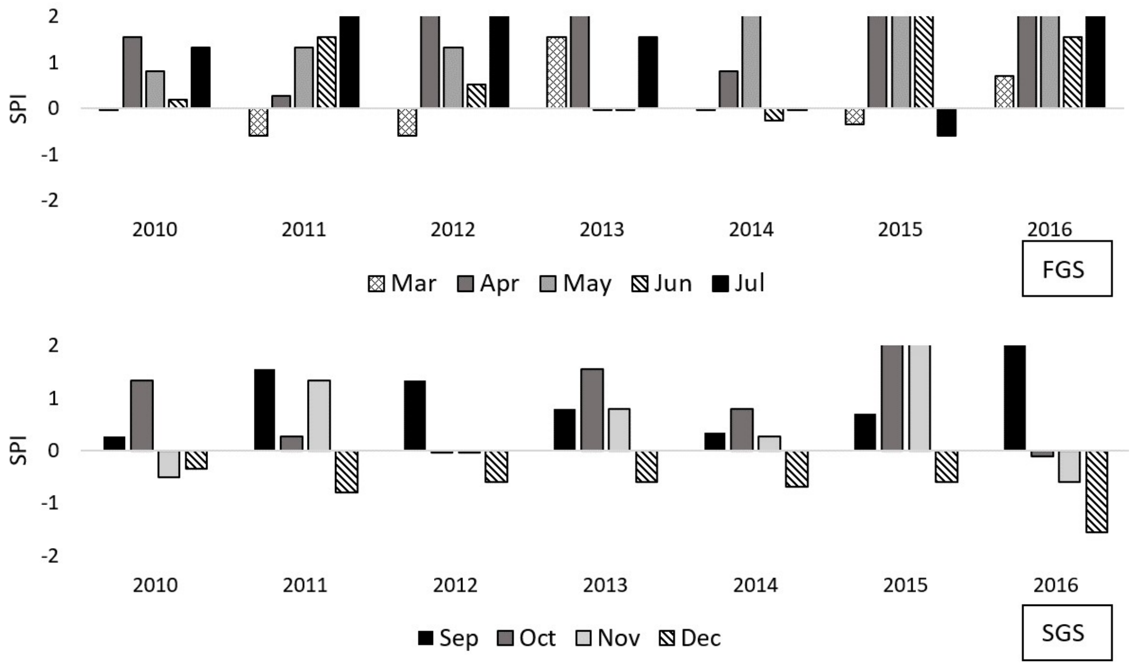

Figure 2.3: Comparison of monthly Standard Precipitation Index (SPI) values in Kapchorwa calculated from the TAMSAT data (source: https://www.tamsat.org.uk/data/archive), of the first (FGS) (March-July) and second growing seasons (SGS) (September-December). Shown are the years 2010-2016. Drought is then measured by: mild drought (0 $<$ SPI $<$ -0.99), moderate drought (-1.0 $<$ SPI $<$ -1.49), severe drought (-1.5 $<$ SPI $<$ -1.99), and extreme drought ($<$ -2.00).

A.9).

The results of the higher maize grain nutrient concentrations and higher yields in Kapchorwa compared to Teso South during the FGS were mirrored in the soil analyses. Kapchorwa had significantly higher total soil concentrations of all nutrients. Additionally, Kapchorwa had a higher pH, eCEC, N and C content, and percentage of silt and clay than Teso South (Table 3.2). In summary, these results showed that the soil fertility was higher in Kapchorwa than in Teso South.

Regarding nutrient concentration from the FGS to the SGS, the predominant trend in Kapchorwa was a decrease whereas, the predominant trend in Teso South was an increase (mean values in Table A.2 and A.4). The increase or decrease of nutrient concentration between seasons observed in maize grain nutrient concentration, could also be seen in the other crops collected in the respective study region. When looking at the maize grain nutrient concentrations in Kapchorwa, it is apparent that only micronutrients (Fe, Cu, and Mn, with the exception of Zn) showed a significant decrease in concentration from FGS to SGS, whereas decreasing macronutrient means were not significant. The decreasing trend observed in matooke, however, was much stronger than in maize as all nutrients (macro and micronutrients) were significantly reduced from the FGS to the SGS (Table 2.2). Maize grain nutrient concentrations in Teso South, on the other hand, increased predominantly for P, Ca, Mg, Fe, and Zn. The remaining nutrients with the exception of K and S decreased, albeit not signifi-cantly (Table 2.2). Cassava tubers in Teso South also showed significantly increased nutrient concen-trations during the SGS when compared to the FGS, with the exception of K, Fe, Cu, and Mn. In cassava, macronutrient concentrations (except K) significantly increased from FGS to SGS while Fe and Cu showed much smaller insignificant increases between the FGS and the SGS. Zn in cassava tubers showed a significant increase between the FGS and SGS (Table 2.2).

2.3.3 Analysis of SPI and maize nutrient concentration

The relationships of maize nutrient concentration to the two SPI critical levels included linear as well as quadratic relationships. SPI1 was significantly higher in Teso South (0.32) when compared to Kapchorwa (-0.73), as well as SPI2 (Teso South: -0.61; Kapchorwa: -1.47) (Table A.6). The SPIs of the FGS were always higher than the SPI in the SGS across both regions. The difference between the SPI FGS and SGS was higher in Kapchorwa for both SPIs (Table A.6). Kapchorwa had negative SPI SGS values whereas the same values were positive for Teso South (Table A.6).

Table 2.2: Percent differences between the means of first growing season (FGS) and second growing season (SGS) calculated for each nutrient per region and crop. Negative values indicate a decrease between the FGS and the SGS whereas positive values mark an increase between FGS and SGS. Marked are levels of significance. p<0.05*; p<0.005**; p<0.0005*** on the significantly higher factor. Table with detailed descriptive data can be found in the supplementary material (Table A.2-A.5).

		Teso South, Kenya		Kapchorwa, Uganda	
% difference between FGS and SGS	Variable	Maize Grain	Cassava Tuber	Maize Grain	Matooke Fruit
	Yield	-2%	-67%*	-28%*	-1%
Macronutrients	Mg	19%*	23%*	-12%	-68%***
	P	49%**	52%***	-2%	-27%***
	S	-9%*	59%**	-23%	-77%***
	K	-6%	25%	-48%	-33%***
	Ca	79%***	60%**	-4%	-86%***
Micronutrients	Fe	68%***	15%	-67%*	-83%***
	Cu	12%	8%	-89%**	4%
	Zn	41%**	12%*	-17%	24%*
	Mn	17%	-51%**	-81%**	-99%***

Table 2.3: Percent of surveyed land used to cultivate maize and cassava in Teso South and maize and matooke in Kapchorwa and yield gap in the respective season. The yield gap was calculated using the country average, from the FAOSTAT dataset, using values from 2016 (Source: http://www.fao.org/faostat/en/).

		Teso South, Kenya			Kapchrowa, Uganda		
	Season	Total	Maize Grain	Cassava Tuber	Total	Maize Grain	Matooke Fruit
% of Land Cultivated	FGS	69%	43%	26%	49%	34%	15%
	SGS	65%	39%	29%	38%	17%	21%
% Yield Gap	FGS	-	68%	89%	-	6%	36%
	SGS	-	68%	96%	-	33%	38%

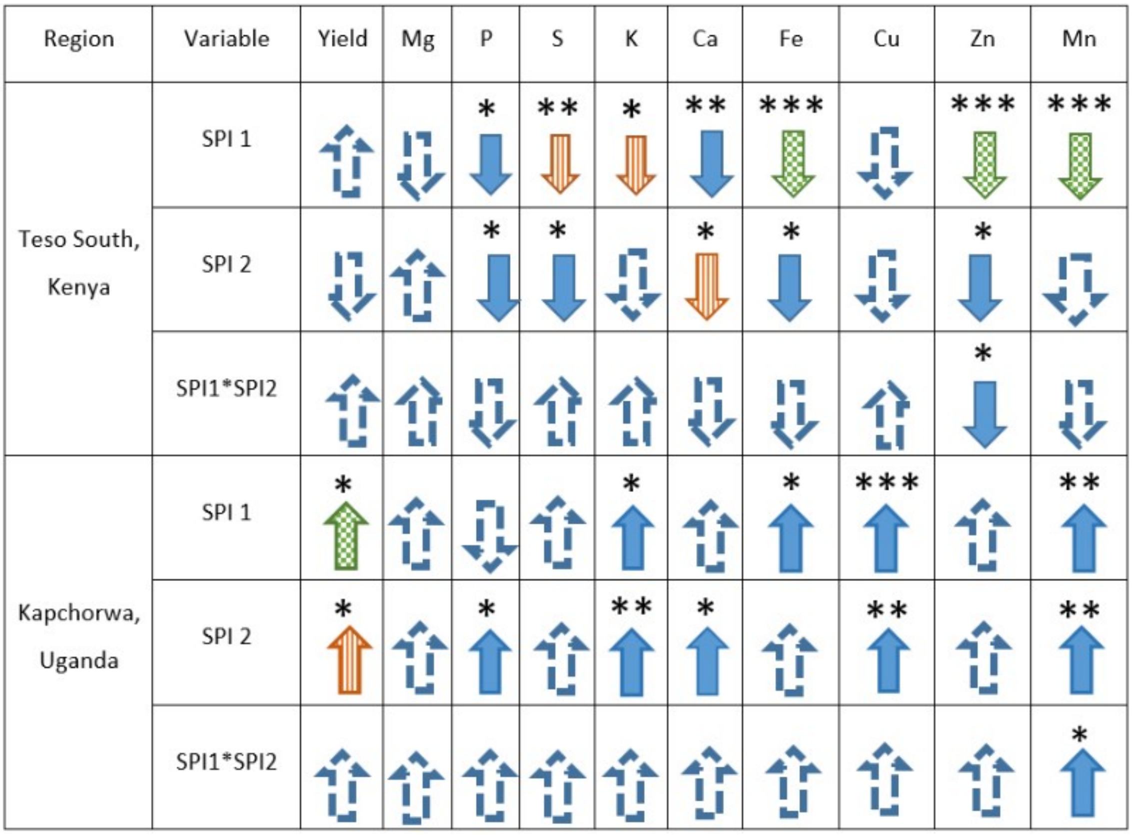

Figure 2.4: Comparison of the effect of Standard Precipitation Index (SPI) values at two critical growth stages of maize in Teso South, Kenya, and Kapchorwa, Uganda, based on the local cropping calendar, on the mineral nutrient concentration. The arrows show the direction of the interaction (pointing upwards: positive, pointing downwards: negative). Empty arrows show non-significant trends. Colours signify the polynomial degree, blue is linear, green checkers are quadratic, and orange stripes are cubic. Stars signify the level of significance $p \leq 0.05$*; $p \leq 0.005$**; $p \leq 0.0005$***. Table with values in the supplementary material (Table A.7).

For maize grain in Teso South, SPI1 showed strong significant associations with nutrient concentrations, covering both macro-and micronutrients (Figure 2.4). SPI2 also showed many significant associations, however showing no significant associations with K and Mn as in SPI1. Looking at the association between SPI1*SPI2 only one significant negative association was found with Zn (Figure 2.4). In Kapchorwa, all of significant relationships were positive. Fewer associations were seen in Kapchorwa than in Teso South in both SPIs (Figure 2.4).

2.3.4 Regional Nutrient Production

In Teso South, over half of the surveyed land was used to cultivate maize and cassava during the FGS and SGS (Table 2.3). The mean yield of maize produced from the sampled households during the FGS, was the same as during the SGS. For cassava, the yield gap increased from

Table 2.4: Mean nutrients content in (g/ha) by maize, cassava and matooke collected at Teso South, Kenya and Kapchorwa, Uganda. Nutrients were compared between seasons: FGS (first growing season from Mar-Aug 2016) and SGS (second growing season from Sep-Dec 2016). Asterisks (*) signify level of significance, categorized into: p<0.05*; p<0.005**; p<0.0005***.

			Mg	P	S	K	Ca	Fe	Cu	Zn	Mn
Teso South	Maize Grain (g/ha)	FGS	404	1428	406	2390	22	16	1.7	16	1.6
		SGS	437	1873	399	2304	84**	27	2.4	19	1.8
	Cassava Tuber (g/ha)	FGS	16*	51*	6.3	494*	12	2.5**	0.16**	0.46*	0.45**
		SGS	1.8	4.7	1	39	4.1	0.21	0.01	0.04	0.01
Kapchorwa	Maize Grain (g/ha)	FGS	702	2858	894*	5737	176	80**	29***	34	9.7**
		SGS	622	2443	432	3687	148	32	3.8	24	2.1
	Matooke Fruit (g/ha)	FGS	60**	52	48**	639	192***	7.1***	0.12	0.14	14***
		SGS	18	37	10	423	24	1.1	0.09	0.17	0.14

very high to an almost complete failure during the SGS. In Kapchorwa, maize and matooke were two of the most important crops, making up almost half of all surveyed cultivated land during the FGS and a bit less during the SGS (Table 2.3). The mean maize yield in the sampled households amounted to 2.18 t/ha during the FGS and 1.55 t/ha during the SGS. The average maize yield gap of Kapchorwa increased from almost nothing to losing half of the harvest. Matooke also showed a yield reduction from the FGS to the SGS, but the reduction was very small. The only difference seen in the assimilated maize grain nutrients in Teso South was that the translocation of Ca to the edible tissue was significantly higher during the SGS than the FGS. The nutrients assimilated by cassava in Teso South was different from maize. In this case, all values were significantly higher in the FGS when compared to the SGS, with the exceptions of Ca and S where the difference was not significant (Table 2.4).

Maize grain nutrient amount in Kapchorwa showed a clear and significantly higher nutrient accumulation for S and most micronutrients except Zn. All of the other nutrient values were higher in the FGS than in the SGS, however, the difference was not significant. Matooke fruits showed similar results to maize grain in Kapchorwa. All nutrients with the exception of P, K, Cu, and Zn were assimilated in a significantly higher amount during the FGS than during the SGS (Table 2.4). In both regions, maize had the highest amount of nutrients accumulated during the drought period when compared to the other crops.

2.3.5 δ ^{13}C Measurements

Maize grain samples showed a decrease (more negative) in their δ ^{13}C values from the FGS to the SGS, being more severe in Kapchorwa than in Teso South (Figure A.6). Both matooke and cassava on the other hand showed an increase (less negative) in δ ^{13}C values between the FGS and the SGS (Figure A.6). Although the δ ^{15}N values showed some minor differences between the seasons the differences were not consistent between plant types (C3, C4) (Table A.8).

2.3.6 Altitude and Nutrient Concentration

There were no significant correlations or regressions between altitude and nutrient concentration of any of the measured nutrients in any of the crops and between yields of either crop at different altitudes.

2.4 Discussion

2.4.1 Plant nutrient composition compared to soil fertility

Maize nutrient concentrations and yields were significantly higher in Kapchorwa than Teso South for all nutrients with the exceptions of P and S, during FGS due to a higher total soil fertility in Kapchorwa (Marschner and Rengel, 2011). The lack of statistical significance for these two nutrients was mainly due to the high natural variance of P and S concentrations found in Kapchorwa. The higher variance of all values measured in Kapchorwa was attributed to a higher natural heterogeneity of abiotic and biotic factors (such as the soil parent material), indirectly related to altitude.

2.4.2 Drought and its effect on nutrient concentrations

The increase of precipitation over time could mainly be attributed to an already observed effect of climate change, causing a general increase in total yearly rainfall in East Africa (Hulme et al., 2001; Weber et al., 2018). As the SPI is only a precipitation indicator, the use of the Standardized Precipi-tation and Evapotranspiration Index (SPEI) would have been a better choice as an indicator, as it also contains information on the evapotranspiration. The SPEI, however, was not used due to missing data for 2016, and a lacking spatial resolution for the research area.

Kapchorwa showed SPI values indicative of a mild to severe drought throughout the months of the SGS. Teso South, on the other hand, showed SPI values that are not indicative of a drought (with the exception of December), and by SPI definition could not be referred to as one. Observing, however, that all of the SPI values during the SGS 2016 were a lot lower than in previous years, Teso South is still assumed to have a sizeable precipitation deficit. Another reason for the lack of a drought in Teso South is that the SPI calculation is based on historic data. This, coupled with the recent effects of increasing precipitation due to climate change in East Africa (Weber et al., 2018), could potentially underestimate droughts. The observed drought in this study affected large parts of East Africa as part of the La Nina 2016 drought (Lim and Hendon, 2017).

The presence of temporal water stress during growth was clearly reflected in the altered δ ^{13}C signatures of maize grain, cassava tuber and matooke fruit between seasons. For maize, the decrease in δ ^{13}C values in the SGS indicated the presence of an experienced drought period, typical for a C4 plant (Clay et al., 2001). Moreover, the larger decrease in δ ^{13}C values in Kapchorwa points to a more severe drought than in Teso South, confirming thus the differences of the respective SPI indices. In contrast, in C3 plant species, an increase in δ ^{13}C values is also indicative of an experienced drought (Clay et al., 2001; Schmitter et al., 2011), as was observed in Kapchorwa and Teso for Cassava and Matooke in the SGS. δ ^{15}N decreased for most samples during the drought season. The respective changes in δ ^{15}N, were very small, and therefore suggested to not have any impact on the interpretation of the δ ^{13}C values (Hussain et al., 2015; Tuan et al., 2015).

Kapchorwa, having faced a severe drought, confirmed the main hypothesis, stating that nutrient concentration in edible parts of crops would significantly decrease during drought, an observation that had also been found in other studies (Okogbenin et al., 2013; Oktem, 2008). Teso South, on the other hand, had a milder drought and showed the opposite effect of significantly increasing nutrient concentration during drought, and therefore rejected the hypothesis. Both crop species collected in Kapchorwa (matooke and maize) and Teso South (cassava and maize) showed the same results within each country. A yield decline from normal to drought season (FGS to SGS 2016) was apparent in all crops and statistically significant in maize grain and matooke fruits in Kapchorwa, and in cassava tubers in Teso South.

Kapchorwa, Uganda

The decrease of nutrient concentrations in both crops in response to drought was most likely due to a decrease in water uptake and therefore the inability of the plant to take up and translocate nutrients into the harvested product (Andresen et al., 2018; Page and Feller, 2015). In the case of these two crops, matooke seemed to have a more severe reaction to drought than maize, considering that all nutrient concentrations decreased by a higher degree than in maize. Matooke has also been identified by other authors as being drought sensitive (Kayongo et al., 2015; Mahouachi, 2007; Ravi et al., 2013; Van Asten et al., 2011). While, maize showed a general decreasing micronutrient concentration trend, both macronutrients and micronutrients decreased significantly in matooke. Multiple reasons can account for the greater difference in nutrient concentration. Matooke could show a stronger reduction in nutrient concentration due to the longer distance nutrients had to travel from source (roots) to sink (leaves/fruits), compared to maize. Other mechanisms could also play a part, such the differences of nutrient loading efficiency during drought. These would include, for example, the mechanisms of phloem unloading into the developing fruit or seed, which is species specific and is not yet well understood (Clemens and Ma, 2016). Additionally, the ability to maintain phloem transport during drought differs between species and is described as stronger in maize than in matooke (Sevanto, 2014). Nutrient uptake through the roots may also be limited during drought as matooke roots are very sensitive to physical constraints (Van Asten et al., 2011).

The higher reduction of particularly micronutrients in maize grain compared to macronutrients can be due to one of two hypotheses. The first more likely hypothesis would be that due to drought, the maize plants were no longer able to take up nutrients from the soil and, therefore, for the remaining grain filling, remobilised nutrients mainly from leaves and other plant parts (Etienne et al., 2018; Lemoine et al., 2013; Maillard et al., 2015; Page and Feller, 2015). Remobilisation, however, is phloem-driven, has certain limitations on micronutrient transport (Maillard et al., 2015; Sevanto, 2018).

Macronutrients are stated to be more phloem mobile than most micronutrients, with the exception of Ca, stated to not be phloem mobile (Etienne et al., 2018; Maillard et al., 2015). Potential Ca phloem immobility was not observed in this study, as Ca was not found in a decreased concentration in the edible part, compared to other macronutrients. The difference in observation was most likely due to the function of Ca as a structural element, found most often in the cell walls of plant organs (Marschner, 2012), and may therefore have been translocated into the maize grain before drought initiation. While some studies have found lacking remobilisation of both macro- and micronutrients (Etienne et al., 2018), others have found relatively good remobilisation (Maillard et al., 2015; Oktem, 2008). The results of the present study support the results of Maillard et al., 2015, as the macronutrients in the SGS were not significantly different from FGS, whereas the micronutrients show greater differences, suggesting difficulties in remobilisation and phloem transport. The second hypothesis would be that a reduction of nutrient uptake by the roots could also have triggered an earlier grain maturation (Saini and Westgate, 2000), cutting short grain nutrient loading – thereby explaining the decrease in nutrient concentration during the drought (Etienne et al., 2018).

Teso South, Kenya

In Teso South, a milder drought and later onset caused an increase in the nutrient concentration in both maize grain and cassava tubers. A mild drought during the final stage of grain filling is considered almost beneficial, as it accelerates kernel drying (Barron et al., 2003). Maize is able to maintain a favourable water status for some time after drought onset during kernel filling. Drought reportedly favours N reallocation in the plant, causing kernels that have been through a drought to contain a higher protein level then others (Etienne et al., 2018). As most micronutrients are transported via proteins acting as carriers, it is assumed that many micronutrients are also translocated within the N reallocation. However, extra supply to the seeds could be brought by the catabolism of polymers that may contain micronutrients, as a consequence of senescence, as an effect of drought stress (Etienne et al., 2018). One exception is Ca and Mn, both of which are reportedly not very mobile (Maillard et al., 2015). While Mn concentration in the grain does not change much in the current study, the Ca concentration in the maize grain increases significantly from FGS to SGS. This would mean that Ca, in contrast to previous studies, was more efficiently mobilized and transported than Mn. The observations made in Teso South have been found in a few other studies during controlled deficit irrigation trials (Ge et al., 2010; Kara et al., 2014).

Nutrient concentrations in the cassava tubers increased significantly from the FGS to the SGS, while yield decreased significantly. The total results for cassava were more severe than for maize. Cassava is known as being drought tolerant (Daryanto et al., 2016), and some of its water stress management methods could affect root nutrient concentration. Drought stressed cassava releases abscisic acid, closing their stomata in response to external vapour pressure deficit, regardless of soil water conditions. As a result of the closed stomata, less transpiration leads to more nutrients and resources stored in the sink root, explaining the higher nutrient concentration found in the present study (El-Sharkawy, 2004). Vegetative growth is reduced (Alves and Setter, 2000) allowing more resources to be allocated to the roots. The high yield loss can be explained through the findings of cassava drought trials by reduced yield due to loss of leaf biomass (El-Sharkawy, 2004; Okogbenin et al., 2013; Pardales Jr. and Esquibel, 1966). Another reason for the higher susceptibility to drought of cassava yield could be due to the differences in photosynthesis mechanisms. Maize is a C4 plant, which has a lower level of photorespiration and therefore a higher carbon assimilation than C3 plants, and is therefore able to maintain photosynthesis for a while with closed stomata (Lopes et al., 2011).

2.4.3 The effect of drought onset and severity on nutrient concentration

Drought onset and severity were key in the effect on nutrient concentration and yield. A mild drought caused an increase in nutrient concentrations, while a severe drought caused a reduction in nutrient concentrations. Regarding the critical stages of maize, SPI1 seemed to be much more important for the maintenance of yield and nutrient concentration than SPI2, in both Teso South and Kapchorwa. The earlier drought onset in Kapchorwa meant that SPI1 (grain filling) had already been affected by drought. In Teso South, on the other hand, the drought began late enough to not yet affect SPI1. Intensity was also a deciding factor in the drought effect on nutrient concentration. The drought intensity was much higher in Kapchorwa than in Teso South during the entire drought period, observable by the lower SPI values in Kapchorwa for the entire season. Both areas were then affected by drought during SPI2. As the nutrient concentration in Teso South increased while Kapchorwa decreased, SPI1 is considered to be the most critical stage for drought. The effect of onset and intensity could also be seen in the present research in the yield values. While there was a slight yield decrease in Teso South, the yield decrease in Kapchorwa was sizeable. The results found in regards to the SPI and yield reduction were similar to results found in other studies (Daryanto et al., 2016; Etienne et al., 2018; Gao et al., 2018; Maillard et al., 2015).

2.4.4 Implications on Food Security

In most crops, the yield decrease surpassed the benefit of increased nutrient concentration, therefore in total accumulating less nutrients than during a year with normal rainfall. The results also showed that during a normal season, cassava and matooke had a higher concentration of both nutrients. During the drought season, however, most nutrients were accumulated by maize. This change in nutrient accumulation is most likely due to the lower drought susceptibility of maize compared to the other two crops.

In Teso South, there were two results. Maize grain in Teso South showed a smaller yield reduction compared to cassava, and boasted a significantly higher Ca production in the SGS than during the FGS. Cassava, on the other hand, decreased so severely in yield, that the increase in nutrients accumulated were no longer detectable and all values in the FGS were significantly higher than in the SGS. In Kapchorwa, the trends for maize grain showed that the yield reduction and the reduction in nutrient concentration joint to a significantly lower nutrient accumulation for most micronutrients. Other nutrients also decreased in amount but not significantly. Matooke, affected most severely by drought, showed the most and highest significant differences in nutrient accumulation between FGS and SGS.

Drought has severe implications on food security as in most cases the nutrient concentration and total amount of nutrients accumulated are severely decreased, additionally to a yield decrease. Therefore, not only was the amount of available foods reduced (Masih et al., 2014), but its quality diminished, causing a double-burden during severe drought. Additionally, the same drought effect was seen in two different plant species per country, in different plant organs. It may be safe to assume that other crops, possibly including nutrient dense crops, may react in a similar way. The impact of drought on plant mineral nutrient concentration can also have significant effects on the health of people living in the immediate environment, and/or consume the food grown in that area. Particularly the strong drought effect on micronutrients contents is worrisome as human micronutrient deficiencies such as Fe and Zn represent some of the most common deficiencies found in East Africa (Yang et al., 2013). Observations on changing oil and protein compositions have also been made in trials relating to food composition under drought (Barutcular et al., 2016; Kara et al., 2014; Panozzo and Eagles, 1999; Singh et al., 2012).

2.5 Conclusion

The answer to the question "do we need more drought for better nutrition" therefore is "it depends". Severe drought decreased the nutrient concentration, yields, and total nutrients accumulated. Milder droughts increased the nutrient concentrations of the edible parts. The yields during milder drought, however, decreased. The total nutrients accumulated, as a combination of yields and nutrient concentration depended on the magnitude of change in the other two factors. Droughts can very strongly affect not only the quantity but also the quality of produced foods and therefore food and nutrition security, particularly in areas with local food markets or semi-subsistence farmers. In the case of severe drought, this has led to a drought "double-burden" decreasing yield and its quality. This paper found that severity and onset of drought are key in the effect they have, not only on yields produced but also on nutrient content and concentration of foods produced. Mainly micronutrient concentrations and presence in food were affected during drought. Low phloem mobility and therefore lacking translocation in the plants seem to be the main reason. Micronutrients require special attention during drought, as they are more likely to become deficient, thereby endangering consumer's health.

There is much room for further research to understand the drought effects on food composition, particularly under field conditions. This would include looking into topics such as deficit irrigation and the underlying mechanisms of plant drought stress. Further, to understand the actual ramifica-tions of an increased or decreased nutrient concentration on human consumer health would involve testing other food components such as anti-nutrients (e.g. phytates, tannins, and lectins), fats, sugars, vitamins and proteins. An option may also be breeding for adapted crops that maintain yields and enhanced nutrient profiles during times of drought, to better withstand the effects of severe drought.

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

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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 concentration 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 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.

3.1 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 food (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 mineral 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), which are influenced by the environment, soil, 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 concentration 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. The fertilisation with very few macronutrients (mainly N) effectively depletes 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 has been reported to be highly variable (Cobo et al., 2010b). It 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. Mediterranean), regarding 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 concentration. Joy et al. (2015), for example showed the effect of calcareous and non-calcareous soils on crop mineral composition. While single interactions between elements/nutrients are known (Baxter, 2010), effects of multiple deficiencies have not been studied in detail (Fageria, 2001). Additionally, research on the combined effects of environmental and farm management decisions on food nutrient composition and concentration 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. Different food types (grains, tubers, and fruits) are also important to compare as different parts provide different plant functions and should not be expected to react the same way to changes in the environment.

3.2 Material and Methods

3.2.1 Research Framework

The main aim of this paper was to evaluate 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, whilst not being high in nutrients, do represent foods that are commonly consumed in large amounts by all, and were therefore 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. Fertiliser application was measured by field and grouped to organic fertilisers (manure and crop residues) and inorganic fertilisers (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 parts – 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 the perennial species of fruits and tubers. Considering the different farm management methods, fertilisation was expected to have a positive effect on yield and nutrient concentration 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 concentration and yield, following a decreasing gradient of soil fertility.

3.2.2 Study Sites

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 1420-2000 mm/year with two rain seasons (Jaetzold et al., 2009). The altitude ranges from 1200-1400 m.a.s.l. with average yearly temperatures from 21-22°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.

Kapchorwa, Uganda

Kapchorwa (1.359817°, 34.45045°; 1.450219°, 34.44643°) 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).

3.2.3 Data Collection

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 3.1). 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 (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 (Figure A.7). 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

Table 3.1: Number of paired edible part 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 viewed in Figure A.1

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

the same fields selected for soil sampling (Table 3.1). 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).

3.2.4 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 1M 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).

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 3.2; maize grain results Table A.9; cassava tuber results Table A.11; matooke fruit results Table A.12).

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 3.2) . 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 A.9).

Nutrient concentrations in Kapchorwan' maize grain were significantly higher than in Teso South for all nutrients measured (Figure 3.1; Table A.9). Additionally, the range was greater in Kapchorwa than in Teso South for all maize grain nutrients with the exception of P (Figure 3.1). The greatest differences between the two areas was found in Cu, Mn, and Fe, where the differences between means were $>$ 70% (Figure 3.1; Table A.9) (Fischer et al., 2019).

3.2.5 Statistical Analysis

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 - Appendix B).

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 - Appendix B).

Soil values (trace elemental content 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 (Figure 3.1), 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.) et al., 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 A.16).

Canonical Correspondence Analysis (CCA)

To understand whether site-specific soil and management factors have an effect on the food nutrient composition, a Canonical 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 fertiliser (OrganFert), and inorganic fertiliser (InorgFert)) (Table A.10). 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 A.10). The CCAs were analysed by identifying response variable clusters and identifying the most influencing explanatory variables by their vicinity and vector length.

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 - Appedix B). 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.

3.3 Results

3.3.1 Descriptive Analysis

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 bothEast Africa (EA) (silt: 42%; clay: 3% higher) and Sub-Saharan Africa (SSA) (silt: 7%; clay: 37% higher) in the AfSIS database (Table 3.2; Figure A.8). 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%) (Figure A.8).

Food Nutrient Concentration

In general, the maize grain nutrient concentrations of Teso South were above those of the Global Food Composition Table average (Figure 3.1) 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 (Figure 3.1). The Global and Ugandan

Table 3.2: 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	18.9	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	21.3	21.3	39.3	0.06	52.8***	8.75	53.5	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 $p < 0.10$.

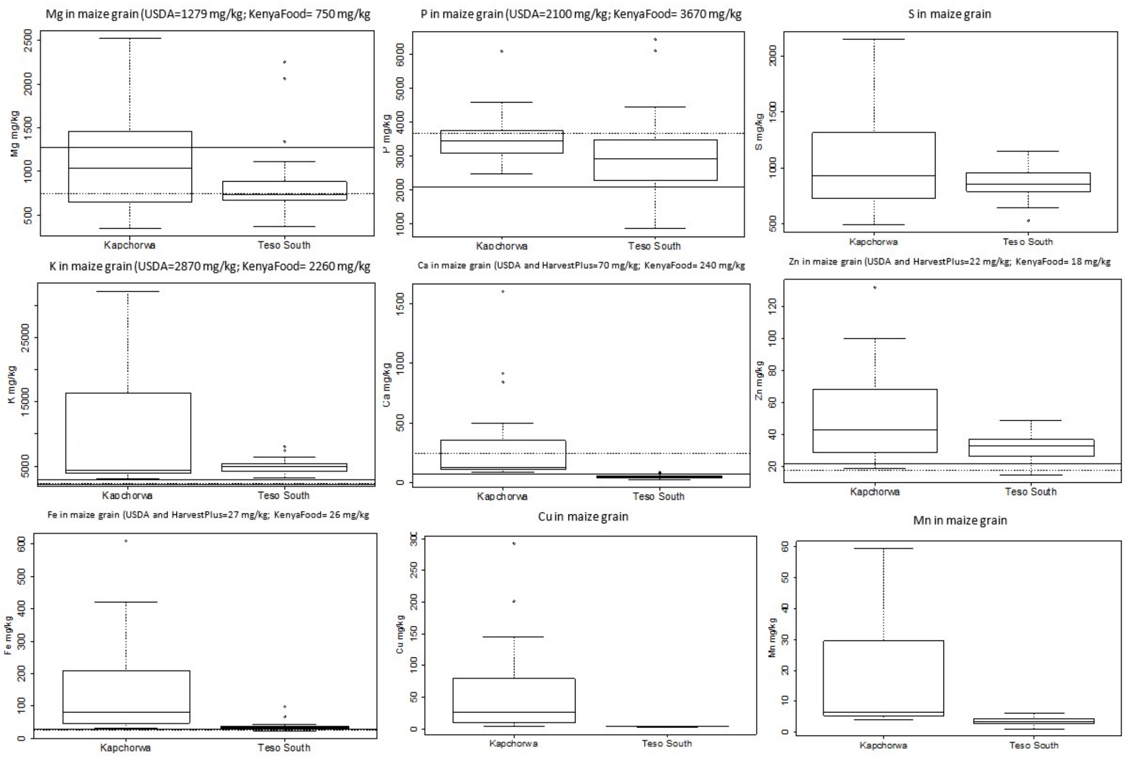

Figure 3.1: Boxplots showing the comparison between the nutrient concentrations measured in maize grain collected in Teso South, Kenya and Kapchorwa, Uganda (July-August 2016). The lines indicate the means from nutrient composition databases as comparisons. The dotted line represents the Kenyan food 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.

maize grain Composition Table values were below the Kapchorwan values, with the exception of Mg (global value: 1270 mg/kg; Kapchorwa 1071 mg/kg) (Figure 3.1).

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) (Figure A.9). 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

(Figure A.10).

Distance, Biodiversity, and Fertilisation

In Teso South, the distances between the house of the farmer to the maize (64m ± 21) or cassava field (62m ± 38) was not significantly different. However, in Kapchorwa, the staple crop matooke (255m ± 499) showed a larger distance between house and fields than maize (104m ± 128) (Figure A.11). In Teso South a higher number of cassava fields received organic fertilizer (maize 13% fields; cassava 27% fields), whereas about half of all maize fields received inorganic fertilizer (Table A.15). Similarly, in Kapchorwa, more maize fields received inorganic fertiliser (27%) than matooke fields (17%), while more matooke fields received organic fertilizer (45% matooke fields; maize in Kapchorwa 20%). The amounts of fertilisers used in all cases were very low. The maximum used amounts were organic fertilizer in cassava fields (0.09 kg/m^2 ± 0.29). Inorganic fertilisers 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 0.310.26 and cassava Richness 1.8 ± 1.3; Diversity 0.17±0.25) (Figure A.12).

3.3.2 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 (Figure 3.2). 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 (Figure 3.2). 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 3.3). These were followed by non-significant yet still high ranking properties

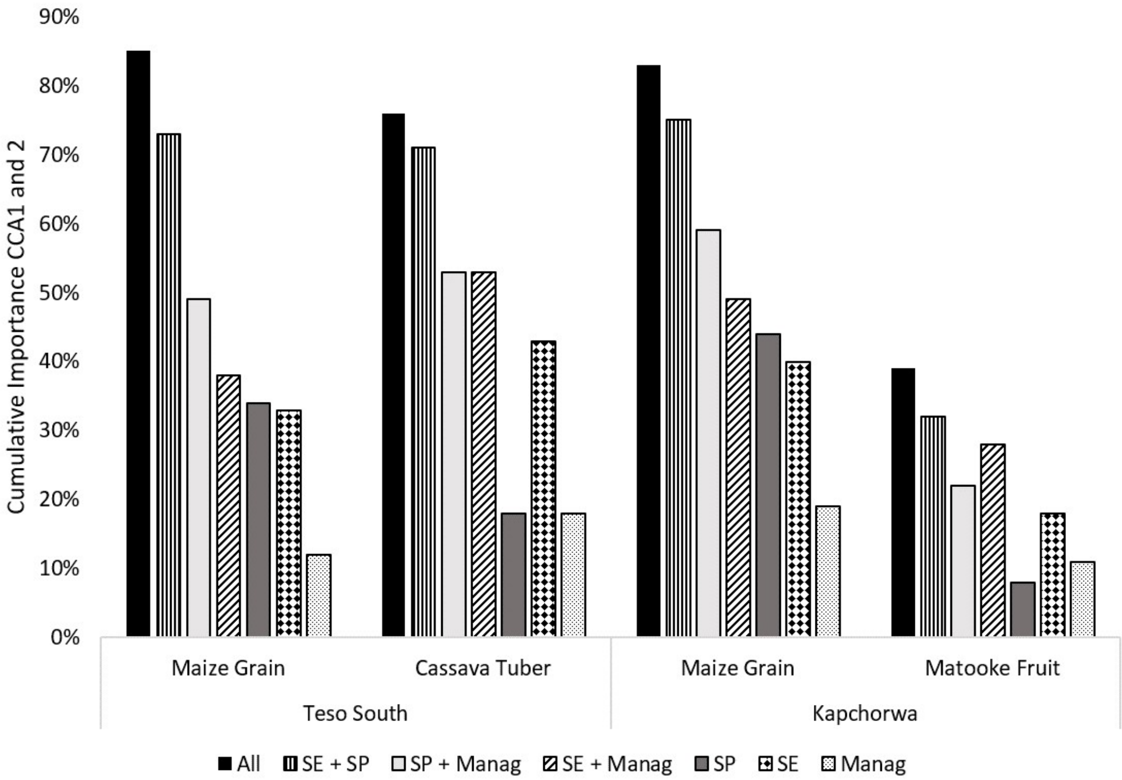

Figure 3.2: Comparison of the Canonical Correspondence Analysis (CCA) combinations measured with the cumulative importance of the first two CCA's (CCA1 and CCA2), the cumulative importance also describes the data fit. Per crop nutrient content 6 different variable permutations are shown (SE: Soil Elements (14 variables); SP: Soil Properties (8 variables); Manag: management factors (5 variables)). Variable descriptions in Table A.10.

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 3.3). The CCA from Teso South features a main grain nutrient concentration cluster (with exceptions of grain Mg and P) (Figure 3.3-A). 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 (Figure 3.3-A). 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 concentration and yield were pH, soil N, species richness, soil Ca, and soil C (Table 3.4). Non-significant but still high ranking variables included species diversity, organic fertilizers and inorganic fertilizers (Table 3.4). 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 (Figure 3.3-B). 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) (Figure 3.3-B). As yield and the main nutrient cluster were situated on opposite sides of the CCA (Figure 3.3-B), 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 (Table A.13 and Table A.14). Matooke was marginally affected ($p = 0.073$) by inorganic fertilisers in soil elements + management (Table A.14). 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 concentration 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

Table 3.3: 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 A.9.

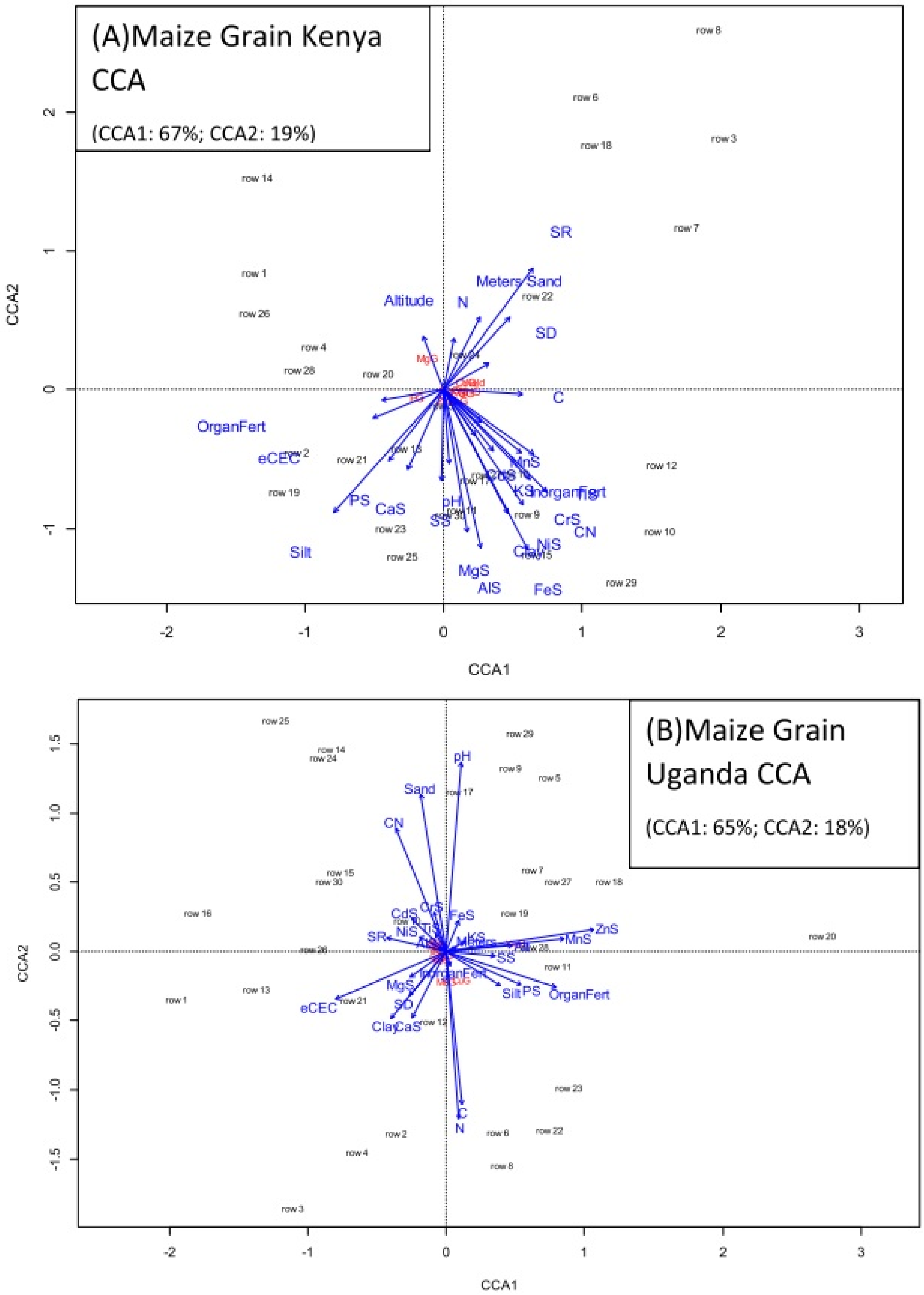

Figure 3.3: Figures A and B represent the Canonical Correspondence Analysis (CCA) biplot diagrams that show each crop (A) maize grain in Teso South, Kenya; (B) maize grain in Kapchorwa, Uganda. The plot shows the response variables in red (nutrient concentrations in food parts Mg, P, S, K, Ca, Fe, Mn, 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 3.4: 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 - Kapchora, 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 A.9.

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 (Figure 3.4-A), and was therefore shown as an explanatory variable in an additional CCA, where its vector is pointing away from the main nutrient cluster (Figure A.13). 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 fertilizer (both Type I and III), and in the permutation Crop + Soil Elements + Management Factors with altitude (both Type I and III) (Table A.13). Other rankings of cassava show repeated Type I and III significance of altitude, organic fertilizer, 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 nutrients 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) (Figure 3.4-B). Tuber S was above the main nutrient cluster and was not directly positively associated with any variable. Negative associations however included organic fertilizer and silt (not in the permutation rank test). Tuber P and Mn showed positive associations with organic fertilizer, 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 (Figure 3.4-B). Yield was positively associated with soil Fe and soil C (not in the permutation rank test).

3.4 Discussion

3.4.1 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

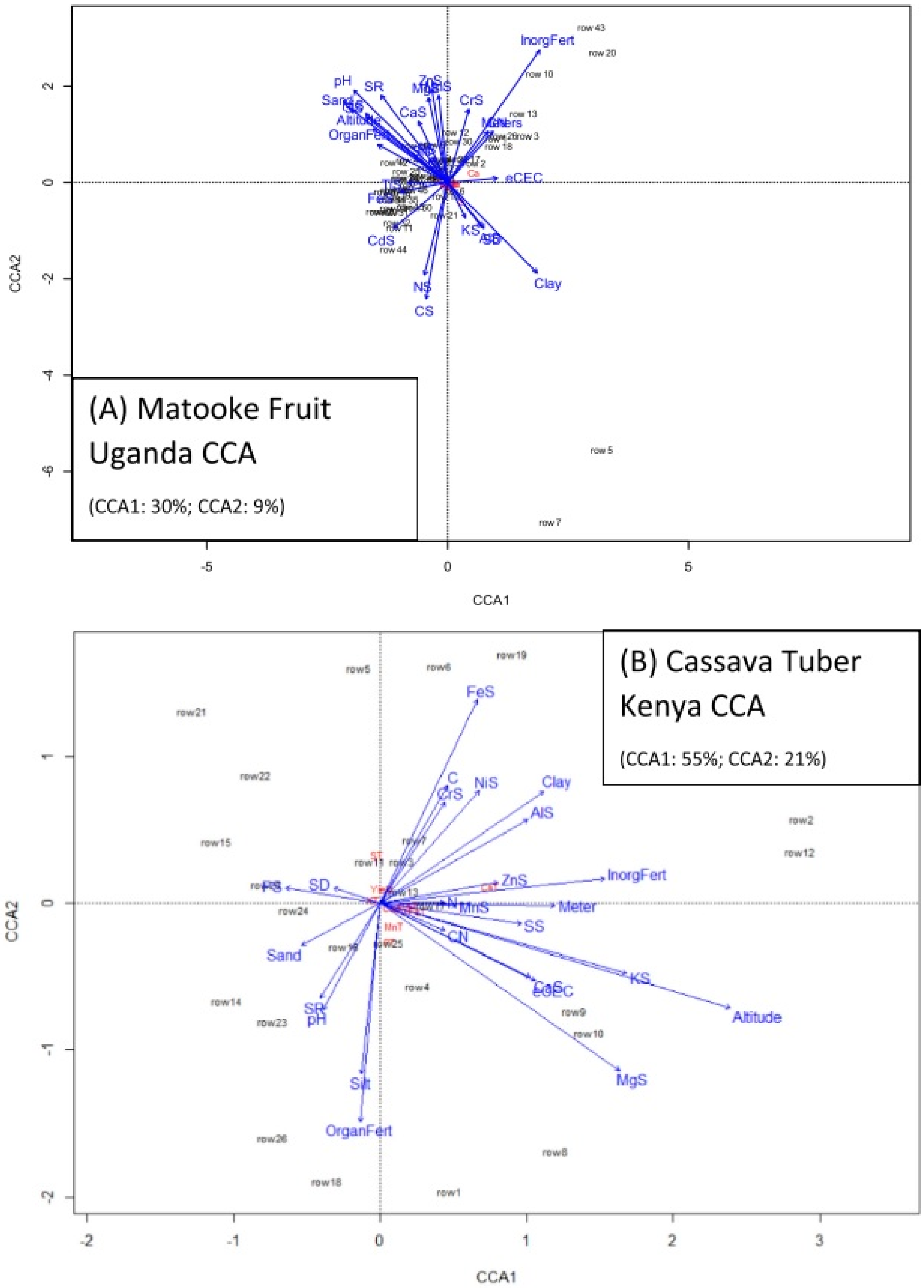

Figure 3.4: Figures A and B represent the Canonical Correspondence Analysis (CCA) biplot diagrams that show each crop (A) matooke fruit in Kapchorwa, Uganda; (B) Cassava tuber in Teso South, Kenya. The plot shows the response variables in red (nutrient concentrations in food parts Mg, P, S, K, Ca, Fe, 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.

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 fertilisers used in both areas. These findings are corroborated by other researchers who have identified large nutrient imbalances in agricultural fields across SSA (Cobo et al., 2010b).

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).

3.4.2 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 concentration 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 concentration 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 part consumed as food was important for the final nutrient concentration. 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 concentration in tubers. This could be due to cassava tubers being a storage part, instead of a generative part (e.g. grain and fruit) as the other plant parts in this study were. Generative parts are usually sink limited, whereas storage parts (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.

3.4.3 Environmental effects on food nutient concentrations

Permutation Rank Test

The main variables that significantly affected the CCA distribution differed between countries and crops. This meant that different crops grown in the same location, or on different 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. 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., 2016). Nutrient concentrations of maize in Kapchorwa (higher fertility), on the other hand, had a higher effect of pH, 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., 2016). 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 concentration.

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 amount of fertilizer use, as well as their low variability present in Teso South. The positive association of crop diversity with nutrient concentration 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 deficiency has been identified as an increasing worldwide problem, as there has been a sharp decline of Mg content 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 the yield, grain Mn, and grain Cu rather than the other nutrients. Yields of maize grain in Kapchorwa, unlike maize in Teso South, were not located near the main grain nutrient cluster, and were 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 its 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 Asten, 2010). The potential consequences on fruit nutrient concentration have however not been investigated so far. Fruit Ca and S were negatively correlated with the main matooke nutrient cluster. In 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 concentration 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 concentration (particularly with tuber P and inorganic fertilizer) 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 concentration and yield. This was surprising as similar studies had found significant decreasing level 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.

3.4.4 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 concentration 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.

3.4.5 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 the nutrient concentration 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 fertilisers. While fertilisers 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 fertilizer 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 parts would show results (positive or negative) to soil amendments relatively quickly, perennial generative and perennial storage food parts 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.

3.5 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 part type and life-span of the plant will affect the magnitude of direct environmental effects on food nutrient concentration. Generative annual food parts (grain) had higher correlations to environmental factors, than storage perennial (tubers) or generative perennial parts (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 fertilizer used in this area specifically rather than a conclusion on organic fertilisers 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, 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.

4 Missing association between nutrient concentrations in leaves and edible parts of food crops – a neglected food security issue

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Abstract

Crop nutrient deficiencies are determined based on leaf nutrient composition, and rarely on food composition. Consequently, it remains unclear whether leaf nutrients are useable to form conclusions on quality of produced foods. This study aimed to investigate the relationships between plant macro- (Mg, P, S, K, Ca) and micronutrient (Fe, Zn, Mn, Cu) concentrations of leaves and edible parts of typical East African staple crops: *Zea mays, Manihot esculenta*, and *Musa acuminata*. Low phloem mobility nutrients Ca, Mn, Fe, Zn, and Cu showed the largest differences in correlations between leaves and edible parts. Perennial crops showed lower correlations between nutrient concentrations of leaves and edible parts than annuals. Leaves may provide information on plant health, however do not provide enough information to gauge both yields and food quality, particularly regarding micronutrients. Therefore, agricultural and nutritional scientists should harmonize methods to develop sustainable management options for increased food and nutrition security.

4.1 Introduction

The second goal "Zero Hunger" of the Sustainable Development Goals (SDG) combines sustainable agricultural food production with ending hunger and all forms of malnutrition by 2030 (SDG, 2019). In this goal, the aims of agriculture and nutrition lead into each other, as agronomists aim to produce high quantity and quality foods, whereas nutritionists aim to secure and provide safe and healthy foods to meet the nutritional needs of the population. The goal to link agricultural food production and nutrition is important as plant-based foods in particular are one of the main sources of vitamins, minerals, and bioactive compounds for humans, and are vital for their development and health.

Hidden hunger (micronutrient deficiencies) globally affects two billion people (Von Grebmer et al., 2014) and are widespread in lower and middle-income countries (The Global Nutrition Report, 2018). The most prevalent trace elemental human deficiencies occur as Fe and Zn deficiencies. Anaemia levels in Africa are estimated at 39% for women and 59% for children $<$5 years (WHO, 2017), often caused by nutritional deficiencies, in particular iron deficiency. Zinc deficiency is globally estimated to affect around two billion people (Kabata-Pendias and Szteke, 2015). Simultaneously, agriculture is facing a similar problem of increasing crop nutrient deficiencies, particularly micronutrients. While Zn was found to be deficient in about 50% of the world's soils, Mn and Cu were each found to be deficient in 10-15% of soils (Knez and Graham, 2013).

Agriculture extracts nutrients from the soil as harvestable materials (yields). If extracted nutrients from crop uptake are not replaced, or the levels of factors influencing their availability (i.e. pH or organic matter levels) are not maintained, soil fertility declines and soils become degraded. Soil degradation is a severe problem, both for quantity and quality of foods, as soils of differing fertilities produce foods with significant differences in nutritional quality and yield (Fischer et al., 2019). Soil degradation can, therefore, cause crop nutrient deficiencies, which, can also have an impact on human health.

Crop nutrient deficiencies are defined differently depending on the discipline involved - agricultural or nutritional sciences. Agronomists measure soil fertility (factors affecting nutrient phyto-availability), and leaf nutrient concentrations to gauge plants' response to soil and fertilizers. Leaf nutrient concentrations are compared to a series of critical plant nutritional values (categorized into deficient, critical, adequate, and toxic levels). Nutrient deficiencies occur when the selected nutrient in the leaf tissue is low enough to elicit a negative yield response (Fageria et al., 2011). Monitoring leaves allows a nutrient deficiency correction (e.g.

through fertilisation) to avoid potential yield losses, however it leaves out the edible part. In contrast, nutritionists measure the nutrient concentration of the edible part of the crop (raw and/or cooked). The food nutrient concentrations are then compared to average nutrient concentrations in food composition tables (Elmadfa and Meyer, 2010), however disregarding the environment in which, the crop was cultivated.

We investigate whether a crop with a deficient leaf nutrient concentration produces food with the same deficiency. Differences in nutrient concentrations between the two crop parts could be due to varying nutrient mobility within the crop. Xylem and phloem are parts of the plants vascular system, moving nutrients within the crop. While the xylem moves nutrients taken up by the roots upwards through the crop (mass flow – pulled by leaf transpiration), the phloem transports leaf assimilates throughout the plant (source to sink) (Etienne et al., 2018). During vegetative plant growth, most nutrients are moved to the developing leaves to ensure assimilate production for the crop. During the reproductive stage (fruit development), nutrients are remobilised from the leaves and the shoot into the developing reproductive part. This process occurs mainly via the phloem, as the xylem is limited to its strict upward motion. While many nutrients (Mg, P, K, and S) are phloem mobile, micronutrients (Fe, Zn, and Cu) and particularly Mn and Ca have a much lower mobility (Etienne et al., 2018, Maillard et al., 2015). Therefore, many nutrients that are present in the edible part may not originate from remobilisation but from other sources, for example from the soil (Bender et al., 2013). This would, however, imply that particularly micronutrients and Ca concentrations of a reproductive part have no direct relationship with the same nutrient concentrations of a leaf. Additionally, lack of nutrient remobilisation may vary among crops (annual or perennial) and crop (grain, tuber, or fruit) types, due to structural and functional differences, as well as due to different soil types of varying fertility levels.

The main aim of this paper is to analyse to what extent leaf nutrient concentrations of Mg, P, S, K, Ca, Fe, Cu, Mn, and Zn are correlated with corresponding nutrient concentration of the edible parts of maize (*Zea mays* L.), cassava (*Manihot esculenta* Crantz), and matooke (East African Highland Banana - *Musa acuminata* Colla). It is expected that since leaves and edible parts are often different plant parts with different functions, the nutrient concentrations of different elements will not be correlated. Specifically, the research questions are: (i) Do nutrient concentrations in leaves and edible parts correlate, and do the correlations relate to nutrient mobility? (ii) Do the nutrient concentrations in leaves and edible parts show the same correlations to yield? (iii) Do the correlations between nutrient concentrations in different plant organs (leaves and edible part) and yield differ on different soil types? (iv) Do the correlations between nutrient concentrations in different plant organs (leaves and edible parts) differ between annual and perennial crops, or between storage and generative crop organs?

4.2 Methods

4.2.1 Study Sites

Teso South, Kenya

Teso South, Kenya (0.4592722°, 34.10924°; 0.6357222°, 34.27789° (Figure 3.1)) in Busia county extends 330 km^2. It ranges from 1200-1400 m a.s.l. and has an average rainfall range of 1420-2000 mm/year, split into two rainy seasons from March-May and September-November (Jaetzold et al., 2009). The soils are orthic Acrisols and orthic Ferralsols, derived from basement rock with moderate depth and low fertility (Jaetzold et al., 2009).

Kapchorwa, Uganda

The research area in Kapchorwa, Uganda (1.359817°, 34.45045°; 1.450219°, 34.44643° (Figure 3.1)) covers a surface area of 297 km^2 with an altitude of 1000-3000 m a.s.l. on Mt. Elgon. Average rainfall ranges from 1200-2200 mm/year, depending on altitude, and split into two rainy seasons from March-May and September-November (De Bauw et al., 2016). Mt. Elgon is the largest and oldest extinct shield volcano of the Pliocene in the Great Rift Valley (Knapen et al., 2006). The soils are mainly nutrient-rich Nitisols, derived from basaltic volcanic ash (Mugagga et al., 2012).

4.2.2 Data Collection

This study was part of the "Crops for Healthy Diets – Linking Agriculture and Nutrition" (HealthyLAND) project, and followed the project's household sampling design "Probability Proportional to Size (PPS)" based on Kish (1995), detailed in Fischer et al. (2019). The final sample size used in this study was 72 households per research area. Corresponding crop samples were collected during July-August 2016.

The two research areas were selected for their opposing soil types (Kapchorwa with a higher, and Teso South with a lower soil fertility), as well as for their low fertilizer use, thereby giving the possibility of detecting direct connections between soils, leaves and edible parts. Three fields were sampled per household, i.e. the closest field to the household, the mid-

Table 4.1: Number of samples collected in Teso South, Kenya and Kapchorwa, Uganda in July-August 2016. The ear leaf from maize was collected during silking. From cassava and matooke the youngest most developed leaf was sampled. Edible parts were collected when ripe and ready to consume.

Country	Plant parts	Sample number
Teso South, Kenya	Maize leaves	65
	Maize grain	30
	Cassava leaves	30
	Cassava tubers	26
Kapchorwa, Uganda	Maize leaves	25
	Maize grain	30
	Matooke leaves	53
	Matooke fruits	52

distance field, and the farthest field. Distance to the household is part of the model as it was part of the sample collection criteria to capture whether there is a significant fertility gradient (Tittonell et al., 2016). Four soil samples were taken (topsoil at 0-20 cm) per field and mixed to form a composite sample. The chemical and physical properties measured were pH in KCl (Lewandowski et al., 1997), texture (clay (<0.002 mm), silt (0.002-0.05 mm) and sand (0.05-2.0 mm)), effective Cation Exchange Capacity (eCEC), both based on Pansu and Gautheyrou (2006), and total Nitrogen (N) and Carbon (C) content using a Vario MAX CN-Analyser (Elementar Analysesysteme GmbH, Hanau, Germany). Total elemental concentrations of Mg, P, S, K, Ca, Fe, Zn, Mn, and Cu were measured in all samples (plants and soil) using a portable X-Ray Fluorescence Spectrometer (Tracer 5i pXRF – Bruker Elemental, Kennewick, WA, USA). Further details on measurements, devices and methods are found in Fischer et al. (2019).

Three crop samples were taken per field on three sampled fields per farm from randomly selected plants. In Teso South maize leaves and grains were collected, and cassava leaves and tubers were collected. In Kapchorwa, maize leaves and grains, and matooke leaves and fruits were collected (Table 4.1). Maize grains were collected when ripe, and maize ear leaves were sampled during the silking stage, as the growing conditions around the silking stage of maize is one of the most critical factors influencing yield (Kovács and Vyn, 2017). The youngest fully developed cassava and matooke leaves were collected from plants during their vegetative growth periods, as in the reproductive stage nutrient levels can change due to remobilisation (Reuters and Robinson, 1997). Yields per field and crop were also recorded and converted into tons per hectare (t/ha).

4.2.3 Statistical Analysis

The elemental values measured with the pXRF were left-censored, meaning lower values were below the level of detection of the equipment. A maximum likelihood method by Piepho et al. (2002) was used to estimate the censored values, for variables that had <80% censored data. The method is explained in Fischer et al. (2019).

Descriptive Analysis

Leaf nutrient compositions were compared to critical values from literature. For maize three sources were found (Fageria et al., 2011; Marschner, 2012;Reuters and Robinson, 1997). The sources were grouped and the highest and lowest adequacy value were used for the analysis (Table A.21). For cassava and matooke only one source was used for comparable critical values (Reuters and Robinson, 1997), as the other sources found cited this reference. The critical levels of different nutrients for maize, matooke and cassava were available for a number of different geographic locations. For the comparisons with the measured values, the average nutrient adequacy range across all geographic regions available was calculated for each nutrient. The nutrient concentrations of edible plant parts were compared to food composition tables in Fischer et al. (2020) (Table 4.2).

Maize leaf and grain nutrients (Table 4.2), as well as soil values (Table 3.2), were compared between research areas using "surveyreg" for sample survey data in SAS University Edition 2018 (see code in supplementary materials), using the weights from the PPS sampling.

Nutrient concentration correlations

Matching cassava leaves and tubers, as well as matooke leaves and fruits were collected on the same field during the sampling campaign. However, due to the sampling at one point in time maize, leaves and grain were not collected on the same fields. The sampling method (randomly selecting households from the PPS), however, allows for the coverage of soil chemical and physical properties and farm management (i.e. fertilisation) variable variance (Fischer et al., 2020) (Table 3.2).

To compare the nutrient concentrations between leaves and yields, edible parts and yields, and leaves and edible parts per region, a bivariate linear mixed model with Residual Maximum Likelihood (REML) was used, following the methods described in Piepho (2018). The bivariate mixed model was an extension of two separate univariate models (Eq.1; y_1 and y_2), describing the effect of all relevant factors on each response variable (Equation 1).

$$y_1 = m_1 + v_1 + vh_1 + e_1 \tag{4.1}$$

$$y_2 = m_2 + v_2 + vh_2 + e_2 \tag{4.2}$$

Where

y	response variable
m	mean
v	village
vh	village*household
e	error

The univariate models described the mean, the traits (y_1 and y_2), the distance, the nested field selection for sample collection, and the error term (Equation 1). The errors were assumed to have zero mean and trait-specific variance. The two univariate models were extended to fit a bivariate analysis with correlation for each type of effect, by assuming each effect was random. The marginal variance and the covariance of the response variables were, therefore, defined by the sums of variance and covariance of the corresponding effects (Equation 2):

$$\sigma_{y(1,2)} = cov(y_1, y_2) = \sigma_{v(1,2)} + \sigma_{vh(1,2)} + \sigma_{e(1,2)} \tag{4.3}$$

The marginal (total) correlation is defined as (Equation 3):

$$corr(y_1, y_2) = \rho_{y(1,2)} = \sigma_{y(1,2)}/\sigma_{y(1)} * \sigma_{y(2)} \tag{4.4}$$

Where the variance is:

$$\sigma^2_{y(1)} = var(y_1) = \sigma^2_{v(1)} + \sigma^2_{vh(1)} + \sigma^2_{e(1)} \tag{4.5}$$

$$\sigma^2_{y(2)} = var(y_2) = \sigma^2_{v(2)} + \sigma^2_{vh(2)} + \sigma^2_{e(2)} \tag{4.6}$$

And

$$\sigma_{y(1,2)} = cov(y_1, y_2), \sigma^2_{y(1)} = var(y_1), and \sigma^2_{y(2)} = var(y_2) \tag{4.7}$$

Using REML has the advantage of being able to work with missing data, as well as providing efficient estimates for variance components. Since maize grains and leaves could not be collected on the same fields, correlations were estimated for leaf nutrient concentrations and yield and grain nutrient concentrations and yield. Nutrient concentrations of matooke and cassava leaves and edible parts were collected on the same fields, and therefore correlations were estimated between all dataset pairs.

The best fit model per pairing was selected using the lowest Akaike-Information-Criterion (AIC) and Bayesian-Information-Criterion (BIC) (Table A.17). The marginal correlations were denoted with $\rho_{y(1,2)}$ (Piepho, 2018). Comparisons between sample correlations (r) and marginal correlations showed similar values (Table A.18-A.20). The statistical analysis was done using SAS University Edition 2018 (All SAS codes in the supplementary materials). Correlations were discussed if $\rho_{y(1,2)}$ was above 0.20 or below -0.20.

4.3 Results

4.3.1 Descriptive Analysis

Grain in both regions showed higher nutrient concentrations for P, Fe, Cu and Zn than in leaves, while leaves showed higher concentrations for S, Ca, Mn, K, and Mg compared to grain (Table 4.2). Cassava leaves showed a higher nutrient concentration for all nutrients compared to tubers, with the exception of Fe and Cu which were very similar in both parts (Table 4.2). Matooke leaf nutrient concentrations were higher for most nutrients with the exceptions of Cu and Zn where fruits showed a higher nutrient concentration than leaves (Table 4.2).

Both Teso South and Kapchorwa showed lower maize leaf nutrient concentrations than the proposed adequate nutrient levels for Mg, P, S, Zn and Cu (Table 4.2). Cassava leaves showed deficient values for Mg, P, S, Fe, and Cu when compared to critical reference values. K, Ca, Zn and Mn are all within nutrient adequacy levels. Matooke leaves Mg, P, Ca, Fe and Mn were within their adequate level, whereas S, K, Cu, and Zn were deficient Table 4.2.

Table 4.2: Comparison between the nutrient concentrations means (± standard deviation) in leaves and edible parts of maize (*Zea mays* L.) collected in Teso South, Kenya (maize grain n=30, maize leaves n=65), and Kapchorwa, Uganda (maize grain n=31, maize leaves n=25), cassava (*Manihot esculenta* Crantz) collected in Teso South, Kenya (cassava tuber n= 27, cassava leaves n=30), and matooke (*Musa acuminata* Colla) collected in Kapchorwa, Uganda (matooke fruit n= 52, matooke leaves n=53). The nutrient concentrations of the edible parts are compared to the food composition tables of the USDA (maize code: 20314, cassava code: 11134, matooke code: 5001 – available at https://ndb.nal.usda.gov/ndb/) and from the Kenyan Food Composition Table of the FAO (Kenya) (maize code: 01018, cassava code: 02007 available at: http://www.fao.org/3/I8897EN/i8897en.pdf) and have been adapted from Fischer et al. (2020). The adequate range of nutrients for cassava, and banana leaves (as a substitute for matooke) were taken from Reuters and Robinson (1997). For maize the lowest and highest leaf nutrient adequacy level was taken from Reuters and Robinson (1997), Fageria et al. (2011), and Marschner (2012).

	MAIZE						CASSAVA				MATOOKE			
	Databases		Kapchorwa, Uganda		Teso South, Kenya		Databases		Teso South, Kenya		Databases		Kapchorwa, Uganda	
	Grain mean nutrient concentration (mg/kg)	Leaf adequate range (mg/kg)	Grain	Leaf	Grain	Leaf	Tuber mean nutrient concentration (mg/kg)	Leaf adequate range (mg/kg)	Tuber	Leaf	Fruit mean nutrient concentration (mg/kg)	Leaf adequate range (mg/kg)	Fruit	Leaf
Mg	USDA: 1279 Kenya: 750	1500-3500	1071.38* ± 522	1422* ± 230	861 ± 404	1291 ± 499	USDA: 210 Kenya: 130	2500-5000	362 ± 115	1994 ± 404	USDA: N.A.	2000 - 4600	1017 ± 336	2715 ± 493
P	USDA: 2100 Kenya: 3670	2200-4000	3482.53* ± 714	1983*** ± 96.2	2967 ± 1290	1684 ± 645	USDA: 270 Kenya: 210	3600-5000	862 ± 289	2433 ± 565	USDA: N.A.	2000-2500	1510 ± 329	2373 ± 240
S	USDA: N.A. Kenya: N.A.	1000-2400	1030.9* ± 419	1327*** ± 160	861 ± 136	1029 ± 222	USDA: N.A. Kenya: N.A.	3000-4000	106 ± 81.9	2627 ± 545	USDA: N.A.	2300-2700	462 ± 385	2138 ± 170
K	USDA: 2870 Kenya: 2260	13700-50000	8152.42** ± 7540	16307* ± 2611	4990 ± 1120	15767 ± 3916	USDA: 2710 Kenya: 2500	12000-20000	8370 ± 2640	13726 ± 3228	USDA: N.A.	30000-40000	24499 ± 3254	28989 ± 2181
Ca	USDA: 70 Kenya: 240	2100-5000	242.09** ± 329	4018 ± 442	46.2 ± 13.6	4373** ± 1263	USDA: 160 Kenya: 330	6000-15000	327 ± 214	8614 ± 2618	USDA: N.A.	8000-12000	433 ± 369	8375 ± 1125
Fe	USDA: 27 Kenya: 26	21-251	122.58*** ± 141	83.6 ± 76.3	36.4 ± 14.3	106*** ± 33.5	USDA: 27 Kenya: 9	60-200	52.2 ± 13.7	51 ± 41	USDA: 160	70-200	89.3 ± 61.1	104 ± 86
Cu	USDA: N.A. Kenya: N.A.	6-20	55.23*** ± 66.8	4.34 ± 0.98	3.47 ± 0.41	4.4 ± 1.63	USDA: N.A. Kenya: N.A.	7-15	3.23 ± 0.53	4.9 ± 1.21	USDA: N.A.	7-20	20.9 ± 9.9	5.22 ± 1.01
Zn	USDA: 22 Kenya: 18	20-70	49.33*** ± 26.7	18.1** ± 2.77	31.9 ± 7.96	15.9 ± 10.3	USDA: 3.4 Kenya: 3.4	40-100	9.4 ± 2.85	51 ± 16	USDA: 20	21-35	36.2 ± 28.2	5.97 ± 1.56
Mn	USDA: N.A. Kenya: N.A.	20-150	16.32*** ± 16.5	72.7 ± 9.15	3.44 ± 1.28	106*** ± 33.5	USDA: N.A. Kenya: N.A.	50-250	7.86 ± 2.41	247 ± 85	USDA: N.A.	100-2200	20.1 ± 12.3	623.02 ± 145.2

Asterisks (*) define level of significance, categorized into $p < 0.05$*; $p < 0.005$**; $p < 0.0005$***. N.A. stands for Not Available.

Maize leaf nutrient concentrations of Mg, P, S, K, and Zn were significantly higher in Kapchorwa than in Teso South (Table 4.2). In contrast, Ca and Mn concentrations were significantly higher in Teso South than in Kapchorwa, while Fe was not significantly different between regions (Table 4.2).

4.3.2 Correlation Analysis

In Kapchorwa, leaf nutrients negatively ($\rho_{y(1,2)} \geq$ 0.20) correlated with yield were K, Fe, and Mn, while Ca and Zn were strongly positively correlated with yield (Table 4.3). Grain P was negatively correlated with yield ($\rho_{y(1,2)}$ -0.39) while grain Cu ($\rho_{y(1,2)}$ 0.21) was positively correlated with yield (Table 4.3).

Table 4.3: Correlation coefficients for (i) maize leaf nutrient concentrations (NC) correlated with grain yield, and (ii) maize grain nutrient concentrations (NC) correlated with yield, from farmers' fields in Kapchorwa, Uganda and Teso South, Kenya. Values -0.20$\leq \rho_{y(1,2)} \geq$ 0.20 are in bold.

	Kapchorwa, Uganda		Teso South, Kenya	
Nutrients	Leaf-NC vs. Yield	Grain-NC vs. Yield	Leaf-NC vs. Yield	Grain-NC vs. Yield
Mg	-0.01	-0.11	0.08	0.02
P	0.09	**-0.39**	0.04	**-0.53**
K	**-0.42**	0.05	0.15	**-0.33**
S	0.01	0.02	**0.23**	**-0.43**
Ca	**0.49**	0.09	0.19	**-0.30**
Fe	**-0.41**	0.13	0.07	**-0.59**
Zn	**0.20**	0.16	-0.02	**-0.51**
Mn	**-0.21**	0.15	-0.13	**-0.71**
Cu	0.03	**0.21**	-0.14	**0.41**

Restricted maximum likelihood (REML) estimation models with the resulting marginal correlations $\rho_{y(1,2)}$, including the treatment effects (village, household and field selection). Model selection in Table A.17.

In Teso South, only leaf S was stongly positively correlated with yield $\rho_{y(1,2)}$(Table 4.3). Grain nutrient concentrations in Teso South were all negatively correlated with yields with the exception of Cu. The strongest negative correlation was with Mn, and the smallest with Mg.

Cassava leaf nutrient concentrations showed stronger correlations with yield than tuber nutrient concentrations in Teso South (Table 4.4). Cassava leaf nutrient concentration correlations with yield ranged from $\rho_{y(1,2)}$ -0.39 to -0.65 for the negative correlations (Mg, S, Ca, Fe, and Zn) and $\rho_{y(1,2)}$ 0.22 to 0.42 for the positive correlations with K and Cu. Tuber

Table 4.4: Correlation coefficients for (i) cassava and matooke leaf nutrient concentrations (NC) correlated with yield, and (ii) cassava tuber and matooke fruit nutrient concentrations (NC) correlated with yield, from farmers' fields in Kapchorwa, Uganda (matooke) and Teso South, Kenya (cassava). Values -0.20≤ $\rho_{y(1,2)} \geq$ 0.20 are in bold.

	Teso South, Kenya		Kapchorwa, Uganda	
Nutrients	Cassava leaves - NC	Cassava tubers - NC	Matooke leaves - NC	Matooke fruits -NC
Mg	**-0.39**	-0.03	**-0.36**	**-0.22**
P	-0.11	-0.15	0.04	0.10
K	**0.22**	-0.15	0.02	**-0.33**
S	**-0.65**	0.17	-0.01	**-0.27**
Ca	**-0.55**	-0.03	0.10	-0.02
Fe	**-0.47**	**-0.23**	0.14	-0.04
Zn	**-0.55**	-0.06	-0.02	0.12
Mn	0.12	0.07	0.18	0.01
Cu	**0.42**	**0.22**	**-0.20**	0.05

Restricted maximum likelihood (REML) estimation models with the resulting marginal correlations $\rho_{y(1,2)}$, including the treatment effects (village, household and field selection). Model selection in Table A.17.

nutrient concentrations only showed two correlations above the cut-off (≤-0.2 or ≥0.2) i.e. Fe with $\rho_{y(1,2)}$ -0.23 and Cu with $\rho_{y(1,2)}$ 0.22 (Table 4.4).

Matooke leaf and fruit nutrient concentrations showed very few strong correlations to yield. Only leaf Fe showed a positive correlation to yield with $\rho_{y(1,2)}$ 0.21, while fruit Mg, K, and S showed negative correlations (Table 4.4).

Most leaf and cassava tuber nutrients were positively correlated, besides the exception of Mn $\rho_{y(1,2)}$ -0.47) (Figure 4.1). P, K, and S showed the strongest correlations between $\rho_{y(1,2)}$ 0.51 to 0.75 (Figure 4.1). In general, macronutrients (with the exceptions of Mg and Ca) had a stronger correlation than micronutrients (Figure 4.1).

Most leaf and fruit nutrients of matooke from Kapchorwa, Uganda, were positively correlated, although the correlations remained mostly weak. The highest correlations were with Mg $\rho_{y(1,2)}$ -0.25) and P $\rho_{y(1,2)}$ 0.34) (Figure 4.2).

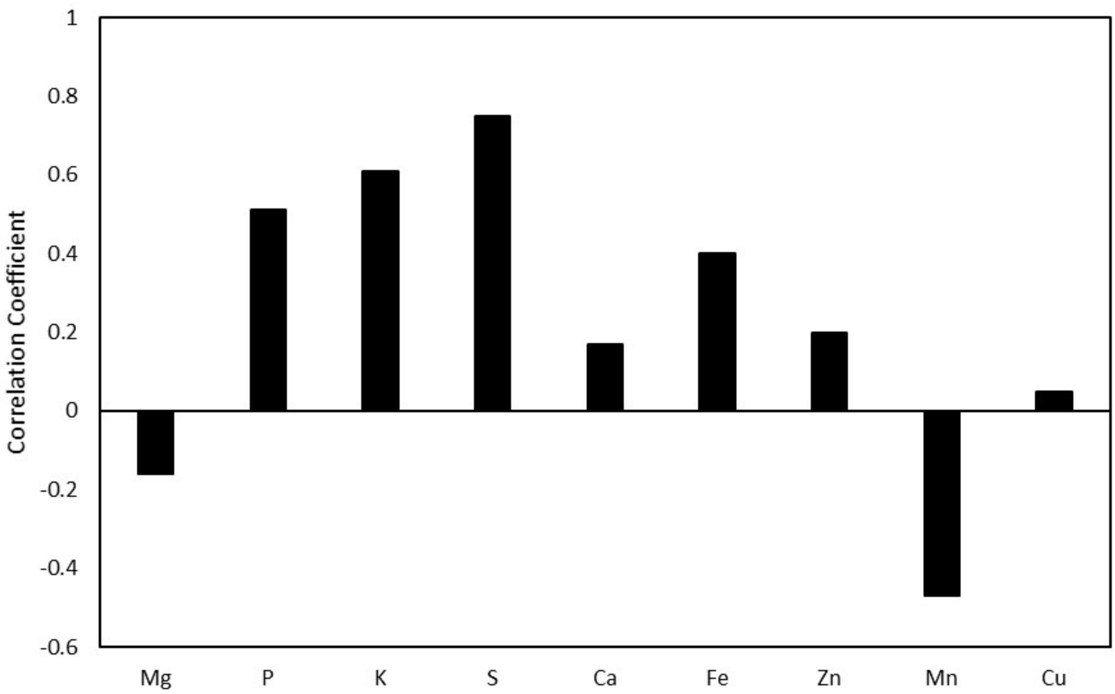

Figure 4.1: Correlation coefficients for relationship between cassava leaves and tubers nutrient concentrations, from farmers' fields in Teso South, Kenya. Restricted maximum likelihood (REML) estimation models, including the treatment effects (village, household and field selection). Model selection in Table A.17. Values discussed were above and below the cut-offs -0.20$\leq \rho_{y(1,2)} \geq$ 0.20.

4.4 Discussion

4.4.1 Are nutrient concentrations in edible parts related to phloem nutrient mobility?

Nutrient mobility in the plant is of key importance for the nutrient distribution between leaves and edible parts. While for example, Kapchorwan maize leaf Ca, Fe, Mn, and Zn were strongly correlated to yield, the same grain elements showed extremely weak correlations. Due most likely to their transportation differences as Ca, Fe, Mn, and Zn have a low phloem mobility (particularly Ca and Mn) and their remobilisation from leaf to grain is therefore very limited (Etienne et al., 2018; Maillard et al., 2015). Consequently, it is more probable that phloem immobile nutrients mainly originate directly from the soil rather than being remobilised from other plant parts (Bender et al., 2013). Such nutrient transport specificity of different nutrients have not only been observed in maize but also in peas (*Pisum sativum* L.) (Sankaran and Grusak, 2014) and matooke (Moreira and Fageria, 2009).

Differences in nutrient transportation modes could also be observed in cassava. Leaf

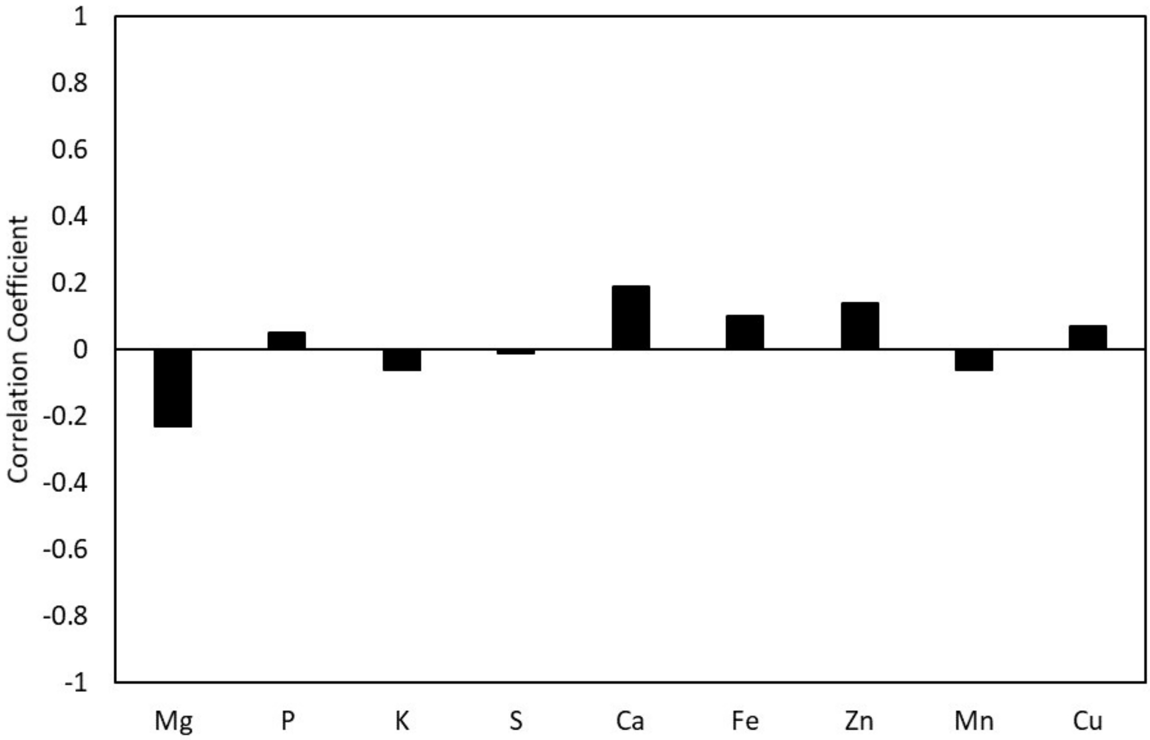

Figure 4.2: Correlation Coefficients for relationship between matooke leaves and fruit nutrient concentrations, from farmers' fields in Kapchorwa, Uganda. Restricted maximum likelihood (REML) estimation models, including the treatment effects (village, household and field selection). Model selection in Table A.17. Values discussed were above and below the cut-oofs -0.20$\leq \rho_{y(1,2)} \geq$ 0.20.

nutrients had a stronger correlation to yield than tuber nutrients. Leaf Ca, Fe, and Zn all showed negative correlations to yield and low correlations to tuber Ca, Fe, and Zn concentrations. This was most likely due to the phloem immobility causing a lack of nutrient remobilisation among crop parts (Etienne et al., 2018). As the cassava tuber is the storage organ of the crop, and is vital for plant survival, more research on the storage and subsequent transport of particularly micronutrients into and out of the tuber would be vital to understand its importance for micronutrient homeostasis in the plant. Additionally, cassava is an important food crop, and understanding when nutrients are highest in the tuber could benefit the consumers, considering the flexibility in timing of its harvest.

In matooke, only very few correlations could be identified between nutrient concentrations of either leaf or fruit with yield, as well as between leaves and fruits, making it impossible to form conclusions on nutrient remobilisation between both parts. Leaf and fruit Mg were both negatively correlated with yield. This may be due to a low amount of Mg totally available, or due to an antagonistic effect with K, leading to a competitive uptake (Laekemariam et al., 2018). Fruit K had a negative correlation to yield, and to leaf K. The difference of fruit K to yield could be explained by K (and water) being described as the driver of bunch yield, as K plays a large part in translocating assimilates into the developing fruits (Taulya, 2013). Therefore, K presence in fruits may have had a higher importance to yield than leaf K, and hence the correlation of yield with fruit was more affected by K deficiency.

The lack of expected correlations found between matooke leaves, fruits and yields could discount the value of leaf measurements for nutrient concentration corrections using fertilisers, as these are unlikely to affect fruit nutrient concentrations, and therefore points to an increased research need, particularly for perennial crops (Srivastava and Malhotra, 2017). Fischer et al. (2020) in fact showed that environmental factors and farm management, including fertilisation, had little effect on matooke fruit nutrient concentrations. The lack of connection and effect of some nutrients not being transported well in the phloem, was shown for Zn in banana by Moreira and Fageria, 2009, who found a very low to no connection of Zn concentrations in fruits and leaves.

4.4.2 The importance of timing during nutrient uptake

Timing of nutrient uptake can be very important for the nutrient concentrations within the edible part compared to the nutrient concentrations in the leaf, in light of the nutrient transport specificity. As outlined in 4.1, it is unlikely that the bulk of the phloem immobile nutrients (i.e. Fe, Mn, Cu, Zn, Ca, and Mn) in the edible parts originated from plant sources such as leaves or stems. Therefore particularly the nutrients that are xylem mobile, must have been taken up directly from the soil. Since leaf measurements are usually done before the reproductive period of the plant begins, and the edible part at the end of the reproductive period (Reuters and Robinson, 1997), there is a difference in time between the uptake and subsequent measurement of leaf nutrients and the uptake and measurement of nutrients of the edible part. The importance of time for general nutrient uptake patterns is not new, i.e. there is the concept of critical nutrient uptake stages for many crops (Barron et al., 2003). Differences in temporal patterns of nutrient uptake for nitrogen for example have also been used to improve fertilizer efficiency (Meng et al., 2016). The importance of timing for plant nutrition can also be seen in their variance in leaf tissue at different moments in time, in different crop species (Fageria et al., 2011; Gaspar et al., 2018; Palmer et al., 2014). The importance of timing for the nutrient concentrations in edible crop parts (particularly considering environmental changes during the season, effects of ripening, pre-mature harvesting, or considering edible parts that are not generative (i.e. tubers)) has however not been researched as thoroughly.

In maize from Kapchorwa, the different correlations to yield can also be explained by different uptake stages, affected by demand differences during crop developmental stages. Bender et al., 2013) observed in maize that nutrient uptake was different for every nutrient and associated to different maturity stages of the crop. They suggested that P, S, Zn, and Cu should be present season long in the soil for uptake, whereas K, Mn, Mg, and Fe are mainly taken up during vegetative growth. However, since K, Mn, and Fe were three of the nutrients mainly taken up during vegetative growth and showed the greatest difference in results between correlations of leaves and grain and yields, the assumption by Bender et al. (2013) may not be fully correct. Neither Mn nor Fe are very phloem mobile, and a fertiliser trial with K (K input increased leaf K but not grain K in the trial by Yuhui et al. (2019)) showed a difference in uptake between leaves and grain. Therefore, there must be either a constant, or a second, nutrient uptake period for K, Fe, and Mn during the reproductive period. The temporal difference between different critical uptake stages could also include a change in environmental or management factors (cessation of rain, pest occurrence, fertilisation addition etc.), affecting nutrient phytoavailability. This could be the cause of the difference of correlations seen in P, where grain P is negatively correlated with yield, whereas leaf P does not show a correlation with yield. P has been described as a nutrient that should be available all season long (Bender et al., 2013). The negative correlation may, therefore, stem from a disruption in uptake at a critical period.

The importance of timing could also be seen in the nutrient concentrations in maize in Teso South. Since the sampled maize grain and leaves were sown at different times, the discrepancies in correlations may also be explained by differences in abiotic conditions such as rainfall and temperature changes during the season and particularly during critical stages (Barron et al., 2003). However, the long rain season 2016 was considered to be normal (Fischer et al., 2019), and yield levels between grain and leaf sample fields did not show significant differences.

Perennial crops have longer life-cycles and must maintain normal plant function during the reproductive stage. This is at times beneficial, as in some perennial species nutrient uptake from the soil can be paused during growth and development stages and the resources of the plant itself used (Rennenberg and Schmidt, 2010). While this is favourable for the crop as it can survive small stretches of disadvantageous factors, it makes the identification of critical stages, potentially affecting different crop parts, difficult to identify (Srivastava and Malhotra, 2017).

4.4.3 Is there a difference between annual and perennial crops or generative and storage edible parts?

Whether crops are annual or perennial had an effect on nutrient distributions within the crops. This was expected as it had already been observed that the edible parts of perennial crops were less affected by soil properties than annual crops (Fischer et al., 2020). The reason could be that perennial crops maintain normal plant function during their reproductive period unlike annual crops. Perennial crops often also have a higher biomass, making them more nutrient efficient than annuals (Srivastava and Malhotra, 2017). The low correlation in perennial crops could be seen in the comparison of matooke and maize – both producing generative plant parts: a fruit and a grain, while maize showed high nutrient correlations to yield, matooke's correlations were very low.

Depending on the role or function of the plant part for plant survival, nutrient concentrations will fluctuate depending on the measurement timing and nature of the plant parts function (Srivastava and Malhotra, 2017). Generative (maize grain and matooke fruit) and storage parts (cassava tuber) have different functions. Whereas grain and fruits are sinks, tubers can be both sinks and sources depending on the requirements and health of the entire plant. In cassava for example, leaves are sources and assimilate secondary metabolites for the rest of the crop, whereas tubers are sinks, for nutrient (macro- and micronutrients, starches, and others) storage (Engels et al., 2011), and therefore depend on crop growth rates and soil nutrient availability (Howeler, 2002. More research is needed to understand nutrient homeostasis, regarding different food types classified by their functions within the plant, as well as considering different crop growth types.

4.4.4 Does soil fertility affect the nutrient distribution between different plant parts?

Nutrient distribution in maize, between different plant parts, is heavily affected by soil fertility. Poorer soils in Teso South, with a significantly lower eCEC, N and C content than in Kapchorwa (Fischer et al., 2020), led to reduced nutrient availability, and hence a significantly lower nutrient concentration was present in the edible parts. Almost all correlations between nutrients and yield in Teso South for both crop parts (with the exceptions of leaf S, Ca, Zn, and Cu) were negative. It is important to note that particularly the grain, seems to be more severely affected by the lower soil fertility in terms of correlations between nutrient concentrations and yields than the leaf. The differences observed could be due to a combination of lacking remobilisation (e.g. Ca in leaves were at the upper level of adequacy whereas in grains Ca was deficient) and lacking phytoavailability of nutrients throughout the crops life-span, particularly during high nutrient uptake stages that affected the edible part of the crop (Bender et al., 2013).

The nutrient uptake and distribution effect of a lower fertility soil could also be observed in cassava. The higher leaf nutrient concentrations and more positive correlations to yield of K, S, Mn and Cu, showed the better adaptation of cassava than maize to poor soil conditions including a lower pH (Howeler, 2002). There was, however, not much indication to support the report by Howeler (2002) that cassava can maintain a better yield than other crops in soils with low P availability, as both maize and cassava show negative correlations between P in leaf and tuber/grain to yield. This could be due to the low level of mycorrhization of cassava, with low levels of P fertilisation, in a soil with low P level, potentially making P one of the most limiting factors for cassava production (Aliyu et al., 2019) in Teso South.

4.4.5 Implications for agriculture and nutrition and recommendations

The widespread occurrence of hidden hunger in humans and the supposed decrease of nutrient concentration in foods (Guo et al., 2016) gives agriculture the responsibility to increase efforts to produce foods both in high quantity and quality. So far, fertilizer recommendations and other farm management methods (focus on soil health, agroecosystems, increased biodiversity, inter- and multicropping) have never directly targeted improvements to the nutrient concentrations of the edible part, but have simply inferred its improvement based on general crop health coupled with yields. Currently, no research could be found stating that an increased yield and healthy crop also leads to a high nutrient concentration in the edible part.

Fertilisation is propagated as the most direct method to correct crop nutrition deficiencies. To this day, foliar applications, are suggested to rectify many nutrient deficiencies in crops (Fageria et al., 2011). Foliar application was selected as the most efficient form of fertilisation (particularly of micronutrients – rarely for elements taken up in large amounts such as N), as it avoids the soil. In the case of crop mobile nutrients, e.g. foliar P, application has been found to be very effective for both enhancing leaf and grain P levels (Girma et al., 2007). However, due to the limited mobility of many micronutrients, foliar application would not benefit food nutrient concentration (White and Broadley, 2009). The low remobilisation of certain nutrients (particularly micronutrients and Ca), and their importance for human nutrition (Fe and Zn – severe worldwide deficiencies), fertiliser trials should be planned to maximize fertilizer efficiency while improving both quality and quantity of foods rather than only aim to increase yields.

Nutrient deficiencies, whether in humans, plants or soils, are never just singular nutrients, and usually show up as multiple deficiencies (Kihara et al., 2020). While it is important to understand the movement and behaviour of nutrients in organisms such as plants, as many uptake and distribution pathways (as we have seen here) are nutrient type specific, it is also important to consider solutions that impact all nutrients instead of just a few. Fertilisation is necessary to maintain production, however it would be advisable to mix chemical fertilizers with organic residues such as manures to also work on improving soil organic matter, to improve growing conditions and aim towards supplying all crops with a constant flow of nutrients throughout their growing period.

4.4.6 Using bivariate mixed models for correlation analysis

The statistical approach of this paper was to test the association of two variables, using a correlation analysis (Bewick et al., 2003). The choice of using REML was due to the presence of missing data. Missing data is a very common problem, particularly during field trials, and can be limiting, particularly due to a lack of further options for statistical analysis (Onofri et al., 2019). Estimating missing values using REML can, therefore, allow for more precise statistical analysis that otherwise missing data would not allow. Hence, it is important to develop, test, and use methods that allow for missing data, while providing robust results. Even so, using the marginal correlation does not prove causality (Bewick et al., 2003). In this paper, enough literature and process information is present on nutrient movements within the plant to compare and discuss the results without falsely implying causality.

4.5 Conclusion

The results of this research clearly demonstrate that nutrient concentrations in different plant organs have different correlations to yield, depending on (i) nutrient mobility and uptake timing; (ii) nutrient amount required for each crop part; (iii) annual or perennial growth type; and (iv) soil type. While phloem mobile nutrients (particularly P, S, and K) often exhibited higher correlations to yield and between plant parts, micronutrients and Ca were less associated with yield. Whether a crop was annual or perennial also influenced the correlations between nutrient concentration and yield as perennial crops maintained their normal function, whereas annual food crops remobilised phloem mobile nutrients from all crop parts available during grain filling, as well as continuously taking up nutrients from the soil. When considering generative edible parts, differences in conclusions on deficiencies in food parts or leaves could also occur due to sample collection timing. Measuring only leaves, would therefore, discount any changes in factors influencing nutrient's phytoavailability between vegetative and completed reproductive plant stages, therefore discounting any changes to plant nutrient uptake. This point is particularly relevant for phloem immobile nutrients, as they are usually not remobilised from other plant parts. Storage crop parts reacted showed different correlations to yields and to leaves from generative parts as they provide an added function to crop survival during stress periods. Low soil fertility led to stronger nutrient deficiencies in the edible part than in the leaves potentially leading to nutrient deficiencies in both crops and humans.

Measuring only leaves could lead to misinterpretations for edible part nutrient concentrations, as they do not show the same concentrations, edible parts are not often measured, and different nutrient amounts are required for human and plant nutrition. Public health relevant micronutrient could be particularly affected by this as they show the lowest correlations to leaf nutrient concentrations. Measuring only leaves could also lead to a propagation of management methods that either do not affect or negatively impact nutrient concentrations of the edible parts. Considering the global impact of malnutrition, agronomists and nutritionists should harmonize their methods to incorporate the implications and impact of environment and management factors on food and nutrition security.

5 General Discussion

The main research focus of this thesis was to understand environmental and farm management effects on the quantity and quality of the edible part of three important East African staple food crops. Due to global change encompassing a changing climate, an increasing human population, an increasing food demand, and a degrading soil, food production needs to adapt. The main challenge in this adaptation is to maintain yields, or better yet increase yields, while sustainably producing high quality foods. The preeminent problem faced by food production today is two-fold. On the one side, yields, and production, are threatened by an increased incidence of extreme weather events due to climate change and degrading soils. On the other side, an increasing human population has led to an increase in food demand, which in turn has resulted in an expansion of agricultural land, thereby producing foods on soils of varying fertility. The usage of fertilizers has increased to maintain production on soils of low fertility, which is also causing environmental pollution and depleting finite resources. Concurrently, efforts have been made to increase sustainable production by, for example, increasing agrobiodiversity. The current effects on food production from factors such as climate change, degrading soils, and soils of poor fertility have so far been mainly tested on yields – or quantity produced.

The main goal of this thesis was, therefore, to analyse the effects of environment and farm management on food nutrient concentrations (quality) as well as quantity, to understand whether there are any driving factors affecting both quantity and quality, and whether the effects of the variables are strong enough to potentially affect food and nutrition security. In this chapter, the effects of drought (Chapter 2), soil fertility and farm management (Chapter 2-3), and agronomic measurement methods (Chapter 4), on the produced quality and quantity of different foods will be critically discussed, as an integrated assessment of the results of chapters 2-4.

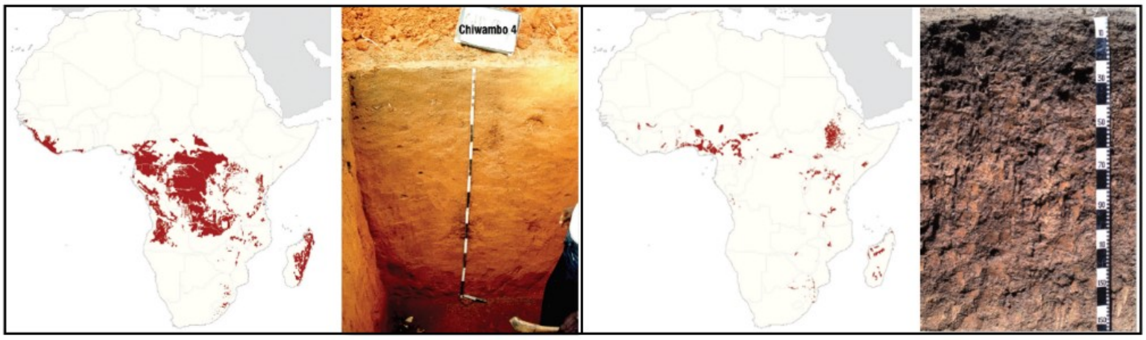

Figure 5.1: Distribution of (a) Ferralsols and (b) Nitisols in Sub-Saharan Africa. Ferralsols were the dominant soils in the research area in Teso South, Kenya, whereas Nitisols were the dominant soils in the research area of Kapchorwa, Uganda. The maps are taken from the "Soil Atlas of Africa" by Jones et al. (2013a); pg. 53 and 55).

5.1 The effect of soils on food and nutrition security

Human health is largely dependent on plants for food. Plants in turn are dependent on soils for nutrients, and therefore, human health also depends on soil. The effect of a particular soil, to human health, through the diet depends largely on the locality of its food system (Oliver and Gregory, 2015) (as foods originating from other soils can have other nutritional properties), and is further discussed in section 5.1.3. Soil fertility can, however, also vary greatly even on a small scale (Cobo et al., 2010b), thereby potentially affecting food nutrient composition.

Soil properties measured included a measurement of the total elemental soil concentration. Some soil-borne plant available nutrients were also measured (exchangeable K, Ca, Mg, and Al). However, only the measurements of the total elemental concentration were used in the final models as more total elements were measured than available. The combination of total soil elements and total nutrient concentrations of the edible part and leaf tissue provided enough information to address the research questions on compariong soils, plants and separate plant parts (Römheld, 2012).

5.1.1 The effect of soil type on food quality

Soil fertility varies on different spatial levels and through that variance, affects food quantity and quality. In East Africa, for example, soils from volcanic origins such as Mt. Elgon in Kapchorwa (Nitisols) are more fertile, whereas soils in Teso South are less fertile (Ferralsols).

On the African Continent soils developed under tropical or substropical conditions. Ferralsols cover about 10% of the surface of Africa, whereas Nitisols cover around 2% (Jones et al., 2013a; Figure 5.1). While Ferralsols and Nitisols are not spread so widely across SSA, the comparison of measured soil chemical and physical properties (texture, SOM content, trace elemental concentration, etc.) from collected samples with the African Soil Information Service (AfSIS), showed that the soils of Teso South were widely representative of the soils of SSA (Chapter 3; Figure A.8). The soils sampled in Kapchorwa, on the other hand, were representative of a much smaller group of AfSIS measured soil properties (Chapter 3; Figure A.8).

While soil variance among different soil types and large topographic formations are expected, soils can also vary on a smaller scale, such as on field level (Cobo et al., 2010a). Soil types are a product of climate, parent materials, topography, time and flora and fauna activities (Blume et al., 2016). Field scale variance on the other hand, is a product of soil type, farm and soil management (e.g. land use, input use), and topography. To understand the ramifications of soil variance on food quantity and quality, and food and nutrition security, both larger and smaller scale variances, of soil fertility need to be taken into consideration. In this thesis, soil variance on a larger scale was included, through the comparison between the two research areas. On a smaller scale, soil variance was included through field level sampling in both research areas. In-field soil variance was considered negligible for the present research questions, as the foods harvested per field (their nutrient concentrations potentially affected by soil heterogeneity) were mixed before consumption (as a farm household would normally do). Therefore, although the in-field variance was still present, the in-field soil effects on food quality and by further extension potentially affecting human health, were less pronounced. Soil variance was higher on a larger scale (between the two areas), than within either area (smaller scale). This was also expected since a volcanic Nitisol and an old weathered Ferralsol are very different soil types. The soil variance on the smaller field scale showed a higher variance in Kapchorwan' Nitisols, than in the Ferrlasols of Teso South, which was expected since the topography in Kapchorwa has a very high variance, whereas the topography in Teso South is relatively homogenous. The increased variance in soil fertility of a heterogeneous landscape could also be seen in the food nutrient concentrations. Food samples collected in Kapchorwa showed a higher variance in their yields and food nutrient concentrations than food samples collected in Teso South (Chapter 3). Other studies have, however, found smaller scale variance to be greater than larger scale variance. In the case of a comparison of more similar soils, larger scale variance could be lower than smaller scale variance. It is, therefore, encouraged to look at variance on multiple spatial levels, as it can occur on any (Lin et al., 2005). In addition, most data concerning nutrient budgets and nutrient variance on different spatial scales has

Table 5.1: Average macro- and micronutrients and yield of maize grain in percent from low to high soil fertility in the two research areas Teso South, Kenya (low fertility) to Kapchorwa, Uganda (high fertility). Samples of maize grain were collected in July/August 2016 from farmer fields.

Nutrients and Yield	Average percent increase from low to high soil fertility
Macronutrients	24%
Micronutrients	69%
Yields	74%

been gathered on N, P, and K (Cobo et al., 2010a). Comparable data on other nutrients, particularly micronutrients, is rare, thereby also making conclusions on their concentration variance on different spatial scales difficult.

One of the main research questions of this thesis, through the comparison between resultant food quality on a more and a less fertile soil, was whether people living in an area with a higher soil fertility could have a comparative health or food and nutrition security advantage, to people living in areas with a lower soil fertility. The results of Chapter 2 clearly showed that the region with the higher soil fertility produced crops with significantly higher yields and food nutrient concentrations. Since the effect was consistent over two different food types per region (matooke fruit and maize grain in Kapchorwa (higher fertility), and cassava tuber and maize grain in Teso South (lower fertility)), other foods are highly likely to be affected in a similar way. The findings also covered leaves that are used as food, as the nutrient concentrations in (maize) leaves from higher fertility areas were predominantly higher than in lower fertility areas (Chapter 4). Other studies have also noted differences between soil type and edible part nutrient concentrations. Joy et al. (2015), for example, compared the effects of calcareous and non-calcareous soils on food nutrient compositions, and found high risks of human deficiency of Ca, Se, and Zn from foods grown on non-calcareous soils. In this thesis, the magnitude of the difference in edible-part nutrient concentrations and yields between the two research areas was unanticipated, even though it was already known that soils can affect food quality (Wang and Frei, 2011). The differences in edible part nutrient concentrations and yields between high and low soil fertility were significantly higher in high fertility areas (Table 5.1). It is, therefore, highly likely that human nutrient intake in lower soil fertility areas is also significantly lower.

The potential effect is magnified by the rural setting, combined with semi-subsistent agriculture, and local food systems (Oliver and Gregory, 2015), described further in section 5.1.3. Soil fertility, therefore, can significantly affect human health, by producing foods that have significant differences in quality and a significant difference in quantity. This difference is particularly evident when seeing the contrast between high and low fertility soils, and the difference in micronutrient concentrations and yield. Effects on food and nutrition security are also expected, as micronutrients, which are more commonly seen as human deficiencies (such as Fe and Zn) show a greater difference between soil fertilities than macronutrients in maize grain (Table 5.1). The potential effect on food and nutrition security is plausible, as similar effects have been observed for single nutrients such as selenium in Finland (Alfthan et al., 2015) and iodine in Nigeria (Ubom, 1991).

The comparison of the soils of the research area to soils of SSA through soil property comparison with the African Soil Information System (AfSIS) (Chapter 3) showed that soil properties of the lower soil fertility area (Teso South) were largely representative of the soils of SSA. Therefore, excluding other factors such as climate and genotype, similar lower yields and food quality, as in Teso South, are assumed to be produced across SSA, compared to areas similar to Kapchorwa.

The comparison shown in this thesis of edible-part nutrient concentrations and yields between high and low fertility soil, gives an indication of what could happen to food quantity and quality when cultivated on soils that are becoming increasingly degraded (gradient of high fertility to low fertility, from Kapchorwa to Teso South) (Table 5.1). Soil degradation can come in many different forms, most of which actively limit plant nutrient availability. In this thesis, soil degradation is defined as desertification, salinization, erosion, compaction, invasive species encroachment, Al toxicity, severe nutrient and SOM loss, and soils that are naturally low in fertility (Gibbs and Salmon, 2015).

The soils of Kapchorwa and the soils of Teso South represent a strong comparison between a relatively fertile soil, and a degraded soil very low in fertility, and provide a scenario showing the decline of food quality and quantity with increasingly worldwide degrading soils. Due to a global growing population food and feed production should be increased by around 70% between 2005 and 2050 to achieve food security (Kirchmann et al., 2008; Kopittke et al., 2019). This staggering number becomes worrisome when considering the already high prevalence of degraded soils worldwide (40% of soils estimated to be deficient in Cu, Mo, and Mn, and about half deficient in Zn (Knez and Graham, 2013)). On top of this, agricultural land is being expanded onto areas unsuited for agriculture (Muchena et al., 2005; Vanlauwe et al., 2014a). Soil degradation and its negative effects on decreased production (food quantity) have been in discussion for some time (Kopittke et al., 2019). Decreasing food quality has however only been mentioned in the context of climate change (Soares et al., 2019) (further discussed in Section 5.5), and not linked to soil degradation. Due to the worldwide increasing surface area of degraded soils, and the concurrent expansion of agricultural land, loss of food quality as a result of soil degradation could already be a larger and more rapidly expanding problem for food and nutrition security, and human health, than previously anticipated.

5.1.2 The effects of soil properties on food quality

Soil fertility is dependent on many different factors, such as basement rock, parent material, soil forming factors, slope, land use history, and management factors (Blume et al., 2016). Soils provide most nutrients for crops. They also provide a habitat for microorganisms that make nutrients more available to crops. In the research areas, the nutrient concentrations in annual crops were strongly affected by soil organic matter (SOM) and texture, whereas perennial crops were more affected by nutrient concentrations of the soil (Chapter 3). The importance of SOM for food nutrient concentration was also observed by Wood and Baudron (2018). They found that soils with higher SOM content produced wheat with a higher Zn and protein content. SOM will be discussed here in more detail, as it represents the main manageable factor (Wood and Baudron, 2018). Texture, although also seen to be very important for plant nutrient availability (Chapter 3) is not considered manageable, as it is not easily altered by farm management methods. In the area of higher soil fertility (Kapchorwa), SOM showed a significant effect on food nutrient concentrations. The significant effect of SOM was highly important for food quality and quantity, since SOM represented the main source of nutrients for the crop as fertilizer usage was very low. A similar effect could also be seen in the lower fertility soils, where SOM concentrations were extremely low. Fertilizer use was slightly higher on the low fertility soils (Teso South), and showed an, albeit insignificant, positive effect for food nutrient concentrations. Since fertilizer use was very low (consequences discussed further in section 5.3), managing and maintaining a certain level of SOM becomes vital, as SOM is the most important source for crop available nutrients. Managing SOM is, however, difficult, particularly in low fertility soils. SOM in agricultural systems comes from organic material input into the soil. Attempting to increase SOM through plant and animal residues from a low fertility soil is extremely challenging as often not enough biomass can be produced (Vanlauwe et al., 2014b). The nutritional quality of the biomass used to add organic matter to soils is dependent on the available nutrients of the soil. If the nutrient concentrations of soils are low the amount of nutrients taken up by crops (or other plants used as organic fertilizer) would also be low, thereby decreasing the nutritional quality of the organic materials. Using own organic biomass to increase the SOM is essentially cycling already present nutrients of a defined system (i.e. a farm). Since in low fertility soils, nutrient availability is also low, the nutritional quality of the organic materials used to increase SOM could also be very low. The positive qualities of increasing SOM, such as increasing microbial biomass and stabilising eCEC (Wood and Baudron, 2018) are, however, so important that even with a lower SOM quality, its increase is beneficial.

Initially, it was hypothesized that the pH would be the most important factor in crop nutrient concentrations as it had been described as such (McGrath et al., 2014). The soil pH was, however, not significant for any of the food nutrient concentrations measured (Chapter 3). This may be due to pH being an integral factor that strongly influenced other variables (such as eCEC). Another reason could be that other variables showed comparably higher variance than pH. Enough research has shown the importance of pH for plant nutrient availability, so that although it was not significant in this analysis, its importance in general is not discounted.

5.1.3 The importance of linking soil types to food composition tables

The soil with a lower level of nutrient concentrations, lower pH, lower SOM and a higher sand percentage showed worse growing conditions, as crops were produced with lower yield and nutrient concentrations (Chapter 3). Since soils are the basis of the food system and severely affect both the quantity and the quality of foods produced, they should be taken into consideration when assessing and comparing the health and food and nutrition security status of local rural populations. The variance of nutrient composition in foods caused by soils is highly relevant for food and nutrition security. To fully understand the interactions between soils and the quality of produced food, food quality should be used as a response factor during agricultural trials. A research focussed more on nutrient concentrations and quality, rather than only quantity and yields has already begun. Herrero et al. (2017), for example, have looked into global nutrient imports and exports, based on farm size, therefore emphasizing nutrients rather than yields.

Food composition tables are used to document the different nutrients present in foods (Elmadfa and Meyer, 2010), and are usually produced on a national level. Taking the results of this thesis into account, producing food composition tables based on soil types rather than countries could reduce the high variance currently seen in and between values measured in the food composition tables. Using soil types would also make more sense, as soils across countries can be highly heterogeneous, thereby also causing a high variance in food nutrient concentrations. Using soil types as a basis would limit the food compositional variance to a smaller spatial scale of soil fertility variance, and eliminate the variance found at a larger spatial scale between soil types (which as described in 5.1.1 can be sizeable). Soil types as a basis for food composition tables would also allow for the identification of certain "hotspots" of potential food and nutrition insecurity. If a soil type has an inherent low soil fertility, the foods produced would also be prone to low nutrient concentrations and yields.

Farm management, particularly fertilisation, is assumed to play an important role in food quantity and quality. In this thesis, the measured management factors (distance of field to household, fertilisation, and crop diversity) did not show any significant effects on food nutrient concentrations or yields (Chapter 3). This in-significant result could partially be due to the low amount of fertiliser application and the low variance in crop diversity found. Although management could be an important factor for food quantity and quality, soil is a better indicator to identify nutrient depletion "hotspots". Soil maps already exist and soil types do not vary quickly over time. Management, on the other hand, is a compound volatile factor that is affected by a number of socio-economic exogenous variables, and therefore not suited to being used as an indicator to find nutrient deficiency "hotspots". Simplifying the factor of finding hotspots to soils also makes sense as soil fertility was one of the main factors found when assessing spatial determinants of poverty (others being slope, distance to resources, elevation and land use) (Okwi et al., 2007). Low soil fertility has also been identified as being linked to chronic poverty, as low fertility provides less stability against shocks (droughts, prices, access to fertilizers) than higher soil fertility (Barrett and Bevis, 2015). In addition, the nutrients most dependent on the soils are the nutrients that are least fertilised. These would include all nutrients with the exceptions of N, P, and K, therefore also including most nutrients relevant for human health (such as Ca, Fe, and Zn). The identification of these "hotspots" could help in mitigating effects of shocks as these areas could be the most vulnerable, due to an already low quantity and quality produced during normal times, and therefore have a low buffer capacity.

5.1.4 Links between soils and consumed foods

Food and human health are strongly interlinked. Soil and human health, although linked through agriculturally produced food, have a more complex relationship. Soils do play a very important role in the quantity and quality of foods produced, as different soil types and levels of fertility can severely affect the quantity and quality produced. The direct effect of different quantity and quality foods produced by different soil types on human health is almost impossible to measure as foods are often sourced from various locations (for example, own production, markets, and/or supermarkets). Therefore, the foods consumed often originate from a variety of soils, diluting the direct soil effect on health.

Soils effect on human health is assumed to be highly related to the locality of the food system individuals reside in. The more local the food system, the more direct the effects (Oliver and Gregory, 2015). However, even if the foods consumed are largely locally produced and consumed, the foods chosen for consumption themselves will also affect human health, as different foods contain different levels of nutrients. Food preparation and cooking also play an important role as these processes can seriously affect nutrient bioavailability in the body (Burdock and Crawford, 2015). This means that even if a certain amount of nutrients is measured in foods, the nutrients are not necessarily all available to humans. Therefore, while it is important to take soils into account to measure the quality and quantity of foods produced, it is also important to take the locality of the food system, the dietary diversity, and food preparation into account, to fully understand environmental effects on human health.

5.2 The role of farm management in producing high quality foods

The type of management and the decisions associated with management depend on many different factors, such as environment, soil type, level of knowledge of the decision-maker, availability of resources (mechanisation, fertilizers, etc.), and socio-economic background of the farmer (Giller et al., 2006; Tittonell et al., 2016). The main management factors reportedly having the most notable effect on yields and nutrient concentrations in crops were (i) organic and inorganic fertilizers (Hattab et al., 2019); (ii) crop diversity due to an increase of beneficial ecosystem services (DeClerck et al., 2011); and (iii) distance to household, due to differences in resource allocation (Tittonell et al., 2016). Adding inorganic fertilizers is a direct addition of nutrients, while organic fertilisers depend on the type added (can be direct through addition of available nutrients, and indirect through addition of structural materials that are slow in their decomposition). Increasing crop diversity is an indirect method of increasing soil nutrient availability, or reducing plant stress through ecosystem services. Distance to the household could be a function of both amounts of fertilizers allocated or crop diversity levels.

5.2.1 The role of organic and inorganic fertilizers for food quality

Organic and inorganic fertilisation did not show any significant results in their effect on food nutrient concentrations or yields in the research areas (Chapter 3). The insignificant results were most likely due to the low amount of fertilisation used, as other sources discussed here have shown direct and indirect effects of fertilisation on produced food quantity and quality. Fertilisers play an important role in food and nutrition security, as they provide nutrients for crop growth and therefore food production. Nitrogen fertilizer in the U.S.A., for example, was calculated to being responsible for 41% of the corn harvest (Stewart et al., 2005). In the tropics where older and highly weathered soils dominate, fertilisation is important to maintain production (Stewart et al., 2005). Over-fertilisation should be avoided due to high environmental costs, and to avoid natural finite resource depletion of essential elements (such as P) (Stein et al., 2017).

Different types of fertilisers are used in agriculture, and can be roughly divided into inorganic fertilizers (industrially produced) and organic fertilizers (plant and animal residues). Organic fertilizers are viewed as having more benefits regarding sustainable and safe food production, as they are less associated with environmental pollution and chemical residues in food as inorganic fertilizers are (Hattab et al., 2019; Malik et al., 2020). Some research has found that the use of organic fertilizers does show about 20-50% lower crop production when compared to inorganic fertilizer use (Kirchmann et al., 2008). Others have found that long-term organic input trials have shown that organic fertilizer can achieve similar yields on high fertility soils compared to conventional input systems (Adamtey et al., 2016). Organic fertilizers do however, provide a longer term positive benefit to soils, for example, through an increase of SOM. Potential lower productivity is however, a cause for concern as agricultural land would have to be further expanded to produce enough food for the global population (Timsina, 2018).

Applying fertilisers and also receiving the expected results of healthier plants can, however, be quite tricky. Under farmers practice in tropical conditions, for example, recovery of nutrients can be as low as 22% (Tuan et al., 2015). Fertiliser application should, however, be tailored towards the plant type, soil type, and the nutrient in question. Any other form of application may not allow the plant to take up the nutrient, as fertilizer nutrients can be bound by the soil and made unavailable for the plant, or lacking nutrient transport within the plant may affect nutrient concentrations in the edible part (Yang et al., 2007). Increasing fertilizer efficiency by using a mix of both organic and inorganic fertilizers, and measuring their efficiency by the yield and the food nutrient concentrations could increase food safety as well as yields.

Both types of fertilizers have positive and negative effects on plant growth. While inorganic fertilizers are highly available for plants, over-fertilisation of inorganic fertilizers can cause soil pH changes, negatively affect microbes, and contaminate groundwater (Timsina, 2018). Inorganic fertilizers have clear amounts, of albeit, mostly few nutrients (most frequently N, P, K), whereas organic fertilizers show a highly varying nutrient content (Timsina, 2018). The nutrient concentrations of organic fertilizers is highly variable (Giller et al., 2009) and, due to differences in decomposition times, also varies in nutrient release times (Giller, 2000). Organic fertilizers, however, do provide services to the soil, such as increasing the SOM, improving soil structure and supporting microbial activity (Han et al., 2016).

Organic or inorganic fertilisers affect edible parts differently. Inorganic fertilizers (under use in conventional farming systems) have not shown significant differences in dry matter or nitrate content of vegetables (Herencia et al., 2011), possibly due to an already fertile soil. Conventional farming using inorganic fertilizers, however, were found to leave significantly higher traces of heavy metals (Fe, Mg, Mn, K, Ca, Na, Zn, Cu, Ni, and Cd) in foods as compared to organic farming systems (Hattab et al., 2019). The increase of heavy metals could be due to the tendency of some crops to accumulate heavy metals, but also due to heavy metals being present in inputs such as fertilizers and pesticides, or due to the inadvertent increase of heavy metal plant availability by eliciting changes in the soil (Atafar et al., 2010).

Producing food crops on a continuous basis requires the use of fertilisers (both organic and inorganic) to maintain both yield and quality of production. Fertilizer access is unevenly spread across the world. In East Africa, for example, access to fertilizers is limited, particularly in smallholder households (Jindo et al., 2020). Socio-economic factors, therefore, cannot be left out when promoting sustainable agricultural production (Jindo et al., 2020).

Crop health and nutrient concentrations are measured using yields and leaf nutrient concentrations. Fertilizer use is, however, not often compared or associated with edible part nutrient concentrations. One of the known effects on food nutrient concentrations of fertilisation is the dilution effect (Davis, 2009; Riedell, 2010). The dilution effect is defined as an increased crop yield, without a proportional increase in nutrient concentration (Marles, 2017). In this thesis, a potential dilution effect was observed in areas with an increased soil fertility, and not in conjunction with high yielding varieties (Chapter 3). This finding, therefore, expands the sphere of impact previously known about the dilution effect, by projecting the effects of a dilution effect onto food quality as well as yield. It is assumed that an increase of fertilisation could also exacerbate the dilution effect. Since most research concerning the dilution effect has been done in correspondence to high yielding varieties, data on the interactions between non-high yielding crop varieties, soils, and moderate fertilizer amounts are not commonly found.

Fertilisation has also been used as a method to combat malnutrition by fertilising specific micronutrients (an example of biofortification) that are known to be deficient in a population or simply to improve soil conditions and improve nutrient availability (Bouis and Saltzman, 2017; De Valença et al., 2017). Biofortification is considered a nutrient-sensitive indirect intervention (the other type being nutrient-specific direct, such as dietary diversification and micronutrient supplementation), and is the process of increasing bioavailability or content of nutrients during plant growth either genetically or agronomically (De Valença et al., 2017). There are many different methods that can be used, some being (i) foliar fertilisation; (ii) integrated soil fertility management (ISFM); and (iii) application of specific fertilizers, such as Se and Zn. Some genetic biofortification includes for example Fe-Pearl Millet and Fe-beans, both sown to increase Fe in their target population (Bouis and Saltzman, 2017).

A focus on single nutrient biofortification could be ineffective in the long-term, as deficiencies are rarely present as single nutrients and usually occur as multi-nutrient deficiencies in soils and in living organisms (Bailey et al., 2015; De Valença et al., 2017), further discussed in section 5.5.2. Another problem associated with biofortification technology is that most micronutrient deficiencies occur in regions that are economically constrained (Tulchinsky, 2010). Access and particularly longer-term application of the different technologies are not very likely in developing countries. Most likely, and most adaptable, would be the integrated soil fertility management (ISFM), as it includes the use of both organic and inorganic fertilizers, therefore reducing dependence on the costlier inorganic fertilizers. ISFM is defined as "a set of soil fertility management practices that necessarily include the use of mineral fertilizers, organic inputs and improved germplasms combined with the knowledge to adapt these practices to local conditions" (Vanlauwe et al., 2010; pg. 19). Only depending on organic fertilisation is usually not possible, due to the frequently limited availability of nutrient rich materials. Including inorganic fertilizers could increase micronutrient availability of deficient nutrients. Using inorganic fertilizers adds plant available nutrients to the soil and can therefore increase the uptake of certain nutrients (De Valença et al., 2017). Increasing access to inorganic fertilizers is key for an ISFM, however, comes with many difficulties. Fertilizer prices (for example urea) are highly varied across SSA, as well as within countries, often depending on the vicinity to roads or markets. The greater the distance, the higher the transportation costs and therefore, the higher the prices (Cedrez et al., 2020). To increase and equalize access to inorganic fertilizers, the price heterogeneity should be taken into account, as well as using government subsidies with fade-out strategies, that have already been shown to be beneficial for food production (Houlton et al., 2019).

5.2.2 The role of crop diversity for food and nutrition security

In this thesis, crop diversity was measured as crop richness and crop diversity per field. Positive effects of crop diversity could be seen in maize grain in poor fertility soils (higher crop diversity showed a higher nutrient concentration and yield with increasing diversity), while no effect was observed in higher fertility soils (Chapter 3). The positive effect was most likely due to the indirect beneficial effects of ecosystem services decreasing plant stress and increasing nutrient availability. The effect of crop diversity on food nutrient concentrations has not been covered much in scientific literature, however, indirect effects have been seen, for example, through an increase in crop yields when rotating food crops, such as maize with grain legumes (Stagnari et al., 2017). A higher crop diversity, when including different food groups, can have an important effect on human health and well-being. Factors feeding into the positive effect are increasing resilience to climate change and other shocks (Jassogne et al., 2013; Altieri et al., 2015), and potentially increasing household access and availability to a higher diversity of foods and, therefore, the household's dietary diversity (DeClerck et al., 2011). An increased dietary diversity has a high correlation to a higher nutrient intake in the household, and could therefore positively impact human health (DeClerck et al., 2011).

An increased crop diversity has become almost synonymous with sustainable agriculture (He et al., 2019). A higher crop diversity can provide ecosystem services (provisioning, regulating, supporting and cultural), thereby minimizing the need for, and use of chemical inputs (Hajjar et al., 2008; McDaniel et al., 2014; He et al., 2019). Monocultures are more efficient at producing larger yields, but are dependent on a continuous high input (e.g. fertilizers and plant protection chemicals), labour, and mechanisation level. Increasing crop diversity and, therefore, increasing agrobiodiversity and ecosystem services should be a global aim (i) for resource limited farmers, as functional agrobiodiversity would decrease the necessity for chemical inputs and therefore, save resources; and (ii) for wealthy commercial farmers for the same reasons, as well as reducing environmental pollution through reduced input use. To gain the full benefits of crop diversity, it is, however, vital that crop composition per field is well organised to avoid nutrient, water or light competition (Huang et al., 2015; Isbell et al., 2017). Management strategies should also be matched (Zhang et al., 2007), as a badly managed high crop diversity can be highly nutrient extractive and therefore unsustainable. A badly managed and highly extractive diverse system would be to intercrop different crops, and during the harvest remove the entire plant, and not replace any residues into the soil. Using this method, all of the available nutrients taken up in the plant's biomass are removed instead of just what is contained in the edible part, and the rest returned to the field as mulch or compost. This method is more extractive with a higher diversity than with just one crop, as multiple nutrients are removed that covered the needs of several crops. Another difficulty could be finding the most productive and complementing species composition to avoid yield losses through competition (Isbell et al., 2017). Functional diversity is necessary to maximize the probability of gaining a benefit from a higher crop diversity (Hajjar et al., 2008), by for example, mixing annual and perennial species, or deep and shallow rooting crops, and varying the crops in time (crop rotation, seasonal change) and space (planting in rows or mixed field). Through the varying functional diversity, as well as crop species diversity, competition can be avoided. Increasing diversity would also increase resilience, as the probability of a crop species surviving a shock (for example, pest, disease, or drought) is increased, therefore providing the associated household with more security (Jassogne et al., 2013).

5.2.3 The importance of the distance to the household on food quality

The variable "distance to the household" showed no effects on yields or edible part nutrient concentrations (Chapter 3). The lack of gradients found similar to Tittonell et al. (2016) may be due to the general low fertilizer or pest/herbicide input amount, or a difference in socio-economic structure of the households. Different types of inputs may also behave differently. While inorganic fertilizer use is often lower than organic fertilizer use (for example manure), due to a lack of access and availability (Rufino et al., 2007), manure distribution could be unequal across the fields due to a high weight and handling difficulty. Low input use was one of the scenarios mentioned by Tittonell et al. (2016) under which fertility gradients are difficult to identify. Other reasons could be high soil heterogeneity such as in Kapchorwa, where fertility gradients based on farm resource management may remain undetected due to high natural soil variance. In Teso South on the other hand, fields were located very close to the household, the variance in soil properties was comparably low, and inputs were also very low. The lack of variance in properties or input amounts could have also led to a lack of fertility gradients. Although the field's distance to the household did not show any effect on the edible part nutrient concentrations, soil nutrient levels, or yields in this thesis, do not make it an unimportant variable, as it has shown significant gradients in other studies (Tittonell et al., 2005, Tittonell et al., 2016). Another important factor could be the physical distance of the fields to the household. However, although fields in Teso South were in general closer to the household than fields in Kapchorwa, no significant effect of distance was found.

5.3 Plant nutrient function is important for food quality

The plant, similar to the human body, is an organism containing different parts that all have a role in maintaining the survival of the plant as well as allowing for reproduction. As each plant part has a different role to play (e.g. leaf for photosynthesis, stem for transport, and roots for uptake), each part also requires different amounts of nutrients to function (Engels et al., 2011; Bender et al., 2013). Different plant parts such as fruits, grains, leaves, stems, and tubers, are also used as foods, and contain different levels of nutrients (Chapter 4). These differences could be seen clearly between, for example, the cassava tuber, which acts as a nutrient storage (El-Sharkawy, 2004), and reproductive sink parts, for example, maize grain and matooke fruit (Chapters 2-4). With the functional differences in mind, it comes as no surprise that due to the variance in function of edible parts, nutrient concentrations in edible parts also vary when exposed to different environmental stressors. These differences could be seen clearly regarding effects to different soil fertilities (Chapter 3) and to drought stress (Chapter 2). Strong differences in nutrient concentrations could also be seen between annual and perennial crops (Chapter 3 and 4). Whereas annual crops were directly affected by environmental factors, perennial crops showed a larger buffer capacity on the nutrient concentrations of food, making them more nutrient efficient than annual crops (Srivastava and Malhotra, 2017) (Chapter 3).

5.3.1 Can plant stress be used to produce better foods?

Stress can affect the nutrient concentrations of the edible parts of crops. This thesis showed the effects of both drought stress (Chapter 2) and nutrient stress (Chapter 2-4) on quality and quantity of foods produced. Mild drought showed a positive effect on food quality, whereas severe drought was inherently negative. Nutritional stress (low soil fertility) showed a negative effect for both crop types tested. Stress is therefore not necessarily negative, and can even lead to an increase in nutrient concentrations and nutrient yields (nutrient yield = nutrient concentrations*yield) (Chapter 2). Since environmental stress does, however, affect many aspects of plant development, such as photosynthesis and nutrient uptake, oftentimes the yield is negatively affected (Leng and Hall, 2019). The intensity of the effect on edible part nutrient concentration, however, depends strongly on the intensity and longevity of the stressor, the crop type (Soares et al., 2019), and continuous access to crop available nutrients. Long-term exposure to stress can therefore severely change the chemical composition in crops and the quality of agricultural produce (Wang and Frei, 2011). Crop type is also important as maize, for example, proved more drought resistant than either cassava or matooke, as it lost less yield and had a comparably lower loss of edible part nutrient concentration than either other crop (Chapter 2). Although cassava is generally known as a drought-resistant crop, its drought resistance refers to total plant survival by entering a type of dormancy, rather than maintaining a high yield (Daryanto et al., 2016). As positive results of stress on food quality, without reducing the quantity is a possibility (Chapter 2), more research should be involved in studying different stress levels and their use potential for producing foods with a higher nutritive value.

This thesis focusses mainly on plant macro- and micronutrients. These elements are directly taken up from the soil, and not produced by the plant. They are vital for survival for both plants and humans. Other substances that are produced by plants, are also vital for human health, such as proteins, lipids, and vitamin precursors amongst others (Yang et al., 2013).

Nitrogen is vital to plants and animals, and is found in many important compounds such as proteins, nucleic acids, co-enzymes, and hormones (Hawkesford et al., 2012). Proteins are ubiquitous in both plants and humans, they are essential, and perform a variety of very important tasks. The basic building blocks of proteins are amino acids, defined by a nitrogen based amino group ($–NH_2$) and a carboxyl group (-COOH). Some amino acids also contain sulphur (Bresinsky et al., 2008). Proteins are part of many important plant systems, and provide many functions, such as being part of the cell structure and providing stability, storage functions, as well as acting as enzymes in different reactions. Plant stress affects the composition and amount of different proteins in the plant, beginning with nitrogen uptake. During severe drought in maize, it has been observed that % N and P nutrient acquisition is reduced (Bista et al., 2018). Leaf proteins in cassava during drought also showed a strong fluctuation in protein types, some increasing whereas others decreased, depending on their function and building blocks (Shan et al., 2018). The most prominent example of environmental factors and climate change affecting protein composition is wheat grain quality. Elevated CO_2 levels have shown to alter protein composition of wheat grain, and decrease dough quality below the required amount for bread making. Constantly increased temperatures have also shown a decrease in dough quality due to a change in protein composition. The combination of the two factors (CO_2 + temperature), and including drought during grain filling (occurring with increasing frequency due to climate change), pose a serious challenge for maintaining current wheat production (Nuttall et al., 2017). Wheat provides a very important food source and its previously mentioned reduced production may negatively impact large parts of the world. Apart from wheat and other staple crops, protein composition and the effects of climate change on protein composition has not been extensively researched so far.

Plant stress such as severe drought affects elemental concentration in the edible parts to the point where it could exacerbate potential famine by including a lower food quality and therefore increasing hidden hunger incidence. Other nutrients such as vitamins are similar to essential elements in that they are essential for humans, and one of the greater causes of human micronutrient deficiencies (e.g. Vitamin A), and their concentration can be affected by environmental factors. The main difference to essential elements is that vitamins are produced in the plant, and not directly taken up from the soil. Many vitamins act as antioxidants in the plant. Ascorbate (Vitamin C) for example captures and neutralises reactive oxygen species (ROS), thereby protecting cellular signalling and macromolecules. Carotenoids (precursors to Vitamin A) and tocopherols (Vitamin E) work to stop the accumulation of ROS in the plastid (Asensi-Fabado and Munné-Bosch, 2010). ROS are a vital signalling and protective compound (e.g. triggering controlled cell death, acting as a poison for pests) in plants when present in lower amounts. ROS bursts occur mainly as a result of environmental stress such as drought, flood, temperature extremes, salt stress, ultraviolet light, pest affliction, and nutrient deficiency (Chen and Yang, 2020). As excessive ROS presence can, however, cause damage to plant structures and compounds, the production of antioxidants is increased to control ROS production and spread (Sharma et al., 2012). Increased antioxidant compounds could, for example, be detected in various cultivars of rice (*Oryza sativa* L.) and beans (*Phaseolus vulgaris* L.) under drought stress (Das and Roychoudhury, 2014). An elevated presence and production of antioxidants in plant tissue would, however, also be dependent on the intensity and length of the environmental stress, although details on which conditions particularly increase the vitamin concentration are not known. The important thing to capture is the point at which the positive aspects (maximum pro-vitamin content) outweigh the negative effects of too much damage done through increased ROS. Therefore, the presence of abiotic and biotic stress could increase antioxidant concentrations in plant tissue. It is important to mention, however, that the literature cited here did not specifically test edible parts, and therefore, unless the leaves are the edible part, further research is needed. Vitamin biosynthesis pathways are still poorly understood, even though they are such an important source of nutrients, and would, therefore, benefit from more research (Asensi-Fabado and Munné-Bosch, 2010). Using vitamins as an example, can show that not only essential elements are affected by environmental effects, but also other plant assimilates, that could affect produced food quality. In general, however, mild stress seems to positively affect food nutrient concentration without major yield consequences.

Heavy metals such as cadmium (Cd), mercury (Hg), arsenic (As), and lead (Pb), but also Cu, Zn and Mn, can be taken up by crops in toxic amounts, and can therefore elicit plant stress. Oftentimes, these heavy metals can (i) damage the plant and decrease yield (Nagajyoti et al., 2010) and (ii) also cause harm to humans, if the heavy metals end up in the crop's edible part. Most research regarding heavy metals accumulation has been focussed on vegetables, since these are often accumulators of various nutrients (such as carrots, spinach, lettuce, radish, and zucchini) (Intawongse and Dean, 2006). Heavy metal incidence, although also occurring due to pollution (such as mining (Intawongse and Dean, 2006)), also occurs naturally, for example, in areas, with a history of volcanism (Ma et al., 2019). Although these areas do show a high level of heavy metals in the soil, the plant availability and final presence in food would depend on (i) the soil type and properties and, therefore, general plant availability; (ii) the type of plant, some naturally accumulate heavy metals others do not and; (iii) the type of plant tissue used as food and the transport method used to get there. Phloem-fed tissue (such as fruit tissue) is, for example, a bad dietary source of Ca (White and Broadley, 2003), as Ca is not phloem-mobile. Xylem-fed tissue (such as leaves) is a good source of Ca, as Ca is xylem-mobile. Heavy metals have been measured in all sorts of plant tissue used for food (roots, leaves, and fruits). Producing categorical lists for food types (grains, fruits, tubers, etc.) in which heavy metals have been found, would greatly help in making recommendations on what crops are best suited to what polluted area. In this way, production and in turn dietary diversity could be maximized, while concurrently minimizing exposure. For example, Taghipour and Mosaferi (2013) found high levels of Cd in tubers (carrots, radishes, and potatoes) and leaves, but comparably lower amounts in beans and tomatoes, suggesting a xylem-led transportation of Cd in the crops. Based on this result, areas with high levels of Cd could focus more on fruit-crops or other phloem-fed foods, and procure their leaf and tuber crops (xylem-fed foods) from non-polluted areas.

5.3.2 Nutrient long-distance transportation in the plant as a deciding factor for food nutrient concentrations

Long-distance nutrient transport of essential elements was one of the recurring topics in understanding differences in nutrient concentrations in almost every analysis of this thesis. Nutrients transported predominantly in the xylem (i.e. Fe, Mn, Cu, Zn and Ca), for example, showed the greatest concentration difference in edible parts between a normal and a drought season. As the xylem is susceptible to embolism, this transport method was constricted under severe drought. As a result of the transport interruption, food quality was low, particularly regarding micronutrients and Ca (Chapter 2). Micronutrients and Ca showed the lowest correlations between leaves and edible parts (Chapter 4), therefore showing a very low level of association between nutrients in leaves and edible parts. The differences in long-distance transport are particularly relevant for consideration in matters of food and nutrition security, as they affect nutrients with the highest registered human deficiencies (for example Ca, Fe, and Zn) (Joy et al., 2014; WHO, 2017).

Drought was identified in this thesis as a factor affecting long-distance transport of micronutrients and Ca to the edible part and, therefore, potentially affecting food and nutrition security. Nutrient transport differences, however, also showed another important aspect. In agricultural trials or surveys, crop leaves are often analysed to gauge plant health and potential yield. Differences in correlations between leaf nutrient concentrations and edible nutrient concentrations and yields, as well as between leaf and edible parts showed that leaf nutrient concentrations did not give good estimates on food quality. Particularly micronutrients and Ca showed low correlations between the two plant parts (Chapter 4). Nutrient remobilisation (for example nutrients moved from leaves to reproductive part) is mainly done via the phloem. Micronutrients cannot be efficiently transported “laterally” throughout the plant, as they do not transport well in the phloem (Maillard et al., 2015; Etienne et al., 2018). Nutrient uptake for reproductive edible parts (for example fruits or grains) occurs at different times (Bender et al., 2013). These results impact agricultural research, when regarding for example, fertilizer application timing. When crops are grown for human consumption, the aim should be to produce crops with higher nutrient concentrations and yields. By using the leaf as a measurement of nutrient sufficiency, the separate timing of nutrient uptake between leaf and edible part, and the lack of remobilisation of micronutrients and Ca into the edible part, is not accounted for. The timing of fertilizer application, has to therefore, either match the critical stage uptake period during edible part nutrient filling, or nutrients should be made available throughout the season (Bender et al., 2013). Critical uptake periods are easily defined in annual species, but more difficult in perennial species, as they have a higher buffer capacity and, therefore, do not show results of amendments as quickly as annuals (Srivastava and Malhotra, 2017). This may also be due to perennial crops having simultaneous vegetative and reproductive growth.

Nutrient transport is also relevant when considering biofortification, particularly leaf spraying. If the sprayed nutrient is not phloem mobile, and the leaf is not consumed as food, chances are low that the edible part is fortified (White and Broadley, 2009). While increasing agrobiodiversity and dietary diversity is important, considering single nutrient actions (uptake, transport, and function) within the plant is also vital, as these are highly nutrient-specific.

The transport of all plant assimilates moves from source to sink. Therefore, the movement of all nutrients that are not essential elements or water, travelling in the xylem and directly taken up from the soil, occurs through the phloem. The main transport assimilate in the phloem, is sugar, followed by proteins, hormones, and minerals (Bresinsky et al., 2008). Organic acids such as malate and citrate are also present in the phloem sap (White, 2012b). Environmental effects, such as drought, on phloem transport and phloem sap content have not been extensively recorded. Since, however, xylem and phloem are in hydraulic equilibrium, a change in xylem water content is assumed to also affect phloem transport. Drought or reduced xylem water is assumed to increase carbohydrate concentrations in the sieve tubes and increases the viscosity of the solute. Whether the viscosity increase can cause blockage is, however, not known (Sevanto, 2018).

5.4 Climate change as a "double-burden" on human health

5.4.1 The effects of climate change on food production

Climate change is one of the main causes for large-scale global change occurring in the world. Its effects can be divided into long-term continuous effects, such as increasing global temperature, ozone and CO_2 concentrations, and short-term sudden effects, affecting specific seasons and geographic areas, such as floods, droughts or temperature extremes (Soares et al., 2019). Climate change effects, particularly extreme weather events such as drought, are bound to occur more frequently in the future (Cai et al., 2014; Lim and Hendon, 2017). In the context of food security mitigation, strategies need to be developed to secure food production during shocks, as well as reducing factors accelerating climate change, such as greenhouse gas emissions. Extreme weather events mainly impact rain-fed agricultural systems (around 95% of cereal production in SSA), particularly resource poor smallholder farmers, who in general have fewer coping strategies for drought (Husak et al., 2013).

By the year 2025, 65% of the world's population could be living under water-stressed environments (Nezhadahmadi et al., 2013). This enforces the importance to understand short-term climate change effects such as drought, on quantity and quality of foods produced.

However, very little research has been done to understand the ramifications of drought on the nutrient concentrations of the edible part. The effects of climate change could be seen in this thesis, as an El Niño Southern Oscillation (ENSO) event caused a drought during one of the main growing seasons. Whereas a mild drought had a positive effect on the edible part nutrient concentrations, without significantly detracting from the yield, a severe drought had a strong negative effect on both nutrient concentrations of edible parts as well as yields (Chapter 2). The main effects (highest reductions) were seen in the concentrations of micronutrients and Ca, making the results highly relevant for food and nutrition security (Chapter 2). Severe droughts could, therefore, cause a "double burden" on the local population, as not only the quantity of foods is reduced, but also the quality. Yield effects of drought have been frequently studied, as a low food production can lead to famine (Leng and Hall, 2019) (for example, the Horn of Africa during the 2016 ENSO event (Qu et al., 2019)). Severe drought can, therefore, not only elicit famine, but also increase the incidence of hidden hunger to a higher degree than previously expected. Considering the irreversible effects of hidden hunger, particularly during early childhood (Schwarzenberg and Georgieff, 2018), this extra drought effect should not be ignored.

Long-term climate change effects on yields and nutrient concentrations, such as increased CO_2, global temperatures, and ozone concentrations have enjoyed slightly more attention in research than short-term effects, particularly regarding food nutrient concentrations. A higher CO_2 concentration, for example, has been found to lead to a fertilisation effect in crops (Soares et al., 2019). With rising concentrations, however, comes an over-fertilisation effect. Authors have suggested this effect to be a "carbohydrate-dilution" related to a larger production of carbohydrates in the plant, marginalising other nutrients (Myers et al., 2014), coupled with an increased total growth. This could negatively affect nutrient concentrations in edible parts, particularly in crops grown on poor soils, through a lack of available nutrients to compensate the increased growht (Briat et al., 2015). CO_2 "fertilization" has outweighed the benefits as its concentration increases (St.Clair and Lynch, 2010). Myers et al. (2017) have found lower concentrations of Zn and Fe in grains and legumes due to increased CO_2 concentrations. Finding inverse relationships of yields and nutrients including minerals, vitamins, and proteins, compared to historic values should, however, also be analysed with caution. Some "dilution effect" findings were more related to differences in the genotype (high and low yielding genotypes) rather than being related to climate change (Davis, 2009). Climate change is a multifactorial stress (Gray and Brady, 2016). Combinations of different effects, such as increased ozone and temperature despite the increased CO_2 fertilization, have shown that ozone combined with higher temperatures could reduce crop yields in the U.S.A. and Europe (Tai and Val Martin, 2017).

Short-term climate change effects have a higher and more immediate impact on human health than long-term effects. That is not to say that long-term effects do not impact human health. Short-term effects such as sudden seasonal changes do, however, tend to impact people with the lowest resilience, low resource access and buffering capacity, for example, rain-fed resource poor smallholder farmers, and other resource poor farmers. In East Africa for example, 50% variability of maize yield can be attributed to sudden changes in rainfall and temperature (Voosen, 2020), therefore causing uncertainty for food and nutrition security. The high impact on human health of short-term effects, such as changes to rainfall and rainfall patterns is mainly due to a high dependence on natural resources (Coughlan de Perez et al., 2019), and little access or availability to weather predictions (Voosen, 2020), drought-resistant varieties, irrigation technology, or water saving containers, amongst others. Climate shocks have effects on the entire population in its range, and on its future population as early life shocks (for example, in utero or early childhood), exacerbated through the "double-burden" droughts of lower quantity and quality of foods, can lead to lasting negative effects throughout life. Bauer and Mburu (2017) found a strong correlation between drought and child malnutrition (in children under age five) in Marsabit, Kenya, where pastoralism is the main livelihood, therefore featuring a high weather dependence for food availability. These results, and the strong negative effects of drought on child health, have raised concerns over the apparent low impact of the current aid programs. As climate shocks are becoming increasingly frequent (Cai et al., 2014), the recovery time for farmers after the shock shortens as well. Particularly in SSA, the capacity to absorb shocks is low, due to a rapid population growth, and low economic and institutional coping capacity (Perez et al., 2015). Following the results of this thesis, particularly the significant reduction of micronutrients and Ca in foods in all crops measured, drought emergency aid might be able to mitigate hidden hunger incidence in children, through a blanket supplementation of particularly micronutrients and Ca of the population affected by drought.

While food aid (in this case from the U.S.A.) does contain micronutrient enriched cereal products, the bulk of food aid are staple crops (Webb, 2011). The rations provided to households are targeted to cover the needs of the household, but do not include nutritionally-dense foods unless there is a specific targeted member of the household. Discussions to include a higher diversity of foods are ongoing, however, also wrought with concerns over stability of foods (fruits and vegetables), and increased costs of packaging and transport (Webb, 2011).

The recommendation, therefore, to target particular nutrients population wide, as a result of a drought, and not just in targeted households were effects of malnutrition and hidden hunger can already be measured, stands as an opportunity to avoid the propagation of further hidden hunger incidence.

Solutions need to be found to deal with the issues arising from recurring shocks, particularly for short-term shocks. While long-term climate change effects such as rising temperatures and greenhouse gases affect the entire world, seasonal climate shocks are very local and therefore, also easily moved down on the mitigation priority list by global players. Seasonal climate shocks, particularly when occurring more frequently, could have a cumulative effect on public health, food prices, and food, land and water access – all factors that have been known to spark conflict and mass migration (Kaczan and Orgill-Meyer, 2020; Mazhin et al., 2020). Therefore, mitigating short-term as well as long-term shock effects should become a global priority.

5.4.2 What can research do to mitigate the impact of climate change on food production?

Including food nutrient concentrations as well as yields as a response factor in agricultural trials would increase understanding of the effects of environment on food quality. Using this understanding, the effects on food and nutrition security of potential "nutrient depletion" resultant effects of events such as severe drought or floods could be mitigated. Including both food quality and quantity as response factors during climate shocks would also raise awareness and allow the formulation of strategies to avoid the "double-burden" of low quantity and low quality foods, thereby alleviating famine effects. The effects on food and nutrition of long-term climate change could also be followed by using food quality as a response variable. Mg, for example, has been described as the "forgotten nutrient" and has been found to be deficient on many agricultural soils featuring mainly N, P and K fertilisation (Cakmak and Yazici, 2010). The lack of Mg can also be seen (along with Zn, Fe, I, and Se) in declining grain nutrient concentrations compared to historical data (Guo et al., 2016).

Breeding is a practice to improve agricultural products by selecting better performing varieties in different categories. These categories until recently were focussed more on yield, taste, and colour, rather than on nutritional quality (Robinson et al., 2019). The most famous example of breeding for yield, against abiotic stress, and for improved composition qualities (particularly gluten content related to qualities required for baking) is wheat (Venske et al., 2019). Breeding to increase specific nutritional qualities is called biofortification and includes all agronomic methods to improve nutritional quality in agricultural products (Robinson et al., 2019). Biofortification can come in different forms, such as genetic changes to allow crops to assimilate more of a certain nutrient, or for example, through extra fertilisation with micronutrients. Some examples of this would include Vitamin A maize in Zambia, and Fe beans and pearl millets in India, all three showing significant increases in the biofortified nutrient in the test population (Bouis and Saltzman, 2017). Fertilising nutrients has proven to be efficient when regarding Zn and Se in cereals, and has significantly increased the nutrient concentrations of both nutrients in cereal grains (De Valença et al., 2017).

The problem with breeding and biofortification is, however, that currently only single traits are focussed on for development. Regarding hidden hunger, single nutrient deficiencies in populations are rare, and regions and populations more often feature multiple deficiencies (Bailey et al., 2015). Therefore, focussing on single nutrients does not seem like a viable solution for hidden hunger.

It is also vital to focus on the full bandwidth of crops available including indigenous varieties to secure future food and nutrition security. Currently, much research is invested in cereal and legume crops, which are arguably not as well adapted to where they are cultivated when compared to indigenous crops (Manners and Etten, 2018). Research on indigenous crops is, however, difficult since they are frequently highly relevant to specific areas, and not often widely marketed, making research highly specific, and therefore difficult to (i) gain funding for, and (ii) difficult to publish, thereby removing incentives for national and international researchers. Additionally, there is very little data available for many crops apart from the much studied maize, rice, wheat, and soybean, making comparisons and contextualisation difficult (Chapter 2-4). Focussing more on an increase in diversity of agricultural produce, instead of the current focus on staple crops (Pingali, 2015), would not only increase climate change resilience, but would also have the potential to positively affect household level dietary diversity and, therefore, human health. The tendency to switch to better adapted (often indigenous) crops during climate change progression is a documented coping strategy of many farmers (Manners and Etten, 2018), its occurrence most likely being a function of the length and severity of the shock, the resilience of the farmer, and the access to different seeds. Increasing diversity also increases the probability of selecting crop species more adapted to different climatic shocks (for example drought or pest resistant) and, therefore, able to retain a higher amount of yield and food quality.

Farmers’ access and availability to seeds of diverse and indigenous crops can be problematic. Increasing the focus on a higher diversity could also lead to formulating new methods for local climate change shock adaptability. Creating, for example, decentralized extreme weather response seed banks with a focus on different indigenous or traditional crops, adaptable to different situations (drought resistant crops, crops that can survive waterlogging, or high temperatures), would improve access of rural households to seeds of different crops. National agricultural research institutes such as the Kenyan Agricultural and Livestock Research Organisation (KALRO) or the Ugandan National Agricultural Research Organisation (NARO), would be well suited to host such seed banks as they are present in rural areas, have the infrastructure to set up nurseries, and are experienced in technology dissemination and training. Seed fairs would be another method to increase seed security for climate shocks, in some areas this is an already known and available method of drought management (Orindi and Ochieng, 2005). Yet another possibility would be to select target farmers in the regions to act as seed distributors should shocks occur. As farmer-to-farmer seed transactions are extremely important particularly in rural areas, local farmer seed networks should be targeted when thinking of climate change mitigation, as they are very efficient in seed dissemination (Coomes et al., 2015). Apart from the above mentioned, many other initiatives for improving climate resilience exist, such as weather index insurance, which has shown positive results in for example Kenya (Sibiko and Qaim, 2020). These will, however, not be covered here.

5.5 Food quality - why agricultural research needs a (partial) paradigm shift

Hidden hunger is affecting millions of people all over the world. This gives agriculture as the supplier and the producer the responsibility to maximize efforts to produce high quantity and quality foods. This thesis has shown that food quality is just as, if not more, susceptible to environmental and management effects. Therefore, efforts should be made to further understand interactions between food quality and the environment and management effects to avoid possible "nutrient depletion" scenarios, and an increase of hidden hunger.

5.5.1 Shifting the focus – quantity versus quality

Nutritional research has grown beyond its green revolution focus on increasing the production of staple crops. This was mainly due to the green revolution's ability to increase per capita calories and decrease food prices, thereby decreasing the threat of famine. The focus on developing few staple crops and decreasing malnutrition (energy deficiency) potentially had an increasing effect on the prevalence of hidden hunger (Welch, 2002). Agricultural research has, however, not followed suite, and has largely continued focussing on staple crop production, and providing these with enough nutrients to maintain yield (Khoshgoftarmanesh et al., 2010). Food quality measurements have been severely neglected. This is problematic, as this thesis has shown that environment (particularly soil) and farm management choices, can have significant effects on food quality (Chapters 2-4). Agriculture, as the food supplier could, therefore, potentially cause a sizeable effect on food as well as on nutrition security that so far has not been given much attention.

Different large-scale initiatives exist, aiming at reducing hidden hunger and increasing sustainable agricultural practices. The initiative of "Closing the yield gap" attempts to close the gap of current to potential yield, by improving crop varieties and input levels to increase production (Van Ittersum et al., 2016), and seems reminiscent of the green revolution strategy. In ending hidden hunger, however, "closing the yield gap" does not play a large part, nor does it seem to make many attempts at sustainable agriculture, but is focussed more on the market oriented strategy of increasing yields of staple crops. Due to high climate change vulnerability, and often a very low access and availability of inputs for particularly smallholder farmers of SSA, "closing the yield gap" does, however, not seem like an appropriate solution for sustainably ending hunger. A better strategy may be to use Integrated Soil Fertility Management (ISFM), which involves a focus on combining both organic and inorganic inputs (Sheahan and Barrett, 2017), since large-scale application of only inorganic fertilisers can also cause high levels of environmental pollution (Malik et al., 2020). Focussing on a small number of crops also exacerbates farmers' climate change vulnerability, as the probability of planting a crop species that can withstand climate change effects, to either secure income or food production for the household, is reduced. Therefore, increasing crop and general farm biodiversity provides a solid basis and a realistic solution for smallholder farmers to face climate change effects or other global challenges. The opinions discussed here have left out market and economic demands, which would of course affect farmers planting behaviours and decisions. However, since no research on markets or economy was done in this thesis, they will not be discussed here.

Another initiative is the 4 per 1000 initiative[1], which works on increasing Soil Organic Carbon (SOC) stocks by 0.4% per year to reduce global emissions of greenhouse gases (Kopittke et al., 2019). The practical methods chosen by the initiative, involving the cycling of organic materials and including agroforestry and, therefore, more diversity into farming systems would increase SOC (Corbeels et al., 2019). The methods used in carbon cycling and returning carbon to the soil address the same cycling pathway used by many nutrients. This is an important

[1]Available at https://www.4p1000.org/

approach, as by focussing on carbon to increase the general soil nutrient concentration, soil fertility can be maintained and sustainably increased. A sustainable initiative such as 4 per 1000 could be leveraged, and a human health aspect included by, for example, incorporating a human nutrition aspect in the stage of crop selection. Emphasis here could be placed on nutritious crops and multi-crop systems, which benefit both soil fertility and human health.

5.5.2 Shifting the focus – did Liebig get it all wrong?

Agricultural research has mainly focussed on single nutrients, these often being the macronutrients N, P, and K. Other essential macro- and micronutrients are not receiving the same amount of attention (Khoshgoftarmanesh et al., 2010), and deficiencies therefore risk going unnoticed. The focus on single nutrients goes back to the "law of minimum" by Justus von Liebig, stating that growth is constrained by the scarcest resource or limiting factor (Gorban et al., 2011). Crop nutrient status, measured in plant tissue, is used as a diagnostic tool to place the crop nutrient into a category of deficiency, sufficiency or toxicity (Reuters and Robinson, 1997). This method allows for a high fertilizer use efficiency, as it reduces over-fertilisation. Food quality is often left out of the measurement, with unknown ramifications of the added fertilizer. While it is assumed that increasing plant health and yield would also increase food quality, the fact remains that in some cases stressed food actually retains a higher nutrient concentration (discussed in section 5.4.1.) and that nutrient concentrations in different plant parts do not necessarily correlate. Focussing on single nutrient deficiencies may also not be entirely realistic, as in a soil with poor fertility often more than nutrient is deficient (Kihara et al., 2020). Researchers using compositional data analysis have stated that "the law of minimum" also does not allow for the effect of nutrient interactions (Parent et al., 2013). Nutrient interactions (when simplifying to interactions between nutrient pairs) are present in three forms: zero-interaction, synergistic and antagonistic. Synergistic interactions can be exploited by combining the nutrients into one fertilizer (such as N x K) while for antagonistic relationships, fertilizer combinations as well as timing should be separated. While most macronutrients show synergistic relationships, antagonistic relationships have been observed with divalent cations (i.e. Mg, Ca, Cu, etc.) (Rietra et al., 2017). Interactions become particularly important when the concentration of two elements are near the critical deficiency concentration. An example of this could be the relationship between K and Mg, when one nutrient is increased the other can become deficient (Römheld, 2012). Therefore, when correcting one nutrient deficiency, another nutrient could be adversely affected, with unknown ramifications for food quality.

Using compositional data analysis and nutrient balances can be useful for inner-species comparisons on the performance of different cultivars, or the effects of different environmental factors on nutrient balances. On the one hand, it does involve a certain number of assumptions, mainly as the entire ionome (all of the mineral nutrients in a cell tissue or organism (Baxter, 2015)) is usually not measured, and therefore, some nutrients can only be assumed in the analysis (Parent et al., 2013). On the other hand, using the total concentrations of nutrients in the edible part also allows for food classification into food composition tables, which are vital for nutritionists, public health workers and the food industry (Elmadfa and Meyer, 2010).

Including research both on single nutrients and the ionome is important. It is important to understand the function and transport of single elements since the plant functions are (such as uptake and transport) highly nutrient-specific (White, 2012b,White, 2012a). Understanding the ionome and nutrient interactions become important when also considering the full diversity of nutrients needed for health.

Shifting to a focus on food would also require shifting toward an increased agricultural diversity. While this thesis discussed the effects of soil and environment on three different types of foods (grain, tuber and fruit), the foods in question are all classified as staple crops, and are not nutrient dense. The research done in this thesis should be continued on other crop types that are considered nutrient dense to see whether similar results are found.

5.6 Building interdisciplinarity - using databases as a tool to combine agriculture and nutrition

Many different databases ranging from precipitation to food and leaf nutrient composition were used in this thesis. While the databases were largely open source and easily accessible, the data currently available is at times of questionable quality. Food nutrient composition tables, for example, capture the nutrient contents of the edible parts but often do not list the origin, or the number, of the samples, only the country of collection (USDA, 2018). The problem with not mentioning the geographic origin of the sample is that (i) countries can contain many different soil types and (ii) the high variance that soil fertility can have even on a small scale, and therefore the impact of the soil on food nutrient concentrations can be very large. This could also be seen in the variance of nutrient concentrations of the edible parts particularly in Kapchorwa, which had a much more heterogeneous landscape than Teso South (Chapter 4). A Ferralsol will not be able to produce the same type, quality or amount of yield that a Nitisol (in otherwise comparable conditions) could. Assuming a mean nutrient concentration per country, particularly for a country with a high soil heterogeneity, will skew food nutrient composition to either a deficient or an adequate side, making the data presented quite useless and far from reality. It would be more reasonable to set up food composition databases (focussed on crop varieties) based on geographic formations (e.g. plains, hills, and volcanoes), basement rock, parent material, or soil type – as this would most likely provide a higher correlation to food nutrient concentrations than averaging samples across an entire country. Naming the date of sample collection of the food composition sample would also be of great interest; as was seen in this thesis (Chapter 2) nutrient concentration can vary greatly due to sudden climate shocks. Another problem with food composition tables is that they are compiled on a national level. The values compiled are, however, not separated by geographical origin, therefore completely leaving out the effects of environmental heterogeneity.

Plant tissue nutrient concentration databases supply researchers with levels of deficiency, sufficiency or toxicity of different nutrients (usually of the leaves) and relate these to yield. Leaf nutrient concentration databases have, however, been criticised for not being up to date, particularly regarding the values of high yielding varieties (Kovács and Vyn, 2017). A similar construct as the International Network of Food Data Systems (INFOODS) food composition database of FAO could be produced – although as mentioned above for food composition, using soils as a basis instead of country level would be beneficial. FAO has an infrastructure in place with INFOODS and data collection capacity from FAOSTAT to manage and consistently update leaf nutrient concentration databases (similarly to the already present food databases). The databases concerning different plant parts could also be linked so that food, plant tissue, and soil composition databases are found in one location, listed by cultivar. This would allow for an easier cooperation between nutritionists and agronomists by sharing information and building a "data bridge" between the disciplines.

Weather data for SSA in general, and East Africa specifically, was difficult to come by – particularly in the resolution needed to properly cover the two research areas. Most weather data available for SSA is model based, and therefore also prone to errors (Lennard et al., 2018). This thesis used only precipitation data from TAMSAT, as this data was both model and weather station based, therefore making it one of the more precise precipitation databases for SSA (Kimani et al., 2017). Efforts have been made to increase weather station frequency throughout SSA, to improve weather predictions and models, through projects such as the Trans-African HydroMeteorological Observatory (TAHMO)[2], building weather stations at schools and linking them to an online platform – however, there is still a long way ahead to

[2]Available at https://www.metergroup.com/de/environment/fallstudien/tahmo-wetter-initiative/

close the data gap.

5.7 Concluding remarks and final recommendations

The effects of the environment and farm management on food nutrient concentrations and yields were analysed in two research areas with opposing soil types on three different food crops. Soils of different fertilities produced crops with significant differences in their nutrient concentrations as well as yield. A drought in the research area allowed for the evaluation of drought stress on the food nutrient concentrations of different food crops. The results showed that a severe drought can cause a "double burden" of malnutrition, as both the quantity and the quality of produced foods is reduced. A mild drought increased food quality, while also maintaining quantity in the more drought resistant crops. Essential elements are transported differently within the plant. Micronutrients and Ca, for example, are transported mainly in the xylem, while most macronutrients are transported in the phloem. As the xylem is very susceptible to drought, micronutrients and Ca concentrations in the edible parts were most heavily affected during drought. When considering the soils, SOM was the most important factor positively affecting edible part nutrient concentrations, in the absence of adequate fertilizer inputs. Perennial crops showed a higher buffer capacity when considering soil factors than annual crops. It is, therefore, likely that soil amendments would show a delayed response in the nutrient concentrations of perennial crops edible parts than in annual crops. The function of the edible part (generative or storage) was also highly relevant, as the function and the timing of harvest would directly affect nutrient concentrations of foods. Leaves are often measured in agronomic trials to gauge plant health and yields. Measuring leaves, however does not give any indication on the nutrient concentrations of the edible part, particularly when considering micronutrients and Ca as these cannot be remobilised from other plant parts. This thesis has shown that food quality is just as susceptible as, if not more susceptible than food quality to environmental and farm management effects.

Due to the high incidence of hidden hunger in the world, concurrent with climate change and degrading soils, agriculture as the food supplier has a responsibility to attempt to produce high quantity and most of all quality foods. Food quality is particularly relevant, as it has been neglected in agricultural research. The results, however, show that particularly, in lieu of increasing soil degradation, coupled with increased findings of the dilution effect (climate change (CO_2-fertilisation) and high yielding varieties), focussing on food quality is vital to avoid a negative impact on food and nutrition security. Since mainly micronutrients and

Ca were affected by environmental factors, and also showed the lowest correlations between leaf and edible parts, environmental and farm management factors such as soil degradation and over-fertilisation causing dilution, may have already contributed more to hidden hunger than previously expected. There are many different recommendations available that could contribute to improve this situation. For one, increasing diversity in the diet as well as increasing agrobiodiversity would contribute to human health. Increasing ecosystem services and focussing on sustainable agricultural methods such as increasing SOM could also improve quality and quantity of produced foods.

Creating more consolidated databases between data used by nutritionists and agronomists would increase the possibilities for necessary collaboration. Using for example, soil type as the basis of databases organised by cultivar and containing different tissue (including food) nutrient compositions, would give a holistic view of crop and food nutrient content as well as decreasing the variability introduced by different soil types. This database would allow for the development of new crop models, and identify areas of potential "nutrient depletion" based on climate or economic shocks (for example affecting fertilizer availability).

Nutrient transport methods have shown to be important in all aspects of food and food nutrient composition from proteins to vitamins, minerals, and even potentially toxic heavy metals. Focussing on which nutrients could be affected most during climate shocks, for example, could decrease hidden hunger susceptibility of entire regions by utilizing tailored emergency aid. Moderately stressed plants often happen to be more nutritious plants, therefore the usage of plant stress to maximize food nutrient concentrations should be further researched to avoid yield losses.

Fertile soil is a finite resource, and through population increase and a changing climate, it is becoming increasingly endangered. Calls for immediate action are being continuously published to save the world and its resources. This thesis has shown that soil degradation and climate change effects may have already caused more damage to human health than previously expected. Therefore, I would like to add to the urgent calls for action to increase sustainable agricultural food production, and to increase and protect biodiversity in all facets of food production. Ending hunger and improving food and nutrition security for all, particularly when faced with global change issues such as degrading soils and a changing climate, requires a collaborative effort by all disciplines.

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A Appendix - Figures and Tables

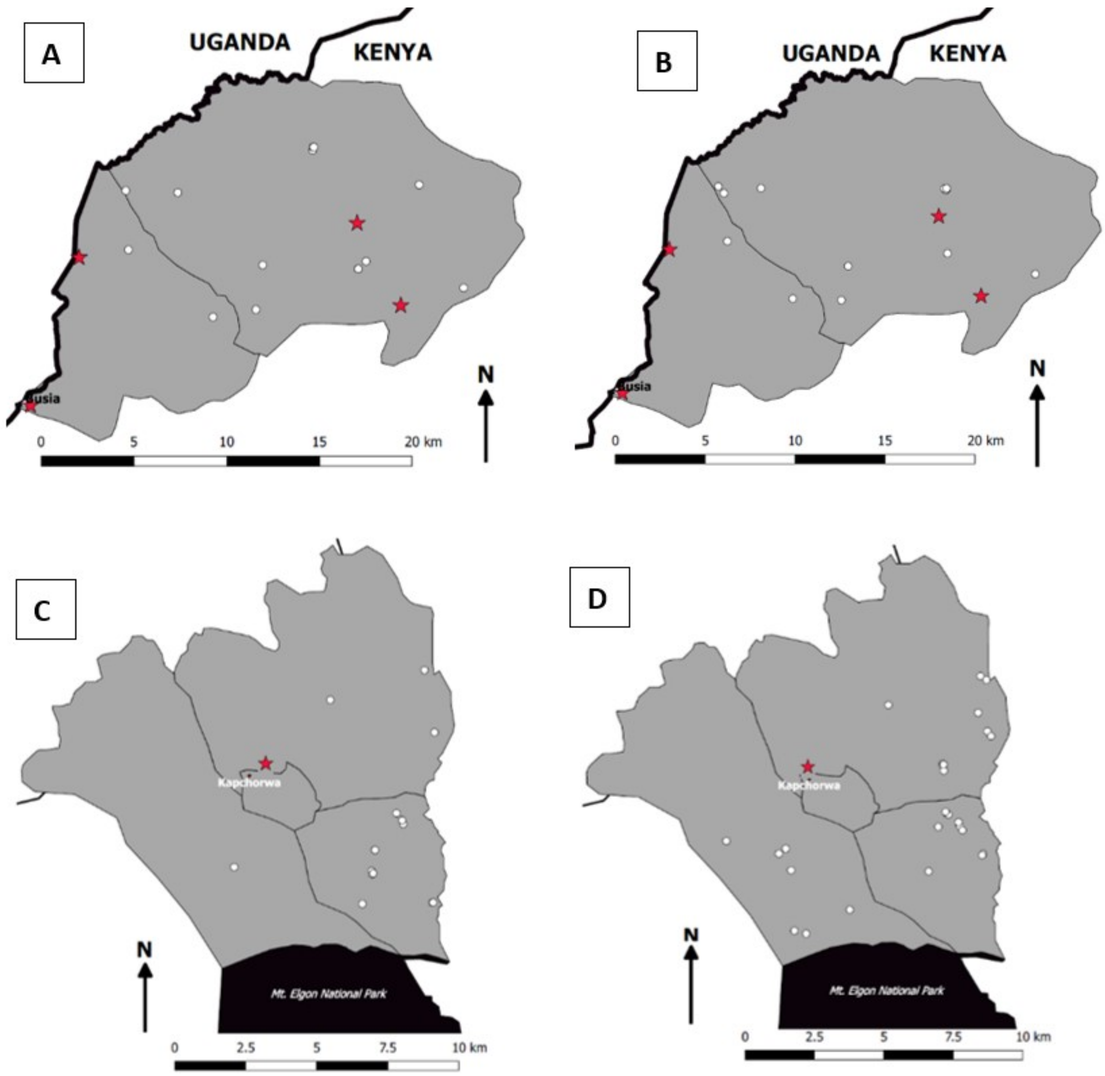


Figure A.1: Sample sites of (A) maize grain (*Zea mays* L.) in Teso South, Kenya; (B) cassava tuber (*Manihot esculenta* Crantz); (C) maize grain (*Zea mays* L.); and (D) matooke fruit (*Musa acuminata* Colla). Circles mark the locations of sample collection in both normal and drought season. Red stars mark rain gauge locations.

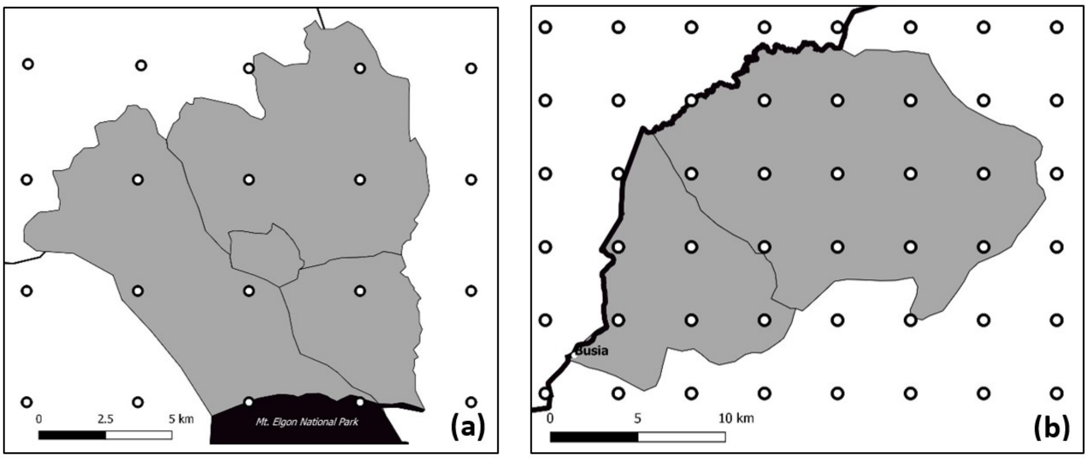


Figure A.2: Grid points from the TAMSAT database (https://www.tamsat.org.uk/data/archive) in both research areas (a) Kapchorwa, Uganda with 20 data points, and (b) Teso South, Kenya with 48 data points.

Table A.1: Crop development stages described maize by Barron et al. (2003).

Development stage	Days after sowing
Stage 1: emergence and establishment	1-30
Stage 2: vegetative development	31-60
Stage 3: tasseling, flowering, and grain filling	61-90
Stage 4: grain filling and drying	91-120

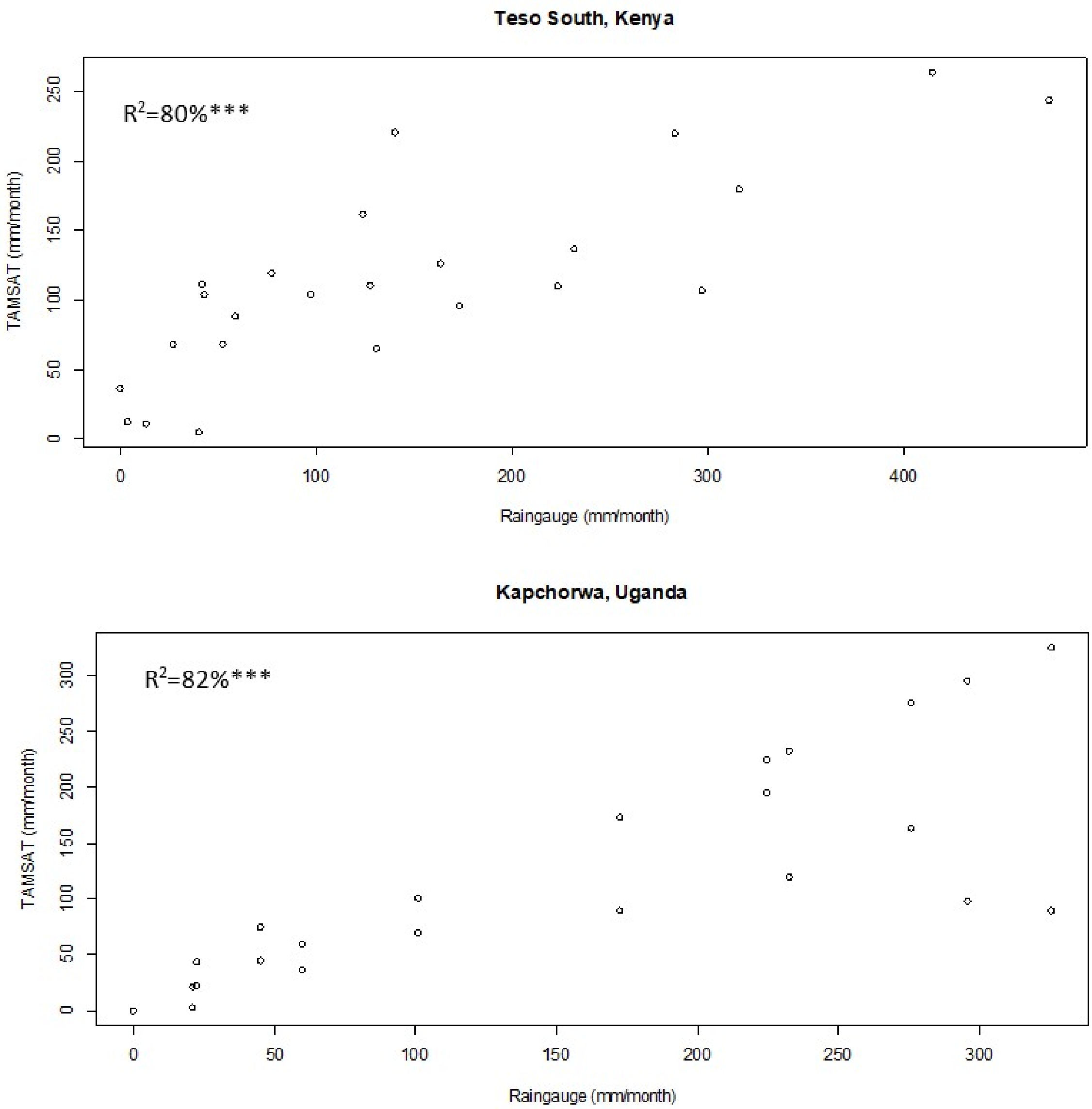
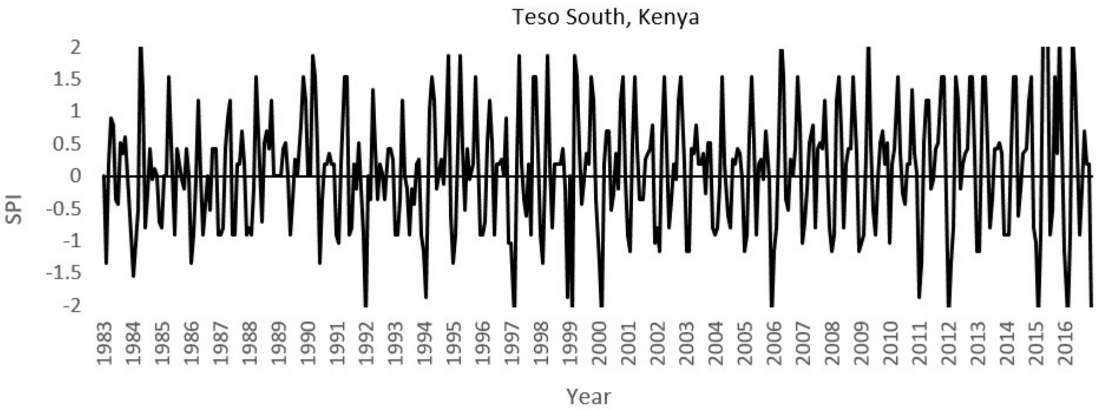


Figure A.3: Correlation between the collected rain gauge data in Teso South, Kenya and Kapchorwa, Uganda, using the average of the four rain gauges found for two years 2015 and 2016, in total the values average precipitation of 24 months, per month, compared to the same time-frame downloaded from the TAMSAT database (https://www.tamsat.org.uk/), using the monthly average of 48 data points for Teso South and 20 data points for Kapchorwa.



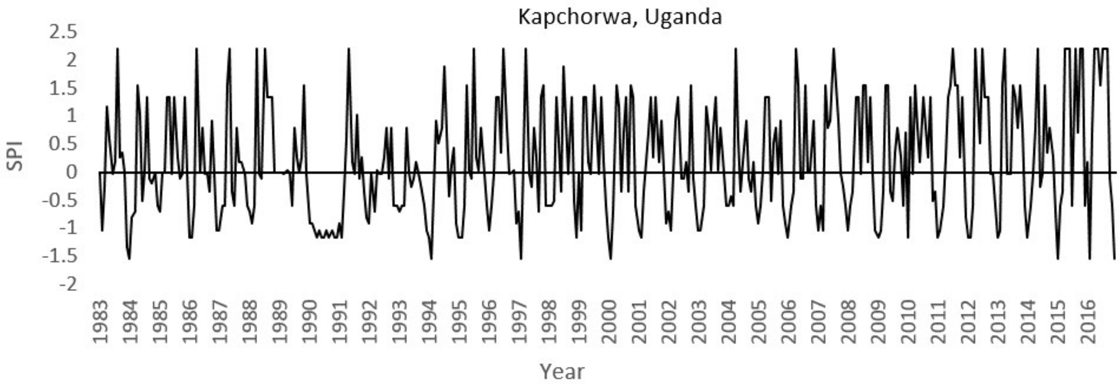


Figure A.4: Standardized Precipitation Index (SPI) calculated per month in Teso South and Kapchorwa from the TAMSAT dataset. Time frame: 1983-2016. Negative values signify drought, positive values signify more rain than normal, scale is between SPI index -2 and 2.

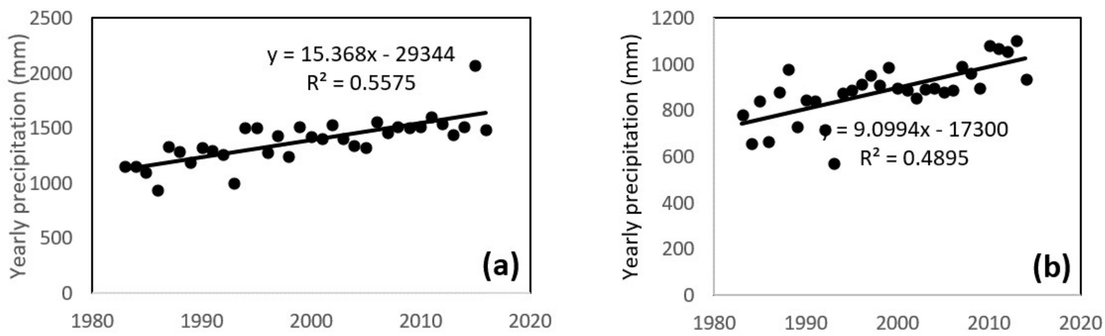


Figure A.5: Correlation of years and precipitation from the TAMSAT database from 1983 -2017. (a) Teso South, Kenya (n=48); (b) Kapchorwa, Uganda (n=20).

Table A.2: Mean nutrient concentration and yields of maize grain in Kapchorwa, Uganda. Marked are levels of significance. p<0.05*; p<0.005**; p<0.0005*** on the significantly higher factor. Shown are means and standard deviation (SD).

Maize Grain Uganda	Variable	First Growing Season (FGS mean)	SD FGS	Second Growing Season (SGS mean)	SD SGS	Percent difference between FGS and SGS
Yield (t/ha)	Yield	2.18*	1.13	1.55	1.64	28%
Macro (mg/kg)	Mg	1042	477	915	230	12%
	P	3414	506	3493	735	2%
	S	997	300	763	109	23%
	K	8568	6529	4467	475	48%
	Ca	209	142	200	195	4%
Micro (mg/kg)	Fe	144*	165	47	7.03	67%
	Cu	57.6**	60.1	6.5	6.51	89%
	Zn	46.2	25.1	38	3.93	17%
	Mn	15.7**	14.6	2.9	1.62	81%

Table A.3: Mean nutrient concentration and yields of matooke fruit in Kapchorwa, Uganda. Marked are levels of significance. p<0.05*; p<0.005**; p<0.0005*** on the significantly higher factor. Shown are means and standard deviations (SD).

Matooke Fruit, Uganda	Variable	First Growing Season (FGS mean)	SD FGS	Second Growing Season (SGS mean)	SD SGS	Percent difference between FGS and SGS
Yield	Yield	2.77	1.94	2.73	2.61	1%
	Mg	2842***	504	906	141	68%
	P	2331***	234	1699	322	27%
	S	2116***	194	483	185	77%
	K	28845***	2367	19198	2217	33%
	Ca	8510***	1226	1204	120	86%
	Mn	640***	142	6.87	2.96	99%
	Fe	335***	60.5	56.8	32.1	83%
	Cu	5.30	1.06	5.08	1.69	4%
	Zn	5.94*	1.57	7.39	1.52	24%

Table A.4: Mean nutrient concentration and yields of maize grain in Teso South, Kenya. Marked are levels of significance. p<0.05*; p<0.005**; p<0.0005*** on the significantly higher factor. Shown are means and standard deviation (SD).

Maize Grain, Kenya	Variable	First Growing Season (FGS mean)	SD FGS	Second Growing Season (SGS mean)	SD SGS	Percent difference between FGS and SGS
Yield	Yield	0.46	0.28	0.47	0.36	2%
	Mg	785	373	968*	192	19%
	P	2554	1326	3805**	426	49%
	S	869*	139	794	26.5	9%
	K	4963	1221	4661	527	6%
	Ca	42.5	11.8	191***	94.7	79%
	Fe	34.3	10.4	57.7***	16.1	68%
	Cu	3.53	0.43	3.96	1.20	12%
	Zn	28.8	7.16	40.6**	3.54	41%
	Mn	3.60	1.31	4.21	1.10	17%

Table A.5: Mean nutrient concentration and yields of cassava tuber, Teso South, Kenya. Marked are levels of significance. $p<0.05$*; $p<0.005$**; $p<0.0005$*** on the significantly higher factor. Shown are means and standard deviation (SD).

Cassava Tuber, Kenya		First Growing Season (FGS mean)	FGS SD	Second Growing Season (SGS mean)	SGS SD	Percent difference between FGS and SGS
Yield	Yield	1.24*	1.65	0.41	1.34	67%
	Mg	366	126	452*	101	23%
	P	713	199	1083***	66.1	52%
	S	102	85.6	246**	29.8	59%
	K	7259	2195	9051	439	25%
	Ca	403	263	998**	140	60%
	Mn	6.46**	1.82	3.19	0.92	51%
	Fe	57.4	12.2	65.8	15.2	15%
	Cu	3.04	0.56	3.29	0.75	8%
	Zn	9.15	3.64	10.3*	0.65	12%

Table A.6: Comparison of the Standardized Precipitation Index (SPI) in Teso South, Kenya and Kapchorwa, Uganda, during two critical phases of maize during drought; SPI1 signifying SPI at tasselling, flowering and grain filling, while SPI2 is the second critical phase at grain filling and drying. The mean of the total SPI across both seasons, and then the mean per season (FGS and SGS) as well as the corresponding standard deviation is shown. Lastly shown is the difference of SPI between the means of FGS and SGS.

Region		Mean SPI1	Standard Deviation SPI1	Difference between SPI1 FGS and SGS	Mean SPI2	Standard Deviation SPI2	Difference between SPI2 FGS and SGS
Teso South	Total SPI	0.86	0.83		-0.09	1.11	
	FGS	1.26	0.90	0.94	0.30	0.91	0.91
	SGS	0.32	0.23		-0.61	1.18	
Kapchorwa	Total	0.66	1.31		0.47	1.79	
	FGS	1.62	0.32	2.35	1.80	0.30	3.27
	SGS	-0.73	0.41		-1.47	0.27	

Table A.7: Regression between the Standardized Precipitation Index (SPI) values of the two critical stages in maize (SPI1 and SPI2) compared to the maize nutrient concentration in Teso South, Kenya and Kapchorwa, Uganda. Shown are the regression coefficients and p-values of the comparisons between SPI1, SPI2 and SPI1*SPI2. More regression coefficients means polynomial regressions. Marked are levels of significance. *p<0.05; **p<0.005; ***p<0.0005 on the significantly higher factor.

		Teso South			Kapchorwa		
		SPI1	SPI2	SPI1*SPI2	SPI1	SPI2	SPI1*SPI2
Yield	Regression Coefficient(s)	0.01	-0.01	0.04	-0.44 /0.34	1.40/-0.27/0.39	0.33
	p value	0.94	0.86	0.52	0.02*	0.04*	0.22
Mg	Regression Coefficient(s)	-0.02	0.005	0.002	0.01	0.003	0.007
	p value	0.52	0.73	0.95	0.61	0.88	0.71
P	Regression Coefficient(s)	0.0.8/-0.09	-0.05	-0.06	-0.005	0.07	0.002
	p value	0.04*	0.02*	0.28	0.64	0.03*	0.89
S	Regression Coefficient(s)	0.02/0.03/-0.02	-0.008/-0.009	0.002	0.03	0.02	0.03
	p value	0.006**	0.03*	0.87	0.07	0.41	0.11
K	Regression Coefficient(s)	0.05/-0.02	0.003	0.001	0.06	0.24	0.06
	p value	0.04*	0.84	0.95	0.08	0.008**	0.07
Ca	Regression Coefficient(s)	-0.18	0.34/-0.12/-0.15	-0.06	0.03	0.1	0.03
	p value	0.02*	0.003**	0.3	0.4	0.03*	0.54
Fe	Regression Coefficient(s)	0.13/-0.10	-0.05	-0.02	0.11	0.07	0.05
	p value	0.001**	0.03*	0.31	0.03*	0.11	0.28
Cu	Regression Coefficient(s)	-0.02	-0.02	0.03	0.28	0.2	0.14
	p value	0.4	0.08	0.22	0.0004***	0.005**	0.11
Zn	Regression Coefficient(s)	0.10/-0.08	-0.04	-0.06	0.01	0.006	0.04
	p value	0.0002***	0.04*	0.02*	0.56	0.77	0.21
Mn	Regression Coefficient(s)	0.26/-0.15	-0.03	-0.05	0.23	0.16	0.16
	p value	0.0001***	0.14	0.1	0.0007**	0.008**	0.01*

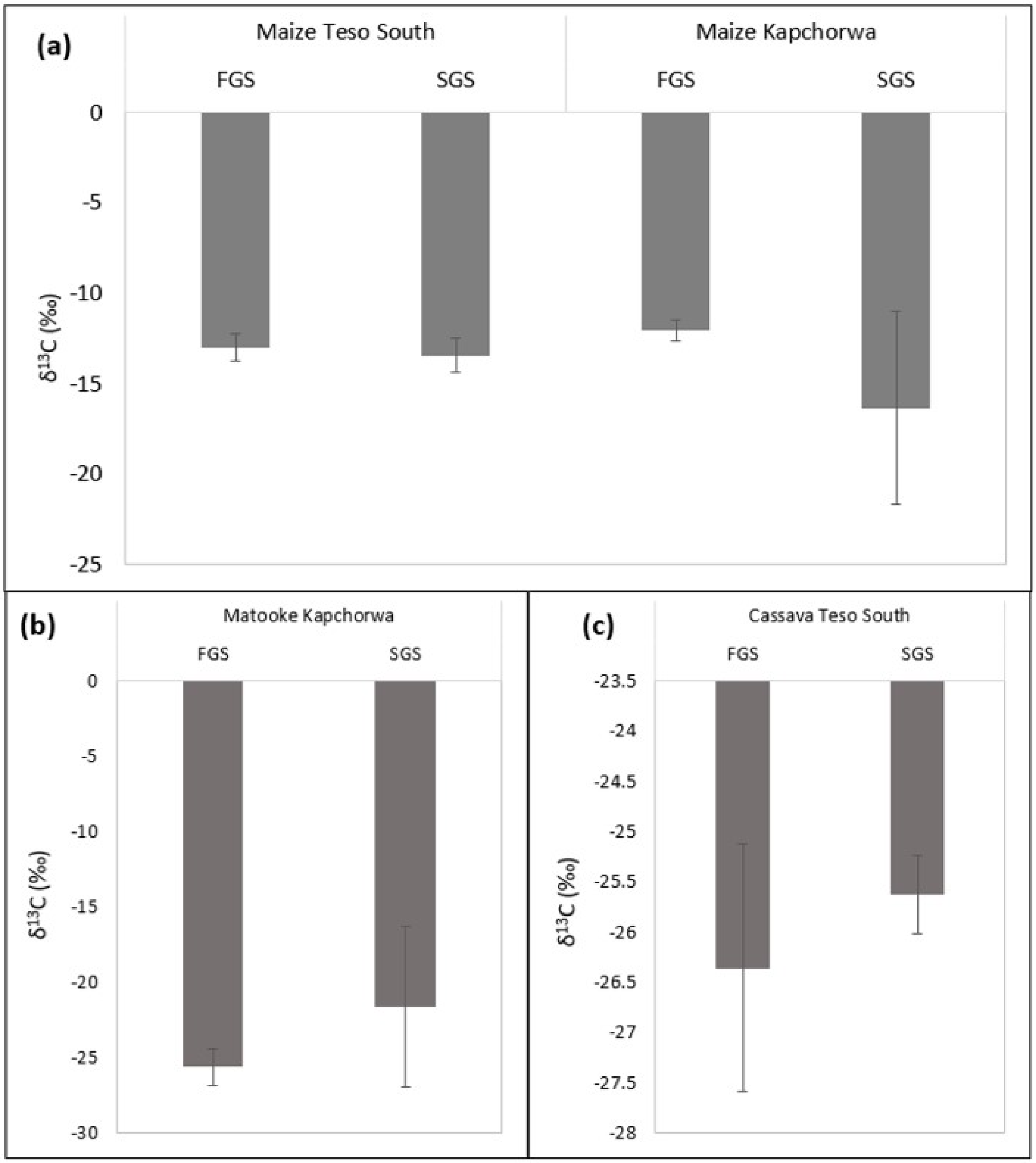


Figure A.6: δ13C measurements for different crops comparing the normal season (FGS, Mar-Aug 2016) to the drought season (SGS, Oct-Dec 2016). (a) Maize in Teso South, Kenya and Kapchorwa, Uganda. (b) Matooke in Kapchorwa, Uganda; (c) Cassava in Teso South, Kenya.

Table A.8: δ13C and δ15N mean measurements and standard deviations of n=8 samples of each maize grain and cassava tuber in Teso South, Kenya and maize grain and matooke fruit in Kapchorwa, Uganda. The samples were compared from the same sites in the FGS (Mar-Aug 2016) and the SGS (Oct-Dec 2016).

Region	Plant part	Season	Mean δ13C/12C	SD	Mean δ15N/14N	SD
Teso South, Kenya	Maize Grain	FGS	-13.02	0.73	5.17	0.5
		SGS	-13.47	0.93	3.63	0.1
	Cassava Tuber	FGS	-26.36	1.23	4.47	1.85
		SGS	-25.62	0.39	4.46	0.32
Kapchorwa, Uganda	Maize Grain	FGS	-12.07	0.56	3.89	3.2
		SGS	-16.37	5.34	4.03	0.61
	Matooke Fruit	FGS	-25.65	1.2	4.54	2.08
		SGS	-21.66	5.32	3.49	1.05

Table A.9: Comparison of maize grain nutrient concentration (mg/kg) between samples collected in Kapchorwa (n= 30) and Teso South (n=31) during the first growing season (FGS) 2016. SD signifies standard deviation, while max and min show the maximum and minimum data points.

	Teso South, Kenya					Kapchorwa, Uganda				
Maize grain	Mean	Median	SD	Max	Min	Mean	Median	SD	Max	Min
Yield (t/ha)	0.49	0.42	0.34	1.5	0.03	2.05***	1.99	1.1	5.95	0.12
Mg (mg/kg)	861	741	404	2251	379	1071	1036	522	2519	350
P (mg/kg)	2967	2911	1289	6450	859	3532*	3463	714	6092	2476
S (mg/kg)	861	859	136	1147	528	1046	927	420	2150	489
K (mg/kg)	4989	4883	1116	8010	3198	9120*	4373	7537	32237	3042
Ca (mg/kg)	46	43	14	83	23	290***	123	329	1607	86
Fe (mg/kg)	36	34	14	99	22	141***	80	141	610	30
Cu (mg/kg)	3.2	4.7	0	4.1	3.1	55***	26	67	292	3.4
Zn (mg/kg)	32	33	8.2	49	15	50*	43	27	132	19
Mn (mg/kg)	3.4	3.2	1	6.3	0.99	16***	7.9	17	60	4.9

Marked are levels of significance, where *$p<0.05$; **$p<0.005$; ***$p<0.0005$ on the significantly higher means.

Table A.10: Description of the variable groups used in the Canonical Correspondence Analysis (CCA).

ID	Variables
Maize Grain Kenya	Maize grain nutrient concentration (mg/kg) and yield (t/ha) in Teso South, specifically the elements MgG, PG, SG, KG, CaG, MnG, CuG, FeG, and ZnG
Maize Grain Uganda	Maize grain nutrient concentration (mg/kg) and yield (t/ha) in Kapchorwa, specifically the elements MgG, PG, SG, KG, CaG, MnG, CuG, FeG, and ZnG
Cassava Tuber Kenya	Cassava tuber nutrient concentration (mg/kg) and yield (t/ha) in Teso South, specifically the elements MgT, PT, ST, KT, CaT, MnT, CuT, FeT, and ZnT.
Matooke Fruit Uganda	Matooke fruit nutrient concentration (mg/kg) and yield (t/ha) in Kapchorwa, specifically the elements MgF, PF, SF, KF, CaF, MnF, CuF, FeF, and ZnF.
Soil Properties	Soil Properties, specifically texture (sand, silt, clay), eCEC, pH, altitude, Nitrogen content (N), Carbon content (C), and Carbon/Nitrogen ratio (CN)
Soil Elements	Soil elemental concentration (mg/kg) specifically the elements MgS, AlS, PS, SS, KS, CaS, TiS, CrS, MnS, FeS, NiS, ZnS, SeS, and CdS
Management Effects	Anthropogenic effect, specifically distance to household (Meters), Species Richness (SR), Species Diversity (SD), Organic fertiliser (OrganFert) (kg/m2), and Inorganic fertiliser (InorgFert) (kg/ m2).

G, T or F (respectively Grain, Tuber, or Fruit) is added to mark maize grain, cassava tuber and matooke fruit and differentiate soil and plant nutrients. Soil nutrients receive an S.

Table A.11: Nutrient concentrations and yields of cassava tuber collected in Teso South (n=27). Shown are means, medians, and standard deviation (Stan Dev). Samples were collected during the long rain season (July-August) 2016. Table adapted from Fischer et al. 2019.

Cassava Tuber Teso South, Kenya	Mean	Median	StanDev	Max	Min
Yield (t/ha)	1.41	0.76	1.94	8.88	0.1
Mg (mg/kg)	362	309	115	739	278
P (mg/kg)	862	816	289	1590	434
S (mg/kg)	106	70.5	81.9	277	11.5
K (mg/kg)	8370	8120	2640	14280	3398
Ca (mg/kg)	327	310	214	987	70
Mn (mg/kg)	7.86	7.83	2.41	13.2	3.61
Fe (mg/kg)	52.2	52.7	13.7	74	30.5
Cu (mg/kg)	3.23	3.00	0.53	4.00	2.00
Zn (mg/kg)	9.40	8.75	2.85	18.5	5.00

Table A.12: Nutrient concentrations and yields of matooke fruit collected in Kapchorwa, Uganda (n=54). Shown are means, medians, and standard deviation (Stan Dev). Samples were collected during the long rain season (July-August) 2016. Table adapted from Fischer et al. 2019.

Matooke Fruit Kapchorwa, Uganda	Mean	Median	StanDev	Max	Min
Yield (t/ha)	3.47	3.11	2.69	13	0.71
Mg (mg/kg)	1017	967	336	2532	568
P (mg/kg)	1510	1480	329	2634	977
S (mg/kg)	462	373	385	2387	248
K (mg/kg)	24499	23714	3254	37145	18931
Ca (mg/kg)	433	308	369	1645	46
Mn (mg/kg)	20.1	18.3	12.3	77.5	5.5
Fe (mg/kg)	89.3	73	61.1	373.5	32.3
Cu (mg/kg)	20.9	19.5	9.9	41.5	8
Zn (mg/kg)	36.2	28.8	28.2	95.5	3.5

Table A.13: Results of the Anova permutation rank test done in R using the package vegan. The test ranked the effects of the explanatory variables (soil and management variables) on the nutrient concentration and yield of cassava tuber collected in Teso South, Kenya. The tables show the Type I and Type III effects.

Cassava Tuber Anova

		Variable	DF	ChiSquare	F	Pr(>F)
All variables						
		NO SIGNIFICANCE				
Soil Properties + Soil Elements						
		NO SIGNIFICANCE				
Soil Elements and Management Factors						
Type I	1	Altitude	1	0.0099408	5.7389	0.007**
	2	Meter	1	0.0032215	1.8598	0.137
	3	Organic Fertilizer	1	0.001958	1.1304	0.328
	4	FeS	1	0.0020365	1.1757	0.333
	5	SR	1	0.0016117	0.9304	0.422
Type III	1	Altitude	1	0.0043882	2.5333	0.075.
	2	FeS	1	0.0022142	1.2783	0.292
	3	SR	1	0.001432	0.8267	0.484
	4	MnS	1	0.0013533	0.7813	0.492
Soil Properties and Management Factors						
Type I	1	Altitude	1	0.0092487	8.6864	0.001***
	2	Organic Fertilizer	1	0.0092487	2.8581	0.049*
	3	Meter	1	0.0025392	2.3848	0.092.
	4	SR	1	0.0022985	2.1588	0.106
	5	pH	1	0.0021584	2.0272	0.114
Type III	1	Altitude	1	0.0092487	8.6864	0.001***
	2	Organic Fertilizer	1	0.0030995	2.9111	0.051.
	3	eCEC	1	0.0020352	1.9114	0.135
	4	Sand	1	0.0018429	1.7309	0.148
	5	Inorganic Fertilizer	1	0.0020386	1.9146	0.155
Management Factors						
Type I	1	Altitude	1	0.0099408	8.9912	0.001***
	2	Meter	1	0.0032215	2.9138	0.048*

	3	Organic Fertilizer	1	0.001958	1.771	0.143
	4	SR	1	0.0016117	1.4577	0.214
	5	Inorganic Fertilizer	1	0.0007688	0.6954	0.541
Type III	1	Altitude	1	0.0099408	8.9912	0.002**
	2	Meter	1	0.0030387	2.7484	0.041*
	3	Inorganic Fertilizer	1	0.0028204	2.551	0.059.
	4	Organic Fertilizer	1	0.0023688	2.1426	0.111
	5	SR	1	0.0016098	1.456	0.208
Soil Elements						
Type I	1	MgS	1	0.0044002	2.7346	0.061.
	2	TiS	1	0.002942	1.8284	0.163
	3	ZnS	1	0.0023095	1.4353	0.22
	4	MnS	1	0.0022983	1.4283	0.235
	5	KS	1	0.0012346	0.7673	0.521
Type III	1	KS	1	0.0036122	2.2449	0.089.
	2	ZnS	1	0.0031579	1.9626	0.099.
	3	SS	1	0.0028669	1.7817	0.136
	4	CrS	1	0.0023463	1.4581	0.217
	5	NiS	1	0.0019912	1.2375	0.278
Soil Properties						
		NO SIGNIFICANCE				

Table A.17: Model selection from the bivariate linear mixed model (code from (Piepho 2018)) , to estimate correlations between nutrient concentrations in leaves (L) and yield, grain (G), tuber (T), and fruit (F) and yield using samples collected from maize, cassava and matooke from Teso South, Kenya and Kapchorwa, Uganda.

Model Selection for Maize Kapchorwa			
	Field	Field HH	Field HH Vill
MgL/Yield	X		
PL/Yield	X		
KL/Yield	X		
SL/Yield		X	
CaL/Yield	X		
FeL/Yield	X		

ZnL/Yield		X	
MnL/Yield	X		
CuL/Yield	X		
MgG/Yield	X		
PG/Yield		X	
KG/Yield	X		
SG/Yield	X		
CaG/Yield	X		
FeG/Yield	X		
ZnG/Yield	X		
MnG/Yield	X		
CuG/Yield		X	
Model Selection for Maize Teso South			
	Field	Field HH	Field HH Vill
MgL/Yield		X	
PL/Yield		X	
KL/Yield		X	
SL/Yield		X	
CaL/Yield		X	
FeL/Yield		X	
ZnL/Yield		X	
MnL/Yield		X	
CuL/Yield		X	
		X	
MgG/Yield		X	
PG/Yield		X	
KG/Yield	X		
SG/Yield	X		
CaG/Yield	X		
FeG/Yield	X		
ZnG/Yield		X	
MnG/Yield		X	

CuG/Yield	X		
Model Selection for Cassava in Teso South			
	Field	Field HH	Field HH Vill
MgL/MgT	X		
PL/PT	X		
KL/KT	X		
SL/ST	X		
CaL/CaT	X		
FeL/FeT	X		
ZnL/ZnT	X		
MnL/MnT	X		
CuL/CuT	X		
MgL/Yield	X		
PL/Yield	X		
KL/Yield	X		
SL/Yield		X	
CaL/Yield	X		
FeL/Yield	X		
ZnL/Yield	X		
MnL/Yield	X		
CuL/Yield	X		
MgT/Yield	X		
PT/Yield	X		
KT/Yield	X		
ST/Yield	X		
CaT/Yield	X		
FeT/Yield	X		
ZnT/Yield	X		
MnT/Yield	X		
CuT/Yield	X		
Model Selection for Matooke in Kapchorwa			

	Field	Field HH	Field HH Vill
MgL/MgF	X		
PL/PF		X	
KL/KF	X		
SL/SF	X		
CaL/CaF	X		
FeL/FeF	X		
ZnL/ZnF	X		
MnL/MnF	X		
CuL/CuF	X		
MgL/Yield	X		
PL/Yield		X	
KL/Yield	X		
SL/Yield	X		
CaL/Yield	X		
FeL/Yield		X	
ZnL/Yield		X	
MnL/Yield		X	
CuL/Yield	X		
MgF/Yield	X		
PF/Yield		X	
KF/Yield	X		
SF/Yield	X		
CaF/Yield	X		
FeF/Yield	X		
ZnF/Yield		X	
MnF/Yield	X		
CuF/Yield	X		

Table A.14: Results of the Anova permutation rank test done in R using the package vegan. The test ranked the effects of the explanatory variables (soil and management variables) on the nutrient concentration and yield of matooke fruit collected in Kapchorwa, Uganda. The tables show the Type I and Type III effects.

Matooke Fruit Anova

Variable			DF	ChiSquare	F	Pr(>F)
All variables						
	NO SIGNIFICANCE					
Soil Properties and Soil Elements						
	NO SIGNIFICANCE					
Soil Elements and Management factors						
	NO SIGNIFICANCE					
Type I	NO SIGNIFICANCE					
Type III	1	Inorganic Fertilizer	1	0.0015424	2.5687	0.073.
	2	Species Richness	1	0.0011608	1.9306	0.106
	3	NiS	1	0.0011766	1.9569	0.122
	4	CrS	1	0.0011094	1.8451	0.130
	5	SS	1	0.0007882	1.3109	0.268
Soil Properties and Management Factors						
	NO SIGNIFICANCE					
Management Factors						
	NO SIGNIFICANCE					
Soil Elements						
	NO SIGNIFICANCE					
Soil Properties						
	NO SIGNIFICANCE					

Table A.15: Comparison of fertilizer use and amounts used of organic fertiliser (OrganicFert: manure and crop residues), and inorganic fertiliser (InorganFert: DAP, CAN, Urea, and NPK) calculated into kg/m^2. Also shown are the mean and the standard deviation (SD) of the fertilisers used.

		Use Frequency		Amount Used (kg/m^2)			
		OrganicFert	InorganFert	OrganicFert		InorganFert	
				Mean	SD	Mean	SD
Teso South	Maize fields	13%	57%	0.05	0.14	0.03	0.02
	Cassava fields	27%	31%	0.09	0.29	0.01	0.02
Kapchorwa	Maize fields	20%	27%	0.02	0.01	0.02	0.03
	Matooke fields	45%	17%	0.05	0.09	0.04	0.06

Table A.16: Comparison of the three composition tables, showing for which Element the database has reference values. X marks presence. Kenya: The Kenyan food composition table of the FAO for Kenya (available at: http://www.fao.org/3/I8897EN/i8897en.pdf) was used (maize code: 01018; cassava code: 02007) (FAO and Government of Kenya, 2018); 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); and Global: 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).

	Elements	Kenya	Uganda	Global
Macro	Mg	X		X
	P	X		X
	S			
	K	X		X
	Ca	X	X	X
Micro	Fe	X	X	X
	Zn	X	X	X
	Mn			
	Cu			

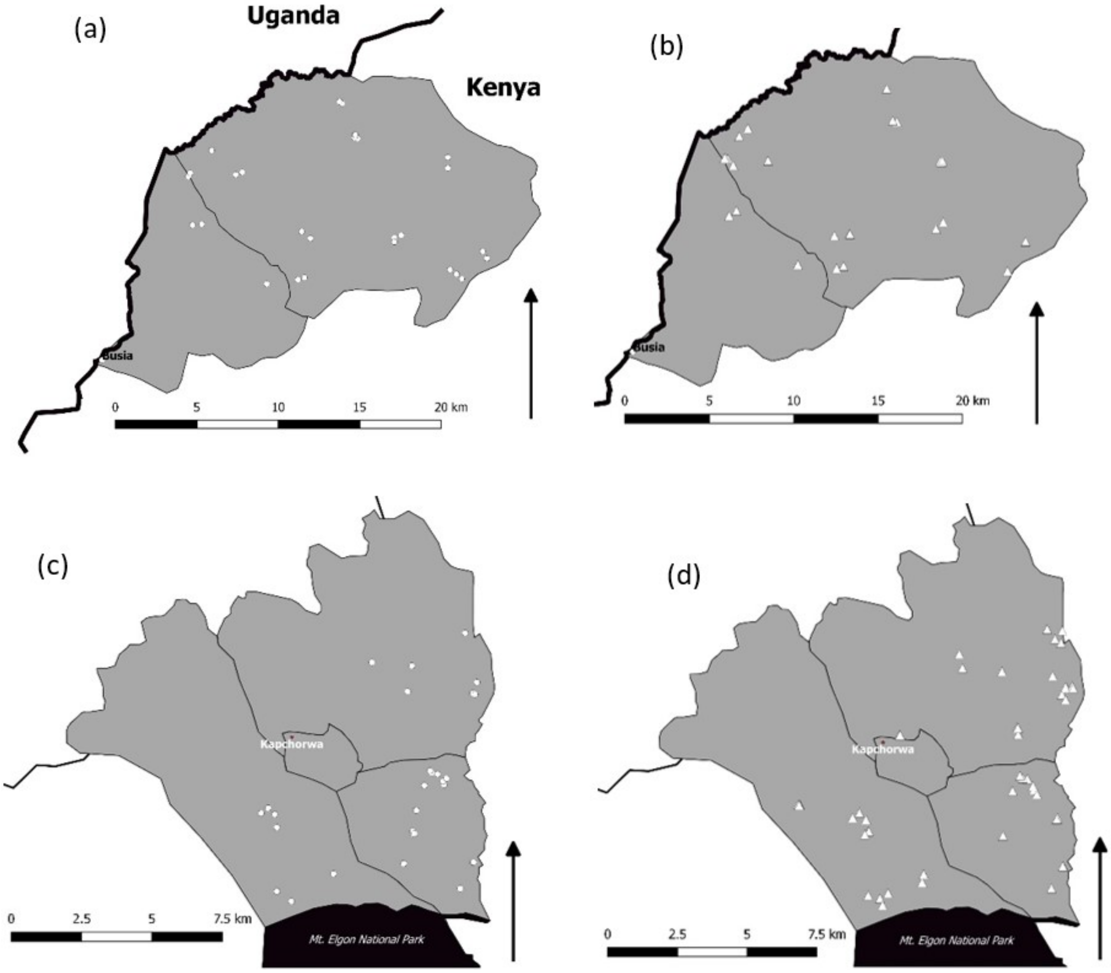


Figure A.7: Sample collection sites in Teso South, Kenya and Kapchorwa, Uganda of (a) maize grain and coupled soil samples in Teso South, Kenya (n=31); (b) cassava tuber and coupled soil samples in Teso South, Kenya (n=27); (c) maize grain and coupled soil samples in Kapchorwa, Uganda (n=30); (d) matooke fruit and coupled soil samples in Kapchorwa, Uganda (n=54). Figure adapted from Fischer et al. (2019).

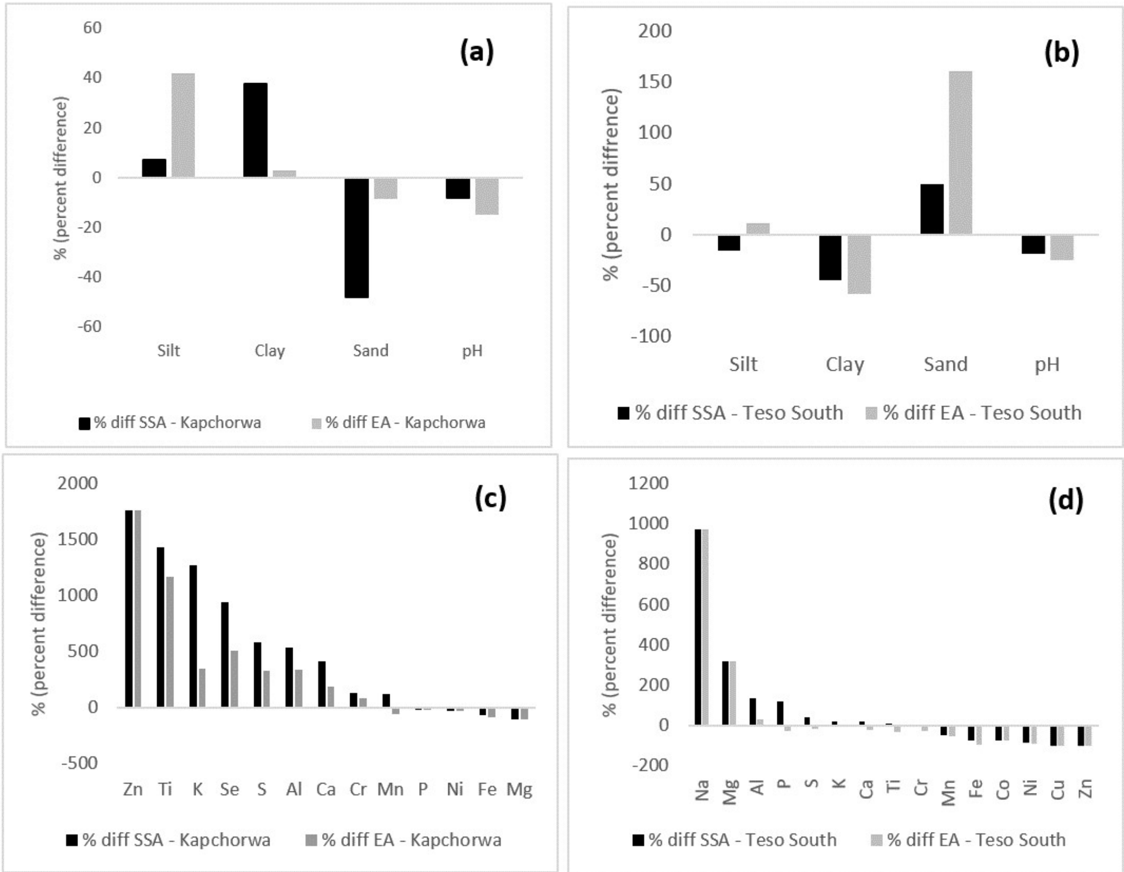


Figure A.8: The diagrams described the percent difference of the median measured soil samples collected from Kapchorwa and Teso South and the median calculated from the African Soil Information Service (AfSIS) data (http://africasoils.net/). The closer to zero, the closer the medians in the databases are to each other. (a) Comparison between Kapchorwa soil properties measured in percent difference of medians between collected values and AfSIS database; (b) Comparison between Teso South soil properties measured in percent difference of medians between collected values and AfSIS database; (c) Comparison between Kapchorwa soil elemental concentration measured in percent difference of medians between collected values and AfSIS database; (d) Comparison between Teso South soil elemental concentration measured in percent difference of medians between collected values and AfSIS database. EA is defined as East Africa and SSA is defined as Sub-Saharan Africa. Data was collected in 2016.

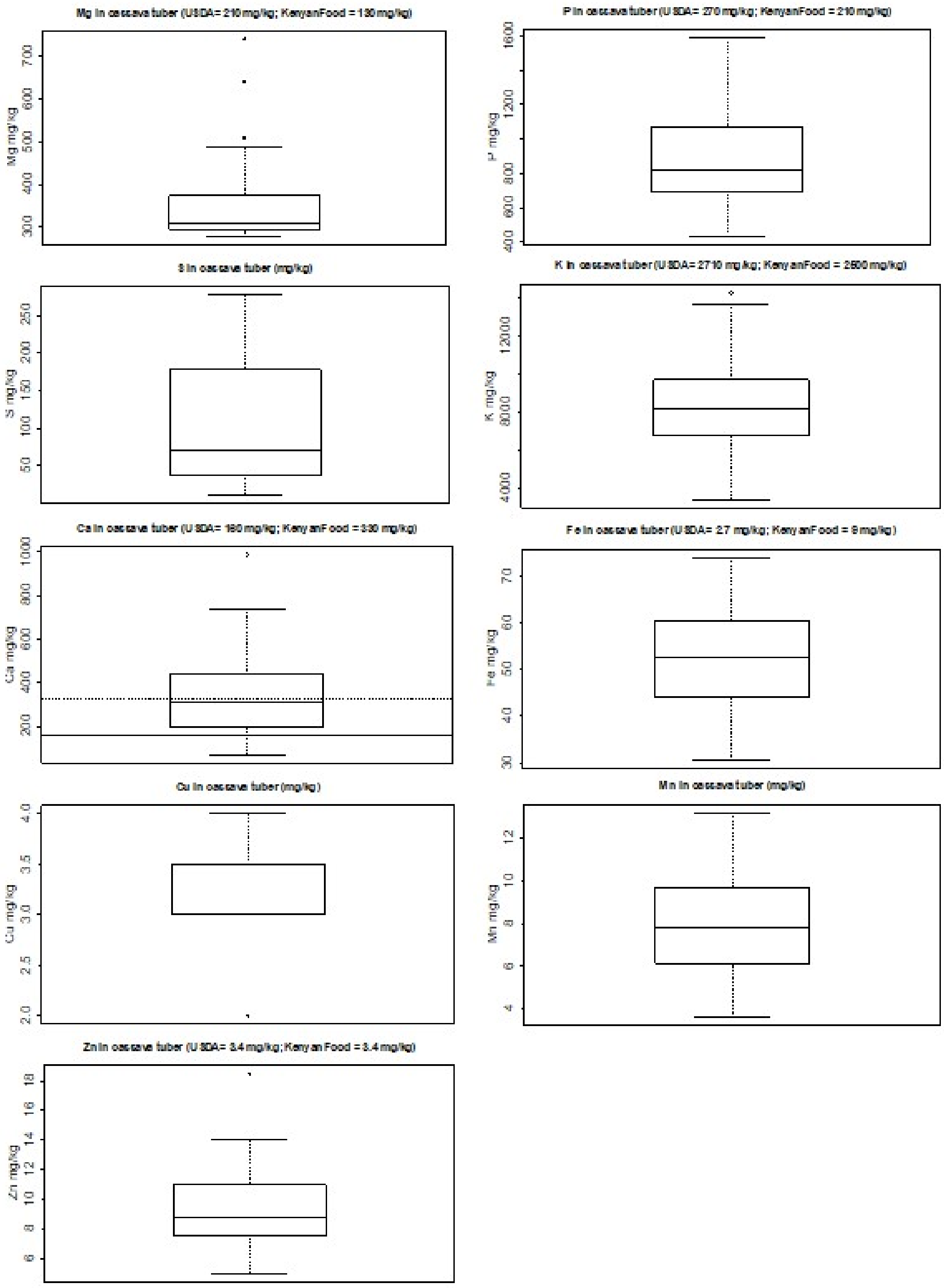


Figure A.9: Nutrient concentration of cassava tubers (n=27) collected in Teso South, Kenya during the long rain season (March-August) 2016. The nutrient concentration of the collected tubers is compared to the nutrient databases of the USDA (https://ndb.nal.usda.gov/ndb/) and the Kenyan food composition table (http://www.kilimo.go.ke/wp-content/uploads/2018/10/KENYA-FOOD-COMPOSITION-TABLES-2018.pdf)

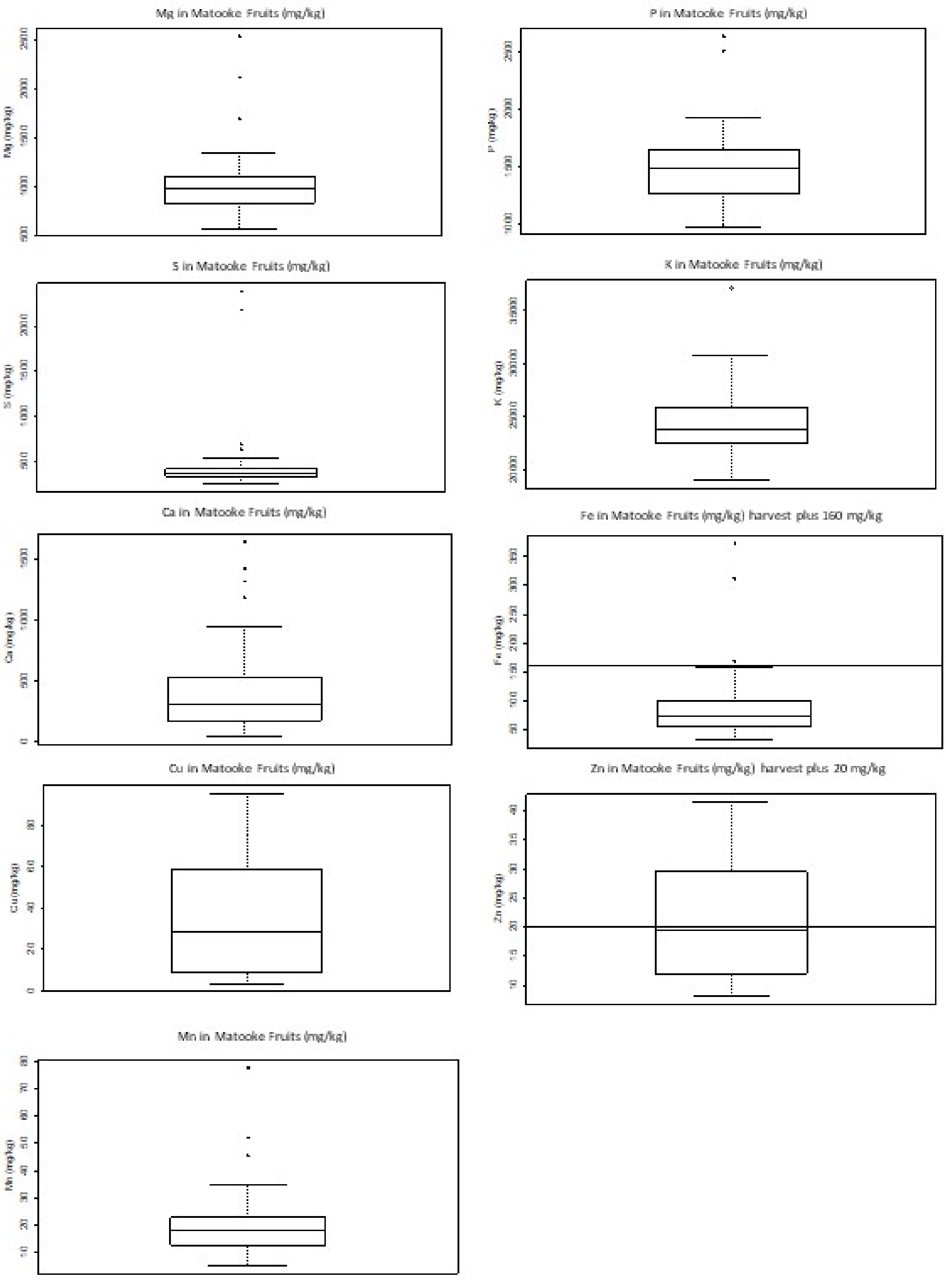


Figure A.10: Nutrient concentration of matooke fruit (n=54) collected in Kapchorwa, Uganda during the long rain season (March-August) 2016. The nutrient concentration of the collected fruits was compared to the HarvestPlus food composition table made for Uganda in https://www.harvestplus.org/node/562)

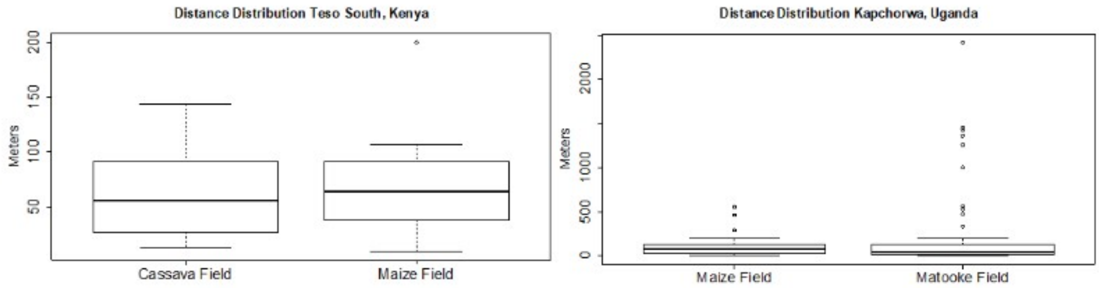


Figure A.11: Distance distribution in Teso South and Kapchorwa referring to the distance of the field to the household in meters measured using google maps. Data collected in 2016.

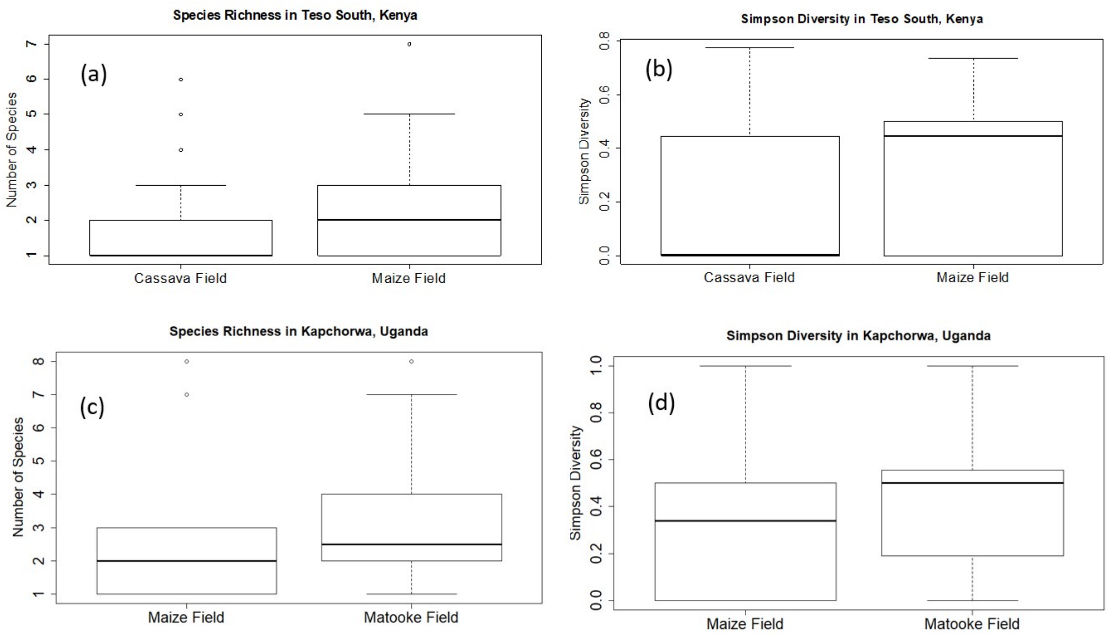


Figure A.12: Comparison of species richness and diversity on the fields were the crop samples were collected in the different regions. (a) shows the species richness in Teso South, Kenya per field of both collected maize and cassava; (b) shows the Simpson diversity in Teso South, Kenya per field of both collected maize and cassava. (c) shows the species richness in Kapchorwa, Uganda per field of both collected maize and matooke; (d) shows the Simpson diversity per field in Kapchorwa, Uganda of both collected maize and matooke. Data was collected in 2016.

Table A.18: Marginal correlations calculated using the bivariate linear mixed model (code from (Piepho 2018)) and compared to the sample correlation analysis paired with the p-value in brackets. The table shows correlations between leaf and yield and grain and yield from maize samples collected in Teso South, Kenya and Kapchorwa, Uganda.

	Teso South, Kenya		Kapchorwa, Uganda	
Maize Leaves	Marginal Corr	Sample Corr	Marginal Corr	Sample Corr
MgL/Yield	0.08	-0.12 (0.36)	-0.01	0.02 (0.91)
PL/Yield	0.04	-0.15 (0.27)	0.09	0.01 (0.95)
KL/Yield	0.15	-0.04 (0.77)	-0.42	-0.31 (0.17)
SL/Yield	0.23	0.20 (0.13)	0.01	-0.12 (0.63)
CaL/Yield	0.19	0.01 (0.94)	0.49	0.31 (0.19)
FeL/Yield	0.07	0.008 (0.95)	-0.41	-0.26 (0.27)
ZnL/Yield	-0.02	0.03 (0.83)	0.20	0.09 (0.69)
MnL/Yield	-0.03	-0.13 (0.34)	-0.21	-0.16 (0.51)
CuL/Yield	-0.14	-0.14 (0.30)	0.03	0.04 (0.87)
Maize Grain	Marginal Corr	Sample Corr	Marginal Corr	Sample Corr
MgG/Yield	0.02	-0.08 (0.71)	-0.11	-0.11 (0.58)
PG/Yield	-0.53	-0.17 (0.40)	-0.39	-0.15 (0.45)
KG/Yield	-0.33	-0.29 (0.15)	0.05	0.07 (0.72)
SG/Yield	-0.43	-0.42 (0.03*)	0.02	0.08 (0.67)
CaG/Yield	-0.30	-0.27 (0.18)	0.09	0.09 (0.63)
FeG/Yield	-0.59	-0.60 (0.001**)	0.13	0.14 (0.48)
ZnG/Yield	-0.51	-0.19 (0.35)	0.16	0.31 (0.10)
MnG/Yield	-0.71	-0.29 (0.15)	0.15	0.11 (0.55)
CuG/Yield	0.41	0.33 (0.10)	0.21	0.40 (0.03*)

Table A.19: Marginal correlations calculated using the bivariate linear mixed model (code from (Piepho 2018)) and compared to the sample correlation analysis paired with the p-value in brackets. The table shows correlations between leaf and yield, fruit and yield, and fruit and leaves from matooke samples collected in Kapchorwa, Uganda.

Matooke, Kapchorwa		
Leaf and Fruit		
	Marginal Corr	Sample Corr
MgL/MgF	-0.23	0.23 (0.11)
PL/PF	0.05	0.29 (0.04*)
KL/KF	-0.06	-0.05 (0.71)
SL/SF	-0.01	0.003 (0.99)
CaL/CaF	0.19	0.21 (0.15)
FeL/FeF	0.10	0.02 (0.91)
ZnL/ZnF	0.14	0.13 (0.36)
MnL/MnF	-0.06	-0.06 (0.67)
CuL/CuF	0.07	0.06 (0.68)
Leaf and Yield		
MgL/Yield	-0.36	-0.28 (0.04)
PL/Yield	0.04	0.11 (0.44)
KL/Yield	0.02	0.06 (0.69)
SL/Yield	-0.01	-0.10 (0.47)
CaL/Yield	0.10	0.11 (0.44)
FeL/Yield	0.14	0.21 (0.13)
ZnL/Yield	0.02	-0.006 (0.97)
MnL/Yield	0.18	-0.05 (0.74)
CuL/Yield	-0.20	-0.19 (0.18)
Fruit and Yield		
MgF/Yield	-0.22	-0.11 (0.44)
PF/Yield	0.10	-0.06 (0.66)
KF/Yield	-0.33	-0.26 (0.06)
SF/Yield	-0.27	-0.16 (0.26)
CaF/Yield	-0.02	-0.05 (0.74)
FeF/Yield	-0.04	-0.03 (0.82)
ZnF/Yield	0.12	0.06 (0.69)
MnF/Yield	0.01	0.04 (0.76)
CuF/Yield	0.05	0.03 (0.84)

Table A.20: Marginal correlations calculated using the bivariate linear mixed model (code from (Piepho 2018)) and compared to the sample correlation analysis paired with the p-value in brackets. The table shows correlations between leaf and yield, tuber and yield, and tuber and leaves from cassava samples collected in Teso South, Kenya.

Cassava, Teso South		
Leaf and Tuber		
	Marginal Corr	Sample Corr
MgL/MgT	-0.16	-0.10 (0.75)
PL/PT	0.51	0.54 (0.07)
KL/KT	0.61	0.51 (0.09)
SL/ST	0.75	0.29 (0.35)
CaL/CaT	0.17	0.21 (0.52)
FeL/FeT	0.40	0.36 (0.25)
ZnL/ZnT	0.20	0.29 (0.35)
MnL/MnT	-0.47	-0.53 (0.08)
CuL/CuT	0.05	0.11 (0.73)
Leaf and Yield		
MgL/Yield	-0.39	-0.23 (0.5)
PL/Yield	-0.11	-0.07 (0.83)
KL/Yield	0.22	0.21 (0.54)
SL/Yield	-0.65	0.30 (0.36)
CaL/Yield	-0.55	-0.45 (0.17)
FeL/Yield	-0.47	-0.34 (0.30)
ZnL/Yield	-0.55	-0.29 (0.38)
MnL/Yield	0.12	0.26 (0.45)
CuL/Yield	0.42	0.38 (0.25)
Tuber and Yield		
MgT/Yield	-0.03	-0.04 (0.87)
PT/Yield	-0.15	-0.14 (0.57)
KT/Yield	-0.15	-0.03 (0.89)
ST/Yield	0.17	0.22 (0.36)
CaT/Yield	-0.03	-0.12 (0.62)
FeT/Yield	-0.23	-0.22 (0.36)
ZnT/Yield	-0.06	-0.11 (0.64)
MnT/Yield	0.07	0.08 (0.73)
CuT/Yield	0.22	0.25 (0.28)

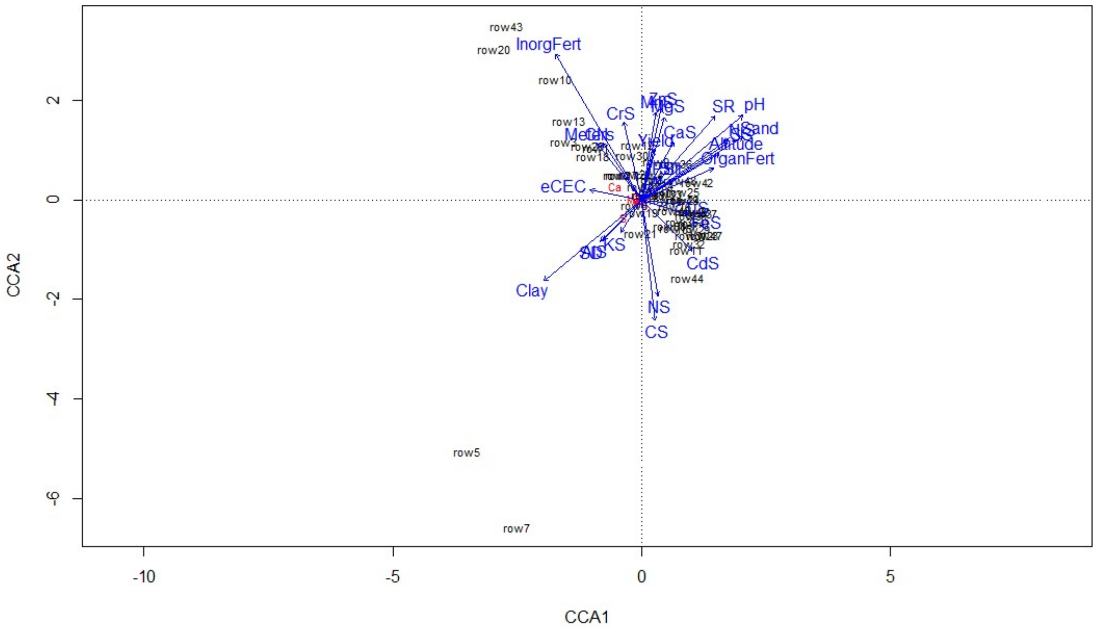


Figure A.13: Canonical Correspondence Analysis (CCA) of matooke in Kapchorwa, Uganda. This CCA shows yield as an explanatory variable rather than a response variable as Figure 3.4 in the main text, Chapter 3.

Table A.21: Comparison of the different adequacy values of maize leaf nutrient concentrations (in mg/kg) from three different sources.

	Reuters and Robinson, 1997[3]	Fageria, 2011[1]	Marschner, 2012[2]
Mg	1800-3500	2100-4000	1500-3500
P	2200-3400	2500-4000	N.A.
S	1600-2200	1000-2400	N.A.
K	13700-14600	17000-30000	20000-50000
Ca	2100-5000	2100-5000	N.A.
Fe	21-251	21-250	50-150
Mn	20-150	20-150	N.A.
Cu	6-20	6-20	N.A.
Zn	20-70	20-70	N.A.

1. Fageria, N.K., Baligar, V.C., Jones, C.A., 2011. Growth and mineral nutrition of field crops, Third. ed. CRC Press, Boca Raton. 2. Marschner, P., 2012. Marschner ' s Mineral Nutrition of Higher Plants Third Edition 1–651. https://doi.org/10.1016/B978-0-12-384905-2.X0001-5 3. Reuters, D.J., Robinson, J.B., 1997. Plant Analysis - an interpretation manual, 2nd Editio. ed. Csiro Publishing, Collingwood.

B Appendix - Codes used for Statistical Analysis

B.1 SURVEYREG

```
Comparing nutrient concentrations between different regions
 of Teso South and Kapchorwa.

PROC IMPORT DATAFILE=REFFILE
DBMS=XLSX
OUT=mgklrssrs1;
GETNAMES=YES;
RUN;

PROC CONTENTS DATA=mgklrssrs1; RUN;

ods graphics on;
title 'Comparison Nutrients Teso South and Kapchorwa';
proc surveymeans data=mgklrssrs1 total=226593 ;
Class Country;
cluster Village;
Strata Region;
   var  Yield logMg logP logS logK logCa logFe logZn logMn logCu;
   weight Weight;
run;

ods graphics on;
```

```
title 'Comparison Nutrients Kenya';
proc surveyreg data=mgklrssrs1 total=226593;
Class Country;
cluster Village;
Strata Region;
   weight Weight;
   class Season;
   model logMg = Country; (example for nutrient comparison)
run;
```

Comparing the crop nutrient concentration between the FGS and SGS of both regions { same method used for the comparison of the nutrient amount produced.

```
PROC IMPORT DATAFILE=REFFILE
DBMS=XLSX
OUT=mgulrssrsspiweight;
GETNAMES=YES;
RUN;

PROC CONTENTS DATA=mgulrssrsspiweight; RUN;

ods graphics on;
title 'Comparison Nutrients Uganda';
proc surveymeans data=mgulrssrsspiweight total=41016 ;
(total for Kenya: 185577; total for Uganda 41016)
cluster Village;
Strata Region;
   var  Yield logMg logP logS logK logCa logFe logZn logMn logCu;
   weight Weight;
run;

ods graphics on;
title 'Comparison Nutrients Kenya';
proc surveyreg data=mgulrssrsspiweight total=41016 ;
```

```
(total for Kenya: 185577; total for Uganda 41016)
Class Season;
cluster Village;
Strata Region;
   weight Weight;
   model logMg = Season;
run;
```

Comparing the maize nutrient concentration and SPI1 and SPI2 per region

```
PROC IMPORT DATAFILE=REFFILE
DBMS=XLSX
OUT=mguandklrsweight1;
GETNAMES=YES;
RUN;

PROC CONTENTS DATA=mguandklrsweight1; RUN;

proc print data=mguandklrsweight1; run;

ods graphics on;
title 'Comparison Nutrients Uganda and Kenya MG LRS';
proc surveymeans data=mguandklrsweight1 total=41016 ;
(total for Kenya: 185577; total for Uganda 41016)
cluster Village;
Strata Region;
   var  Yield logMg logP logS logK logCa logFe logZn logMn logCu;
   weight Weight;
run;

ods graphics on;
title 'Comparison Nutrients MGU and MGK LRS';
proc surveyreg data=mguandklrsweight1 total=41016 ;
(total for Kenya: 185577; total for Uganda 41016)
```

```
cluster Village;
Strata Region;
   weight Weight;
   model logMg = spi1/solution;
(polynomial spi1 spi1*spi1/solution)(interaction spi1 spi2 spi1*spi2/solution)
run;
```

B.2 Canonical Correspondence Analysis and permutation anova in R Studio

```
install.packages("vegan")
library(vegan)
install.packages("labdsv")
library(labdsv)

data(CCAmgkplantsingle)
data(logmgkfertcorr)

vare.cca <- cca(matnew ~
Meters + SD + SR +  InorgFert + OrganFert +
Alt +  MgS + AlS + PS + SS + KS + CaS + TiS +
CrS + MnS + FeS + NiS + ZnS + CdS + TiS +
  pH + NS + CS + CN + Clay + Silt + Sand + Clay
+ eCEC, data=matnewsoil)
vare.cca
plot(vare.cca)
summary(vare.cca)

anova(vare.cca)
anova(vare.cca, by = "terms", permu = 500)
anova(vare.cca, by = "mar", permu = 500)
```

B.3 SAS Code for bivariate mixed model in SAS

Method based on Piepho, H.P., 2018. Allowing for the structure of a designed experiment when estimating and testing trait correlations. J. Agric. Sci. 156, 59–70. https://doi.org/10.1017/S0021859618000059

```
data logmzu2;
set logmzu;
y=logyield; trait='logyield'; output;
y=logCuG; trait='logCuG'; output;
run;

proc mixed data=logmzu2 covtest maxiter=1000;
where trait in ('logyield', 'logCuG');
class Vill Dis HH trait field;
model y= trait Dis trait*Dis/ outp=residuals noint;
random   trait/sub=Vill type=un  solution V Vcorr; all three models done
random   trait/sub=HH type=un  solution V Vcorr;
repeated trait/sub=field type= un ;
/*parms (.1)(.1)(.1)/lowerb=.,-0.999,.,.
upperb=.,0.999.;*/ Different parms depending on the model.
run;
```

The starting values from the first set of models used in the next set
 of models to select the final model.

```
ods output solutionR=BLUP;
proc mixed data=logmzu2 covtest maxiter=1000;
where trait in ('logyield', 'logCuG');
class Vill Dis HH trait field;
model y= trait Dis trait*Dis/ outp=residuals noint;
repeated trait/sub=field type= unr ;
parms (0.2875)(0.1454)(0.07672)/lowerb=.,.,-0.999,
(parms depending on previous model run)
```

```
upperb=.,.,0.999;
run;
ods output solutionR=BLUP;
proc mixed data=logmzu2 covtest maxiter=1000;
where trait in ('logyield', 'logCuG');
class Vill Dis HH trait field;
model y= trait Dis trait*Dis/ outp=residuals noint;
random   trait/sub=HH type=unr  solution V Vcorr;
repeated trait/sub=field type= unr ;
parms (0.2160)(0.01349)(0.07802)(0.1038)(0.1310)(0.01604)
/lowerb=.,.,-0.999,.,.,-0.999
upperb=.,.,0.999,.,.,0.999;
run;
ods output solutionR=BLUP;
proc mixed data=logmzu2 covtest maxiter=1000;
where trait in ('logyield', 'logCuG');
class Vill Dis HH trait field;
model y= trait Dis trait*Dis/ outp=residuals noint;
random   trait/sub=Vill type=unr  solution V Vcorr;
random   trait/sub=HH type=unr  solution V Vcorr;
repeated trait/sub=field type= unr ;
parms (0.02625)(0)(-0.01198)(0.1950)(0.01270)(0.08383)(0.09591)(0.1312)(0.01679)
/lowerb=.,.,-0.999,.,.,-0.999,.,.,-0.999
upperb=.,.,0.999,.,.,0.999,.,.,0.999;
run;

ods output FitStatistics=fitHA;
proc mixed data=logmzu2 maxiter=1000;
where trait in ('logCuG', 'logyield');
class field HH trait Vill Dis;
model y=trait Dis trait*Dis;
random   trait/sub=HH type=unr  solution V Vcorr;
(above model used here for LRT)
repeated trait/sub=field type= unr ;
```

```
parms (0.2160)(0.01349)(0.07802)(0.1038)(0.1310)(0.01604)
/lowerb=.,.,-0.999,.,.,-0.999
upperb=.,.,0.999,.,.,0.999;
run;

ods output FitStatistics=fitH0;
proc mixed data=logmzu2 maxiter=1000;
where trait in ('logCuG', 'logyield');
class field HH trait Dis Vill;
model y=trait trait*Dis Dis;
repeated trait/sub=field type=UN(1);/*null hypothese - ganz uncorreliert*/
run;

data fitHA; set fitHA; valueHA=value; run;
data fitH0; set fitH0; valueH0=value; run;

data LRT; /*wenn nicht signifikant passt*/
merge fitHA fitH0;
if N=1;
T=valueH0-valueHA;
pvalue=1-probchi(T,1);
run;

proc print data=LRT;
run;
```

C General Summary

Hidden hunger affects two billion people worldwide, particularly children and pregnant women. Human health and well-being are dependent on the quality and quantity of food consumed, particularly of plant-based foods. Plants source their nutrients from the soil. Essential nutrients for both, plants and humans, therefore, predominantly originate from the soil. The level of dependence, and the factors affecting the human-plant-soil nutrient dependence are not well described. Very little is known about the influence of environmental factors (e.g. soil types and abiotic factors, such as weather), or farm management choices (e.g. fertilisation or agrobiodiversity), on nutrient concentrations of edible crop parts. Complicating further research into the food-environment nexus is the lack of communication and shared data or methods between agronomy and nutrition, the two main disciplines involved in food provisioning. The main aim of this thesis was, therefore, to analyse the effects of soil fertility, farm management, and abiotic factors such as drought, on the quantity (yields) and quality (nutrient concentrations) of essential macro- (Mg, P, S, K, Ca) and micronutrients (Fe, Zn, Mn, and Cu), of the edible parts of three East African staple food crops, i.e. maize (*Zea mays* L.), cassava (*Manihot esculenta* Crantz), and matooke (East African Highland Banana (*Musa acuminata* Colla)), and discuss the resulting implications for food and nutrition security.

Two research areas were selected in East Africa, one with a high fertility soil (Kapchorwa, Uganda - Nitisol) and one with a low fertility soil (Teso South, Kenya – Ferralsol). In each region, 72 households were randomly selected, and leaf and edible crop parts, and soil samples collected on three fields per household, organised by distance (closest, mid-distance, and farthest field). Maize and cassava were collected in Teso South, maize and matooke were collected in Kapchorwa. Yields, fertilizer usage, and species richness (SR) and diversity (SD) were recorded per field. The total nutrient concentrations were measured in all samples collected (soils and plant parts), using a portable X-Ray Fluorescent Spectrometer (pXRF) (Tracer 5i - Bruker). A drought occurring in the second rain season of 2016 provided the opportunity to analyse water stress effects on crop quantity and quality (Chapter 2). Drought intensity was measured using the values calculated with the Standard Precipitation Index (SPI).

Edible part samples and yields collected in both seasons were compared using the SurveyReg procedure of SAS. Soil chemical and physical properties (texture, pH, eCEC, total N and C, and total elemental concentrations), together with farm management variables, were compared to edible part nutrient concentrations and yields using a Canonical Correspondence Analysis (CCA) (Chapter 3). To understand the strength of association between the measurements routinely done by agronomists (leaf measurement) and nutritionists (edible part measurement), samples of each crop were collected, and were compared to each other and to yields, using a bivariate linear mixed model (Chapter 4).

The drought in Kapchorwa (SPI: -1.14 to -0.32) was more severe and began 2 months prior to Teso South (SPI: 0.09 to 0.55). During the severe drought, nutrient concentrations in Kapchorwa decreased significantly from normal to drought season in both crops. In contrast, during the moderate drought in Teso South, nutrient concentrations increased significantly in both crops. Lacking nutrient phloem mobility is suggested to play a vital role in mobilisation of micronutrients (Fe, Mn, and Cu), as shown by their decreased concentration under severe drought in the yields of both crops in Kapchorwa (Chapter 2). Soil type had a very strong effect on food nutrient concentrations. Maize grain nutrient concentrations and yields, for example, were significantly higher for all nutrients measured on higher fertility soils. Maize grain had higher correlations with soil factors (CCA $>$ 80%) than cassava tubers (76%) or matooke fruits (39%). In contrast, corresponding correlations to management factors were much weaker (matooke 8%; cassava 20%; maize 39%). The main soil properties affecting food nutrients were organic matter and texture (Chapter 3). Concerning the comparison of nutrient concentrations in different plant parts, low phloem mobile nutrients Ca, Mn, Fe, Zn, and Cu showed the largest differences in correlations between leaves and edible parts. In the same comparison, perennial crops (matooke and cassava) showed lower correlations between leaves and edible parts, than annual crops (maize) (Chapter 4).

Environmental factors, such as drought impacted food nutrient concentrations in two ways. While a mild drought succeeded in increasing nutrient concentrations, while only minimally decreasing yields in maize; severe drought caused a potential “double-burden” for consumers, decreasing both yields and nutrient concentrations, particularly of micronutrients. Considering food nutrient concentrations, 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. Leaves may provide information on plant health, however, do not provide enough information to gauge both yields and food quality, particularly regarding micronutrients. The results also showed that measuring the edible part is vital to assessing food quality, particularly due to the observed effects of nutrient mobility, affecting particularly micronutrients and Ca. The level of impact especially seen in the edible part concentrations of micronutrients and Ca considerably increase the potential impacts of environmental and management factors on food and nutrition security. Agricultural and nutritional scientists should harmonize methods to develop sustainable management options for increased food and nutrition security, for example, by using soil maps as a basis for nutrient composition databases to eliminate a large cause of variance and considering the type of edible part of a crop when planning management strategies. Ending hunger and improving food and nutrition security for all, particularly when confronted with global change issues such as degrading soils and a changing climate, requires a collaborative effort by all disciplines concerned.

D Allgemeine Zusammenfassung

Weltweit leiden zwei Milliarden Menschen an verborgenem Hunger. Besonders Kinder und schwangere Frauen sind betroffen. Die Qualität und die Quantität der konsumierten Nahrung, besonders die der pflanzlichen Nahrung, beeinflusst die Gesundheit und das Wohlbefinden der Menschen. Pflanzen nehmen ihre Nährstoffe aus dem Boden auf. Folglich stammen die essentiellen Makro- und Mikronährstoffe für Pflanzen und damit auch für den Menschen überwiegend aus dem Boden. Das Ausmaß der Boden-Pflanze-Mensch-Nährstoffabhängigkeit und die Faktoren, die diese Verbindungen beeinflussen, sind nur wenig erforscht. Es bestehen große Wissenslücken, inwieweit Umweltfaktoren (z.B. abiotische Faktoren wie Bodentyp und Wetter) und das betriebliche Management (z.B. Düngung und Agrobiodiversität), die Nährstoffkonzentration im essbaren Pflanzenteil beeinflussen. Die Agrar- und Ernährungswissenschaften sind maßgeblich an der Nahrungs- und Ernährungssicherung beteiligt. Der mangelhafte Daten- und Methodenaustausch der Disziplinen erschwert das Verständnis der Beziehungen zwischen Umwelt und Ernährung. Das Forschungsziel dieser Arbeit war, den Einfluss der Bodenfruchtbarkeit, des Betriebsmanagements sowie abiotischer Faktoren auf die Erträge (Quantität) und die Nährstoffkonzentrationen (Qualität, essentielle Makro- (Mg, P, S, K, Ca), und Mikronährstoffen (Fe, Zn, Mn, Cu)) dreier ostafrikanischer Grundnahrungsmittel, und zwar Mais (*Zea mays* L.), Maniok (*Manihot esculenta* Crantz) und Matooke (ostafrikanische Hochlandbanane (*Musa acuminata* Colla)), zu analysieren und daraus resultierende Implikationen für die Nahrungs- und Ernährungssicherung zu diskutieren.

Für die Erhebung der Daten wurden zwei Forschungsgebiete mit unterschiedlicher Bodenfruchtbarkeit in Ostafrika ausgewählt (hohe Bodenfruchtbarkeit: Kapchorwa, Uganda – Nitisole; niedrige Bodenfruchtbarkeit: Teso South, Kenia – Ferralsole). Je Forschungsgebiet wurden 72 landwirtschaftliche Betriebe zufällig ausgewählt. Auf den Betrieben wurden Proben der Blätter, der essbaren Pflanzenteile und Bodenproben gesammelt. Die Proben wurden auf je drei Feldern der Betriebe genommen, welche sich in der Distanz zum Haushalt unterschieden (nah, mittel, weit). Mais- und Maniokproben wurden in Teso South gesammelt. Mais- und Matookeproben wurden in Kapchorwa gesammelt. Erträge, Düngeaufwand, Artenreichtum und -diversität wurden je Feld gemessen. Ein portables X-Ray-Fluorescent-Spectrometer (pXRF) (Tracer 5i – Bruker) wurde verwendet, um die Nährstoffkonzentrationen aller Boden- und Pflanzenproben zu analysieren. Eine eingetretene Dürre in der zweiten Regenperiode 2016 ermöglichte es, die Ertragsquantität und -qualität unter Trockenstress zu analysieren (Kapitel 2). Das Ausmaß der Dürre wurde mittels des standardisierten Niederschlagsindex (SPI) ermittelt. Die essbaren Pflanzenteile und der Ertrag wurden zwischen den einzelnen Regenzeiten mittels der SurveyReg-Prozedur in SAS verglichen. Einflüsse der Bodenchemie und Bodenphysik (Textur, pH, eKAK, gesamtes N und C, gesamte Elementarkonzentration) sowie des betrieblichen Managements wurden mit den Nährstoffkonzentrationen im essbaren Pflanzenteil und den Erträgen unter Anwendung der Kanonischen Korrespondenz-Analyse (CCA) ermittelt (Kapitel 3). Die Nährstoffgehalte der Blätter und der essbaren Pflanzenteile wurden mit den Erträgen durch ein bivariates lineares gemischtes Modell verglichen, um damit die Ergebnisse der gängigen Messmethoden der Agrar- (Blätter) und Ernährungswissenschaften (essbare Pflanzenteile) zu vergleichen, Unterschiede zu identifizieren, und Implikationen für die Nahrungs- und Ernährungssicherung abzuleiten (Kapitel 4).

Die Dürreperiode in Kapchorwa (SPI: -1.14 bis -0.32) war intensiver und begann zwei Monate früher, als in Teso South (SPI: 0.09 bis 0.55). Die Nährstoffgehalte in der intensiven Dürreperiode in Kapchorwa hatten, verglichen mit der normalen Regenzeit, in beiden Pflanzen signifikant abgenommen. Konträr dazu hatten die Nährstoffgehalte in Teso South während der moderaten Dürre in beiden Pflanzen signifikant zugenommen. Die niedrigen Mikronährstoffkonzentrationen im essbaren Pflanzenteil während der intensiven Dürreperiode (Fe, Mn und Cu) lassen darauf schließen, dass die niedrige Nährstoffmobilität im Phloem hierfür verantwortlich war (Kapitel 2). Auch der Bodentyp hatte einen starken Effekt auf die Nährstoffkonzentrationen im essbaren Pflanzenteil. Die Konzentrationen aller gemessenen Nährstoffe im Maiskorn sind auf den fruchtbareren Böden signifikant höher als auf nährstoffärmeren Böden. Die organische Bodensubstanz und die Textur waren die beiden Bodeneigenschaften mit dem größten Einfluss auf die Nährstoffgehalte im essbaren Pflanzenteil (Kapitel 3). Die Nährstoffkonzentrationen im Maiskorn korrelierten am stärksten mit den Bodeneigenschaften (CCA $>$ 80%) ((Maniok (76%), Matooke (36%)). Dem gegenüber stand eine insgesamt niedrigere Korrelation von Managementfaktoren mit Nährstoffkonzentrationen (Matooke 8%, Cassava 20%, Mais 39%). Der Vergleich der Nährstoffkonzentrationen zwischen Blättern und essbaren Pflanzenteilen zeigten, dass die wenig phloemmobilen Nährstoffe (Ca, Mn, Fe, und Cu) die größten Korrelationsunterschiede aufweisen. Die mehrjährigen Pflanzen (Matooke und Maniok) zeigten dabei eine niedrigere Korrelation zwischen den Pflanzenteilen als die einjährige Pflanze (Mais) (Kapitel 4).

Umweltfaktoren, wie zum Beispiel die eingesetzte Dürre, haben die Nährstoffkonzentrationen im essbaren Pflanzenteil in zweierlei Weise beeinflusst: Während eine milde Dürre zu gesteigerten Nährstoffkonzentrationen bei nur sehr geringen Ernteeinbußen bei Mais geführt hat, führte eine starke Dürre zu Nährstoff- (besonders die der Mikronährstoffe) und Ertragseinbußen, welches damit eine doppelte Belastung der Bevölkerung bedeutete. Würden in agrarwissenschaftlichen Versuchen neben den Erträgen die Nährstoffkonzentrationen des essbaren Teils der Pflanze erhoben werden, könnte man der gängigen Annahme, dass nur auf fruchtbaren Böden gesunde und qualitativ hochwertige Nahrung produziert wird, relativieren. Die Analyse der Blätter gibt Auskunft über die Pflanzengesundheit und den Ertrag, erlaubt aber keine Rückschlüsse über die Ertragsqualität, vor allem nicht in Bezug auf Mikronährstoffe und Ca. Die Erkenntnisse zur Nährstoffmobilität, besonders die der Mikronährstoffe und Ca, unterstreichen diese Annahme. Umwelt- und Managementfaktoren haben einen bedeutenden Einfluss auf die Nährstoffkonzentrationen und könnten damit die Nahrungs- und Ernährungssicherheit erheblich beeinflussen. Für eine Steigerung der Nahrungs- und Ernährungssicherheit müssen die Agrarwissenschaften und die Ernährungswissenschaften ihre Forschungsmethoden besser aufeinander abstimmen. Ein erster Schritt könnte die Verbesserung von Datenbanken für Pflanzennährstoffen sein, indem diese mit bestehenden Bodenkarten kombiniert werden. Es gilt die Analysemethoden zu harmonisieren um nachhaltige Handlungsempfehlungen geben zu können. Eine Steigerung der Nahrungs- und Ernährungssicherheit und damit ein Ende des weltweiten Hungerns, gerade auch im Kontext wachsender Herausforderungen einhergehend mit der Klimakrise und einer zunehmenden Bodendegradierung, verlangen einen kollaborativen Einsatz aller beteiligten Disziplinen.