ORIGINAL ARTICLE

Influence of soil properties on bean quality of wild *Coffea arabica* in the natural coffee forests of southwest and southeast Ethiopia

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ABSTRACT

The study was conducted in the natural coffee forest ecosystems of southwest and southeast Ethiopia, where the wild populations of *Coffea arabica* L. naturally grow. Soil is an important environmental factor that performs different important functions in the terrestrial ecosystems, including in the natural coffee forest ecosystems. The objective of this study was to investigate the link between soil properties and bean quality of wild Arabica coffee in the natural coffee forests of Ethiopia. Data on soil parameters and bean characteristics were assessed. Results from simple correlation analysis, stepwise regression analysis and ordination analysis (principal component analysis - PCA, redundancy analysis - RDA) showed that bean size distribution of wild Arabica coffee was clearly related to the soil characteristics of the natural coffee forest ecosystem. Monte Carlo permutation test for the first RDA axis was significant (p=0.0020) with 499 permutations. Forward selection procedure showed that soil pH, Mn, sand, Na, available P and organic matter (OM) significantly contributed to the variability in bean size distribution of wild Arabica coffee. Soil parameters such as soil pH, Mn, pH, CEC, OM, total N, Ca, Na and pH relatively favoured the development of larger beans, whereas higher available P, K and silt contributed to the development of smaller beans. Moreover, the first RDA axis clearly discriminated coffee samples of the southeast coffee forests from those of the southwest coffee forests, and the variation in bean characteristics clearly followed the trend of soil characteristics. Thus, soil is an important environmental factor for the physical quality of wild Arabica coffee.

Key words: Wild Arabica coffee, bean characteristics, coffee forest, natural habitat, soil properties,

INTRODUCTION

Understanding the variability in environmental factors such as soil characteristics and their influence on plant growth is an essential component of site management systems (Coleman *et al*., 1983; Raghubanshi, 1992). This also holds true for the wild Arabica coffee plants growing in the natural coffee forest ecosystems of Ethiopia. The environment where the coffee plant grows inevitably influences its growth, productivity and quality. It is generally agreed that coffee quality is influenced by different factors, such as genetic factor (species, variety), environmental factors (e.g. soil, elevation, climate, slope aspect), geographic origin (latitude, longitude), processing methods (wet, dry), etc. (Decazy *et al.*, 2003; Avelino *et al*., 2005; da Silva *et al*. 2005; Yadessa *et al*., 2008; Barbosa *et al*., 2012; Yadessa *et al*., 2020).

Soil is a complex physical, chemical, and biological substrate (Taiz and Zeiger, 2002), which forms a thin film over Earth's surface in which geological and biological processes intersect (Chapin III *et al*., 2002). It is a natural medium in which plants grow (Brady, 1990; Roy *et al*., 2006). Soil provides plants with water, mineral nutrients, air and anchorage for roots, all of which are essential for plant growth (Wild, 2003; Roy *et al*., 2006). Soils differ in composition (Raven and Johnson, 1999) and hence they vary in their ability to supply nutrients based on the nature of the soil-forming factors (e.g. parent material).

Soil is generally the combined effect of different soil-forming factors (parent material, topography, climate, anthropogenic activities and time) (Jenny, 1941). Variations in soil-forming factors thus inevitably lead to variations in soil properties. As a result, soils can vary widely from place to place, and many factors can influence the chemical and physical properties of the soil at any given location leading to spatial variations. Spatial variations in soil development can result in large variations in soil properties, which in turn influence the availability of nutrient and water for plant growth (Chapin III *et al*., 2002). This variability in soil property imparts the variability in coffee quality in general and bean quality in particular. In this study, it is hypothesized that coffee plots in the Afromontane rainforests of Ethiopia harbouring wild Arabica coffee populations differ considerably in their soil properties and these differences would impart differences in bean quality of coffee. Bean size, for instance, is an important factor in coffee, as many consumers traditionally associate bean size to quality (Prodolliet, 2004; Wintgens, 2004a). It is a commercially important factor since it determines the price, with smaller beans attracting lower prices (Leroy *et al*., 2006). Generally, the more uniform the bean size, the better the heat transfer and hence the more uniform roast (Feria-Morales, 2002; Prodolliet, 2004; Wintgens, 2004a), which has implications on its quality.

Although soil is an important environmental factor that performs different important functions in the terrestrial ecosystems, including in the coffee forest ecosystems, little is known about the influence of soil on coffee quality (Wintgens, 2004a; Yadessa *et al*., 2008). A study by Mintesnot *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. A study by Kilambo *et al*. (2015) showed positive correlation between cup quality and some soil parameters (Ca, Mg, and K). The influence of soil properties on cup quality of wild Arabica coffee in the natural coffee forest ecosystem SW Ethiopia was previously reported by Yadessa *et al*. (2008), but detailed study on the influence of soil properties on its bean quality is lacking. The objective of the present study was thus to assess the link between soil properties and bean quality of wild Arabica coffee in the natural coffee forests of southwest (SW) and southeast (SE) Ethiopia. This is important to generate reliable information that can be used as a guideline for improving coffee quality and expanding Arabica coffee plantations in other parts of the country or elsewhere around the world as the present study is the birthplace or natural habitat of Arabica coffee.

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 *Coffea arabica* L. The specific research sites are Berhane-Kontir or Sheko (Bench-Maji Zone), Bonga (Kaffa Zone), and Yayu (Illubabor Zone) in the SW coffee forests, and Harenna (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).

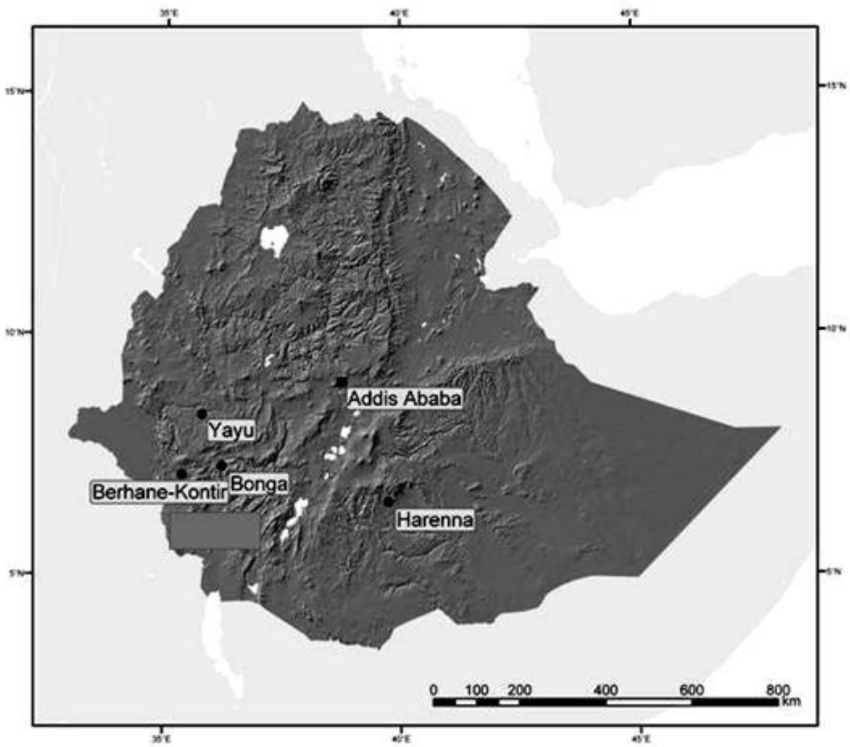

Figure 1. A map of Ethiopia showing the geographical location of the study sites.

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 (SNNPRS) 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 a part of Bale Mountains, which 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. 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 climatic conditions of the Afromontane rainforests in the southeast Ethiopia (Harenna) are under the influence of Indian Ocean with lower annual rainfall but with bimodal pattern, whereas those in the southwest are under the influence of Atlantic Ocean with higher annual rainfall but with mono-modal pattern (Figure 2). In the southwest, precipitation is more abundant and more evenly distributed, but it decreases toward southeast around the Harenna forest.

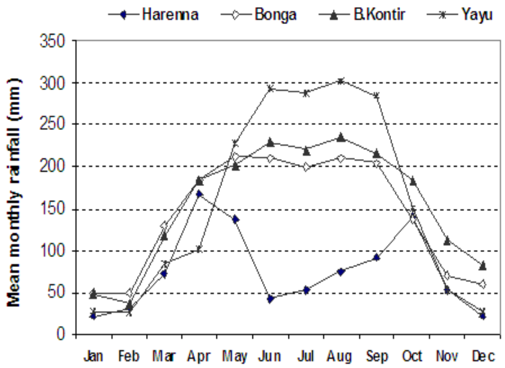

Figure 2. Rainfall patterns of the studied Afromontane rainforests of Ethiopia in the SW and SE Ethiopia.

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 sandier 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 Afromontane rainforests of Ethiopia, wild populations of C. arabica occur across wide ranges of geographical locations, topographic features and soil characteristics (Senbeta, 2006). Summary of soil data of the study sites is shown in Appendix 1. Coffee is the major means of making livelihood for the local community in the study areas.

Coffee cherry harvesting and processing

Cherries were harvested at full maturity, which is usually during peak harvesting period. 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 3.

Figure 3. Coffee cherry collecting and processing activities in the natural coffee forests of Ethiopia

Measurement of coffee bean characteristics

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 (screens 18, 17, 16, 15 and 14) were used, with respective hole diameter of 7.14 mm, 6.75 mm, 6.35 mm, 5.95 mm and 5.55 mm. The size of the screen hole is usually specified in 1/64 inch, and its hole diameter (in mm) is equivalent to screen number multiplied by 1/64 inch (Feria-Morales, 2002; Wintgens, 2004b). The weight fractions retained on each screen were recorded as described in Muschler (2001), and then converted into percentage basis. Bean weight was determined by measuring the average weight of

100 beans (Eskes and Leroy, 2004). Summary data on bean characteristics of wild Arabica coffee in the studied coffee forests is presented in Appendix 2

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). Transects were laid out systematically along the topo-sequence of the studied coffee forest sites. Forty one samples from Berhane Kontir, 19 from Bonga, 34 from Yayu and 20 from Harenna were studied. Coffee cherries were also sampled from the respective plots. Soil samples were analyzed for chemical and physical properties at International Livestock Research Institute (ILRI) Analytical Services Laboratory 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

Multivariate methods, such as ordination analysis (Lepš and Šmilauer, 2003) and correlation analysis were used to assess the relationships between coffee bean physical quality and soil properties. The data were first standardized by subtracting sample means and then dividing the difference by their respective standard deviations (da Silva, 2005) to offset the problem of different measurement scales. Ordination analyses, both principal component analysis (PCA) and redundancy analysis (RDA) were conducted using CANOCO for windows version 4.5 computer program (ter Braak and Smilauer, 2002). 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). Redundancy analysis (RDA), also called a constrained PCA, is a multivariate direct gradient analysis method appropriate where spatial environmental gradients are short (van den Wollenberg, 1977; Jongman *et al*. 1987; Lepš and Šmilauer, 2003). RDA can be best understood as methods for extending multiple regression that has a single response Y and multiple predictors X (e.g. several environmental predictors), to multiple regression involving multiple response variables Y (e.g., several species, traits, etc.) and a common matrix of predictors X (Peres-Neto *et al*., 2006).

Both PCA and RDA methods try to find values of a new variable, which represents an 'optimum' predictor for the values of all the response variables (Lepš and Šmilauer, 2003). In indirect gradient analysis (e.g. PCA), environmental gradients are not studied directly but are inferred from the response variables. Direct gradient analysis (e.g. RDA) differs from indirect gradient analysis in that the response variable is directly and immediately related to measured environmental variables (Palmer, 1993). Thus, in multivariate analysis both unconstrained (PCA) and constrained (RDA) ordination should be used in combination to get reliable results (ter Braak, 1995).

As a preliminary analysis, a detrended correspondence analysis (DCA) was used to define the length of the gradients in standard deviation (SD) units, and this was used as criteria for model selection. It is usually recommended to use unimodal ordination methods for gradients >4SD and linear ordination methods for gradients <3SD, while for gradients between 3 and 4SD, both methods may be suitable. This means that techniques based on the linear response model are suitable for homogeneous data sets, whereas techniques based on unimodal model are suitable for more heterogeneous data sets (Lepš and Šmilauer, 2003; ter Braak and Prentice, 2004). Automatic forward selection of the environmental variables was used to know the relative importance of the considered soil parameters in the input data and the variance explained by them. Monte Carlo permutation tests were used to test the statistical significance of the coffee quality-environment relationship (Lepš and Šmilauer, 2003; Guoqing *et al*., 2008). Stepwise multiple linear regression (SPSS, 2008) was also used to select models correlating bean size with soil properties.

RESULTS

Results showed that bean size distribution of wild Arabica coffee was clearly related to the soil characteristics (substrate quality) of the natural coffee forest ecosystem. The correlation analysis revealed that the proportion of large beans (those retained on screen 18^{+}) was positively correlated with percent base saturation and sand content of the soil, but negatively correlated with silt and clay content. The proportion of bold beans (those retained on screen 17) was positively correlated with soil OM, total N, Na, Ca, pH, Mn and sand content, but negatively correlated with K, silt and clay content. The proportion of good beans (those retained on screen 16) was positively correlated with soil OM, CEC and Mn. To the contrary, the proportion of medium beans (those retained on screen 15) was negatively correlated with soil total N, Ca, pH, Mn and sand content, but positively correlated with K and clay content of the soil. The proportion of small beans (those retained on screen 14) was negatively correlated with soil OM, total N, Ca, CEC, pH, Mn and sand content (Table 1). This shows that each bean size category had strong relationship with some soil variables than with the others (Figure 4a).

Similarly, 100 bean weight, which is also an indicator of bean size, was significantly correlated with most of the measured soil parameters. It was positively correlated with soil OM, total N, Ca, CEC, pH, Mn and sand content, but negatively correlated with available P, K, silt and clay content (Table 1).

Ordination analysis using DCA showed that the length of the longest gradient was less than 3 (i.e. 1.412; Table 2), indicating the relevance of the linear methods for the current analysis. As a result, the unimodal models (e.g. CCA) were dropped, but rather the linear models (PCA and RDA) were used for analyzing the bean size-soil relationship as presented in Table 3 and Table 4, respectively. The successive eigenvalues of the first four RDA axes also show a decreasing trend (Table 4), suggesting a well-structured data set. The RDA eigenvalues are somewhat higher than for the DCA axes, indicating that important explanatory soil parameters are measured and included in the analysis. Accordingly, the first PCA axis captured about 67.9% of the total variance in bean size distribution of the wild Arabica coffee data set, and the four PCA axes altogether explained about 99.1% of the total variance (Table 3). The first RDA axis explained about 35.3% of the variance in the data set, and the four axes altogether explained about 42.5% of the total variance (Table 4).

Table 1. Pearson correlation matrix showing the relationships between bean size distribution and soil properties in the natural coffee forests of Ethiopia†.

Variable	SC18+	SC17	SC16	SC15	SC14	SC14-	100 BW
OM	-0.067	0.210*	0.218*	-0.152	-0.238*	-0.257**	0.312**
Total N	0.007	0.286**	0.129	-0.204*	-0.240*	-0.290**	0.402**
Available P	0.010	-0.120	-0.087	0.055	0.148	0.150	-0.255*
Na	0.087	0.466**	0.185	-0.415**	-0.428**	-0.345**	0.187
K	-0.052	-0.262**	-0.112	0.200*	0.264**	0.230 *	-0.241*
Ca	0.121	0.333**	0.079	-0.314**	-0.269**	-0.243*	0.341**
Mg	-0.109	0.024	0.058	-0.026	0.007	-0.004	0.043
CEC	-0.091	0.166	0.267**	-0.163	-0.208*	-0.229 *	0.206*
pH	0.169	0.481**	0.060	-0.422**	-0.378**	-0.321**	0.316**
PBS	0.196*	0.171	-0.159	-0.173	-0.059	-0.026	0.179
Sand	0.247**	0.290**	-0.075	-0.264**	-0.220*	-0.164	0.497**
Silt	-0.194*	-0.192*	0.081	0.182	0.147	0.077	-0.343**
Clay	-0.235*	-0.302**	0.056	0.269**	0.227*	0.194*	-0.507**
Fe	-0.074	-0.089	0.144	0.049	0.002	-0.019	-0.088
Mn	0.076	0.606**	0.276**	-0.519**	-0.553**	-0.502 **	0.418**
Zn	0.041	0.040	0.098	-0.072	-0.101	-0.065	-0.193

†Abbreviations: 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; SC16 = proportion of beans retained on screen 16; SC15 = proportion of beans retained on screen 15; SC14 = proportion of beans retained on screen 14. and SC14- = proportion of beans that passed through screen 14 but retained on screen size below 14; 100 BW = weight of 100 beans.

Table 2. Summary of a gradient analysis using detrended canonical analysis (DCA) showing the relationships between bean size distribution and soil data in the natural coffee forests.

Axes	1	2	3	4	Total inertia
Eigenvalues:	0.106	0.027	0.006	0.003	0.158
Lengths of gradient:	1.412	0.733	0.541	0.578	
Bean size-soil correlations:	0.697	0.588	0.405	0.429	
Cumulative percentage variance:					
• of bean size data	67.2	84.5	88.3	90.3	
• of bean size - soil relation:	80.30	95.40	0.000	0.000	
Sum of all eigenvalues					0.158
Sum of all canonical eigenvalues					0.064

Table 3. Summary of the gradient analysis using principal component (PCA) showing the relationships between wild Arabica bean size distribution and soil data in the natural coffee forests.

Axes	1	2	3	4	Total variance
Eigenvalues:	0.679	0.221	0.062	0.029	1
Bean size - soil correlations:	0.720	0.526	0.379	0.278	
Cumulative percentage variance:					
• of bean size data :	67.9	90	96.2	99.1	
• of bean size-soil relation:	82.8	97.2	99.3	99.8	
Sum of all eigenvalues					1
Sum of all canonical eigenvalues					0.425

Table 4. Summary of the gradient analysis using redundancy analysis (RDA) showing the relationships between wild Arabica bean size distribution and soil data in the natural coffee forests.

Axes	1	2	3	4	Total variance
Eigenvalues	0.353	0.065	0.004	0.002	1
Bean size - soil correlations:	0.722	0.553	0.249	0.264	
Cumulative percentage variance:					
• of bean size data	35.3	41.8	42.2	42.4	
• of bean size – soil relation:	83.1	98.3	99.4	99.9	
Sum of all eigenvalues					1
Sum of all canonical eigenvalues					0.425
F value	52.906				5.507
P value	0.0020†				0.0020‡

†P value for the RDA axis 1; *‡P values for all RDA axes*

The first two PCA and RDA axes explained about 90% and 41.8% of the total variance in wild Arabica coffee bean size distribution data set, respectively. The bean size-soil correlations were also high 0.720 for PCA axis 1 and 0.722 for RDA axis 1, showing the bean size distribution data were strongly correlated with the measured soil parameters. In comparison, the first axis of the bean size-soil relation explained 82.8% of the total variance in the case of PCA (Table 3) and 83.1% of the total variance in the case of RDA (Table 4), no much deviation. This indicates that PCA and RDA complemented each other.

Generally, soil pH, Mn, organic matter and total nitrogen were positively correlated with bean size; that is, the higher the values of soil pH, Mn, organic matter or total nitrogen, the higher the proportion of larger beans. But the reverse trend was observed for available P and K; that is, higher concentrations of available P and K were associated with smaller beans. There was also a significant relationship between bean size and soil texture. Generally, the higher the sand content, the larger the bean size or the higher the proportion of larger beans. But the higher the fraction of fine soil particles (clay or silt content), the higher the proportion of smaller beans (Table 1; Figure 4a).

Direct gradient analysis using RDA revealed that coffee physical quality was related to soil characteristics of the natural coffee forest ecosystems. Monte Carlo permutation test for the first RDA axis, as well as the overall analysis was significant (p=0.0020) with 499 permutations (Table 4). Soil Mn, sand, pH, Na, available P and organic matter significantly contributed to the variability in bean size distribution of wild Arabica coffee from the natural coffee forests of Ethiopia (Figure 4b). Among them, Mn was the most important soil parameter explaining about 22% of the total variance alone, followed by sand and soil pH each explaining about 16% and 14% of the total variance, respectively. This was also evidenced by the length of the arrow (the longest arrow). As indicated in Figure 4 and Table 1, soil parameters such as Mn, CEC, OM, total N, Ca, Na and pH favored the development of larger beans (those retained on screen 16 and screen 17), whereas higher available P, K and silt contributed to the development of relatively smaller beans (those retained on screen 15, screen 14 and screen 14minus). But the contribution of some soil parameters such as Mg, Fe and Zn to the bean size was almost negligible.

The first RDA axis clearly discriminated samples of the SE coffee forests from those of the SW coffee forests. A clear distinction was found between the SW coffees and the SE coffees; the SE samples (from Harenna) were situated on the right side of the ordination space, whereas samples from the SW were mixed and located on the left side of the ordination space (Figure 4c,d). This means that higher proportion of large, bold and good beans were located on the right side of the ordination space, whereas higher percentage of medium, small and very small beans were situated on the left side of the ordination space. Coffee beans from the SW coffee forests were characterized by relatively higher proportion of medium sized beans (those retained on screen 15) and small sized beans (those retained on screen 14). This is because the higher K, available P and small sized soil particles (silt and clay) have favored the development of such beans in the SW as compared to the SE. This was evidenced by relatively higher K, available P, silt and clay in the SW coffee forest soils (Sheko, Bonga and Yayu) than in the SE coffee forest soils (Harenna) as presented in Appendix 1. The second and other RDA axes were not much important as indicated by their respective low eigenvalues (Table 4).

As shown in Figure 4, the first RDA axis was more strongly correlated with the proportion of bold beans (beans retained on screen 17) than with the proportion of other bean size categories, whereas the proportion of beans retained on screen 18+ (large beans) was weakly correlated with RDA axis 1. It was also less influenced by most soil parameters other than percent base saturation and soil texture (Table 1). Thus, the variability in bean size distribution of wild Arabica coffee is the function of the variability in soil characteristics (substrate composition) of the coffee forest ecosystems. The canonical discriminant analysis (CDA) also clearly discriminated the SW and SE coffee forest sites based on both soil characteristics (Figure 5a) and based on bean characteristics (Figure 5b).

As indicated in Figures 5, the first CDA axis explained about 79% of the variability in soil data set and about 78.9% of the variability in bean size distribution data set, which is almost the same. Thus, the composition of the substrate (soil quality) was the base for most of the variance in bean size distribution of wild Arabica coffee in Ethiopia

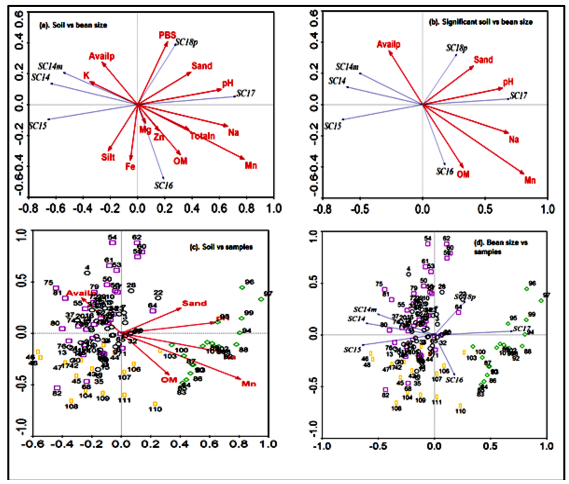

Figure 4. RDA biplot of bean size distribution versus soil properties; abbreviations are as in Table 1. Numbers refer to samples. p=0.002 for Mn, p=0.004 for sand, p=0.012 for pH, p=0.016 for Na, p=0.018 for available P and p=0.032 for organic matter. Green colour refers to plots from Harenna, yellow from Bonga, purple from Yayu, and black from Sheko (B-Kontir).

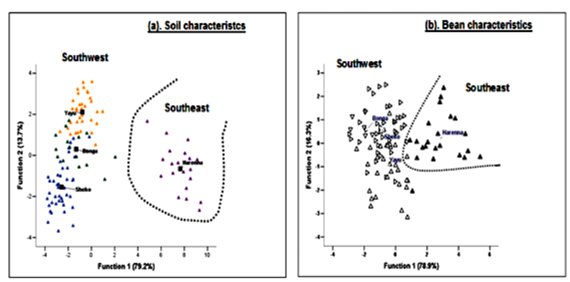

Figure 5. Comparison of canonical discriminant functions of soil characteristics vis-à-vis that of bean characteristics of wild Arabica coffee from the SW and SE natural coffee forests of Ethiopia

Table 5. The relative contribution of different soil parameters to the bean size distribution of wild Arabica coffee in the Afromontane rainforests of Ethiopia using stepwise multiple regression.

Bean size (adjusted R^2)	Soil property	Regression coefficients†			t value	P value
		Unstandardized		Standardized		
		B	Std. Error	Beta		
Screen 18+ (adjusted R^2 = 0.120)	Constant	-7.712	6.386		-1.208	0.230
	Sand	0.115	0.032	0.366	**3.608**	0.000
	OM	-0.607	0.221	-0.286	-2.754	0.007
	pH	2.465	1.103	0.205	2.235	0.027
Screen 17 (adjusted R^2 = 0.431)	Constant	-29.176	13.312		-2.192	0.031
	Mn	0.011	0.004	0.290	2.717	0.008
	pH	6.834	2.265	0.263	**3.017**	0.003
	Na	32.374	12.638	0.226	2.562	0.012
	Sand	0.105	0.051	0.154	2.04	0.044
Screen 16 (adjusted R^2 = 0.068)	Constant	30.365	0.842		36.076	0.000
	Mn	0.007	0.002	0.276	3.002	0.003
Screen 15 (adjusted R^2 = 0.307)	Constant	47.557	9.197		5.171	0.000
	Mn	-0.007	0.003	-0.274	**-2.417**	0.017
	pH	-3.708	1.594	-0.227	**-2.371**	0.020
	Na	-19.553	8.933	-0.213	-2.189	0.031
Screen 14 (adjusted R^2 = 0.299)	Constant	14.879	0.553		26.911	0.000
	Mn	-0.011	0.002	-0.553	-6.924	0.000
Screen 14- (adjusted R^2 = 0.245)	Constant	8.819	0.459		19.209	0.000
	Mn	-0.008	0.001	-0.502	-6.056	0.000

†The t statistics can help you determine the relative importance of each variable in the model; the independent variables are usually measured in different units, and hence the standardized coefficients make the regression coefficients more comparable.

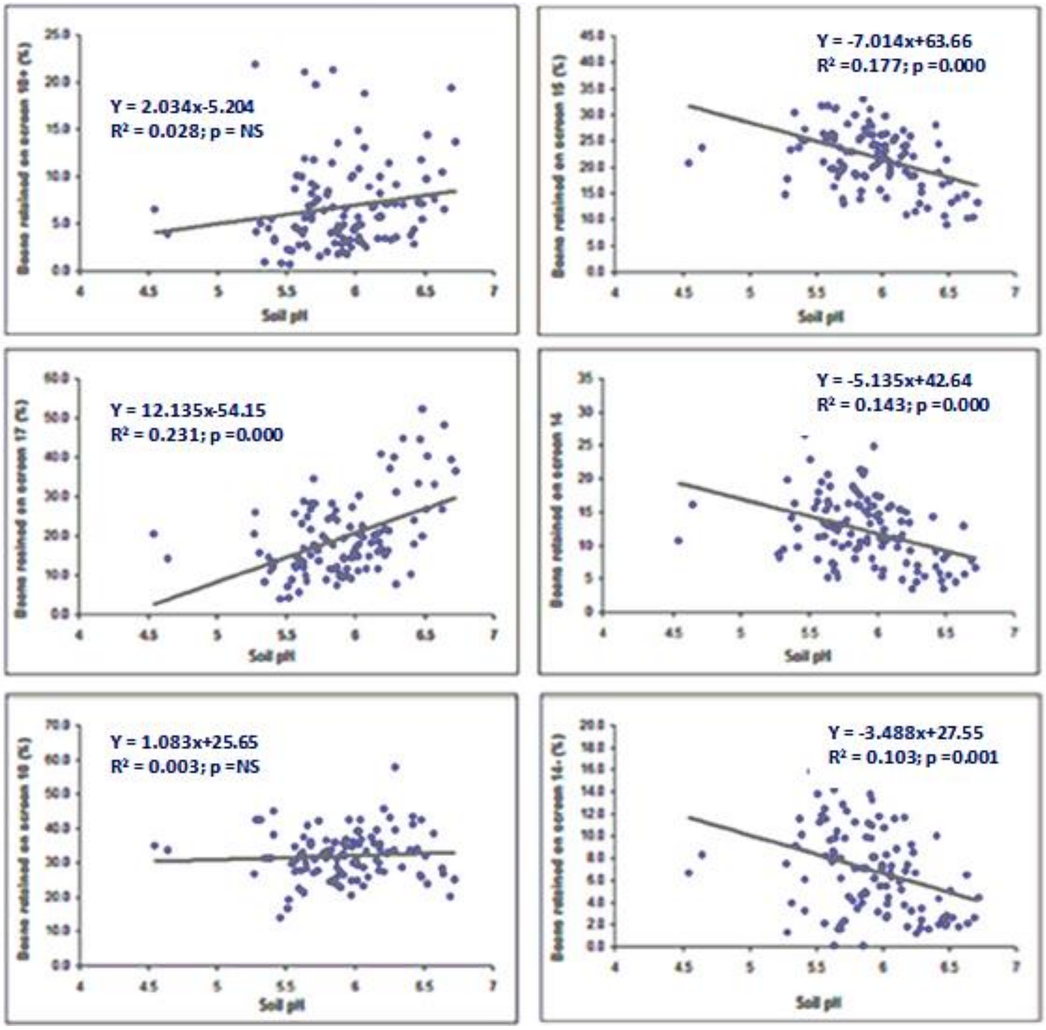

Figure 6. Bean size distribution of wild Arabica coffee as related to soil pH in the Afromontane rainforests of Ethiopia.

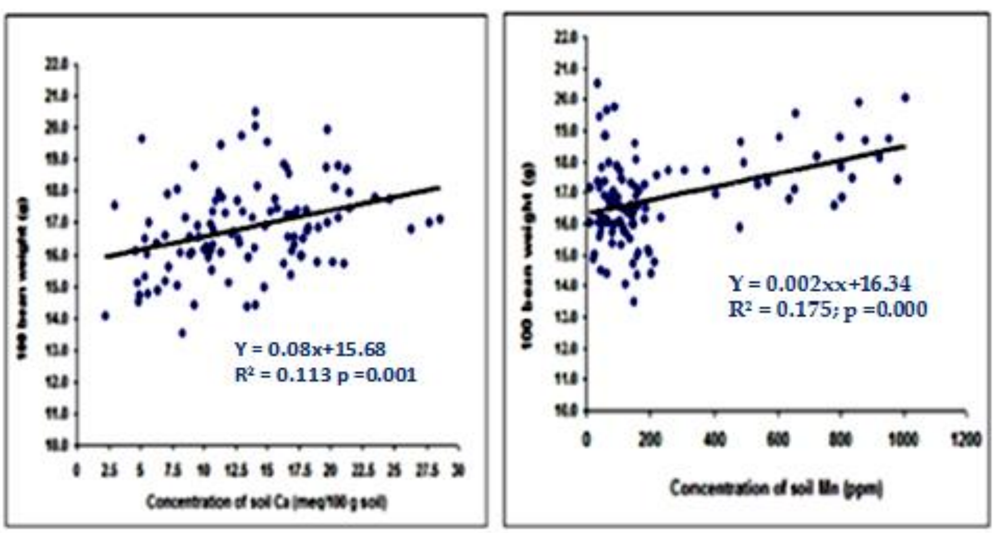

Figure 7. Hundred bean weight of wild Arabica coffee as related to Ca and Mn of the soil in the Afromontane rainforests of Ethiopia

DISCUSSION

The present study clearly showed apparent variation in bean size distribution of wild Arabica coffee with variation in soil characteristics of the natural coffee forests of Ethiopia harbouring the wild populations of *C. arabica*. Both PCA and RDA revealed that bean size is significantly related to the soil characteristics (substrate composition) (Figure 4; Tables 3 and 4), which reconfirms the results obtained by correlation analysis (Table 1). Thus, soil is one of the most important environmental factors contributing to variation in the bean size distribution of wild Arabica coffee. Soil is an important environmental factor for plant growth, and it is a function of the soil-forming factors - climate, organisms, topography, parent material and time (Jenny, 1941). The influence of environmental factors (e.g. elevation, climate, parent material, etc.) is practically the influence of soil-forming factors, and consequently, soil is the foundation for the production of quality coffee. The explanation for this might be because soil performs different important functions in the terrestrial ecosystems. Soil is a reservoir of plant nutrients and water, and the majority of the essential elements for plants are taken from the soil (Lambers *et al*., 1998; Chapin III *et al*., 2002; Juo and Franluebbers, 2003; Tsui *et al*., 2004; Snoeck and Lambot, 2004; Roy *et al*., 2006). The soil also supports a large community of microorganisms capable of transforming soil compounds into mineral forms readily available for root uptake (Snoeck and Vaast, 2004; Decoteau, 2005; Bot and Benites, 2005). Soil organisms are responsible for the decay of organic matter and cycling of both macronutrients and micronutrients (Bot and Benites, 2005). These ecological functions of the soil are thus important for coffee quality.

Soils vary largely with respect to their natural fertility (Roy *et al*., 2006; Hall, 2008), which imparts variability in coffee quality. Soil fertility is meant the capacity of a soil to provide adequate and balanced amounts of nutrients for the growth of plants (Brady, 1990; Gachene and Kimaru, 2003; Juo and Franzluebbers, 2003). Variation in soil fertility is thus of paramount importance for variation in coffee quality. According to the present findings, coffees from relatively more fertile soils (plots with high pH, organic matter, base cations) had higher proportions of bolder beans, whereas those from relatively less fertile soils had higher proportions of smaller beans (Table 1, and Figure 6). This is because fertile soil is required to sustain health plant growth (Hall, 2008), and infertile soil cannot supply the required amounts of essential nutrients, and poor yield and/or poor quality results from the lack of adequate plant nutrition (Alley and Vanlauwe, 2009). This means spatial variations in soil development due to variation in soil-forming factors can result in large variations in soil properties (Chapin III *et al*., 2002), which in turn imparts variation in coffee quality such as bean size.

According to the present study, soil Mn, pH, OM, available P, Na and sand content were the most important variables among the measured soil parameters that significantly influenced the bean size distribution of wild Arabica coffee by using RDA analysis (Figure 4). This was also confirmed by stepwise multiple regression of soil parameters (as independent variables) and the proportion of beans retained on different screen sizes; for instance, about 43% of the variation in the proportion of bold beans of wild Arabica coffee was explained by soil parameters such as Mn, pH, Na and sand content (Table 5). As also revealed by RDA, subsequent regression analysis showed that Mn was the most important parameter for bean size. This shows that in the natural habitat of wild Arabica coffee bolder beans were associated with relatively higher concentrations of soil Mn and higher values of soil pH, while smaller beans were associated with lower soil Mn and pH. This means increase in soil pH (within the current range 4.54 to 6.72) increased the proportion of bold beans, and vice versa. There was also an increasing trend in the proportion of bold beans with increase in the concentration of soil Mn, and vice versa. This could be due to the fact that soil pH determines the availability of soil nutrients (Taiz and Zeiger, 2002; Juo and Franluebbers, 2003), and consequently, natural coffee forests that had higher soil pH, Mn and cations also had higher proportion of bold beans. The proportion of bold beans from the SE (Harenna) was comparatively higher (33.48%) than in the SW (16.42%). The higher soil pH, Mn, Na and sand from the Harenna coffee forest might have favored the development of large or bold beans as compared to other sites (Sheko, Bonga and Yayu) with relatively lower mean values for these soil parameters (see supplementary data). The observed variation in bean size distribution among coffee samples from the natural coffee forests is thus mainly related to variation in soil characteristics.

A study in India also showed that coffee produced in Giris area (with soils higher in Mn content, 217 ppm) is better in quality as compared to the coffee grown in other areas with relatively lower soil Mn content (Chkmagalnur 129 ppm, Mallandur 118 ppm, Aldur zone 115 ppm) (Nagaraja *et al*., 2001). This may be because manganese ions (Mn^{2+}) activate several enzymes in plant cells, particularly decarboxylases and dehydrogenases involved in the Krebs cycle (Taiz and Zeiger, 2002; Fageria, 2009). The best defined function of manganese is in the photosynthetic reaction through which oxygen is produced from water. It is an essential cofactor in the water-oxidizing process (Taiz and Zeiger, 2002; Pallardy, 2008) and thus helping the syntheses of substances required for growth. This could be the reason why manganese was the most important soil parameter influencing bean size. Generally, mineral nutrients are essential for plant growth and development (Roy *et al*., 2006; Barker and Pilbeam, 2007), and they are crucial for biochemical reactions, and for the production of photosynthates (carbohydrates, proteins, fats, vitamins, etc.) (Roy *et al*., 2006), which are required for growth and development.

Ordination analysis also clearly separated samples from the SE natural coffee forests from those in the SW. This could be attributed to higher soil pH, Mn, Na and sand in the SE coffee forest ecosystems which might have favored the development of bold beans (those retained on screen 17) as compared to sites in the SW. This was evidenced by relatively higher mean values for these soil parameters in the SE as compared with those in the SW (see Appendix 1).

Apart from this, 100 bean weight was also positively correlated with soil pH (Table 1; Figure 7). Generally, higher soil pH was associated with heavier beans, whereas lower soil pH was associated with lighter beans. This could be because soil pH is a major factor in determining the availability of nutrients in soils (Taiz and Zeiger, 2002; Lambers *et al*., 2008), especially Ca (which is very important for bean weight). A positive relationship between 100 bean weight versus soil Ca may be due to the fact that Ca is a major constituent of cell walls (Juo and Franzluebbers, 2003; Winston *et al*., 2005) and calcium ions are used in the synthesis of new cell walls (Taiz and Zeiger, 2002; Pallardy, 2008), thus contributing to the variation in cell size or cell wall thickness. The difference in bean weight and/or bean size could be related to the variation in the cell size and /or cell wall thickness (da Silva *et al*., 2005). A study in Ethiopia by Mintesnot *et al*. (2015) also showed that coffee quality attributes improved with increase in the levels of soil CEC, Mg, and pH, while decrease with increase in the levels of available soil Cu, Zn and total N.

This study, which was conducted on wild Arabica coffee in the natural coffee forests of Ethiopia (i.e., in its natural habitat) not found in other countries or other coffee farms or coffee plantations (Yadessa et al., 2020), has a paramount implication for coffee quality. The natural habitat of any plant species, including wild Arabica coffee is the ideal place where ideal natural conditions are prevailing for that plant species, e.g. ideal soil conditions. The soil data from the natural habitat of wild Arabica coffee is optimal for this species; this is why information generated from such studies can be simulated to be used as a guideline for improving coffee quality and expanding Arabica coffee plantations in other parts of the country or elsewhere around the world. On the other hand, improving the performance of coffee plant (e.g. its nutrition) in buffer zones or coffee plantations in this way can help reduce the pressure on the existing natural coffee forests harbouring wild Arabica coffee.

CONCLUSIONS

The present study clearly showed a marked variation in bean quality of wild Arabica coffee with variation in soil characteristics (substrate composition) of the natural coffee forests harbouring the wild populations of *C. arabica*. Results from principal component analysis (PCA), redundancy analysis (RDA) and simple correlation analysis all revealed that the soil is one of the most important environmental factors influencing the quality of wild Arabica coffee in its natural habitat. The bean size distribution was influenced by soil properties, especially soil pH, organic matter, texture, and Mn. The variability in some soil parameters has a greater impact on coffee quality than the variability in some other soil properties. This means soil properties such as CEC, OM, total N, Mn, Ca and pH favored the development of larger beans such as those retained on screen 16 and screen 17, whereas higher available P, K and clay contributed to the development of smaller beans such as those retained on screen 15, screen 14 and screen 14minus. Moreover, canonical discriminant analysis (CDA) revealed that the variability in bean size distribution of wild Arabica coffee is the function of the variability in soil characteristics (substrate composition) of the coffee forest ecosystems. Thus, the composition of the substrate (soil characteristics) was the base for most of the variance in bean size distribution of wild Arabica coffee in Ethiopia. The soil characteristics of the Afromontane rainforests significantly influenced the bean characteristics of wild Arabica coffee. This has a paramount implication for coffee quality in a way that optimum soil condition for Arabica coffee production can be simulated based on the soil conditions of its natural habitat in the Afromontane rainforests of Ethiopia.

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APPENDICES

Appendix 1: Mean values (±standard deviation) for the considered soil parameters from the four natural coffee forests in the SW and SE Ethiopia.

Statistic	B. Kontir (n=41)	Bonga (n=16)	Yayu (n=34)	Harenna (n=20)	*P value*
SOM (% DM)	4.64±1.34c	6.52±1.25b	7.21±2.20b	8.49±1.00a	*0.000*
Total N (% DM	0.32±0.07c	0.41±0.05b	0.41±0.13b	0.52±0.005a	0.000
Avail. P (ppm)	39.99±34.48a	3.44±7.52b	11.22±12.56b	1.94±2.09b	*0.000*
Na (meq/100g)	0.05±0.06c	0.10±0.06b	0.04±0.02	0.16±0.07a	*0.000*
K (meq/100g)	1.23±0.68a	1.34±0.80a	1.07±0.74a	0.56±0.40b	*0.002*
Ca (meq/100g)	11.88±4.87bc	9.40±3.52c	13.15±5.74b	19.18±3.89a	*0.000*
Mg (meq/100g)	3.70±1.77	2.91±1.09	3.04±1.56	3.73±0.58	*NS*
CEC (meq/100g)	29.08±7.39b	34.96±5.05b	32.22±12.33b	43.77±4.69a	*0.000*
BS (%)	56.58±12.57a	39.01±13.68b	53.89±11.83a	54.44±10.23a	*0.000*
pH	5.90±0.24b	5.47±0.43c	5.82±0.22b	6.42±0.18a	*0.000*
Sand (% DM)	20.18±9.07c	29.13±6.37b	43.82±11.14a	46.70±5.92a	*0.000*
Silt (% DM)	37.76±4.76a	34.57±3.37a	28.88±7.76b	27.86±2.70b	*0.000*
Clay (% DM)	42.06±8.02a	36.31±5.49b	27.30±4.69c	25.44±5.95c	*0.000*
Fe (ppm)	57.39±34.98b	246.36±313.99`a	50.93±40.78b	82.61±50.44b	*0.000*
Mn (ppm)	136.91±45.96ab	212.10±158.79b	66.29±28.11b	738.74±179.06a	*0.000*
Zn (ppm)	2.97±1.72a	3.26±01.85a	1.41±0.60b	2.38±0.55ab	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 saturationSOM = soil organic matter1 ppm=1 mg/kg (solid substance). In terms of percents, 1 ppm equals 0.0001 percent.

Appendix 2: Variability in physical bean characteristics of wild Arabica coffee from the four natural coffee forests in SW and SE Ethiopia.

Trait	Site	N	Minimum	Maximum	Mean	SD
Screen 18+ (%)	B-Kontir	40	1.78	14.83	6.20	3.21
(p=NS)	Bonga	17	0.73	21.95	5.72	6.15
	Yayu	34	0.89	21.34	7.36	5.25
	Harenna	23	2.82	19.35	7.43	4.17
Screen 17 (%)	B-Kontir	40	7.41	34.65	18.42**b**	6.63
(p=0.000)	Bonga	17	4.18	28.22	15.01**b**	6.50
	Yayu	34	4.02	30.39	15.26**b**	6.23
	Harenna	23	7.65	52.23	33.48**a**	11.19
Screen 16 (%)	B-Kontir	40	20.76	42.5	31.88**ab**	5.22
(p=0.002)	Bonga	17	19.19	45.26	34.90**a**	6.36
	Yayu	34	13.93	39.4	29.03**b**	5.75
	Harenna	23	20.4	58.01	35.40**a**	8.84
Screen 15 (%)	B-Kontir	40	14	36.44	22.98**a**	4.88
(p=0.000)	Bonga	17	13.14	37.11	24.93**a**	6.53
	Yayu	34	13.86	38.67	24.44**a**	5.80
	Harenna	23	9.07	26.38	14.72**b**	4.64
Screen 14 (%)	B-Kontir	40	5.3	24.88	13.23**a**	4.48
(p=0.000)	Bonga	17	5.15	27.55	12.47**a**	5.44
	Yayu	34	5.31	26.63	14.70**a**	4.53
	Harenna	23	3.6	12.99	6.38**b**	2.18
Screen 14- (%)	B-Kontir	40	0.1	18.58	7.30**a**	4.63
(p=0.000)	Bonga	17	2.32	11.59	7.01**a**	2.61
	Yayu	34	3.89	17.64	9.21**a**	3.29
	Harenna	23	1.09	6.47	2.59**b**	1.21
100 bean weight (g) (p=0.000)	B-Kontir	37	13.53	18.56	16.23**bc**	1.07
	Bonga	7	14.43	16.91	15.73**c**	0.95
	Yayu	32	14.52	20.51	17.08**ab**	1.43
	Harenna	23	13.36	20.06	17.82**a**	1.40

Means followed by similar letters within a column for each trait are not significantly different by using Tukey's Honestly Significant Test at 0.05 level of significance. SD = Standard deviation