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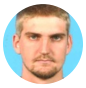

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# Soil fertility gradients and production constraints for coffee and banana on volcanic mountain slopes in the East African Rift: A case study of Mt. Elgon

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ABSTRACT

Volcanic mountains in the East African Rift (*e.g.* Mt. Kenya, Mt. Kilimanjaro, Mt. Elgon) are some of the most productive agricultural regions, often dominated by coffee and banana cultivation. Consequently, these regions suffer from a high and increasing population density with a declining soil fertility status imposing pressure on the available land, which in turn results in encroaching into the national forests. This study documents the soil fertility constraints along the slopes of Mt. Elgon and explores its corresponding gradients in plant nutritional status.

This research links the topography of Mt. Elgon to the prevailing soil types and their current fertility status. It reveals important relations and gradients between soil fertility parameters and its corresponding environment along the slope. Soil pH, soil available P and exchangeable K, Ca and Mg are significantly decreasing with elevation. Thereby, gradients and constraints in macro- and micro-nutrient uptake by coffee and banana are revealed along the toposequence and different altitude-specific nutrient limitations are determined for both crops. K, Mn and Si uptake in both crops is decreasing with elevation along the slope, while the Mo and Ni uptake in both crops is increasing. With increasing elevation, B uptake is only decreasing in coffee and P uptake is only decreasing in banana. In addition, the antagonistic interaction between K and Mg limits the Mg uptake of both crops in the lower areas, while in the high region the Mg uptake is simply limited by low soil availability. It follows that a general fertilizer recommendation cannot be made in these regions and that the soil fertility problems along these slopes should be specifically addressed and appropriately managed according to the local requirements.

## 1. Introduction

Agricultural production in the East African Highlands mostly relies on small-scale farming, which is characterized by labour-intensive agriculture with low inputs and low outputs. Coffee (*Coffea arabica* L.) is a major cash crop in these regions. It serves as a main source of income for small-scale farmers and strongly contributes to the national export revenues. In addition, banana production (*Musa* spp. AAA) serves as a staple or a secondary cash crop (Wairegi and van Asten, 2011). Demand for agricultural outputs increases due to population growth and causes pressure on the available land, leading to decreasing soil fertility (Drechsel et al., 2001). Soils are depleted by erosion, weathering and subsistence agriculture characterized by a lack of adequate replenishment of nutrients by inorganic or organic fertilizers (*e.g.* Stoorvogel et al., 1993; Henao and Baanante, 1999; Sanchez, 2002). On top of a general scarcity and suboptimal management of organic amendments (*i.e.* manure, mulch, crop residues), the limited access to, and use of fertilizers leads to soil nutrient depletion. A general lack of knowledge and understanding of specific nutrient limitations in the relevant soils (Lambrecht et al., 2014) are at the basis of poor fertilizer practices and weakly developed markets.

The resulting declining soil fertility in these highly populated mountainous areas forms a key constraint and is responsible for the low agricultural productivity. (van Asten et al., 2005; Okumu et al., 2011). In combination with an increasing demand for crop production driven by population growth and climate change that pushes Arabica coffee to higher regions, it explains the increasing

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encroachment of agricultural land towards higher elevations on Mt. Elgon (Mugagga et al., 2012; Sassen et al., 2013). This illegal cultivation in the montane forests, generally located at higher elevations of the mountain, is a general and widespread problem; also occurring on many other mountains in East Africa. Similar changes of land use and land cover have also been observed on the slopes of Mt. Kilimanjaro (Soini, 2005; William and Mungo, 2003; Yanda and Shishira, 2001) and similar positive relationships between population pressure and forest clearance in the mid-altitude tropical forests of Kakamega (Kenya) and Budongo (Uganda) were identified by Lung and Schaab (2010).

To decrease pressure on the current available land and natural resources, a more intensive, performant agriculture is needed. This concept is often referred as '*intensification for conservation*' (Sassen, 2014) or '*land sparing*' strategy (Phalan et al., 2011). Understanding soil fertility gradients and dynamics is a crucial step in the development of such strategies. Currently, 'coffee-banana' cropping regions on volcanic mountains on the eastern side of the East African Rift (*e.g.* Mt. Kilimanjaro, Mt. Kenya and Mt. Elgon) are generally considered as 'isolated' agro-ecological zones, especially in terms of land use and soil fertility. And while being similar, their complexity impedes the development and formulation of locally-adapted fertilizer recommendations, that would take into account the specific nutrient needs that can be observed along the slopes of these mountains.

The aim of our research is to better understand such soil fertility constraints on the slopes of a volcanic mountain of the Eastern Rift. This should enable the formulation of adapted, site-specific fertilizer recommendations, in turn leading to more efficient land use, larger productivity and profitability, thereby preventing further soil and environmental degradation at plot and landscape scale.

As a first objective, this study wants to determine the relation between the geomorphology and topography on the one hand and current soil type and fertility status on the other hand, focusing on nutrient requirements of coffee. To this end, the presence of soil fertility gradients – both for macro- and micronutrients – with elevation will be confirmed and their effects on plant nutritional status described.

Finally, to validate and confirm the results obtained with coffee, we undertook a side-comparison with bananas as the test crop to seek possible similarities. This will lead to a comparative analysis of zonal macro-nutrient deficiencies for banana and coffee along the slopes of Mt. Elgon. Nutrient uptake efficiencies of both crops can then be related to their environment.

## 2. Materials and methods

### 2.0. Site description

Mount Elgon, located on the border between Uganda and Kenya, served as a case study in this research, as it is representative for basaltic volcanoes in the region. Mount Elgon was formed during the Pliocene (Davies, 1952) and is therefore the oldest volcanic mountain of the Eastern Rift. We conducted our study on the north-western slopes of Mt. Elgon and the study area covered the 3 Ugandan districts: Kapchorwa, Bulambuli and Sironko. The research site, presented on Fig. 1, (1°8′15″N-1°20′46″N and 34°18′3″E-34°31′33″E) covers the sloping area from 1000 masl (meters above sea level) up to the border of the National Park at *ca.* 2300 masl. This area can be divided into 3 elevation zones separated by 2 escarpments. We distinguished a '*Low Altitude Zone*' between 1000 and 1310 masl, a '*Middle Altitude Zone*' between 1311 and 1800 masl and a '*High Altitude Zone*' between 1801 and 2300 masl.

The rainfall pattern in the region is bimodal (East African Meteorological Department, 1963) with rainfall from March to May and from September to November. The elevation range is associated with a climate gradient. From base (1000 masl) to top (4321 masl) the mean annual temperature decreases from

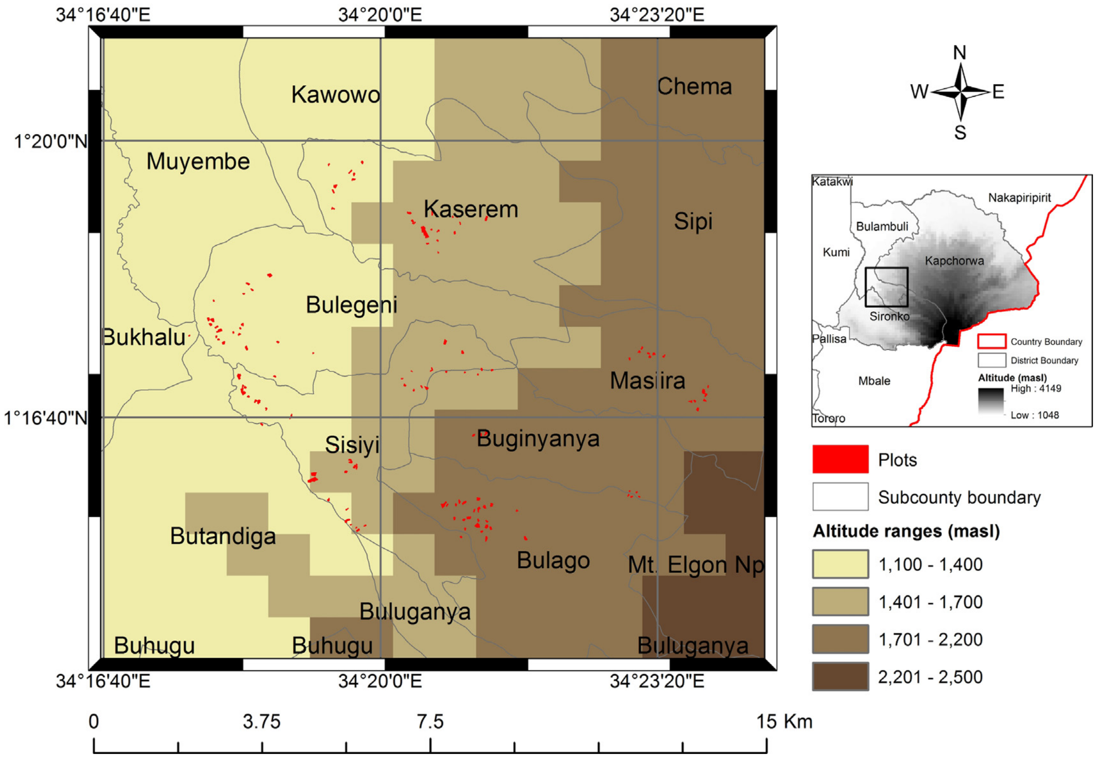


**Fig. 1.** Map of the research area on Mt. Elgon, situated at the eastern border of Uganda. The research sites comprise the 3 Ugandan districts: Kapchorwa, Bulambuli and Sironko; which are located on the northwestern side of Mt. Elgon. (from ArcGIS; Map made by Theresa Liebig).

about 23.5 °C to 1.5 °C while the gradient in mean annual rainfall ranges from 1200 to 2200 mm (NEMA, 2010).

An initial soil profile study in ten different plots (unpublished own data), equally distributed over the entire toposequence, confirmed that the soils on these slopes are predominantly Nitisols (WRB for soil classification (IUSS Working Group, 2015)), developed on basaltic outflows.

We consider Mount Elgon as a 'model mountain', which is justified by the presence of a similar climate-belt and a similar Nitisol-belt (Jones et al., 2013) as on the slopes of both Mount Kenya and Mount Kilimanjaro.

### 2.1. Analyses of soil fertility parameters and macro-nutrient uptake by arabica coffee

We randomly selected 149 smallholder coffee plots within the research area. The coordinates and elevation of each plot were determined with a *'Global Positioning System'* (GPS). Composite soil samples were taken from each plot by sampling the upper 25 cm with an auger at five different points on the plot (four points close to each corner and one in the middle). These composite soil samples were mixed, dried (40 °C for 48–96 h), ground with mortar and pestle and sieved by a 2 mm sieve. The samples were then chemically analysed for pH, soil organic matter (SOM) content, total soil N, soil available P, soil exchangeable K, Ca, Mg and soil available S. The analytical methods are described by Okalebo et al. (1993). Total N was assessed colorimetrically after Kjeldahl digestion with sulphuric acid and selenium as a catalyst. Available P and extractable cations (K, Ca and Mg) were extracted using the Mehlich-3 extraction solution, P was measured colorimetrically using the molybdenum blue method, K was measured using a flame photometer, while the other cations (Ca and Mg) were determined using an atomic absorption spectrophotometer. The sulphur in the soil is extracted by a 1:5 soil-water solution and then quantified by turbidimetry after precipitating as $BaSO_4$.

On each plot, five coffee plants, homogeneously distributed in the plot, were randomly selected for leaf sampling. From each of these five plants, four branches in opposite directions were randomly chosen in the middle of the canopy. From each of these selected branches the third pair of young leaves (the '*critical leaf pair*') was picked during the flowering period as proposed by Snoeck and Lambot (2004). All sampled leaves of one plot were combined to form a composite foliar sample of the plot. These composite leaf samples were dried in an oven (50 °C for 48–96 h), ground with an electric grinder to less than 2 mm, digested and analysed for their foliar N, P, K, Ca, Mg and S content as described by Okalebo et al. (1993). The coffee yield in kg/tree was estimated for each plot by the method described by Cilas and Descroix (2004).

The obtained data were subsequently investigated by the application of 'exploratory multivariate statistical techniques' with the statistical computer program 'R' (R Development Core Team, 2012). First a 'Pair-plot' of the variables was made to screen for interesting interrelations. A Pearson Correlation Matrix was composed and a Factor Analysis carried out to discover coherent variables. The most interesting relations were consequently selected for parameter estimation in 'R'.

### 2.2. Analyses of zonal macro-nutrient deficiencies for coffee

'Compositional Nutrient Diagnosis' (CND) is a method used to diagnose nutrient imbalances in crops by taking nutrient interactions into consideration (Parent and Dafir, 1992). The CND method is based on row-centred log ratios where each nutrient is adjusted to the geometric mean (G) of all the included nutrients and to a filling value $R_d$. CND norms for each nutrient are determined from a 'high yielding population' that is most often segregated by using a third order polynomial, as proposed by Khiari et al. (2001). Wairegi and Van Asten (2012) previously provided CND norms of *Coffea arabica* L. for the nutrients N, P, K, Ca and Mg for Mt. Elgon. Yet, we set out to derive new macro-nutrient norms, including sulphur, because it is considered more reliable to develop norms more specific for the relevant agro-ecological zone and because the dataset is large enough to allow this.

Applying the method of Khiari et al. (2001) on our data to segregate a 'high yielding population' resulted in unrealistic 'split-off values', beyond the maximum observed yield in the experiment. Therefore we choose to determine the 'high yielding split-off value' in an arbitrary way at the highest 15% of the ranked population (Escano, 1981). From this segregated 'high yielding population', norms ($\mu$ and $\sigma$) were extracted for each of the macro-nutrients N, P, K, Ca, Mg and S.

These norms ($\mu$ and $\sigma$) were then applied on an independent dataset of row-centred log ratios, denoted as $V_x$ for the according macro-nutrient X and the filling value $R_d$. Using the norms in this way, specific nutrient indices (CND-I) are derived for each (plot-) observation j:

$$\mathrm{CND} - \mathrm{I}_{Xj} = \frac{(V_{Xj} - \mu_X)}{\sigma_X} \tag{1}$$

A negative index indicates a small concentration of this specific nutrient in the plants relative to the norm and points to a potential deficiency or imbalance. To determine specific zonal deficiencies on the sloping area, the averages of the plot-indices were calculated for the 3 different elevation areas. If a normal distribution of the index group was confirmed with a *'Shapiro-Wilk'* test in 'R', then the student's *t*-test was used to test whether the index average is significantly below zero. The t-values were calculated as follows and were compared with the significance level at $\alpha = 0.05$:

$$t - value = \frac{\mu(I)}{\frac{\sigma(I)}{\sqrt{n}}} \tag{2}$$

If normality of an index-group was not confirmed, then a non-parametric test was used to check whether the centre of the data is significantly below zero. In this case the index groups were tested for significant ($\alpha = 0.05$) deficiency with a *'one-sample sign rank Wilcoxon-test'* in *'R'*. The interpretation of these CND-I averages were also compared with the observed nutrient deficiency symptoms of several coffee plants in the different elevation regions.

### 2.3. Analyses of micro-nutrient uptake by coffee

A selection of 35 plots was made out of the 149 previously randomly selected plots. These 35 plots have been chosen in such a way to ensure that they have a relatively balanced distribution over the research area. To increase the number of observations and to investigate the variation within plots, these 35 plots have been subdivided in one to three sub-plots of *ca.* 300 $m^2$. In this way, composite foliar samples were recollected from 68 sub-plots according to the same sampling method described in paragraph 2.1.

To remove dust and to ensure the purity of the samples, the foliar samples were first cleaned with a brush. The composite samples were then dried in an oven (50 °C for 48–96 h) and manually crushed with a mortar to a particle size smaller than 2 mm. The C and N contents in the samples were determined by dry combustion based on an oxidative digestion under a controlled oxygen supply at high temperature (900 °C). $CO_2$ and $N_2$ were then analysed by Gas Chromatography (GC) (EA1108 from Carlo Erba). All other macro- and micro-nutrient concentrations were determined by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) analysis (Agilent 7700x) after digestion by $HNO_3$.

For the analyses of the micro-nutrient status, the same exploratory multivariate techniques were used as described in 2.1. A Pearson correlation matrix was made to reveal inter-factorial relations and a Factor Analysis was done to investigate the coherence of the variables. These techniques were applied on the micro-nutrient data only, but also with inclusion of the macro-nutrient ICP-results to verify and confirm the macro-nutrient findings of Section 2.1.

### *2.4. Analyses of nutrient uptake by banana*

To validate previous findings on soil fertility and nutrient uptake of different crops, an assessment of the banana plants growing in the same region was made. A selection of ten coffee-banana plots was made out of the 149 previously selected coffee plots. Each of these ten plots was sub-divided in three or four sub-plots which resulted in 39 observations. In each sub-plot the critical leaves of three flowering banana plants were sampled as suggested by Memon et al. (2001) and mixed to obtain a composite foliar sample. The leaf samples were cleaned with a brush, oven dried (50 °C for 48–96 h), manually crushed with a mortar and analysed for their macro- and micro-nutrient content by GC and ICP-MS as described in 2.3.

Subsequently, the same exploratory multivariate statistical analyses were applied on these banana foliar results as described in 2.1.

### *2.5. Analyses of zonal macro-nutrient deficiencies in banana*

CND norms for East African Highland Bananas (*Musa* spp. AAA) are provided by Wairegi and van Asten (2011) for N, P, K, Ca and Mg. Since our dataset was not large enough and no yield data were available to create new CND norms for banana, we used the macro-nutrient norms of Wairegi and van Asten (2011) for the exploration of nutrient deficiencies in banana. These norms were applied on our foliar nutrient data of banana in the same way as described in 2.2. Consequently, the obtained nutrient indices for each sub-plot were used to calculate significant zonal nutrient deficiencies as described in 2.2.

## 3. Results

### *3.1. Gradients and interactions of soil fertility parameters on Mount Elgon and macro-nutrient uptake by coffee*

The Pearson Correlation Matrix of all factors shows a high correlation (r) of −0.86 between *'Altitude'* and *'Soil pH'*. This relation is presented in Fig. 2 and given below in equation (3):

$$[SoilpH] = -0.0016[Elevation(masl)] + 8.7392 \quad (3)$$

The factor loadings of this Factor Analysis are presented in Table 1 and show the coherence of the soil fertility parameters along the slope. The soil pH appears to be highly negatively correlated with the available soil P (−0.73), soil exchangeable Ca (−0.77), Mg (−0.75) and K (−0.67) and hence altitude is highly correlated with soil P (−0.63), soil Ca (−0.63), soil Mg (−0.59) and soil K (−0.49). The relations of available soil P, soil Ca, soil Mg and soil K with altitude and soil pH are presented in Table 2. The observed logarithmic relation of altitude with available soil P is given as an example in Fig. 3.

Soil N is highly correlated (0.93) with the amount of SOM while SOM is relatively weakly correlated with altitude (−0.33) and soil pH (0.25). A negative correlation of −0.46 is observed between foliar K and foliar Mg while a small positive correlation (0.24) is found between foliar K and Ca. None of the variables are observed to be highly correlated with yield (<0.23).

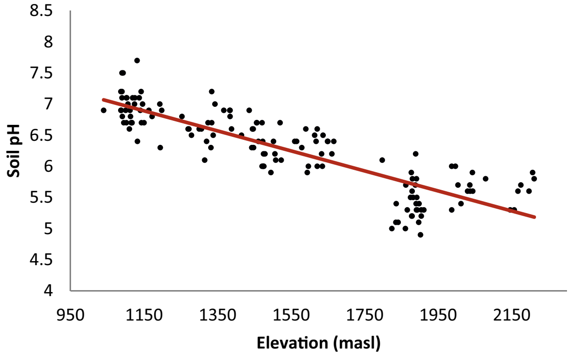


**Fig. 2.** The observed relation between elevation and soil pH of composite soil samples collected from 149 coffee plots along a toposequence on Mount Elgon (Eastern Uganda). Soil pH is observed to decrease linearly with elevation from *ca.* pH 7.5 at 1000 masl to *ca.* pH 4.9 at 2200 masl.

Of all the macro-nutrients in the coffee leaves, only the K concentration has a relatively large correlation coefficient with the altitude (−0.41) and soil pH (0.53). This relation between 'foliar K' and 'soil pH' is linear (Fig. 4). On the other hand, the concentrations of N, P, Ca, Mg and S in the leaves show relatively small correlation coefficients with altitude (0.24, −0.18, −0.06, −0.10 and −0.25) and soil pH (−0.23, 0.12, −0.002, −0.10 and 0.15).

### *3.2. Zonal macro-nutrient deficiencies for coffee*

A 'high yielding population' of 22 plots was segregated as the highest 15 percentage at a yield cut-off value of 2.09 kg/tree. This value is 0.9 kg/tree larger than the cut-off value used by Wairegi and Van Asten (2012). The CND norms, derived and used in this study are presented in Table 3. The averages of the CND indices from the three different altitude areas are provided in Table 4 with the corresponding p-values. A significant nutrient deficiency corresponds with a large percentage of negative indices. In the low altitude area this is the case for N and Mg. In the middle altitude area this is only valid for S and in the high altitude both Mg and S appear significantly below zero.

**Table 1**
Factor Loadings of the Factor Analysis performed on the general dataset of the baseline survey in 2.1. The first factor describes most of the variation and contains much of the '*toposequence descriptors and the corresponding changes in soil properties*'. The second factor describes '*general organic matter aspects*' while the 3d and 4th factor hold '*Foliar Nutrient Issues of K and Mg*' such as their relations with elevation and soil pH and their antagonistic effects.

| | Factor1 | Factor2 | Factor3 | Factor4 |
|---|---|---|---|---|
| yield | | | | −0.255 |
| Alt | −0.561 | −0.191 | −0.504 | −0.440 |
| pH | 0.676 | 0.103 | 0.675 | 0.269 |
| fN | | | −0.314 | |
| fP | | | 0.198 | |
| fK | 0.106 | 0.311 | 0.633 | |
| fCa | −0.146 | 0.226 | | 0.141 |
| fMg | 0.112 | −0.194 | −0.545 | 0.805 |
| fS | 0.234 | 0.306 | 0.108 | −0.153 |
| sOM | 0.173 | 0.977 | | |
| sN | 0.131 | 0.917 | | |
| sP | 0.673 | 0.284 | 0.328 | |
| sCa | 0.947 | 0.112 | 0.202 | |
| sMg | 0.820 | | 0.273 | |
| sK | 0.464 | 0.110 | 0.460 | |
| sS | −0.341 | | | 0.272 |

Alt = Altitude; pH = soil pH; f-nutrient = foliar nutrient; SOM = Soil Organic Matter; s-nutrient = Soil nutrient.

**Table 2**
The estimated relations of soil available P, soil exchangeable Ca, soil exchangeable Mg and soil exchangeable K in function of the soil pH and the elevation in the research area given with the corresponding coefficient of determination ($R^2$). Soil available P and soil exchangeable Ca, Mg and K appear to decrease logarithmically along the slope.

| Estimated function | $R^2$ |
|---|---|
| $\left[Soil\,P\left(\frac{mg}{kg}\right)\right] = 0.002e^{1.8567[Soil\ pH]}$ | $R^2 = 0.69$ |
| $\left[Soil\,Ca\left(\frac{cmol}{kg}\right)\right] = 0.1914e^{0.6758[Soil\ pH]}$ | $R^2 = 0.63$ |
| $\left[SoilMg\left(\frac{cmol}{kg}\right)\right] = 1.1128e^{0.2585[SoilpH]}$ | $R^2 = 0.56$ |
| $\left[SoilK\left(\frac{cmol}{kg}\right)\right] = 0.0085e^{0.7966[SoilpH]}$ | $R^2 = 0.47$ |
| $\left[SoilP\left(\frac{mg}{kg}\right)\right] = 1880.7e^{-0.003[Elevation(masl)]}$ | $R^2 = 0.48$ |
| $\left[SoilCa\left(\frac{cmol}{kg}\right)\right] = 59.47e^{-1E-03[Elevation(masl)]}$ | $R^2 = 0.38$ |
| $\left[SoilMg\left(\frac{cmol}{kg}\right)\right] = 10.036e^{-4E-04[Elevation(masl)]}$ | $R^2 = 0.33$ |
| $\left[SoilK\left(\frac{cmol}{kg}\right)\right] = 6.8224e^{-0.001[Elevation(masl)]}$ | $R^2 = 0.25$ |

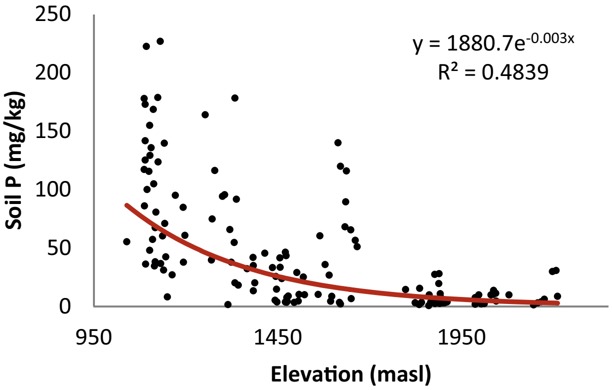


**Fig. 3.** The available soil P in the research area is observed to decrease with elevation. This decreasing available soil P is observed to follow a logarithmic trend.

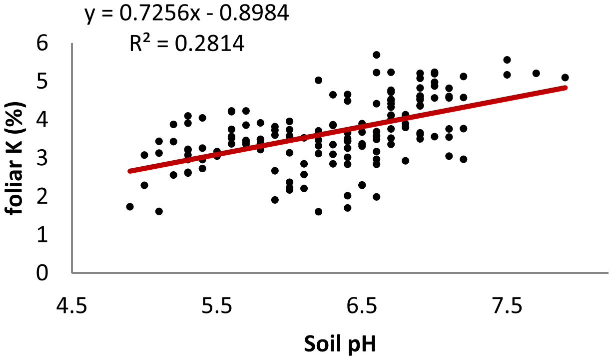


**Fig. 4.** The estimated linear relation between the observed soil pH gradient and the foliar K content of coffee plants on the toposequence along the slope of Mount Elgon. K uptake by coffee is observed to increase with increasing soil pH (from 4.9 up to 7.8) and decreasing elevation (from 2200 masl to 1000 masl).

### *3.3. Gradients and interactions of micro-nutrient uptake by coffee*

The concentrations of Mn, Si and Co in the coffee leaves are observed to be slightly correlated with soil pH and show coefficients of respectively −0.48, 0.38 and −0.36. Other micro-nutrient concentrations of B, Mo and Ni are more strongly related with altitude and soil pH. B, Mo and Ni show correlation coefficients of −0.49, −0.47, 0.57 with altitude and 0.47, 0.49, −0.67 with soil pH. Again, none of the included micro-nutrients show a correlation coefficient with yield exceeding 0.22.

The estimated relation of Ni uptake with altitude and soil pH is observed to be logarithmic and is given as an example in Fig. 5. The results of the Factor Analysis are presented in Table 5 and show the coherence of the soil fertility factors along the slope. Additionally, also a general small Zn concentration (average of 6.05 mg/kg and standard deviation of 2.22) is observed in the leaf tissue of the sampled coffee plants.

### *3.4. Gradients in nutrient uptake by banana*

In the Pearson Correlation Matrix of the banana nutrition data, similar trends emerged in foliar nutrient contents with ‘altitude’ and ‘soil pH’. The amount of P in the banana leaf tissue is strongly correlated with altitude (−0.80) and soil pH (0.81). The K content shows a correlation of −0.46 with altitude and 0.46 with soil pH. Also the amount of foliar silica correlates well both with altitude (−0.70) and soil pH (0.66). Correlations between Mg and K were small and negative (−0.29) the same with Mg and P (−0.30).

For the micro-nutrients, correlations of Mn-, Ni- and Mo-content are observed with altitude (0.78, 0.75, −0.84) and with soil pH (-0.85, −0.76, 0.85). Consequently also (indirect) inter-correlations between these 3 nutrients are observed. In addition, a general small foliar Zn concentration (average of 15.5 mg/kg) is observed in the leaf tissue of the sampled bananas. Table 6 summarizes and compares the different nutrient-uptake gradients between banana and coffee along the soil fertility gradient.

### *3.5. Zonal macro-nutrient deficiencies of banana*

The averages of the CND indices with the corresponding p-values for the three different altitude areas are provided in Table 7. A significant nutrient deficiency for banana corresponds with a large percentage of negative CND-indices. The p-values in Table 7 are underlined if the CND-index average is significantly ($\alpha < 0.05$) below zero. This is observed in the low altitude area for N and Mg, in the middle altitude area only for N and in the high altitude area only for Mg. Indices for S could not be calculated.

## **4. Discussion**

### *4.1. Gradients and interactions of soil fertility parameters and macro-nutrient uptake by coffee*

Soil pH decreases linearly with elevation from *ca.* pH 7.5 at 1000 masl to *ca.* pH 4.9 at 2200 masl. This gradient can be explained by a more intense leaching and acidification at higher elevations,

**Table 3**
Macro-nutrient CND norms from the ‘high yielding population’ of coffee determined as the highest 15%, expressed as means and standard deviations (SD) of the row-centred log ratios V(X) of the nutrient concentrations in percentages.

| Norms: | V(N) | V(P) | V(K) | V(Ca) | V(Mg) | V(S) | N% | P% | K% | Ca% | Mg% | S% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean | 0.86 | −2.32 | 0.89 | −0.40 | −0.79 | −2.50 | 3.09 | 0.13 | 3.26 | 0.98 | 0.60 | 0.11 |
| SD | 0.15 | 0.19 | 0.22 | 0.48 | 0.20 | 0.23 | 0.36 | 0.04 | 0.85 | 0.43 | 0.12 | 0.03 |

**Table 4**
The average CND indices of coffee calculated for the 3 different altitude areas expressed as average and standard deviations (SD) of the zonal plot indices. P-values marked with '*' are calculated according to the non-parametric Wilcoxon test. P-values without '*' are calculated according to the 'student's *t*-test'. Only *p*-values from negative index averages are presented and are underlined if significantly ($\alpha < 0.05$) below zero. The frequency of the occurrence of a negative index is additionally given in percentage. This table shows that nutrient deficiencies in coffee are not homogeneous over the entire region. For the low altitude area N and Mg are significantly deficient and in the middle altitude area only S poses a significant problem. For the high altitude area both S and Mg turn significantly deficient.

| Low altitude | I(N) | I(P) | I(K) | I(Ca) | I(Mg) | I(S) |
|---|---|---|---|---|---|---|
| Average | −1.08 | 0.18 | 0.78 | 0.32 | −0.44 | 0.07 |
| SD | 1.44 | 1.95 | 0.68 | 0.87 | 0.69 | 1.01 |
| p-value (n = 45) | **4.02E-06** | – | – | – | **3.5E-06*** | – |
| % | 73 | 40 | 13 | 24 | 84 | 49 |
| Middle altitude | I(N) | I(P) | I(K) | I(Ca) | I(Mg) | I(S) |
| Average | -0.33 | 0.50 | 0.15 | 0.08 | 0.34 | -0.77 |
| SD | 1.35 | 1.57 | 1.16 | 0.76 | 1.06 | 1.37 |
| p-value (n = 55) | 0.13* | – | – | – | – | **1.7E-05*** |
| % | 47 | 44 | 44 | 40 | 45 | 75 |
| High altitude | I(N) | I(P) | I(K) | I(Ca) | I(Mg) | I(S) |
| Average | −0.12 | 0.09 | −0.05 | 0.47 | −0.21 | −0.49 |
| SD | 0.72 | 1.05 | 0.90 | 0.84 | 0.86 | 0.84 |
| p-value (n = 49) | 0.12 | – | 0.49* | – | **0.044** | **9.4E-05** |
| % | 49 | 40 | 49 | 22 | 67 | 76 |

traditionally following the orographic rainfall gradient and leading to smaller amounts of Ca, Mg K and P (Vitousek and Chadwick, 2013). On the other hand, precipitation from dust clouds following the major wind directions in the lower areas (Matete and BakamaNume, 2010) enriching the soils with cations (K, Mg, Ca) and soil available P has also been reported (Shao et al., 2011). The available P and exchangeable Ca, Mg and K in the soils is consequently observed to decrease with increasing elevation and decreasing soil pH.

The initial *rhyolitic* complex of Mt. Elgon was fully covered in a later stage by the same basaltic outflows (Davies, 1952). The mineralogical heterogeneity at the surface was removed or buried and therefore a mineralogical gradient, that correlates with soil pH and elevation, can be dismissed as an explaining variable of these soil fertility gradients.

The relations of soil K, Mg, Ca and P with altitude and soil pH are estimated by logarithmic functions and show a rapid decrease of soil available concentrations going up the slope. Such non-linear changes of soil fertility parameters along volcanic slopes were previously described by Chadwick et al. (2003) and the orographic climate gradient along the slope is considered as the major driving factor of these trends (Chadwick et al., 2003). Processes of rainfall and leaching occur in each soil type, and as a consequence that the larger amounts of allophane (and the lower bulk density) of Andosols in the study area used by Chadwick et al. (2003) have a modifying role in these processes, they would not make them deviating from the general trends, valid for all soils.

Similar soil fertility gradients as observed in this study can be expected on other volcanic mountains in the East African region with a similar climate (*e.g.* Mt. Kenya, Mt. Kilimanjaro). This can be based on the following reasoning.

First, the three mountains share a similar parent material. The common geologic surface material on these tree mountains is alkali-basaltic (Chorowicz, 2005). From this parent material, in general Nitisols are developed. This is confirmed on the soil map (Jones et al., 2013), where the major soil units on the slopes of these mountains are indeed Nitisols accompanied by Lixisols or Luvisols. The latter are derived from the initial soil type (*i.e.* Nitisols) by the development of an illuviated clay horizon after exposure of sufficient rainfall. In addition, no evidence of volcanic ash deposits is found on Mt. Elgon. On Mt. Kilimanjaro and Mt. Kenya volcanic ash deposits are found, but only on the higher elevations above *ca.* 2000 masl, so these would not influence these general trends of soil fertility on the lower elevations. (Zech et al., 2014; Frei, 1978)

Secondly, with respect to the orographic rainfall gradient, which is considered as the main driving factor for the variation in soil fertility properties along the slope, this orographic rainfall gradient is characteristic for each mountain, especially on the rain intensive sides. Our transect is located on the rain intensive side (northwest) of Mt. Elgon, the oldest mountain of the three. Hence it can be assumed that this transect has been exposed to the largest amount of rainfall since its creation. Likewise one can assume that other transects on similar mountains develop according to the same gradient, after experiencing sufficient rainfall with time.

It is well known that soil pH is an important factor of soil fertility as it has a large influence on other soil fertility parameters and on nutrient uptake capacity of higher plants (Rowell, 1994).

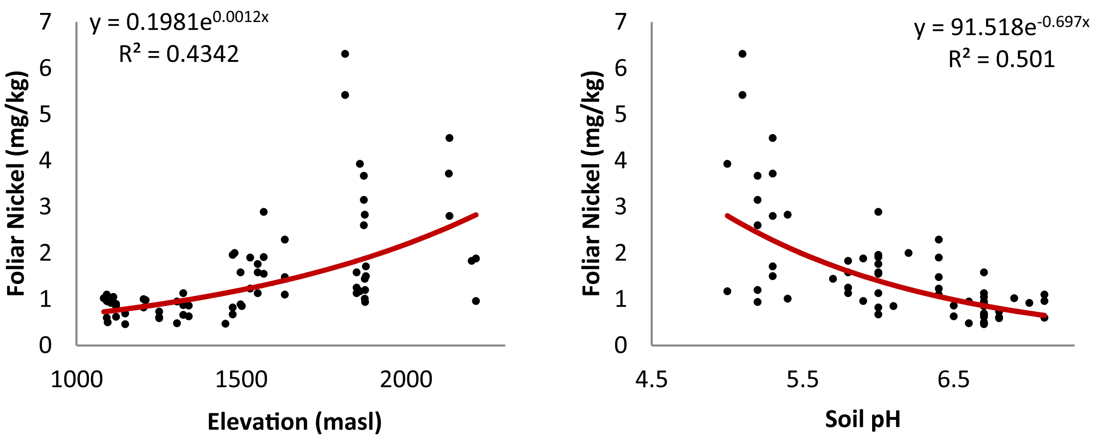


**Fig. 5.** The estimated relation between the foliar nickel content in coffee plants and the elevation (left) and soil pH (right) in the research area. Both trends are observed to follow a logarithmic function and they describe the gradients along the toposequence. These figures shows that the nickel uptake by coffee is highly depending on the location on the slope. Nickel itself is an essential micro-nutrient as it has a direct link with the nitrogen metabolism in the plant.

**Table 5**

Factor loadings of the factor analyse performed on the foliar micro-nutrients and the general plot data. The first factor describes the coherent variance of 'the soil pH, the elevation and the corresponding variance in micro-nutrient uptake by coffee plants'.

| | Factor1 | Factor2 | Factor3 |
|---|---|---|---|
| Yield | −0.207 | 0.140 | |
| Altitude | −0.785 | 0.324 | 0.158 |
| soilpH | 0.950 | −0.277 | −0.123 |
| OM | 0.174 | −0.271 | |
| estCEC | 0.602 | −0.264 | −0.246 |
| N | −0.131 | −0.982 | 0.118 |
| C | −0.188 | 0.203 | 0.958 |
| C/N | | 0.970 | 0.223 |
| B | 0.528 | 0.180 | −0.159 |
| Mn | −0.524 | | |
| Fe | 0.251 | | −0.294 |
| Co | −0.399 | | |
| Ni | −0.627 | 0.180 | 0.113 |
| Cu | | | 0.130 |
| Zn | −0.218 | | |
| Mo | 0.588 | 0.146 | |

OM = Soil Organic Matter; estCEC = estimated Cation Exchange Capacity; C, N, B, Mn, Fe, Co, Ni, Cu, Zn, Mo = The Foliar nutrient concentration; C/N = Carbon to Nitrogen ratio in the leaf tissue.

The observed soil pH gradient has therefore major consequences on plant nutrition and has strong implications for soil fertility management along the slope. (Marschner, 2012; Rowell, 1994)

It is remarkable that the observed gradients in soil Ca, Mg, K and P availability have little impact on the nutrient uptake by coffee. The observed decrease in soil nutrient availability parameters with elevation is only reflected in a decreasing foliar K content along the slope. The K content in the coffee leaves indeed linearly decreases with increasing elevation or decreasing soil pH. All other foliar nutrients do not follow a similar relationship as the soil nutrients with elevation and soil pH. These observations can serve as an extra argument for doing plant tissue analysis instead of soil tests. First, this can show the incapability of soil tests in predicting nutrient uptake by perennial crops or tree crops; and secondly, leaf concentrations are assumed to display a homeostatic situation.

The antagonism between K and Mg uptake by plants is generally known as well as the importance of these nutrient ratios in the soil (Marschner, 2012). On this toposequence an antagonistic effect between K and Mg uptake is observed as foliar Mg increases with a decrease in foliar K content. The K uptake by coffee decreases along the altitude, while the Mg uptake is observed to be subordinate, depending on this K uptake. This initial observed antagonistic interaction is important since it can result in imbalances of K and Mg or induce deficiencies in the plant tissue. Between K and Ca we did not observe any antagonistic effect in uptake.

In general, the SOM content is expected to increase along elevation, since larger mineralization rates can be expected at higher temperatures and thus lower elevations. Nevertheless, the only strong relation of SOM observed in this study, is the expected correlation with soil nitrogen, since most of the N in soils is present in SOM. No other significant relations of SOM with other environmental or soil factors have been observed. This is against expectations and other observations and implies that other factors, not included in this study and probably related to farmer's management or cropping system, highly influence the SOM content.

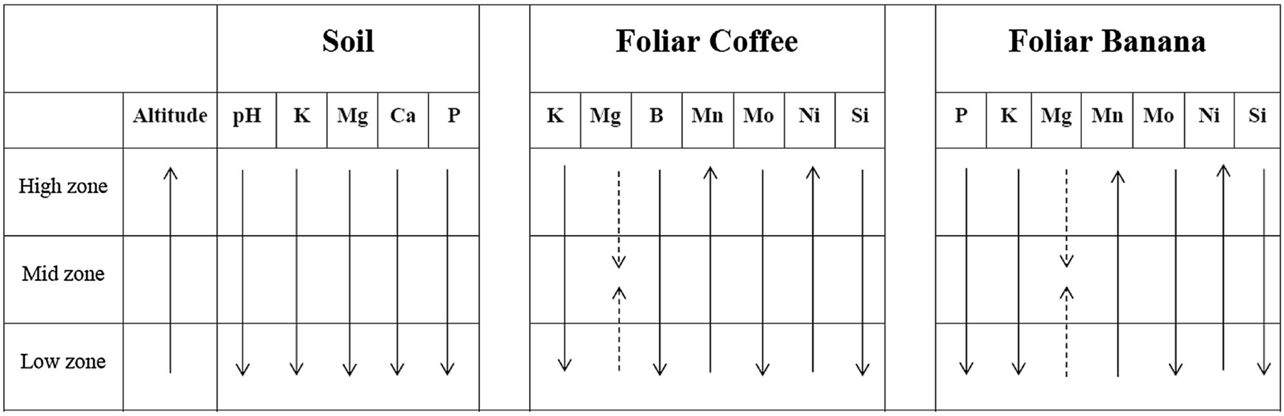
None of the soil and environmental variables were highly correlated with the yield of coffee, which can be explained by the multifactorial dependence of yield, the specific management regimes (*e.g.* pruning) and the variable, inappropriate maintenance of coffee plants by most of the smallholder farmers in Mount Elgon. These facts show that besides addressing soil fertility issues, also the farmers' maintenance of their coffee plants can be optimized to increase the coffee output (Snoeck and Lambot, 2004).

### *4.2. Zonal macro-nutrient deficiencies in coffee*

The CND norms for Arabica coffee obtained in this study (Table 3) are slightly different from the CND norms provided by Wairegi and Van Asten (2012). The mass fraction norms for N,K and Mg in this study are larger (relatively 0.13%, 0.39%, 0.2%) than the norms derived by Wairegi and Van Asten (2012), while the mass fraction norm for Ca is similar and these of P is 0.1% smaller. These differences may be explained by the extra variation introduced by the inclusion of the additional nutrient sulphur. Moreover, the lack of a general applicable method for isolating a high yielding population may induce more variation since the yield cut-off value determined in this study is different than the cut-off value used by Wairegi and Van Asten (2012). Although, the use of these norms is justified since we used a large number of observations to extract a

**Table 6**

Summary of the observed trends of soil fertility parameters and nutrient uptake gradients for coffee and banana along the elevational gradient. The arrows indicate an increasing trend in soil parameters (soil pH, soil exchangeable K, Mg, Ca and soil available P) and nutrient uptake (mass percentage in the leaf tissue) by coffee and banana along the elevational gradient.



| | | Soil | | | | | Foliar Coffee | | | | | | | Foliar Banana | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Altitude | pH | K | Mg | Ca | P | K | Mg | B | Mn | Mo | Ni | Si | P | K | Mg | Mn | Mo | Ni | Si |
| High zone | ↑ | │ | │ | │ | │ | │ | │ | ┆ | │ | ↑ | │ | ↑ | │ | │ | │ | ┆ | ↑ | │ | ↑ | │ |
| Mid zone | │ | │ | │ | │ | │ | │ | │ | ↓<br>↑ | │ | │ | │ | │ | │ | │ | │ | ↓<br>↑ | │ | │ | │ | │ |
| Low zone | │ | ↓ | ↓ | ↓ | ↓ | ↓ | ↓ | ┆ | ↓ | │ | ↓ | │ | ↓ | ↓ | ↓ | ┆ | │ | ↓ | │ | ↓ |

**Table 7**
The average CND indices of banana calculated for the 3 different altitude areas expressed as average and standard deviations (SD) of all the plot indices. P-values marked with '*' are calculated according to the non-parametric Wilcoxon test. P-values without '*' are calculated according to the 'student's *t*-test'. P-values are presented and are underlined if significantly ($\alpha < 0.05$) below zero. The frequency of the occurrence of a negative index is additionally given in percentage. This table shows that nutrient deficiencies in banana are not homogeneous over the entire region. For the low altitude area N and Mg are significantly deficient and in the middle altitude area only N poses a significant problem. For the high altitude area only Mg turn significantly deficient. Indices of S could not be calculated.

| Low: | I(N) | I(P) | I(K) | I(Mg) | I(Ca) |
|---|---|---|---|---|---|
| Average | −1.31 | 3.64 | 0.09 | −1.94 | 0.16 |
| SD | 0.78 | 0.87 | 0.49 | 0.59 | 0.54 |
| p-value | **6.7E-06** | 1 | 0.88* | **2.3E-09** | 0.86 |
| % | 93 | 0 | 33 | 100 | 40 |
| Mid: | I(N) | I(P) | I(K) | I(Mg) | I(Ca) |
| Average | −1.03 | 1.08 | 0.01 | −0.46 | 0.38 |
| SD | 0.64 | 0.88 | 0.64 | 1.04 | 0.71 |
| p-value | **8.8E-05** | 0.10 | 0.51 | 0.08 | 0.95 |
| % | 92 | 8 | 42 | 67 | 33 |
| High: | I(N) | I(P) | I(K) | I(Mg) | I(Ca) |
| Average | −0.12 | 0.02 | −0.25 | −0.49 | 0.43 |
| SD | 1.20 | 0.70 | 1.10 | 0.84 | 0.83 |
| p-value | 0.36 | 0.54 | 0.22 | **0.03** | 0.95 |
| % | 58 | 58 | 58 | 83 | 33 |

similar percentage (15%) for the high yielding group as Wairegi and Van Asten (2012) (12.1%).

Table 4 demonstrates that nutrient deficiencies are not homogeneous over the entire region. It shows that S deficiency becomes a major problem in the middle and high elevation zones, while N majorly forms a restricting factor in the lower regions. One can expect Mg deficiency to occur on soils low in exchangeable Mg, although it is frequently observed even when soil Mg is considered adequate. This situation is often referred to as potassium-induced magnesium deficiency (Kabu and Toop, 1970; Marschner, 2012). In this low region of Mt. Elgon, Mg is sufficiently available in the soil but its uptake is limited by the abundance of exchangeable K. This is very important to take into account, because additional applications of K fertilizers on these lower fields would further restrict, limit and unbalance the Mg uptake. This antagonistic effect is reduced as the K availability and K uptake decreases along the slope. Therefore, Mg deficiency is not more significant in the middle altitude area. In the high altitude area, both soil exchangeable Mg and K are relatively low and therefore, Mg uptake in this high area is simply limited by its availability in the soil. The K uptake does not pose a significant problem in any part of the region, but its decreasing uptake with elevation requires some extra attention especially in the higher regions. Therefore, both K and Mg application would be justified in the high region.

The interpretations of these CND indices in this section correspond with the observations of the nutrient deficiency symptoms of several coffee plants in the different elevation regions.

### 4.3. Gradients and interactions of micro-nutrient uptake by coffee

Soil pH is well known to affect the uptake of several micro-nutrients (Sharma, 2007; Sillanpää, 1982) but as the pH varies with elevation in this study, it can be considered as an indirect effect of altitude. The uptake of B and Mo by coffee is decreasing with decreasing soil pH and increasing altitude, while the uptake of Mn and Ni is observed to increase along this gradient. These findings correspond with the already known effects of soil pH on micro-nutrient availability (Sillanpää, 1982; Mellis et al., 2004; Sharma, 2007) but are now also observed to be related with elevation. For Ni, it is just like the other better known micronutrients an essential nutrient. Because of the relatively recent confirmation of such (Brown et al., 1987), relatively little is known about its occurrence. In view of this, deficiency remains a possibility. A low Ni supply in plants can result in decreased activity of urease and subsequently in urea toxicity. There is a direct link of Ni with the nitrogen metabolism within the plant and therefore it is important to take the Ni availability in account.

Although we observe trends in micro-nutrient uptake (B, Mn, Mo and Ni) and a general small uptake of Zn, regional micro-nutrient deficiencies cannot be detected conclusively since no reliable or site specific micro-nutrient norms are available yet for Arabica coffee and the sampled population in this sub-study is too small to extract reliable micro-nutrient norms.

### 4.4. Gradients in nutrient uptake by banana

The Pearson correlation coefficients show that K and P uptake by banana decreases with elevation. From the foliar concentration averages of the different altitude zones it can be derived that Mg uptake by banana, similar to coffee, first decreases until the middle altitude zone and subsequently increases along the high altitude zone. For the micro-nutrients Mn and Ni uptake by banana is observed to increase with the altitude while Mo-uptake is observed to decrease.

Our study reveals a strong gradient in P uptake by banana along the slope (Table 6) while coffee does not show any response to the P availability gradient in the soil. A similar mass percentage of P (0.18%–0.23%) is required in the tissues of both coffee and banana (Wairegi and van Asten, 2011, 2012; Memon et al., 2001) which seems to contradict the theory of a more efficient P use in the tissue of coffee. These observations indicate a larger P uptake capacity of coffee under low P availability compared to banana. This can possibly be explained by the larger root system volume of coffee (Lynch and Wojciechowski, 2015) or it may point to another improved P uptake strategy of coffee compared to banana, including the exudation of P mobilizing compounds or mycorrhizal association (Ramaekers et al., 2010; Lynch and Clair, 2004).

### 4.5. Zonal macro-nutrient deficiencies in banana

For coffee, a large dataset allowed us to derive new, own norms and apply them on similar data, which are generated in the same way (*e.g.* in terms of timing, yield estimation protocol, sampling procedure, chemical analyses, person). With this perspective, it is always more accurate and an advantage to use norms derived from the same, similarly generated dataset.

If it was possible, it would be better to do this also for banana, but by lack of resources to collect sufficient data in order to create new 'own norms', the norms from the literature (Wairegi and van Asten, 2011) can still be used. Using the existing norms from the literature (Wairegi and van Asten, 2011) (i) could still tell us something about the nutrient status of the plant (large concentration *vs.* small) and this still allows to compare the nutrient status between different altitude zones; (ii) does not change trends in nutrient contents observed along the slope;

In addition, we want to state that the observed differences between our derived norms for coffee and those of Wairegi and Van Asten (2012) do not directly imply that the norms of Wairegi and van Asten (2011) for banana are 'wrong'.

From the zonal index averages of the banana plants (Table 7) it can be derived that N and Mg are significantly deficient in the low altitude area. In the middle altitude area only N turns significantly deficient while in the high altitude area Mg is the most deficient. Potential deficiencies of sulphur for banana could not be examined since no CND norm is available for sulphur.

These observations of zonal nutrient deficiencies for banana are very similar to the observations of the significant zonal nutrient deficiencies for coffee. We can conclude that low N availability forms a major problem for both coffee and banana production on Mt. Elgon, especially in the lower to middle elevation zone. On the other hand also the K-Mg imbalances constrain the production of both crops (coffee and banana) in the region, but this problem is consistently related to elevation and varies along the slope. In the low area Mg uptake is limited by the abundance of K and in the high altitude area Mg uptake is simply limited by its low availability. The decreasing K availability and uptake by banana along the slope requires extra attention in the high altitude areas since banana growth is more sensitive to low K than coffee.

For all previous reasons, soil fertility constraints in these mountainous regions can therefore not be dealt with by a general single fertilizer recommendation, but requires adaptation depending on crop and altitude location. The application of lime in the lower regions would not make sense, but it might be effective in the higher altitudes when pH decreases below 5.2 (Rowell, 1994). On the other hand, the application of acidifying fertilizers in the high regions would further decrease soil pH and might negatively affect soil fertility but it could be used without adverse effects in the lower regions. K applications in the low regions would not be effective and it would only further unbalance Mg uptake and induce stronger Mg deficiencies, while both K and Mg application would be justified in the high region. Although we found trends in B, Mn, Mo, Ni and Si uptake and a general low Zn uptake corresponding with Zn deficiency symptoms on the field, potential micro-nutrient deficiencies in the different regions should be examined more closely before designing region specific recommendations of micro-nutrient management. In addition, we should acknowledge that these findings should first be validated on the field with nutrient trials to determine whether the deficiencies identified can be corrected effectively by specific and adapted additions, leading to a significant yield increase before farmer recommendations can be disseminated.

## 5. Conclusions

Along the slope of Mt. Elgon, strong gradients in soil fertility parameters are observed with elevation and consequently soil fertility is not homogeneous in the region. These varying soil properties influence the availability of plant nutrients and hence their uptake by crops. Overall it can be stated that soils are generally more fertile on the lower parts of the slopes of Mt. Elgon than on the higher parts, but this does not necessarily translate in a total absence of specific plant nutrient limitations in this lower area. Different plant nutritional limitations occur in the different altitude zones. Since the fertility status is different in all zones it is not sufficiently accurate to consider the agricultural belts on these mountain slopes (Mt. Elgon, Mt. Kenya, Mt. Kilimanjaro) as one single agro-ecological zone, especially not in terms of ‘soil fertility’. Soil fertility constraints in these mountainous regions can therefore not be solved by a general fertilizer recommendation, but requires adaptation depending on crop and altitude location.

In general, a large need for a robust method to identify nutrient deficiencies in field environments emerged from this study. However, a combination of different existing methods on different crops can lead to reliable and useful information. In this study, the identified nutrient limitations in the different altitude zones are very similar for both crops (coffee and banana) which strengthens the value and robustness of the findings since both crops share the same niche on the slope.

Since the need for fertilizer recommendations and assistance to local farmers is perceived as very large in these mountain regions, it is timely to set up site specific fertilizer trials as a follow-up to this study. Zone-specific fertilizer recommendations for each individual crop and elevation and addressing all specific nutrient deficiencies, are the final outcome of such task.

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