Science of the Total Environment 658 (2019) 405–415

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

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

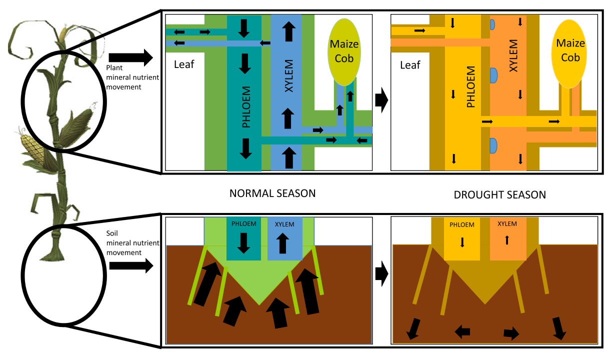
Sahrah Fischer [a,*], Thomas Hilger [a], Hans-Peter Piepho [b], Irmgard Jordan [c], Georg Cadisch [a]

[a] Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg Institute), University of Hohenheim, Germany
[b] Institute of Crop Sciences, University of Hohenheim, Germany
[c] Zentrum für Entwicklungs-und Umweltforschung, Justus-Liebig-Universität Gießen, Germany

HIGHLIGHTS

- Unknown drought effect on food nutrient composition
- Longitudinal study, two food crops in two regions, from normal and drought season
- Severe drought caused decrease, mild drought increase in nutrient concentration
- Micronutrients particularly negatively affected by drought
- Double-burden not always present, depending on the severity of the drought

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 2 October 2018
Received in revised form 11 December 2018
Accepted 11 December 2018
Available online 13 December 2018

Editor: Jay Gan

Keywords:
Climate change
Food composition
Food and nutrition security
Plant nutrient uptake

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 2 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.

* Corresponding author.
E-mail address: sahrah.fischer@uni-hohenheim.de (S. Fischer).

https://doi.org/10.1016/j.scitotenv.2018.12.181
0048-9697/

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.

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 famine (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, 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, 2012). 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, e.g. the protein, mineral and antinutrient composition 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, particularly 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 (ex. 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. Material and methods

2.1. Study sites

2.1.1. 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°) (Fig. S1). 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 to 22.2 °C. The yearly average rainfall ranges from 1420 to 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 cereals 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.

2.1.2. Kapchorwa, Uganda

Kapchorwa is a county in Uganda, situated on the northern face of Mt. Elgon (1.359817°, 34.45045°; 1.450219°, 34.44643°) (Fig. S1). 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 metamorphic 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 varies from 1000 to 3000 m m.a.s.l., and covers an area of 297 km^2. Annual mean temperatures range from 1.5 to 23.5 °C, and the gradient of rainfall ranges from 1200 to 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 rainfall 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 September–December. Again, due to the altitude, the dates vary slightly.

2.2. Data collection

2.2.1. 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 (Figs. S2–5). 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 infrared 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 (Fig. S6).

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 to 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 was both regressed onto altitude using a simple linear regression (lm) in RStudio.

2.2.2. 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 paper for a longitudinal analysis (Table 1; Figs. S2–5). 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.

2.2.3. 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

Table 1
Sample size of all samples collected compared to the sample size of the longitudinal samples, collected from the same fields in both seasons (FGS and SGS 2016), in both regions (Teso South, Kenya; Kapchorwa, Uganda) for the different plant types.

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, Kenya	Maize grain	31	15	30	15
	Cassava tuber	27	14	37	14
Kapchorwa, Uganda	Maize grain	30	15	32	15
	Matooke fruit	54	19	36	19

Analysesysteme GmbH, Hanau, Germany) (Naumann and Bassler, 2012). Additionally, pH was measured in 1 M 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 measured 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).

$\delta^{13}C$ isotope measurements were done to measure the level of water stress that the plants experienced during the SGS. The method is well known and accepted as a proxy measurement for water stress in both C_3 and C_4 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) $\delta^{13}C$ of both crops per research area to the corresponding drought season (SGS) $\delta^{13}C$ using a randomly selected subsample ($n = 8$ per crop) of the collected plant samples. As nutrient uptake can also influence the

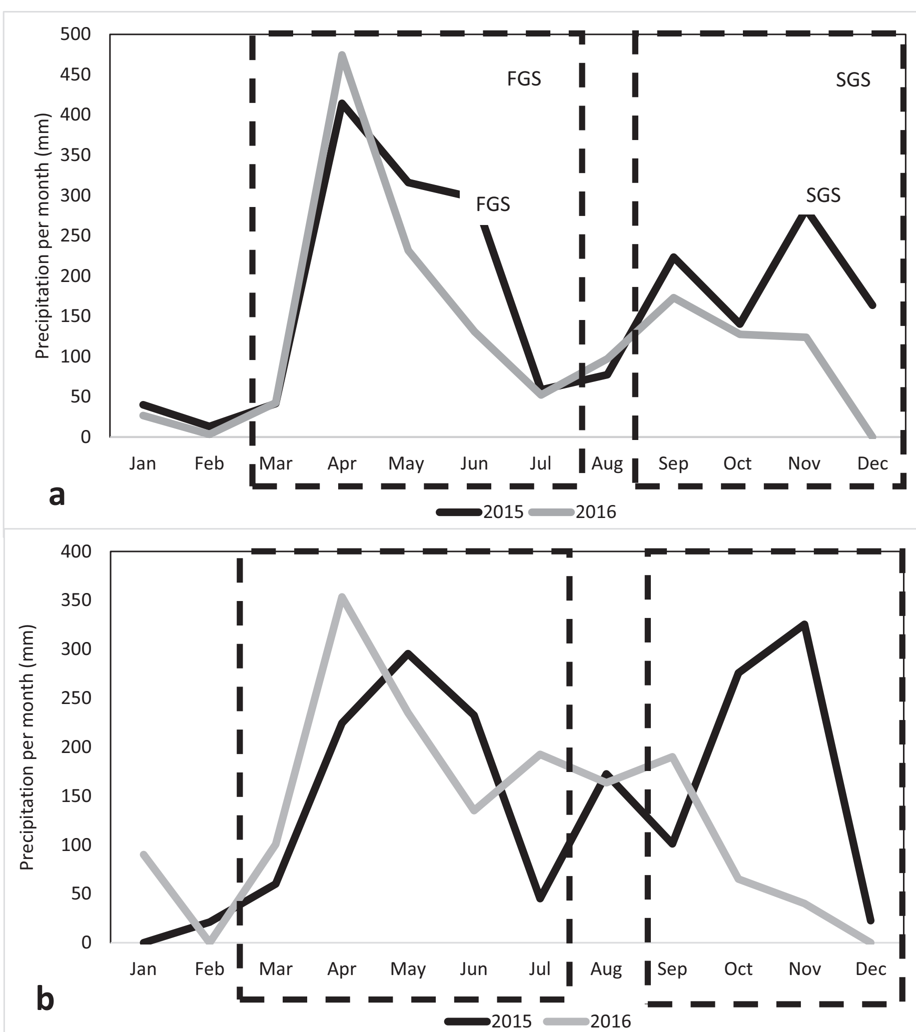


Fig. 1. Sum of precipitation per month, averaged from the four rain gauges located in Teso South, Kenya (a) from 2015 and 2016. (b) Sum of precipitation per month from the rain gauge located in Kapchorwa Town in Kapchorwa, Uganda from 2015 and 2016, highlighted are the FGS and SGS. For the locations of the rain gauges, see maps Figs. S2–5.

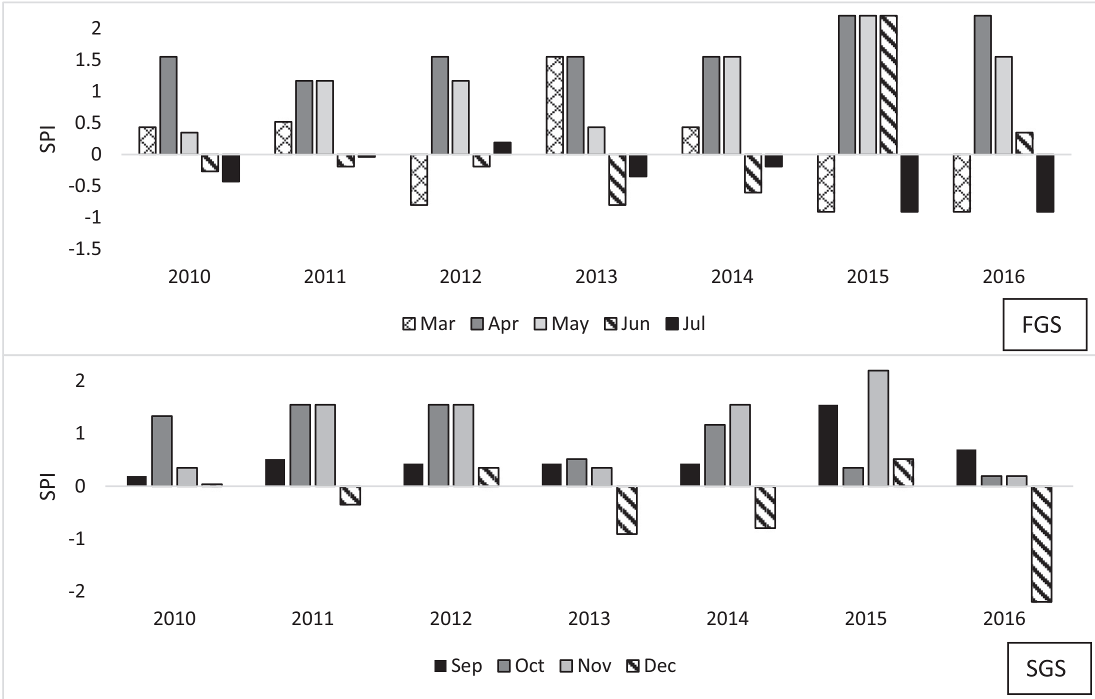


Fig. 2. Comparison of monthly Standardized Precipitation Index (SPI) values in Teso South calculated from the TAMSAT data (source: https://www.tamsat.org.uk/data/archive), of the FGS (March–July) and SGS (September–December). Shown are the years 2010–2016. Drought is then measured by: mild drought (0 < SPI < −0.99), moderate drought (−1.0 < SPI < −1.49), severe drought (−1.5 < SPI < −1.99), and extreme drought (<−2.00).

$\delta^{13}C$ content of plants, $\delta^{15}N$ levels were also analysed. Samples were measured at the University of Hohenheim using a Euro EA Elemental Analyser (Euro Vector) coupled to a Finnigan Delta IRMS (Thermofinnigan, USA).

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, 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 was 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 S1). 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) Nutrients accumulated (g/ha) were calculated for all plant samples collected and were 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, nutrients accumulated 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.

3. Results

3.1. Climate and precipitation

The rain gauge data of both countries (Fig. 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 at the end of September 2016 (Fig. 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 precipitation data of the rain gauges in the study regions. The two datasets correlated strongly (Teso South $R^2 = 0.80^{***}$ (Fig. S7); Kapchorwa $R^2 = 0.82^{***}$ (Fig. S8)). 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 (Figs. S9 and S10) in both countries from 1983 to 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 ($R^2 = 0.49$; $p < 0.05^*$)) (Fig. S11).

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

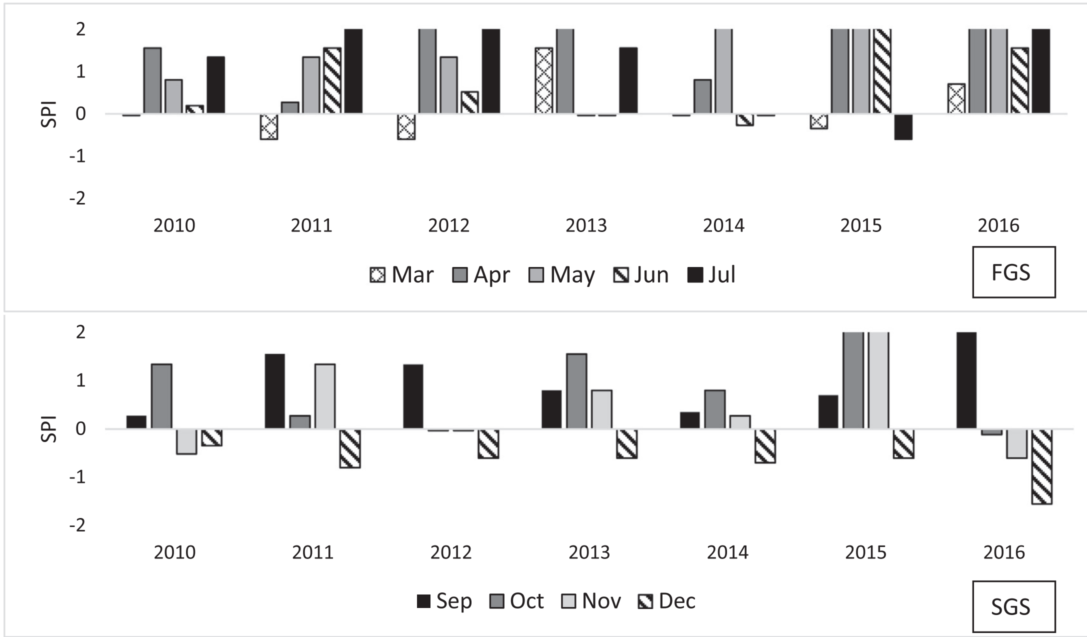


Fig. 3. Comparison of monthly Standardized Precipitation Index (SPI) values in Kapchorwa calculated from the TAMSAT data (source: https://www.tamsat.org.uk/data/archive), of the FGS (March–July) and SGS (September–December). Shown are the years 2010–2016. Drought is then measured by: mild drought (0 < SPI < −0.99), moderate drought (−1.0 < SPI < −1.49), severe drought (−1.5 < SPI < −1.99), and extreme drought (<−2.00).

strong positive values with an SPI ranging from 1.5 to 2, despite the negative value in March, presenting the late onset of rains (Fig. 2). During the SGS decreased levels in SPI were identifiable beginning October with levels far below the previous years, particularly December, showing a severe drought at SPI −2.0 (Fig. 2).

In Kapchorwa, the SPI values of the FGS during 2016 showed strongly positive values when compared to the previous years (Fig. 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.

3.2. Plant analysis

All nutrient concentration means and yields of maize (with the exception of Mg and S), were significantly higher in Kapchorwa than in Teso South during the FGS (Table S2). 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 South and Kapchorwa had similar distributions (Table S2). 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 S2).

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 S3). In summary, these results showed that the soil fertility was higher in Kapchorwa than in Teso South.

Regarding nutrient concentrations 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 S4). 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). 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 significantly (Table 2). Cassava tubers in Teso South also showed significantly increased nutrient concentrations during the SGS when compared to the FGS, with the exception of K, Fe, Cu, and Mn. In cassava, macronutrient concentrations (except K) significantly

Table 2
Percent differences between the means of first growing season 2016 (FGS) and second growing season 2016 (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. Table with detailed descriptive data can be found in the Supplementary material (Table S3).

% difference between FGS and SGS	Variable	Teso South, Kenya		Kapchorwa, Uganda	
		Maize grain	Cassava tuber	Maize grain	Matooke fruit
Yield	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%***

Asterisks (*) signify level of significance, categorized into: $p < 0.05^{*}$; $p < 0.005^{**}$; $p < 0.0005^{***}$.

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).

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 S5). 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 S5). Kapchorwa had negative SPI SGS values whereas the same values were positive for Teso South (Table S5).

For maize grain in Teso South, SPI1 showed strong significant associations with nutrient concentrations, covering both macro-and micronutrients (Table 3). SPI2 also showed many significant associations, however showed 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 (Table 3). In Kapchorwa, all of significant relationships were positive. Fewer associations were seen in Kapchorwa than in Teso South in both SPIs (Table 3).

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 4). 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 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 4). 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 no yield gap 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 significant 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 were 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 5).

Maize grain nutrients accumulated 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 accumulated in a significantly higher amount during the FGS than during the SGS (Table 5). In both regions, maize had the highest amount of nutrients accumulated during the drought period when compared to the other crops.

Table 4
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 averages, from the FAOSTAT dataset (Source: http://www.fao.org/faostat/en/), using values from 2016.

	Season	Teso South, Kenya			Kapchorwa, Uganda		
		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%

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

Table 3
Comparison of the effect of Standardized Precipitation Index (SPI) values at two critical growth stages of maize in Teso South, Kenya, and Kapchorwa, Uganda, based on the local cropping calendar of 2016, 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 is quadratic, and orange stripes is cubic. Table with values in the Supplementary material (Table S6).

Region	Variable	Yield	Mg	P	S	K	Ca	Fe	Cu	Zn	Mn
Teso South, Kenya	SPI 1	⇧	⇩	* ↓	** ↓	* ↓	** ↓	*** ↓	⇩	*** ↓	*** ↓
	SPI 2	⇩	⇧	* ↓	* ↓	⇩	* ↓	* ↓	⇩	* ↓	⇩
	SPI1*SPI2	⇧	⇧	⇩	⇧	⇧	⇩	⇩	⇧	* ↓	⇩
Kapchorwa, Uganda	SPI 1	* ↑	⇧	⇩	⇧	* ↑	⇧	* ↑	*** ↑	⇧	** ↑
	SPI 2	* ↑	⇧	* ↑	⇧	** ↑	* ↑	⇧	** ↑	⇧	** ↑
	SPI1*SPI2	⇧	⇧	⇧	⇧	⇧	⇧	⇧	⇧	⇧	* ↑

Asterisks (*) signify level of significance, categorized into: p < 0.05*; p < 0.005**; p < 0.0005***.

Table 5
Mean nutrients accumulated in (g/ha) by maize, cassava and matooke collected in Teso South and Kapchorwa. Nutrients were compared between seasons: FGS (first growing season from Mar–Aug 2016) and SGS (second growing season from Sep–Dec 2016).

			Mg	P	S	K	Ca	Fe	Cu	Zn	Mn
Teso South, Kenya	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, Uganda	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

Asterisks (*) signify level of significance, categorized into: $p < 0.05^{*}$; $p < 0.005^{**}$; $p < 0.0005^{***}$.

than in Teso South (Fig. S12). Both matooke and cassava, on the other hand, showed an increase (less negative) in $\delta^{13}C$ values between the FGS and the SGS (Fig. S12). Although the $\delta^{15}N$ values showed some minor differences between the seasons the differences were not consistent between plant types (C_3, C_4) (Table S7).

3.6. Altitude and nutrient concentration

There were no significant correlations or associations 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.

4. Discussion

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, 2012). 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.

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 Precipitation 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. Coupled with the recent effects of increasing precipitation due to climate change in East Africa (Weber et al., 2018), this 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 $\delta^{13}C$ signatures of maize grain, cassava tuber and matooke fruit between seasons. For maize, the decrease in $\delta^{13}C$ values in the SGS indicated the presence of an experienced drought period, typical for a C_4 plant (Clay et al., 2001). Moreover, the larger decrease in $\delta^{13}C$ 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 C_3 plant species, an increase in $\delta^{13}C$ values is also indicative of an experienced drought (Clay et al., 2001; Schmitter et al., 2011), as was observed in Kapchorwa and Teso South for Cassava and Matoke in the SGS. $\delta^{15}N$ decreased for most samples during the drought season. The respective changes in $\delta^{15}N$, were very small, and therefore suggested to not have any impact on the interpretation of the $\delta^{13}C$ 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.

4.2.1. 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 showed 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).

4.2.2. 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 (da 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 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 C_4 plant, which has a lower level of photorespiration and therefore a higher carbon assimilation than C_3 plants, and is therefore able to maintain photosynthesis for a while with closed stomata (Lopes et al., 2011).

4.2.3. 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).

4.2.4. Implications for 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 was 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 joined 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).

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. The case of severe drought has led to a drought "double-burden" decreasing yield and 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 ramifications 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.

Acknowledgments

The submitted paper was written within the project "Crops for Healthy Diets – Linking Agriculture and Nutrition" (HealthyLAND). The HealthyLAND project is financially supported by the German Federal Ministry of Food and Agriculture (BMEL) based on the decision of the Parliament of the Federal Republic of Germany through the Federal Office of Agriculture and Food (BLE) (ID: 2813FSNU05).

We would also like to thank and acknowledge the farmers of Teso South, Kenya and Kapchorwa, Uganda.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.12.181.

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