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Sahrah Fischer "Environmental and Farm Management Effects on Food Nutrient Concentrations and Yields of East African Staple Food Crops", University of Hohenheim, 2021

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 foods consumed, particularly of plant-based foods. Therefore, humans receive most of their essential nutrients from plants. Plants in turn source their essential nutrients mainly from the soil. Humans and plants share essential elements such as Magnesium (Mg), Phosphorus (P), Sulfur (S), Potassium (K), Calcium (Ca), Iron (Fe), Zinc (Zn), Manganese (Mn), and Copper (Cu), amongst others. Essential nutrients for both, plants and humans, therefore, predominantly originate from the soil.

Due to an increasing human population, and therefore, the increasing need to produce more foods, agricultural production of plants has either intensified causing soil degradation, or been moved onto soils not suited for agricultural production. Therefore, foods are being produced on soils of highly varying fertility. The variance in soil fertility is worrisome as it is known that soils of lower fertility also produce a lower quantity (or yields) of crops. What is not known however, is how food quality is affected by soils of varying fertility, particularly regarding nutrients such as Mg, S, Ca, Fe, Zn, Mn and Cu that are not often considered during agricultural trials, unlike N, P, and K. This lack of knowledge about the food that we require to survive and remain healthy is surprising since soil and other environmental factors have been shown to strongly affect other consumables, such as wine grapes and wheat quality (also affecting dough quality and baking properties). Therefore, an effect on elemental concentrations in foods can also be assumed - however, so far it has not been studied.

The level of dependence, and the factors affecting the human-plant-soil nutrient dependence are not well described. Additionally, 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. The problem is severe as the main assumption is, soils of low fertility, which by definition contain lower amounts of nutrients would therefore also produce crops with a lower nutrient content, then crops cultivated on soils of higher fertility. This would indicate that people living on soils of lower fertility and consuming the foods produced on said soils could have a lower nutrient intake and therefore a lower health status than people living on soils of higher fertility. Although this hypothesis has been voiced in the past and is logical, potential differences in food nutrient concentrations on different soils have so far not been quantified.

Another problem that has been growing throughout the years is climate change. Climate change brings an increase in the concentrations of multiple green house gases, which have been shown to alter the nutrient concentrations in different organisms. Climate change however also increases the risks of extreme weather events, some of which have caused large scale famine in many regions of the world. While droughts and floods can in their most severe forms completely halt food production, milder forms already affect food production by for example reducing yields. Still unknown, however, is the effect on the food nutrient concentrations.

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 research. Interactions between soils and plants have been studied in depth from an agricultural perspective. Agronomists measure the nutrient contents in soils, and in plants, mainly using the leaves during the vegetative cycle of the plants' life, whereas nutritionists measure the food part and usually exclude the environment. Using leaves during the vegetative state, allows for a fertilizer correction of any nutrient deficiencies found before the generative state, therefore allowing for an increase in yield. Food parts (e.g. grains and fruits) are however, not usually measured. Food parts and leaves often represent different parts of the plant with different functions for the plant, therefore also requiring different amounts and types of nutrients. Therefore, there is no reason to think that if nutrient concentrations are high in leaves, they will also be high in other parts of the plant. So far, it is not known whether the results of the two disciplines are compatible.

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. These crops were selected as they were (i) the basis of the local food system, and therefore highly available to all households, and (ii) were cultivated most frequently, therefore providing the highest geographic coverage for the survey. 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 Si - Bruker). A drought occurring in the second rain season of 2016 provided the opportunity to analyse water stress effects on crop quantity and quality. Drought intensity was measured using the Standard Precipitation Index (SPI). Edible part nutrient concentrations and yields collected in both seasons (normal and drought) were compared using a bivariate mixed model, to allow for the survey selection criteria.

Soil chemical and physical properties (texture, pH, effective Cation Exchange Capacity (eCEC), total Nitrogen (N) and Carbon (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) paired with a permutation ranktest to identify the most important soil properties affecting nutrient concentrations. The CCA and permutation rank test were chosen as they can include all of the measured properties at once, thereby allowing for an analysis of the interactions between the different variables, as well as the identifying the main driving factors of the edible part nutrient concentrations. The two different soil fertilities were compared using maize grain as the crop cultivated on both soil types. The effects of soil properties on edible part nutrient concentrations were also compared between different plant parts: two generative (maize grain and matooke fruit) and one storage crop (cassava tuber), as well as between different growth types: annual (maize) and perennial (cassava and matooke).

As mentioned above, agronomists and nutritionists measure different parts of the plant. 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 compared to each other and to yields, using a bivariate mixed model with residual maximum likelihood to calculate the marginal correlation between the two variables. The bivariate mixed model was used to include the selection procedure of the households, as well as the field selection, which would not have been possible using a normal correlation analysis.

The drought In Kapchorwa was more severe and began two months prior to Teso South. During the severe drought, nutrient concentrations in Kapchorwa decreased significantly from normal to drought season in both crops (maize grain and matooke fruit). In contrast, during the moderate drought in Teso South, nutrient concentrations increased significantly in both crops (maize grain and cassava tuber) measured. Lacking nutrient phloem mobility is suggested to play a vital role in mobilisation of micronutrients (Fe, Mn, and Cu) and Ca, as shown by their decreased concentration under severe drought in the yields of both crops in Kapchorwa. While many macronutrients (e.g. Mg, P, K, and S) travel well in both transportation vessels, the xylem and phloem, Ca, Fe, Mn, Cu and Zn do not travel well in the phloem, and are mainly distributed via the xylem. The xylem however, is drought susceptible, meaning that during a drought the nutrient transportation stops working sooner than the nutrient distribution through the phloem. As a consequence, phloem immobile nutrients are present in plant tissue including foods in a lower amount during a severe drought. The increase in nutrients during the mild drought stems from the plant filling the edible parts, with as many nutrients as possible to allow for survival. For maize this was by filling the generative plant part with nutrients, to allow for succession. Cassava on the other hand is known for its drought resistance, and can survive most droughts by reducing its above ground biomass. The nutrients stored in the below-ground tuber (which also happens to be the food part in question), is then used to regrow the plant when the conditions have improved.

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 (annual) had higher and significant correlations with soil factors (CCA> 80%), while cassava tubers (76%) and matooke fruits (39%) (perennials) did not show significant interactions. The main reason for this could be that the perennial crops in this study have a larger buffer capacity than maize (matooke through its larger biomass, and cassava through the use of the storage root), and can therefore detach from the soil effects to a certain extent. In contrast, corresponding correlations to management factors were much weaker (matooke 8%; cassava 20%; maize 39%) compared to soil factors. Whereas in soils of high fertility, total N and C were the most important soil factors affecting edible part nutrient concentrations, texture was the most important factor in soils of lower fertility. The yields in areas with higher soil fertility were negatively correlated with the nutrient concentrations in edible parts. This indicates a dilution effect, which had previously been observed in high yielding varieties. A positive effect of crop diversity was observed in high fertility areas, and a neutral effect in low fertility areas.

The comparison of the nutrient concentrations of the edible plant part and leaf showed that the nutrient concentrations were not comparable. Using descriptive statistics already showed that while the leaf nutrient concentrations did not show significant differences between the soil types, nutrient concentrations in edible parts showed significant differences between soil types in all nutrients measured. The statistical analysis showed that, 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).

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 new type of "double-burden" for consumers, decreasing both yields and nutrient concentrations, particularly of micronutrients and Ca. This result is worrisome as particularly micronutrients are already often deficient in diets, and can have significant health effects when deficient. As the same effect was found in different plant and food types, there is a significant potential of a higher incidence of malnutrition during drought events, not only due to a lack of quantity, but also because the available quantity would have a lower quality than expected.

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. The presence of a dilution effect, for example, was only been measured in the food, and not in the leaves, indicating that including foods into agronomic trials is vital, as foods can in some cases be affected even more severely by environmental events than leaves. Particularly noteworthy is that different types of edible plant parts (e.g. grain, fruit, and tuber) had different interactions with the soil, and thereby would react differently in response also to different management factors.

Leaves may provide information on plant health, however, do not provide enough information to gauge both yields and food quality (due to the observed effects of nutrient mobility within the plant), particularly regarding micronutrients and Ca. The results of nutritionists and agronomists are therefore not compatible. The function of the edible part is vital to explaining its nutrient concentration, since the function also defines the nutrient filling time, which in turn is affected by environmental factors (as previously shown in the case of drought). 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. One example could be to use soil maps as a basis for nutrient composition databases, instead of country borders, to eliminate a large cause of variance. Another recommendation would be to begin grouping similar food types, either by plant family or broader by plant part (storage, generative, etc.) to understand when and how nutrients are filled into the edible part. Micronutrients and Ca being most affected by all the environmental factors, as well as being the nutrients showing the main difference in the comparison of methods between agronomists and nutritionists shows a very large and serious gap in knowledge. More attention should be payed to the difference in nutrient transportation in plants, since it can cause significant differences in edible parts of foods, and could therefore (as it showed up in all foods measured) also impact human health. The knowledge on nutrient transport efficiencies paired with nutrient composition tables made using soil maps, could be put together with weather data to form an early warning system for nutrient deficiency, or even depletion areas. 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.

List of thesis publications

1. Fischer, S., Hilger, T., Piepho, H., Jordan, I., Cadisch, G., 2021. Missing association between nutrient concentrations in leaves and edible parts of food crops - a neglected food security issue. Food Chem 345: https://doi.org/https://doi.org/10.1016/j.foodchem.2020.128723

2. Fischer, S., Hilger, T., Piepho, H., Jordan, I., Karungi, J., Towett, E., Shepherd, K., Cadisch, G., 2020. Soil and farm management effects on yield and nutrient concentrations of food crops in East Africa. Sci. Total Environ. 716, 1-13. https://doi.org/10.1016/j.scitotenv.2020.137078

3. Fischer, S., Hilger, T., Piepho, H., Jordan, I., Cadisch, G., 2019. Do we need more drought for better nutrition? The effect of precipitation on nutrient concentration in East African food crops. Sci. Total Environ. 658, 405-415. https://doi.org/50048969718350265