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The role of soil nutrient ratios in coffee quality: Their influence on bean size and cup quality in the natural coffee forest ecosystems of Ethiopia

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Nutrients are essential for plant growth and development, and soil nutrient ratios play key roles in coffee quality. The objective of this study was to investigate the influence of soil nutrient ratios on the quality of wild Arabica coffee in Ethiopia. Results revealed that the balance between the soil nutrients was well correlated with coffee quality attributes. The balance between magnesium and calcium (Mg:Ca) and the balance between nitrogen and phosphorus (N:P) were found to be very important factors for bean size. Increase in Ca relative to Mg increased bean size, and vice versa. The higher the concentration of available P in relation to soil organic carbon (P:C) or total N (P:N), the better the cup quality of the coffee, and vice versa. The Mg:K ratio, P:N ratio, P:C ratio and P:Zn ratio were very important factors for cup quality. Although the ratio between Mg and K was important for cup quality, it was not apparent for bean size. The ratio between Ca and Mg was of no or little importance for coffee cup quality as opposed to that of bean size. Therefore, coffee growers should make careful decisions depending on the demands of the buyers/consumers and environmental requirements.

Key words: Arabica coffee, bean size, cup quality, coffee forest, nutrient ratios.

INTRODUCTION

Mineral nutrients are required for normal plant growth and development. Mineral nutrition refers to the supply, availability, absorption, translocation, and utilization of inorganically formed elements for growth and development of crop plants (Fageria, 2009). Next to water, nutrients are the environmental factor that most strongly constrains terrestrial productivity (Lambers et al., 2008). Plants differ in their requirement for nutrients and in their capacity to acquire nutrients from the soil (Koerselman and Meuleman, 1996; Lambers et al., 2008; Martins et al., 2015). Generally, plants require 17 essential nutrients for optimal growth and development

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(Barker and Pilbeam, 2007; Fageria, 2009). These nutrients are essential because they have specific metabolic functions in plants (Hopkins and Hüner, 2009). Macronutrients are required in large quantities and associated with their role in making up the bulk of the carbohydrates, proteins, and lipids of plant cells, whereas micronutrients are required in small amounts and mostly participate in the enzyme activation process of the plant (Barker and Pilbeam, 2007; Fageria, 2009).

Generally, mineral nutrients have many functions in plants; they are constituents of plant tissues, catalysts in various reactions, osmotic regulators, regulators of membrane permeability, etc. (Taiz and Zeiger, 2002; Roy et al., 2006; Pallardy, 2008; Clemente et al., 2018). Many enzymes are active only in the presence of ions such as Mg^{2+}, Mn^{2+}, Ca^{2+}, and K^{+} and these are known as metal activators (Pallardy, 2008). Each essential element thus has a role to play in the biochemistry and physiology of the plant (Hopkins and Hüner, 2009). The outstanding feature of life is the capability of living cells to take up substances from the environment and use these materials for the synthesis of their own cellular components or as an energy source (Mengel and Kirkby, 2001). Mineral nutrients are essential for plant growth and development through the incorporation of these mineral nutrients into organic substances such as pigments, enzyme cofactors, lipids, nucleic acids, and amino acids (Taiz and Zeiger, 2002). And hence nutrients influence the chemical composition and the sensory quality of plant products (Wiesler, 2012; Melke and Ittana, 2015). Nutrients are accumulated by the fruit during its development, and coffee fruits/beans are strong sinks for minerals and carbohydrates (Covre et al., 2016), which affect it quality. Coffee quality is the result of the presence of volatile constituents, caffeine, proteins, amino acids, fatty acids, phenolic compounds, and the action of enzymes on some of these constituents producing compounds affecting coffee quality (Clemente et al., 2015).

Plant growth is limited by the essential element that is most limiting (least available) when all other elements are present in adequate quantities (Liebig's Law of the Minimum). Once its supply is improved, the next limiting nutrient controls plant growth (Roy et al., 2006). Plants exhibit several mechanisms that can increase the supply of the most limiting resource (Chapin III et al., 2002). Thus, integrated plant nutrient management strives to ensure that plants have adequate but not excessive supplies of all essential elements (Alley and Vanlauwe, 2009), which is a prerequisite for product quality. The more the nutrient levels depart from the optimum, the more costly it will be to provide the correct nutrition (Willson, 1985a).

Any nutrient present in less than the optimal balance is likely to limit growth (Chapin III et al., 2002). Generally, coffee plants receiving a balanced nutrition, in which the required elements are supplied in appropriate amounts, are capable of producing quality beans. Coffee plant prospers well in slightly acid soils with a pH of 5.5-6.5 (Mitchell, 1988; Snoeck and Lambot, 2004), where most nutrients are usually more available to plants. When the pH level is less than 4.0, the levels of aluminium and manganese can be high, and this requires liming to correct the toxicity effects (Snoeck and Lambot, 2004).

Coffee is a major agricultural commodity in the world, and its production is economically important to several tropical countries, including Ethiopia, Brazil, Vietnam, Colombia, Indonesia, Mexico and Kenya, among others (Hein and Gatzweiler, 2006). Coffee is the most cultivated and consumed beverage in the world, yielding approximately 90 billion dollars per annum and involving about 500 million people from cultivation to final consumption (DaMatta, 2004). Nutrients are required for both vegetative growth of coffee trees and production of high quality beans and hence nutrient imbalances can affect coffee quality (Njoroge, 1998). Nitrogen and potassium are the two dominant nutrients required for coffee, K being more important in fruit development and N for vegetative growth. Phosphorus is essential for root, flower bud and fruit development, and it plays an important role in energy storage and transfer in crop plants (Fageria, 2009). Calcium, magnesium and other major and micro nutrients are essential for a balanced nutrition of the coffee plant although the required quantities are usually small to minimal in coffee (Willson, 1985b; Mitchell, 1988). When plants are grown without adequate essential nutrients, characteristic deficiency symptoms result (Nagao et al., 1986).

Inadequate supply of an essential element results in a nutritional disorder, and nutritional disorders occur because nutrients have key roles in plant metabolism. Nutrients serve as components of organic compounds, in energy storage, in plant structures, as enzyme cofactors, and in electron transfer reactions. Insufficient supply of an essential element leads to metabolic disorders (Taiz and Zeiger, 2002; Pallardy, 2008; Clemente et al., 2018), indicating that the necessary nutrients should be available at a reasonable amount and in appropriate relative proportions. Since there is usually interaction between nutrients, there should be a balance between soil minerals that determines a soil's productivity, and this should be determined by research. And little is known about the influence of soil on coffee quality in general and the influence of soil nutrient ratios (nutrient balance) in particular. The present study is the first report in its kind. The influence of soil properties (nutrient amounts) on coffee quality in the natural coffee forest ecosystem was previously reported by Yadessa et al. (2008), but the influence of soil nutrient ratios (nutrient balances) was not documented although both are equally important for plant nutrition and coffee quality. Plants require nutrients in balanced amounts (Roy et al., 2006; Hall, 2008), and nutrient interactions are very important aspect in mineral nutrition of plants (Clark and Baligar, 2000; Fageria,

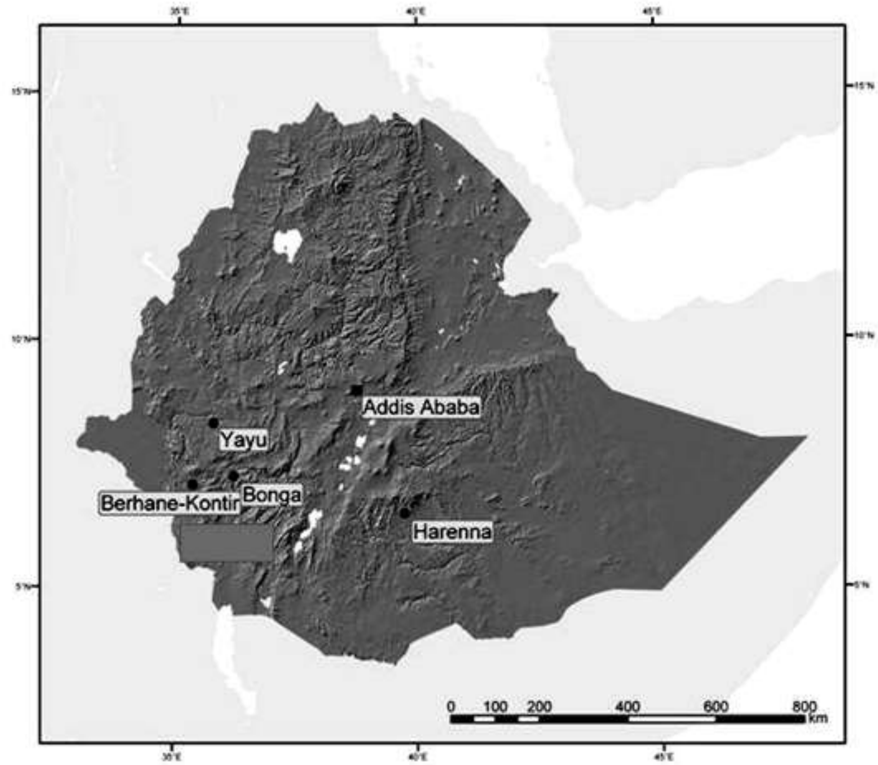


Figure 1. A map of Ethiopia showing the geographical location of the study sites.

2009). Proper coffee nutrition is thus required since it affects coffee quality and the overall productivity of the crop (Melke and Ittana, 2015). It is hypothesized that soil nutrient ratios (nutrient balances) in coffee plots from the natural coffee forest ecosystems are distinct since these Afromontane rainforests are the origin of Arabica coffee. The objective of this study was to assess the influence of soil nutrient ratios (the balance of soil nutrients) on wild Arabica coffee quality in the natural coffee forest ecosystems of southwest and southeast Ethiopia. Research information on soil nutrient ratios from the natural coffee forests of Ethiopia as a home of wild Arabica coffee (*Coffea arabica* L.) with distinct environmental conditions can be used as a guideline for simulating suitable soil nutrient ratios for future commercial production and quality improvement (e.g. fertilizer requirements, site selection, etc.) for Arabica coffee in other parts of Ethiopia or elsewhere.

MATERIALS AND METHODS

The study sites

The study was conducted in the natural coffee forests of southwest and southeast Ethiopia, which harbour the wild populations of *C. arabica* L. (Senbeta, 2006). The specific research sites are Berhane-Kontir or Sheko (in Bench-Maji zone), Bonga (in Kaffa zone), and Yayu (in Illubabor zone) in the SW coffee forests, and Harenna (in Bale zone) in the SE coffee forests of Ethiopia. Sheko, Bonga and Yayu are located west of the Great Rift Valley System, whereas Harenna is located east of the Great Rift Valley System (Figure 1).

The Yayu natural coffee forest is located in the Yayo district, Illubabor Zone of Oromia Regional State in the southwest Ethiopia. Yayu has got its name from the word Yayo, the name of the Oromo sub-clan living in the Illubabor Zone. The soils of the area are red or brownish Ferrisols derived from volcanic parent material (Tafesse, 1996). The total annual rainfall is about 1900 mm with mean temperature of 19.7°C (minimum temperature 7.6°C, maximum temperature 34.7°C) and relative humidity of 80.9% (Kufa, 2006).

The Berhane-Kontir natural coffee forest is also called Sheko forest. It is located in the Sheko district, Bench-Maji zone in the South Nations, Nationalities and Peoples Regional State, and hence the name Sheko forest. It represents the transition between the Afromontane moist forest and the lowland dry forest, located west of the Great Rift Valley (Senbeta, 2006). The total annual rainfall is about 2100 mm with mean temperature of 20.3°C (minimum temperature 13.8°C, maximum temperature 31.4°C) and relative humidity of 68.9% (Kufa, 2006).

The Bonga natural coffee forest is located in Kaffa Zone of the Southern Nations, Nationalities and Peoples Regional State in the southwest Ethiopia. Bonga has got its name from Bonga, the king of Kaffa Kingdom. Nitisols are the most dominant soils in southwestern Ethiopia, prevailing mainly in coffee and tea growing areas such as the Bonga region (Schmitt, 2006). The total annual rainfall is about 1700 mm with mean temperature of 18.2°C (minimum value of 8.7°C, maximum value of 29.9°C) and relative humidity of 80.4% (Kufa, 2006).

The Harenna natural coffee forest is located in Bale Zone of the Oromia Regional State in the south-eastern part of the country. It is

Figure 2. Coffee cherry collecting and processing activities in the natural coffee forests of Ethiopia.
Source: photo by Abebe Yadessa.

a part of Bale Mountains, and the Bale Mountains include the northern plains, bush and woods, the Sannate Plateau, and the southern Harenna forest. The area is known for its floral and faunal diversity and endemicity (Friis, 1986; Hillan, 1988). It is located east of the Great Rift Valley System. The total annual rainfall is about 950 mm with mean temperature of 22.2°C (minimum temperature 10.4°C, maximum temperature 34.4°C) and relative humidity of 63.2% (Kufa, 2006).

The coffee soils in the southwestern areas are highly weathered and originate from volcanic rock. These soils are deep and well drained, have a pH of 5-6, and have medium to high contents of most of the essential elements except nitrogen and phosphorus (Dubale and Mikiru, 1994). Phosphorus is generally low in the coffee soils of Ethiopia (Höfner and Schmitz, 1984; Schmitt, 2006). In its natural habitat where wild Arabica coffee grows, the soils are acidic to slightly acidic and have low available phosphorus (Senbeta, 2006; Muleta et al., 2007). The soils in the southeast are more sandy and less weathered (Yimer et al., 2006), as compared to the clay dominated and highly weathered soils in the southwest (Dubale and Mikiru, 1994). In these natural coffee forests of Ethiopia, wild populations of *C. arabica* occur across wide ranges of geographical locations, topographic features and soil characteristics (Senbeta, 2006). Coffee is the major means of making livelihood for the local community in the study areas.

Sampling procedures and coffee cherry sampling

Before starting coffee cherry sampling, during site selection preliminary information from the local people and key informants were collected to assess their perceptions on what local factors might affect coffee quality. Transects were laid out systematically along the toposequence of the study sites. Forty one samples from Sheko, 19 from Bonga, 34 from Yayu and 20 from Harenna were studied. Moreover, the level of forest management was assessed, rated from 0 to 2, where 0 (no or little management) stands for relatively undisturbed forest, 2 (high management intensity) stands for semi forest (disturbed coffee forest), and 1 (medium management intensity) stands for management intensity in between the two. In semi-forest coffee system, farmers slash weeds, lianas and cut competing shrubs and trees (Senbeta and Denich, 2006).

Coffee cherry harvesting and processing

Cherries were harvested at full maturity, which is usually during peak harvesting period. Coffee cherries matured and harvested first in Berhane-Kontir (Sheko), followed by Bonga and Harenna, and lastly in Yayu according to their maturity order in the field. Red cherries were hand-picked from the coffee trees in the forest and all the samples were then dry processed. The dried cherries were manually depulped and the beans were made ready for different analyses as shown in Figure 2.

Measurement of coffee bean characteristics and cup tasting

Bean size distribution of wild Arabica coffee beans collected from the natural coffee forests was determined by conventional screen analysis; perforated plate screens of different sizes (screen 18, screen 17, screen 16, screen 15 and screen 14) were used, with respective hole diameter of 7.14, 6.75, 6.35, 5.95 and 5.55 mm.

Table 1. Correlation coefficients between soil nutrient ratios versus bean size distribution of wild Arabica coffee from the natural coffee forests of Ethiopia.

Soil nutrient ratios	Proportion of bean retained on different screens§					
	SC 18+	SC 17	SC 16	SC 15	SC 14	SC14-
C:N	-0.049	-0.037	0.119	0.03	-0.057	-0.027
P:C	0.005	-0.113	-0.101	0.052	0.153	0.158
P:N	0.013	-0.121	-0.088	0.055	0.144	0.153
N:P	-0.095	0.295**	0.329**	-0.207*	-0.365**	-0.370**
N:K	0.068	0.092	-0.044	0.001	-0.087	-0.114
Mg:K	-0.05	0.058	-0.056	0.059	-0.021	-0.056
Ca:K	0.116	0.208*	0.009	-0.122	-0.203*	-0.201*
Mg:Ca	-0.317**	-0.324**	-0.056	0.339**	0.321**	0.299**
P:Zn	0.014	-0.106	-0.054	0.052	0.118	0.101
Silt:Clay	0.080	0.222*	0.009	-0.189*	-0.138	-0.173
Silt:Sand	-0.188*	-0.251**	-0.016	0.235*	0.232*	0.184
Clay:Sand	*-0.199**	*-0.266***	*-0.022*	*0.244***	*0.247***	*0.211**

§ Screen 18^+ denotes the proportion of beans retained on screen 18 and above; screen 14- means those beans passed through screen 14 but retained on screen size below 14; and for others it is just the proportion of beans retained on the respective screens; e.g. screen 17 denotes the proportion of beans retained on screen 17 (diameter 17/64th of an inch).

The size of the screen hole is usually specified in 1/64 inch, and the screen hole diameter (in mm) is equivalent to screen number multiplied by 1/64 inch (Feria-Morales, 2002; Wintgens, 2004). Weight fractions retained on each sieve were recorded as described in Muschler (2001), and then converted into percentage basis. Bean size is evaluated either by grading on sieves or by calculating the average weight of 100 beans (Eskes and Leroy, 2004).

Bean length, width and thickness representing the major, intermediate and minor axes respectively, were measured by using digital caliper. Bean shape index was determined as a ratio of bean length to bean width (Montagnon and Bouharmont, 1996). Cup tasting was conducted at the Coffee Quality Inspection and Auction Center in Addis Ababa, Ethiopia by a panel of five experienced cup tasters (three from Ethiopia, two from Germany). The major coffee quality attributes (fragrance, aroma, acidity, body, flavour, aftertaste and overall quality) were assessed using the beverage quality denominations ranging from 1 to 10, corresponding to the total absence (or presence) of the criterion in the coffee, respectively.

Soil sampling and analysis

Soil samples (0-20 cm) were collected from each plot. Five samples were collected per plot and then bulked to obtain a composite sample, and finally one representative sample was taken from the bulk per plot as described in Yadessa et al. (2001, 2009). Soil samples were analyzed for chemical and physical properties following the standard procedures. Soil texture was determined by the Boucoucos hydrometer method (Day, 1965); soil pH by pH meter in a 1:2.5 (v/v) soil: water suspension; organic carbon (O.C.) by the wet oxidation method (Walkley and Black, 1934); available P following the procedures of Bray and Kurtz (1945); and total N by the Kjeldahl method (Jackson, 1958). Cation exchange capacity (CEC) was analyzed after extraction with 1 N ammonium acetate at pH 7 (ammonium acetate method). Micro-nutrients were extracted following the method of Lindsay and Norvell (1978) and the concentrations in the extract were determined using atomic absorption photometer.

Data analysis

Correlation and regression analyses were used to assess the relationships between soil nutrient ratios and coffee quality attributes in the natural coffee forests of Ethiopia. Analysis of variance (ANOVA) was used to assess the variation in soil nutrient ratios and coffee cup quality between the differently managed coffee forest systems. Principal component analysis (PCA) was used to explore the interrelationships between soil nutrient ratios, sensory and bean characteristics. PCA is a data reduction technique whereby new composite variables (or components) are constructed as linear combinations of the original independent variables, which are uncorrelated and usually the first few components capture or explain most of the variation in the entire original data set (Jolliffe, 2002). The statistical analysis was performed using SPSS, version 17 (SPSS, 2008).

RESULTS

The correlation between soil nutrient ratios and coffee bean size distribution is presented in Table 1. The data on soil nutrient ratios are shown in Supplementary data 2. Results showed that the balance between some soil nutrients (soil nutrient ratios) significantly correlated with bean size distribution of wild Arabica coffee. The concentration of magnesium relative to calcium (Mg:Ca) and also the concentration of nitrogen relative to phosphorus (N:P) were found to be very important factors for bean size. There was a positive correlation between bean size and Ca; that is, increase in Ca relative to Mg increased bean size, and vice versa. Regarding soil texture, increasing the proportion of clay in relation to sand (clay:sand) decreased the bean size, as opposed to the case in cup quality. This means there is a positive relationship between soil particle size and coffee bean

Table 2. Correlation coefficients between soil nutrient ratios versus bean weight and shape of wild Arabica coffee from the natural coffee forests of Ethiopia.

Variable	100 BWt	BL	BW	BT	L:W	L:T	W:T
C:N	-0.010	0.025	-0.224*	0.045	0.137	-0.010	-0.158
P:C	-0.252*	-0.394**	0.116	0.011	-0.440**	-0.326**	0.051
P:N	-0.251*	-0.391**	0.111	-0.005	-0.435**	-0.311**	0.063
N:P	0.402**	0.509**	-0.022	-0.038	0.487**	0.435**	0.010
N:K	0.352**	0.362**	0.111	0.001	0.281**	0.296**	0.056
Mg:K	0.302**	0.373**	0.097	-0.028	0.301**	0.324**	0.076
Ca:K	0.399**	0.472**	0.195*	0.004	0.341**	0.383**	0.097
Mg:Ca	-0.437**	-0.359**	-0.114	-0.198*	-0.284**	-0.137	0.127
P:Zn	-0.130	-0.349**	0.057	0.063	-0.366**	-0.328**	-0.028
Silt:Clay	0.268**	0.103	0.079	0.170	0.066	-0.045	-0.117
Silt:Sand	-0.479**	-0.482**	0.013	-0.203*	-0.469**	-0.236*	0.189
Clay:Sand	-0.505**	-0.467**	0.024	-0.257**	-0.463**	-0.187	0.242*

BWt= Bean weight; BL=bean length; BW=bean width; BT=bean thickness; L:W=bean length:bean width ratio (bean shape index).

Table 3. Correlation coefficients between soil nutrient ratios and cup quality traits of wild Arabica coffee from the natural coffee forests of Ethiopia.

Variable	Fragrance	Aroma	Acidity	Flavor	Body	Aftertaste	Overall
C:N	-0.038	-0.076	-0.052	-0.052	-0.038	-0.100	-0.048
P:N	0.237*	0.265**	0.122	0.275**	0.209*	0.317**	0.255**
P:C	0.242*	0.263**	0.111	0.266**	0.204*	0.309**	0.236*
N:P	-0.142	-0.101	0.061	-0.03	-0.03	-0.091	-0.059
N:K	-0.121	-0.238*	-0.060	-0.194	-0.177	-0.247*	-0.169
Mg:K	-0.165	-0.256**	-0.08	-0.237*	-0.186	-0.294**	-0.217*
Ca:K	-0.141	-0.217*	-0.033	-0.155	-0.179	-0225*	-0.135
Ca:Mg	-0.152	-0.17	0.017	-0.044	-0.05	-0.085	-0.007
P:Zn	0.161	0.213*	0.105	0.218*	0.200*	0.225*	0.219*
Silt:Clay	0.045	0.130	0.193	0.073	0.107	0.039	0.122
Silt:Sand	0.279**	0.334**	0.098	0.222*	0.154	0.294**	0.199*
Clay:Sand	0.235*	0.272**	0.043	0.198*	0.107	0.265**	0.148

*, **Correlations are significant at 0.05 and 0.01 level of significance.

size in the natural coffee forest ecosystems. But the ratio between Mg and K (Mg:K), which was important for cup quality (Table 3), was not found to be important for bean size (Table 1). Increasing the concentration of soil total N relative to soil available P, increased bean size, and vice versa. Furthermore, increasing the concentration of soil Ca relative to Ma, increased bean size, and vice versa, indicating the importance of interaction between Ca and Mg for bean size. As indicated in Table 2, changes in soil nutrient ratios led to changes in bean weight, bean length and bean shape. Increase in the concentration of soil Ca with respect to Mg led to increase in bean weight, bean length and bean length-to-width ratio (bean shape index). Similarly, increase in the concentration of soil total N relative to available P or K led to increase in bean weight, bean length, bean length-to-width ratio, and bean length-to-thickness ratio. To the contrary, increase in the concentration of P relative to N or C led to decrease in bean weight, bean length, bean length-to-width ratio, and bean length-to-thickness ratio. This means increase in Ca relative to Mg or increase in N relative to P enhanced the development of elongated coffee beans (beans with higher shape index), whereas increase in P relative to N or C favoured the development of more rounded beans (beans had lower shape index).The balance (ratio) between the different soil nutrients also matters for cup quality shown in Table 3. The higher the concentration of available P in relation to soil organic matter or total N (P:C or P:N), the better the cup quality of the coffee, and vice versa. The relative concentrations of Mg and K (Mg:K), P and N (P:N), P and C (P:C), and P and Zn (P:Zn) were very important factors for cup quality. There was a positive relationship between P:N, P:C and P:Zn ratios versus cup quality traits, whereas an inverse

Table 4. Coffee cup quality traits and soil nutrient ratios as influenced by the level of forest management (forest coffee vs. semi-forest coffee).

Production system	Cup quality traits						
	Fragrance	Aroma	Acidity	Flavour	Body	Aftertaste	Overall
Forest Coffee	5.54	5.22	5.48	4.75	5.53	4.64	5.20
Semiforest Coffee	5.99	5.85	5.99	5.55	6.04	5.36	6.00
P value	0.011	0.004	0.014	0.001	0.024	0.004	0.001
	Soil nutrient ratios						
	P:N	P:C	Mg:K	Silt:sand			
Forest Coffee	17.15	1.69	9.66	0.95			
Semiforest Coffee	75.37	8.61	4.92	1.44			
P value	0.017	0.016	0.015	0.029			

Medium and high level of forest management (scales 1 and 2 in the Materials and Methods section) pooled to form the semiforest coffee, while little level of management (scale 0) alone form forest coffee system.

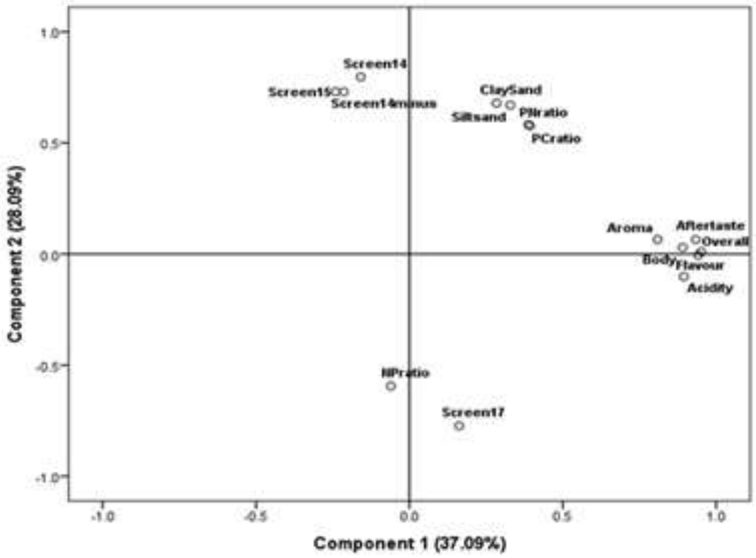
relationship between Mg:K and N:K ratios versus cup quality traits. Although most cup quality traits were significantly correlated with available P and P:N ratio, none of them was significantly correlated with N and N:P ratio. This is interesting and surprising, highlighting the importance of interaction between N and P for cup quality in the natural habitat of wild Arabica coffee, indicating that the more limiting nutrient is more important. Similarly, the relative proportion of clay and sand (clay:sand) was also important for coffee quality. But the ratio between Ca and Mg was of no or little importance for coffee cup quality as opposed to the case of bean physical quality (bean size). Positive relationship between silt:clay ratio versus proportion of bold beans, but negative relationship between silt:clay ratio versus proportion of medium beans shows that beans from less weathered soils (that is, younger soils) are bolder in size and vice versa, since silt: clay ratio and stage of weathering are inversely related (Thompson and Troeh, 1985; FAO, 2001).

Apart from this, results revealed that some soil nutrient ratios were significantly influenced by forest management, indicating that forest disturbance also influence nutrient balance in the natural coffee forest ecosystem (Table 4). The proportion of available P in relation to total N (P:N ratio), the proportion of P in relation soil organic matter or organic carbon (P:C), and the proportion of Mg in relation to K (Mg:K) were significantly different between the forest coffee and semi-forest coffee production systems. This means P:N and P:C ratios were significantly higher under the semi-forest coffee production system (managed forest) than under that of the forest coffee production system (less disturbed forest), but Mg:K ratio was higher under the latter than the former. This could be the probable reason for quality difference between coffees from semi-forest coffee and forest coffee production systems noticed in the present findings (Table 4). Cup quality was better under semi-forest coffee production system (moderately managed) than under forest coffee production system (little managed). As mentioned earlier, the balance between the nutrients or cations found to be very important for cup quality. These ratios also significantly differed across the forest management practices (Table 4), which might be the probable reason for significant difference in cup quality of wild Arabica coffee across the different traditional forest management practices in the natural coffee forest ecosystems of Ethiopia.

As shown in component plot (Figure 3) based on the first two axes, sensory characteristics were more correlated with the first axis (explaining about 37.09% of the variance), whereas bean characteristics were more correlated with the second axis (explaining about 28.09% of the variance). Both axes together explained about 65% of the total variance in the data set. Among soil nutrient ratios, P:N and P:C ratios were more correlated with higher proportion of smaller beans, whereas N:P ratio was more related to higher proportion of bold beans. In PCA plot, N:P ratio was almost perpendicular to cup quality traits, indicating that N:P ratio is not correlated with cup quality but well correlated bean size. Available P, clay, potassium and zinc contributed positively to the cup quality of coffee (that is, they promoted the production of coffees with better aroma, flavour and acidity) (Yadessa et al., 2008), whereas organic matter, total N, Mn and sand content contributed more to bean size (promoted the development of bolder beans) (Supplementary data 3). Plants from nutrient-rich sites tend to produce more biomass per unit nutrient in the plant, whereas plants from nutrient poor sites tend to keep the nutrients they have acquired for a longer time (Lambers et al., 2008), and soils from SE are more nutrient rich as compared to those from SW (Supplementary data 1).

DISCUSSION

The present study demonstrated that soil nutrient ratios



	Component	
	1	2
Screen17	0.162	**-0.773**
Screen15	-0.241	**0.731**
Screen14	-0.159	**0.797**
Screen14minus	-0.214	**0.73**
PCratio	-0.388	**0.584**
PNratio	0.393	**0.576**
NPratio	-0.06	**-0.594**
Siltsand	0.329	**0.67**
ClaySand	0.284	**0.679**
Aroma	**0.809**	0.065
Acidity	**0.894**	-0.102
Flavour	**0.951**	0.011
Body	**0.891**	0.029
Aftertaste	**0.934**	0.065
Overall	**0.942**	-0.005

Figure 3. Component plot in rotated space (left) and rotated component matrix (right) based on soil nutrient ratios, cup quality and bean size; KMO = 0.790, Bartlett's test of sphericity is significant (Chi square = 2130.88, degrees of freedom =105, P=0.000); extraction method: principal components; rotation method: varimax with Kaiser normalization.

(nutrient balances) are important factors for coffee quality. On one hand, the concentration of magnesium relative to calcium (Mg:Ca) was very important for bean physical quality; that is, Mg:Ca was positively correlated with bean size and weight. On the other hand, the concentration of magnesium relative to potassium (Mg:K) and the concentration of phosphorus relative to nitrogen (P:N) were very important for cup quality, the former being negatively correlated with cup quality, whereas the latter positively correlated with cup quality. This shows that higher concentration of Ca in relation to Mg enhances bean physical quality, while higher K in relation to Mg and higher P in relation to N improve cup quality. Coffee quality is lowered when the balance between the base cations move away from the optimum. Njoroge (1998) also reported that a balance of nutrients in the soil is important for better bean quality. According to Snoeck and Lambot (2004), the optimum K:Ca:Mg ratio is approximately 6:76:18% of the sum of the exchangeable bases, which is comparable to 6:74:19% in the present study. In the present findings, for instance, increase of Mg in relation to K (Mg:K) in the coffee soils was associated with a drop in beverage quality (cup quality) as presented in Table 3. This means, on average, Mg is about three times higher than K and Ca is about four times higher than Mg. These nutrients (Ca, Mg and K) are strongly antagonistic to each other, and excess concentration of one element inhibits the uptake of the other (Nguyen et al., 2017). For example, a study in Ethiopia by Laekemariam et al. (2018) showed that K deficiency due to antagonistic effects of Mg was about 54%.

The present study revealed that most cup quality traits were significantly correlated with P:N ratio, but none of them was significantly correlated with N:P ratio (Table 3). This is interesting, and this difference in response could be due to the different functions N and P have in the plant system. A study by De Groot et al. (2003) also showed that N concentration in plant tissue is sensitive to P limitation, but P concentration in the plant tissue is not sensitivity of N limitation, which supports the present finding.

A study in Ethiopia by Mintesinot et al. (2015) showed that coffee quality attributes increased with increase in the levels of soil Mg, but decreased with the increase in the levels of soil total N, although the authors did not mention about the nutrient ratios. A study in Tanzania by Kilambo et al. (2015) reported positive correlation between cup quality and some soil parameters (Ca, Mg, and K), and they also reported that soils with excessive calcium and potassium produce coffees with hard and bitter tasting liquor without mentioning about nutrient balance. In the present study, Ca:K ratio is negatively correlated with coffee aroma (Table 3). A study by Yadessa et al. (2008) revealed that higher levels of soil Mg, Mn and Zn were associated with improved coffee aroma in Ethiopia. A study in Uganda by Ngugi et al. (2016) showed that Mn and Zn were important elements in the determination of organoleptic cup quality in Robusta coffee. A study in Brazil by Clemente et al. (2015) showed that the relative proportion of nitrogen and potassium (N:K ratio) was found to be important factor in cup quality, which is in contrast with the findings of the present study (Table 3). And a study by Nguyen et al. (2017) reported better fruit qualities of pummelo (*Citrus maxima* Merr.) associated for higher soil K:Ca, K:Mg and Ca:Mg ratios in Thailand.

Increasing the supply of only one nutrient stimulates growth, which in turn can induce a deficiency of the other by dilution. Optimal ratios between nutrients in plants are often as important as absolute concentrations (Römheld, 2012). The balance between nutrients is therefore essential for coffee quality; otherwise, the imbalance between them will create undesirable antagonistic effects (Snoeck and Lambot, 2004), which in turn leads to poor quality coffee. Nutrient imbalances (Nojorge, 1998) and deficiencies in nutrients lead to lower quality coffees (Feria-Morales, 1990 cited in Feria-Morales, 2002). For instance, the balance between K, Mg and Ca is very important for coffee quality because K is antagonistic to Mg and Ca (Snoeck and Lambot, 2004). Higher Mg:K ratio leads to a drop in cup quality, and higher Mg:Ca ratio leads to poor bean physical quality, and vice versa. Therefore, plants need proper supply of all macronutrients and micronutrients in a balanced ratio throughout their growth, and the basics of balanced crop nutrition are governed by Liebig's law of the minimum (Roy et al., 2006), which is not exception to coffee plant growth and its quality. Since interactions usually occur between nutrients in nature, no nutrient act alone and the uptake of one nutrient is affected by the other, as also reported by Nguyen et al. (2017) and Laekemariam et al. (2018).

Plant growth is limited by the essential element that is most limiting (least available) when all other elements are present in adequate quantities (Alley and Vanlauwe, 2009). Any nutrient present in less than the optimal balance is likely to limit growth, so plants invest preferentially in absorption of the nutrients that most strongly limit growth, which also holds true for coffee plant. As a result, nutrients that accumulate in excess of plant requirements are absorbed more slowly (Chapin III et al., 2002). Optimal coffee quality is thus directly dependent on a correct ion balance in the soil (Snoeck and Lambot, 2004). This shows that both the availability and the balance between the nutrients in the soil are highly important for coffee quality.

The balance between the different soil nutrients, especially the balance between cations of different valency (e.g. between monovalents and bivalents) matters for cup quality rather than differences within the same valency number. The relative proportion between Mg and K was the most important factor in this regard; it was inversely correlated with most of the organoleptic properties of coffee assessed except for acidity. The ratio between Ca and Mg was of no or little importance for coffee cup quality. The ratio between the cations is very important for coffee because K is antagonistic to Mg and Ca (Snoeck and Lambot, 2004). High concentration of K will often cause Mg deficiency (Purseglove, 1968). A study by Oruko (1977), cited in Njoroge (1985) reported that excessive levels of K and Ca are believed to impair the quality of coffee beans, mainly as a result of imbalance with Mg. According to Willson (1985b), potassium and magnesium are antagonistic; that is, high levels of K in the soil or high K application can cause magnesium deficiency, and high Ca levels in the soil can restrict potassium uptake. A study by Laekemariam et al. (2018) showed that K availability depends on exchangeable K and relative amounts of other cations, and hence soil exchangeable K values alone may not adequately indicate K availability in areas where soil exchangeable Mg concentration is relatively high enough to compete with exchangeable K and cause K deficiency.

Interactions between nutrients occur when the supply of one nutrient affects the absorption, distribution or function of another nutrient. Interactions between ions can occur due to the formation of precipitates or complexes, which are generally most marked when the interacting ions have very different chemical properties (Robson and Pitman, 1983). This is in agreement with the present findings where Mg:K ratio (both with different valences) was much important for coffee cup quality. Thus, both deficiencies of essential nutrients and nutrient imbalances can affect coffee quality. Coffee quality is the resultant of the chemical constituents of coffee, and the action of enzymes on some of these constituents producing compounds affecting coffee quality (Clemente et al., 2015), which is related to soil characteristics where the coffee grows.

In short, increasing the concentration of a nutrient element where it is more limiting is essential for improving coffee quality, which is in line with the basics of plant nutrition (Roy et al., 2006). Increase in soil Zn concentration at Sheko, for instance, did not increase cup quality, but increase in soil Zn concentration increased cup quality at Yayu (Figure 4). This is because Zn might be excess at Sheko natural coffee forest, but it might be deficient at Yayu natural coffee forest (Supplementary data 1). A study in the Los Santos region of Costa Rica by Castro-Tanzia et al. (2012) also showed that where N, P, K and Mg are abundantly added through inorganic fertilizers, Ca has become the most limiting nutrient for coffee production, but cup quality improved when CaO was applied as a fertilizer. A study in Tanzania by Kilambo et al. (2015) showed that soils with adequate P, K, Clay-loam and silt positively influenced the cup taste.

Ethiopia holds a unique position in the world as *C. arabica* L. has its primary centre of diversity (Melke and Ittana, 2015). And the present study on the effect of soil nutrient ratios on coffee quality has wider importance since the natural coffee forests of Ethiopia is a birthplace of wild Arabica coffee, and the information obtained from this study can be used as a model for simulating suitable soil conditions such as nutrient balances for improving coffee quality and for expanding commercial production

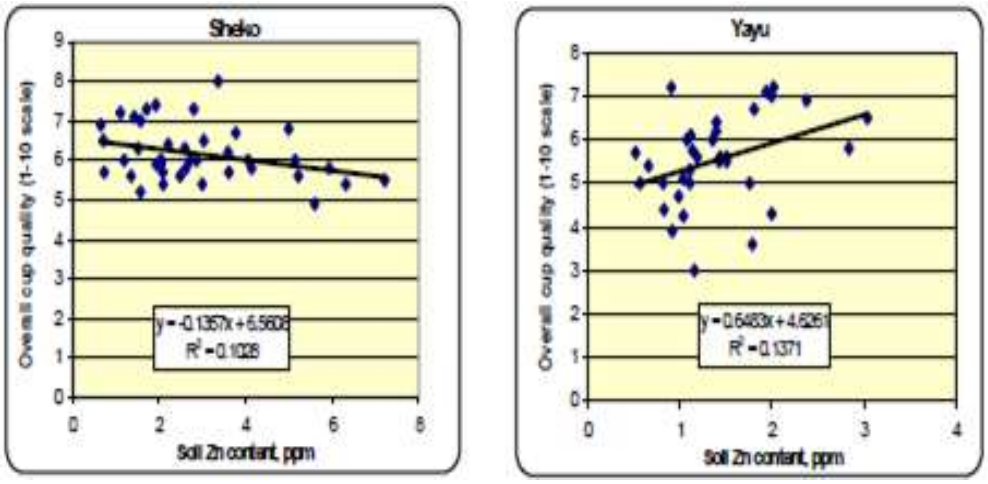


Figure 4. Overall cup quality of wild Arabica coffee as influenced by soil Zn content in Sheko and Yayu natural coffee forests in SW Ethiopia. Source: Yadessa et al. (2008).

of Arabica coffee in other parts of the country or elsewhere.

Conclusions

This study demonstrated that the balance (ratio) between the different soil nutrients matters for coffee quality. The concentration of magnesium relative to calcium (Mg:Ca) and the concentration of nitrogen relative to phosphorus (N:P) were found to be very important factors for bean size. Increase in Ca relative to Mg increased bean size, and vice versa. The higher the concentration of available P in relation to soil organic matter or total N, the better the cup quality of the coffee, and vice versa. The Mg:K ratio, P:N ratio, P:C ratio and P:Zn ratio were very important factors for cup quality. But the ratio between Mg and K, which was important for cup quality, was not important for bean size. The ratio between Ca and Mg was of no or little importance for coffee cup quality as opposed to the case of bean size. As pertaining to the soil texture, increasing the proportion of clay in relation to sand (clay:sand) decreased the bean size, as opposed to the case in cup quality (positive correlation between cup quality and clay). But the ratio between Mg and K, which was important for cup quality, was not found to be important for bean size (bean physical quality).

Generally, soil properties important for cup quality (P, silt, P:N, Mg:K, etc.) were not so important for bean size, whereas soil properties important for bean size (OM, Mn, pH, sand, N:P, Mg:Ca, etc.) are not so important for cup quality. Therefore, coffee growers should make trade-offs between cup quality and bean size depending on the prevailing conditions (consumers' demands, plant responses, environmental conditions, etc.), which could also be researchable issues in the future. In light of the present findings, further studies on the influence of soil nutrient ratios of coffee soils on coffee quality should be conducted based on detailed nutrient inputs and budgets in the future since this is the first paper reporting the role of soil nutrient ratios on coffee quality.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Supplementary data 1. Mean values (±standard deviation) for the soil parameters from the four natural coffee forests in the SW and SE Ethiopia (n=111 samples).

Statistic	SW Soils			SE soils	P value
	B. Kontir (n=41)	Bonga (n=16)	Yayu (n=34)	Harenna (n=20)	
SOM (% DM)	4.64±1.34^{c}	6.52±1.25^{b}	7.21±2.20^{b}	8.49±1.00^{a}	0.000
Total N (% DM	0.32±0.07^{c}	0.41±0.05^{b}	0.41±0.13^{b}	0.52±0.005^{a}	0.000
Avail. P (ppm)	39.99±34.48^{a}	3.44±7.52^{b}	11.22±12.56^{b}	1.94±2.09^{b}	0.000
Na (meq/100 g)	0.05±0.06^{c}	0.10±0.06^{b}	0.04±0.02	0.16±0.07^{a}	0.000
K (meq/100 g)	1.23±0.68^{a}	1.34±0.80^{a}	1.07±0.74^{a}	0.56±0.40^{b}	0.002
Ca (meq/100 g)	11.88±4.87^{bc}	9.40±3.52^{c}	13.15±5.74^{b}	19.18±3.89^{a}	0.000
Mg (meq/100 g)	3.70±1.77	2.91±1.09	3.04±1.56	3.73±0.58	NS
CEC (meq/100 g)	29.08±7.39^{b}	34.96±5.05^{b}	32.22±12.33^{b}	43.77±4.69^{a}	0.000
BS (%)	56.58±12.57^{a}	39.01±13.68^{b}	53.89±11.83^{a}	54.44±10.23^{a}	0.000
pH	5.90±0.24^{b}	5.47±0.43^{c}	5.82±0.22^{b}	6.42±0.18^{a}	0.000
Sand (% DM)	20.18±9.07^{c}	29.13±6.37^{b}	43.82±11.14^{a}	46.70±5.92^{a}	0.000
Silt (% DM)	37.76±4.76^{a}	34.57±3.37^{a}	28.88±7.76^{b}	27.86±2.70^{b}	0.000
Clay (% DM)	42.06±8.02^{a}	36.31±5.49^{b}	27.30±4.69^{c}	25.44±5.95^{c}	0.000
Fe (ppm)	57.39±34.98^{b}	246.36±313.99^{a}	50.93±40.78^{b}	82.61±50.44^{b}	0.000
Mn (ppm)	136.91±45.96^{ab}	212.10±158.79^{b}	66.29±28.11^{b}	738.74±179.06^{a}	0.000
Zn (ppm)	2.97±1.72^{a}	3.26±01.85^{a}	1.41±0.60^{b}	2.38±0.55^{ab}	0.000

Means followed by similar letters within a raw are not significantly different by Tukey's Honestly significant test. DM = dry matter, BS=base saturation, SOM = soil organic matter. 1 ppm=1 mg/kg (solid substance); in terms of percents, 1 ppm equals 0.0001%.

Supplementary data 2. Summary data for soil nutrient ratios across the selected study sites.

Site	Statistic	C:N	P:C	P:N	N:P	N:K	Mg:K	Ca:K	Mg:Ca	P:Zn	Silt:Clay	Silt:Sand	Clay:Sand
Sheko (n=41)	Min.	11.38	0.62	8.02	0.002	0.08	1.29	3.87	0.14	0.50	0.56	0.67	0.54
	Max.	21.64	29.84	484.88	0.1246	3.13	13.60	77.73	0.76	124.89	1.71	4.10	4.97
	Mean	14.34^{b}	9.22^{a}	132.92^{a}	0.03^{c}	0.48^{b}	3.98^{ab}	13.78^{b}	0.32^{a}	16.40^{a}	0.94^{b}	2.19^{a}	2.52^{a}
Bonga (n=16)	Min.	11.29	0.08	1.41	0.01	0.13	0.82	4.33	0.14	0.10	0.63	0.73	0.65
	Max.	21.45	4.98	95.34	0.708	2.24	11.26	33.44	0.44	4.99	1.37	1.92	2.42
	Mean	15.92^{ab}	0.55^{b}	9.61^{b}	0.32^{b}	0.55^{b}	3.02^{b}	9.64^{b}	0.30^{ab}	1.02^{b}	0.97^{ab}	1.25^{b}	1.34^{b}
Yayu (n=34)	Min.	8.10	0.12	1.58	0.007	0.17	1.23	5.93	0.12	0.90	0.73	0.25	0.31
	Max.	40.89	6.13	147.88	0.63	7.60	65.0	168.67	0.54	69.76	1.73	1.91	1.64
	Mean	18.48^{a}	1.49^{b}	28.63^{b}	0.11^{c}	0.93^{ab}	6.52^{ab}	25.61^{b}	0.24^{bc}	8.99^{ab}	1.06^{ab}	0.76^{c}	0.70^{c}
Harenna (n=20)	Min.	14.45	0.06	0.93	0.067	0.34	2.79	12.86	0.11	0.24	0.64	0.42	0.28
	Max.	19.00	0.89	14.87	1.0769	3.44	22.13	134.06	0.31	3.18	1.85	1.02	1.55
	Mean	16.48^{ab}	0.23^{b}	3.79^{b}	0.49^{a}	1.34^{a}	9.30^{a}	49.46^{a}	0.20^{c}	0.80^{b}	1.15^{a}	0.61^{c}	0.57^{c}
P value		0.000	0.000	0.000	0.000	0.013	0.027	0.000	0.000	0.000	0.011	0.000	0.000

Means followed by similar letters within a column (across sites) are not significantly different by Tukey's Honestly significant test. Min.= minimum; Max. = maximum; Units of measurements for the elements as in Supplementary data 1.

Supplementary data 3. Pearson correlation matrix showing the relationships between bean characteristics and soil properties in the natural coffee forests of Ethiopia.

Variable	SC18+	SC17	SC 16	SC 15	SC 14	SC 14-	100 BW	BL	BW	BT
OM	-0.067	0.210*	0.218*	-0.152	-0.238*	-0.257**	0.312**	0.242*	-0.17	0.054
Total N	0.007	0.286**	0.129	-0.204*	-0.240*	-0.290**	0.402**	0.223*	-0.031	0.093
Available P	0.010	-0.120	-0.087	0.055	0.148	0.150	-0.255*	-0.278**	0.100	-0.003
Na	0.087	0.466**	0.185	-0.415**	-0.428**	-0.345**	0.187	0.438**	0.146	-0.131
K	-0.052	-0.262**	-0.112	0.200*	0.264**	0.230 *	-0.241*	-0.214*	-0.115	0.106
Ca	0.121	0.333**	0.079	-0.314**	-0.269**	-0.243*	0.341**	0.151	0.124	0.059
Mg	-0.109	0.024	0.058	-0.026	0.007	-0.004	0.043	-0.008	0.026	0.006
CEC	-0.091	0.166	0.267**	-0.163	-0.208*	-0.229 *	0.206*	0.186	-0.085	-0.042
pH	0.169	0.481**	0.060	-0.422**	-0.378**	-0.321**	0.316**	0.121	0.397**	-0.137
PBS	0.196*	0.171	-0.159	-0.173	-0.059	-0.026	0.179	-0.026	0.229*	0.183
Sand	0.247**	0.290**	-0.075	-0.264**	-0.220*	-0.164	0.497**	0.245*	0.049	0.238*
Silt	-0.194*	-0.192*	0.081	0.182	0.147	0.077	-0.343**	-0.253**	-0.033	-0.114
Clay	-0.235*	-0.302**	0.056	0.269**	0.227*	0.194*	-0.507**	-0.187	-0.050	-0.278**
Fe	-0.074	-0.089	0.144	0.049	0.002	-0.019	-0.088	-0.057	-0.212*	-0.067
Mn	0.076	0.606**	0.276**	-0.519**	-0.553**	-0.502 **	0.418**	0.363**	0.205*	-0.161
Zn	0.041	0.040	0.098	-0.072	-0.101	-0.065	-0.193	0.050	0.063	-0.164

OM = Organic matter; CEC = cation exchange capacity; PBS = percent base saturation; SC18+ = proportion of beans retained on screen 18 and above; SC17 = proportion of beans retained on screen 17; SC 16 = proportion of beans retained on screen 16; SC15 = proportion of beans retained on screen 15; SC14= proportion of beans retained on screen 14; SC14- = proportion of beans that passed through screen 14 (those retained on screens below 14); 100 BW = weight of 100 beans; BL = bean length; BW = bean weight, BT = bean thickness.