

Full Length Research Paper

The major factors influencing coffee quality in Ethiopia: The case of wild Arabica coffee (*Coffea arabica* L.) from its natural habitat of southwest and southeast afro-montane rainforests

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Coffee quality is a complex trait involving sensory and bean characteristics as well as biochemical contents. The objective of this study was to assess the major factors influencing the quality of wild Arabica coffee (*Coffea arabica* L.) in the natural coffee forests of southwest and southeast Ethiopia. Results revealed that both natural (soil, aspect, elevation, climate, geographic location) and human factors (cherry harvesting/ handling, theft, forest management) considerably influenced the quality of wild Arabica coffee. The soil factor affected every component of coffee quality (cup quality, bean characteristics and biochemical contents). The cup quality of coffee varied with soil properties, especially with available P and soil texture. The bean size distribution was also affected by soil properties; there was significant positive relationship between soil pH, sand or Mn and the proportion of bold beans (retained on screen 17). Soil organic matter, total N and sand content were inversely correlated with caffeine content, but available P and clay content were positively correlated with caffeine. Increase in elevation led to increase in bean size up to the elevation of about 1600 m above sea level, but thereafter no more increase in bean size (hump-shaped relationship, not monotonic). Bean size increased with increase in longitude, but it decreased with increase in latitude. Cup quality was also significantly influenced by coffee harvesting and handling, but its influence was not noticed on bean size and biochemical contents. Coffee quality is therefore the resultant of an interaction of different natural and human factors prevailing in the respective area.

Key words: Arabica coffee, bean size, biochemical content, cup quality, environment, management/handling.

INTRODUCTION

Food quality is an important feature because the food people choose depends largely on its quality (Vaclavik and Christian, 2008). According to Caplan (1978), quality

is fitness for a purpose. Quality refers to the degree of excellence of a food and includes all the characteristics of a food that are significant and that make the food

acceptable (Vaclavik and Christian, 2008). The International Organization for Standardization (ISO) defines quality as 'the ability of a set of inherent characteristics of a product, system or process to fulfill requirement of customers and other interested parties' (ISO, 2000). According to Lochner and Mater (1990), quality is a measure of the extent to which customer requirements and expectations are satisfied. Fiske (1990) defined it as 'quality is a fuzzy and relative term and it is in a constant motion'. The quality of a product is not absolute; it always depends upon the requirements of the consumer (Hay and Porter, 2006). Thus, method or group of methods designed to control the quality of a defined product may be applicable in a particular situation, but they are subject to a constant evolution (Costell, 2002). This means quality is a subjective term, and it can have different meanings depending upon the context in which the term is used.

According to Ferial-Morales (2002), the quality of green coffee mostly depends on the way in which the coffee is grown, harvested and processed. Therefore, coffee quality is hard to define and agree on as the definition of quality varies for different stakeholders across the commodity (production-to-consumer) chain. This means what one stakeholder perceives as quality may not be so thought of by another. At the farmer level, coffee quality is a combination of production level, price and ease of culture; at the exporter or importer level, coffee quality is linked to bean size, lack of defects, regularity of provisioning, tonnage available, physical characteristics and price; at the roaster level, coffee quality depends on moisture content, stability of the characteristics, origin, price, biochemical compounds and organoleptic quality; at the consumer level, coffee quality deals with price, taste and flavour, effects on health and alertness, geographical origin, environmental and sociological aspects such as organic coffee, fair trade, shade coffee, etc. (Ferial-Morales, 2002; Leroy et al., 2006; Perriot et al., 2006). It is a joint effort by all the key players of the coffee production-to-consumer chain (Prodolliet, 2004). According to Neilson (2007), quality is embodied not only in taste and/or physical attributes, but also through a plethora of social, environmental, ethical, safety and other concerns. Thus, quality is a key link between different stakeholders in the coffee sector, and hence coffee quality assessment is an important step in coffee trade (Gichimu et al., 2012).

It is generally accepted that coffee quality depends on different factors, such as the species/varieties, the environmental conditions (soil, rainfall, elevation, slope aspect, etc.), geographic locations (latitude, longitude), methods of processing, etc. (Decazy et al., 2003;

Wintgens, 2004a, b; Avelino et al., 2005; da Silva et al., 2005; Knopp et al., 2006; Läderach et al., 2006; Leroy et al., 2006; Läderach, 2007; Yadessa et al., 2008a; Barbosa et al., 2012). And these factors vary from country to country and from place to place, and hence contributing to the quality variations in coffees around the world. Coffee quality is therefore the result of an interaction of these natural and human factors. Although Ethiopia is the birthplace of Arabica coffee, factors influencing coffee quality are less studied in the country as compared to other Arabica coffee producing countries. Since the country is the source of gene pool for Arabica coffee, it would have been the source of Arabica coffee research information in general and its quality in particular. Thus, to grow and produce good quality coffee, species/variety, important environmental factors, management factors, socio-economic factors, etc. that affect coffee quality should be taken into account. It is hypothesized that the major factors that affect the quality of wild Arabica coffee (*Coffea arabica* L.) from the natural coffee forest ecosystems are distinct since these natural coffee forests are the origin of Arabica coffee and found only in Ethiopia (not in other countries like Brazil, Vietnam, Colombia, etc.). Ethiopia has a unique position regarding Arabica coffee world as it is the birthplace or origin of *C. arabica*, and the natural conditions for coffee growing are almost ideal in Ethiopia (Krug and de Poerck, 1968). The objective of the present study was thus to assess the major factors (both natural and human) influencing the quality of wild Arabica coffee (*C. arabica* L.) in the natural coffee forests of southwest and southeast Ethiopia, and then to identify the key factors important for coffee quality.

MATERIALS AND METHODS

Study sites

The study was conducted in the southwest (Berhane-Kontir, Bonga and Yayu) and the southeast (Harenna) natural coffee forest ecosystems of Ethiopia, geographically separated by the Great Rift Valley System. The sites were selected for their landscape diversity so as to study the effects of various environmental factors on coffee quality in these ecologically diverse natural coffee forest ecosystems. 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

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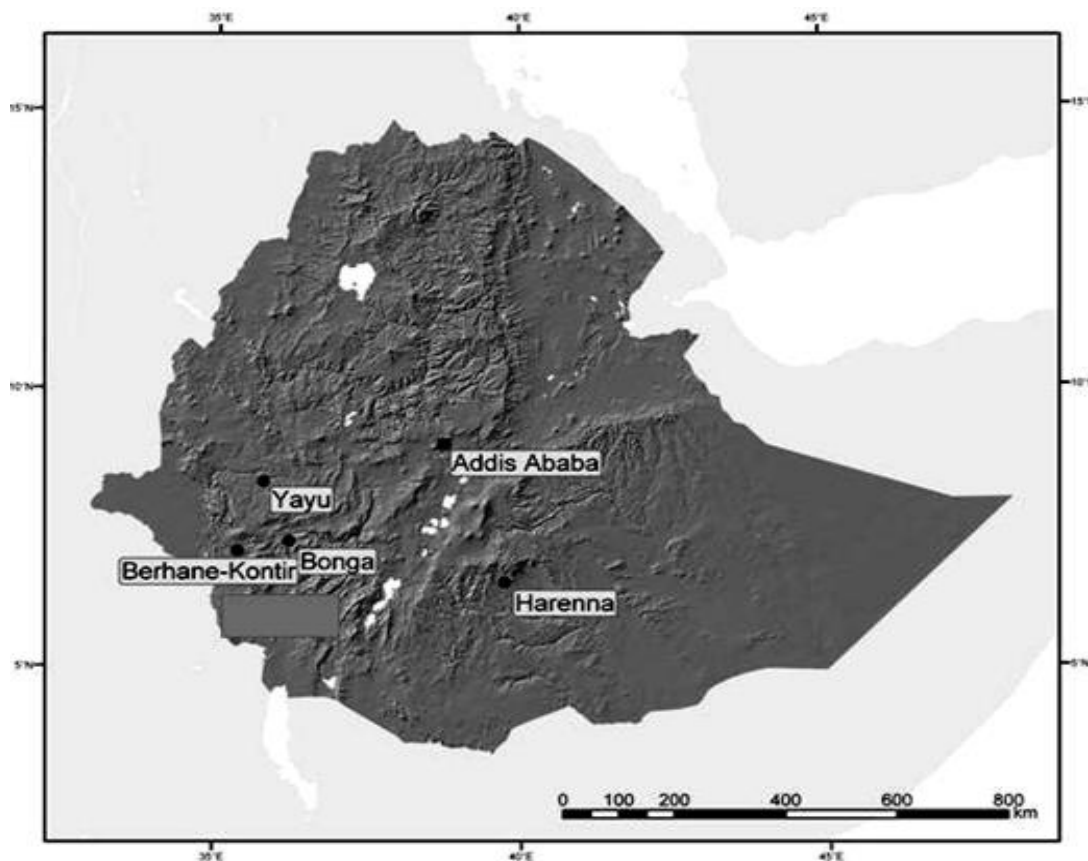


Figure 1. A map of Ethiopia showing the geographical location of the study sites.

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 Harena 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, and the Bale Mountains include the northern plains, bush and woods, the Sannate Plateau, and the southern Harena forest. The area is known for its floral and faunal diversity and endemism (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).

Sampling procedures and coffee cherry sampling

During site selection, preliminary information from the local people and key informants was collected to assess their perceptions on what factors might affect coffee quality. To assess the influence of environmental factors on coffee quality, coffee cherries were sampled from different plots located at different elevation ranges and geographic locations. Depending on the nature of the study site, the existing slope aspects, including valley bottoms or flat plots were also included in the sampling as described in Avelino et al. (2005). Transects were laid out systematically along the topographic aspects of the study coffee forest sites. Forty one samples from Berhane-Kontir, 19 from Bonga, 34 from Yayu and 20 from Harena were studied. Coffee cherries were sampled from the respective plots. Elevation and geographic locations (latitude and longitude) were measured per plot. Garmin GPS was used for measuring geographic coordinates and elevation above sea level.

Coffee cherry harvesting, processing and cup tasting

Cherries were harvested at full maturity, which is usually during peak harvesting period. Coffee cherries mature and were harvested first in Berhane-Kontir (Sheko), followed by Bonga and Harena, and lastly in Yayu according to their maturity order in the field. Red cherries were hand-picked from the coffee trees in the coffee forest and all the samples were then dry processed. The dried cherries were manually depulped and the beans were made ready for different analyses. Bean size distribution of wild Arabica coffee was

determined by conventional screen analysis, as described in Ferial-Morales (2002) and Wintgens (2004a). Weight fractions retained on each sieve were recorded as described in Muschler (2001), and then converted into percentage basis. Cup tasting was conducted at the Coffee Quality Inspection and Auction Center in Addis Ababa, Ethiopia by a panel of 5 experienced cup tasters (three from Ethiopia and 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 samples, respectively. The tasters first assessed the fragrance (dry aroma) by smelling the coffee powder before adding the hot water. After the coffee powder has been infused in hot water, the wet aroma of the brew was assessed. And next the resulting foam was removed before tasting started and then after the tasters assessed the acidity, flavour, body, aftertaste and finally the overall quality.

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 at International Livestock Research Institute (ILRI), Addis Ababa, Ethiopia. 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 method (redundancy analysis) was used to assess the relationships between coffee quality traits and environmental variables. This is because correlation and regression analysis alone may not be suitable when large numbers of variables are involved, and thus different methods should be integrated for comprehensive analysis (Liebhold and Gurevitch, 2002; Zhang and Oxley, 1994). Multivariate analysis provides statistical methods for study of the joint relationships of variables (James and McCulloch, 1990). Moreover, the multivariate approach usually minimizes the problem of multicollinearity effects since the ordination axes are independent (Sokal and Rohlf, 1995), and multivariate analyses are therefore widely used to summarize large data sets (with many variables) by removing the influence of redundant or irrelevant variables in the data set (Dray, 2008; Guoqing et al., 2008).

Redundancy analysis (RDA) is a multivariate direct gradient analysis method appropriate where spatial environmental gradients are short (Jongman et al., 1987; Lepš and Šmilauer, 2003; van der Wollenberg, 1977). 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). Ordination analysis was conducted using CANOCO for windows version 4.5 computer program (terBraak and Šmilauer, 2002).

RESULTS AND DISCUSSION

The present study clearly demonstrated that the quality of wild Arabica coffee was considerably influenced by the environmental conditions and anthropogenic factors prevailing in the natural coffee forest ecosystems from where the samples were collected.

Influence of soil characteristics

Results revealed that there were significant relationships between soil properties and coffee quality traits. The cup quality of wild Arabica coffee was considerably influenced by soil properties, especially by available P (positive relationship) and soil texture (positive relationship with fine particles, but negative relationship with sand) (Table 1). This means higher levels of soil available P and clay or silt were associated with better cup quality, and vice versa. The probable reason for better cup quality of coffee associated with higher available P concentration of the soil might be due to the fact that phosphorus is vital to plant growth and it is involved in several key plant functions. Phosphorus is a structural element in nucleic acids (Hawkesford et al., 2012), and it plays an important role in energy storage and transfer in crop plants. Adenosine diphosphate (ADP) and adenosine triphosphate (ATP) are compounds with high-energy phosphate groups (Fageria, 2009; Hawkesford et al., 2012), and energy is released when a terminal phosphate is split from ADP or ATP (Sanchez, 2007). Both flowering and fruiting are reduced by P deficiency (Pallardy, 2008), and thus available P is a very important soil nutrient for cup quality of coffee. Seed quality improves with P nutrition (Roy et al., 2006), which is in agreement with the findings of the present study. A similar trend was previously reported by Yadessa et al. (2008a) for Sheko and Yayu sites (n=74). Nutrient concentration of the soil and that of coffee leaves in the study sites are presented in Appendix Tables 1 and 2, respectively.

According to the present findings, bean size distribution was also influenced by soil characteristics of the coffee plots, especially soil pH, Mn, organic matter and soil texture. There was significant positive relationship between soil pH or Mn and the proportion of bold beans (proportion of beans retained on screen 17). Generally, higher concentrations of soil organic matter, Mn, pH and sand content were associated with higher proportions of larger/bolder beans, and vice versa (Figure 2 and Appendix Table 3). This could be because mineral nutrients are essential for plant growth and development (Roy et al., 2006; Barker and Pilbeam, 2007). The developing beans normally act as priority sinks for assimilates and minerals (Cannell, 1985), which affects endosperm development and dry matter accumulation and this in turn affects bean size and weight.

A study by Mintesnot et al. (2015) showed that coffee quality attributes increased with increase in the levels of

Table 1. Pearson correlation matrix showing relationships between cup quality traits and soil properties in the four natural coffee forests of Ethiopia (n=102).

Soil parameter	Cup quality traits						
	Fragrance	Aroma	Acidity	Flavour	Body	Aftertaste	Overall
OM	-0.17	-0.089	0.045	-0.06	-0.072	-0.134	-0.039
Total N	-0.168	-0.073	0.076	-0.054	-0.05	-0.103	-0.024
Available P	0.229*	0.284**	0.115	0.257**	0.192	0.301**	0.239*
OC	-0.170	-0.089	0.045	-0.06	-0.072	-0.134	-0.039
Na	-0.120	-0.021	0.005	-0.008	-0.076	-0.083	-0.065
K	0.117	0.177	0.012	0.054	0.11	0.148	0.103
Ca	-0.089	0.085	0.185	0.118	0.105	0.09	0.135
Mg	0.057	0.219*	0.133	0.119	0.117	0.132	0.125
CEC	-0.113	0.039	0.127	0.09	0.069	0.037	0.078
pH	-0.077	0.127	0.175	0.136	0.052	0.098	0.119
PBS	0.046	0.169	0.121	0.070	0.099	0.113	0.126
Sand	-0.297**	-0.321**	-0.076	-0.216*	-0.148	-0.298**	-0.192
Silt	0.333**	0.398**	0.189	0.251*	0.219*	0.320**	0.264**
Clay	0.214*	0.203*	-0.02	0.149	0.067	0.224*	0.102
Fe	-0.054	-0.067	-0.007	-0.024	0.027	-0.033	-0.020
Mn	-0.151	-0.007	0.130	0.103	0.014	0.021	0.048
Zn	0.123	0.19	0.029	0.046	-0.001	0.099	0.027

*, ** = correlations are significant at 0.05 and 0.01 level of significance, respectively.

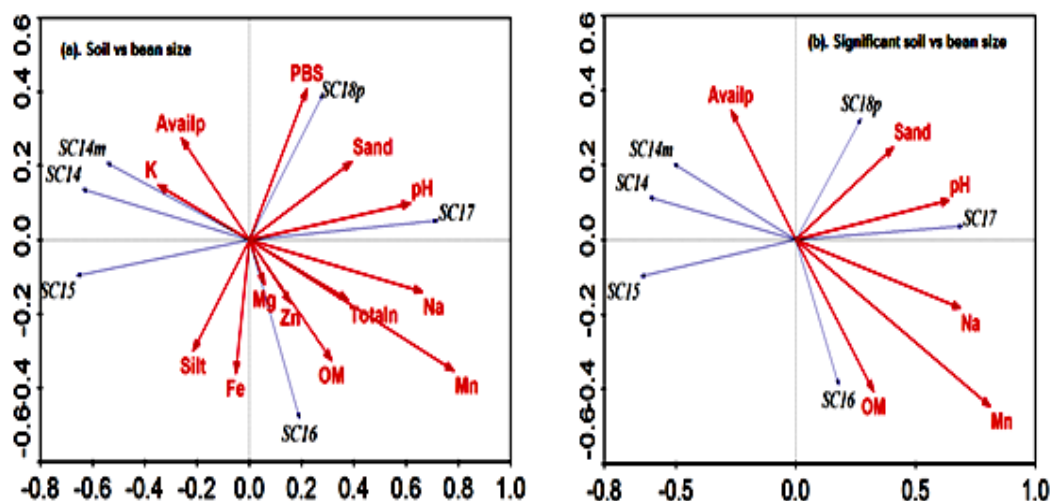


Figure 2. Redundancy analysis (RDA) biplot of bean size distribution versus soil properties; soil versus bean size (a) and significant soil versus bean size (b). Arrows represent the directions of maximum variation of the variables; arrows pointing in the same direction indicate a high positive correlation, arrows crossing at right angles indicate near-zero correlation, whereas arrows pointing in opposite directions indicate high negative correlation; the location of coffee quality scores near environmental vectors suggests the environmental affinities of the trait; $p=0.002$ 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. Appendix Table 3 shows the description of screen sizes.

soil Mg, but decreased with the increase in the levels of soil total N. A study 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. A study by Ngugi et al. (2016) showed that Mn and Zn were important elements in the determination of organoleptic

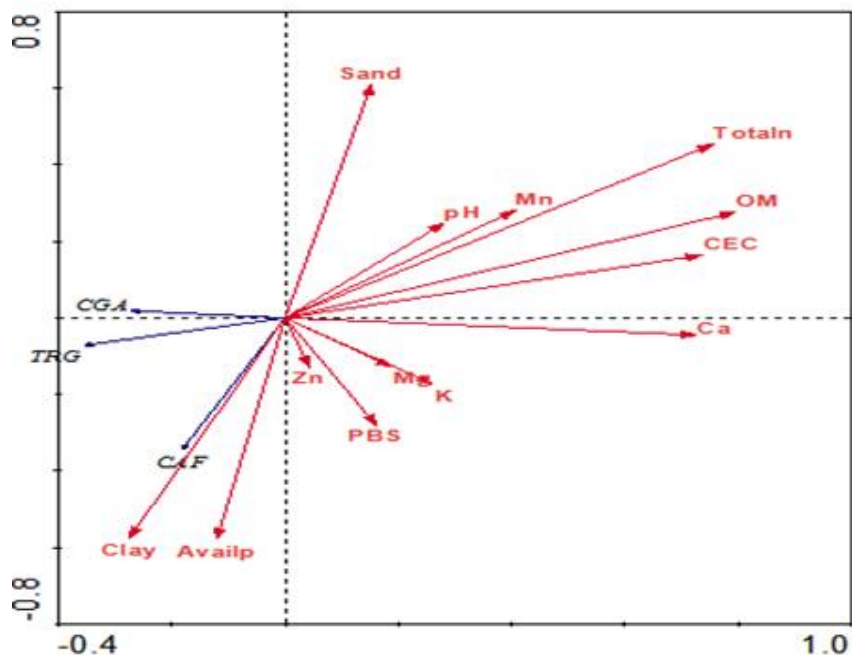


Figure 3. RDA biplot showing the relationships between soil properties and biochemical contents of wild Arabica coffee in the natural coffee forests of Ethiopia. CGA= chlorogenic acid, TRIG= trigonelline, CAF= caffeine.

cup quality in Robusta coffee.

Results also revealed that the biochemical contents of wild Arabica green coffee beans were also influenced by soil properties. Higher concentrations of soil organic matter, total nitrogen and sand content were associated with lower caffeine content; but the higher the clay content, the higher the caffeine content. There was a positive relationship between available P and bean caffeine content. Trigonelline was inversely correlated with most soil parameters. But chlorogenic acid was less influenced by soil properties (Figure 3). The probable reason for low caffeine content under P limited ecosystem or positive correlation of caffeine with available P status of soil and its negative correlation with nitrogen could be due to nutrient interaction or antagonism between N and P. In P limited ecosystem, N uptake is reduced and subsequently N concentration in plant tissue is decreased. The decrease in N concentration with increasing P limitation may be mediated by a decrease in leaf cytokinin levels (de Groot et al., 2003). Cytokinins regulate cell division in shoots and roots and promote movement of nutrients (Taiz and Zeiger, 2002; Hopkins and Hüner, 2009). A study conducted in Brazil by Mazzafera (1999) to investigate the influence of mineral nutrition of coffee on its caffeine contents showed that the omission of P induced the lowest caffeine content.

Generally, both physical and chemical properties of the soil were very important factors for the quality of Arabica

coffee in its natural habitat of southwest and southeast coffee forests of Ethiopia, as they influenced every aspect of coffee quality traits (bean physical quality, cup quality and biochemical contents). Thus, soil is a very important factor of quality in coffee production. This may be because soil property is an output of different soil-forming factors (topography, climate, parent material, living organisms, time) and hence factors that influence soil property most likely influence coffee plant growth and hence its quality.

Influence of elevation above sea level

The effect of elevation much depended on other factors, such as geographic location (latitude, longitude), soil, etc. This is because elevation is an indirect environmental gradient (no direct effect on plant physiology), and the major variable that changes with elevation is temperature, which also changes with latitude and longitude (Austin et al., 1984). Increase in elevation led to an increase in bean size and soil organic matter up to the elevation of about 1600 m above sea level, but thereafter no significant increase (that is, hump-shaped relationship, not monotonic) (Figure 4). This might be attributed to decrease in soil organic matter decomposition and mineralization (organic matter accumulation), which arise due to decrease in temperature with increasing elevation. A study by Alpizar and Bertrand (2004) also showed that

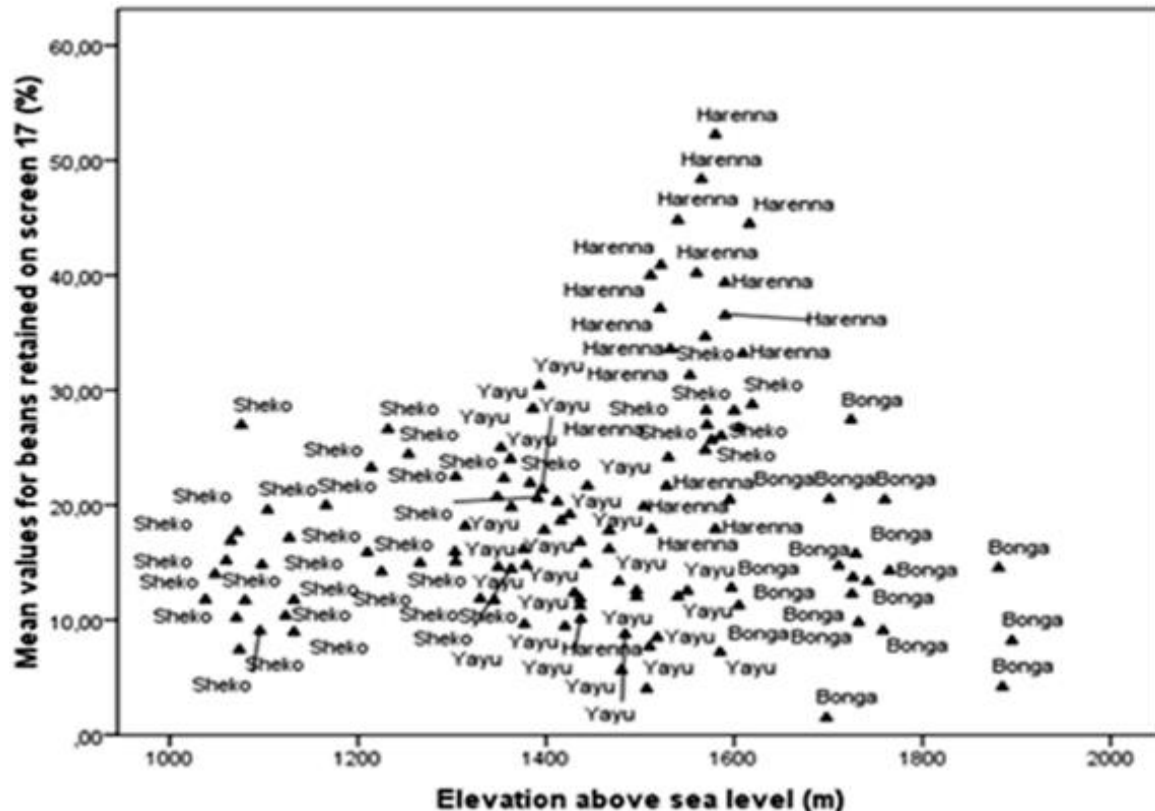


Figure 4. Variability in the proportion of beans retained on screen 17 (bold beans) across the elevation gradients in the natural coffee forests of Ethiopia.

the higher the elevation, higher the proportion of large size beans; and this relation was observed up to an elevation of 1400 m above sea level and then started to decline thereafter. This could be due to reduced nutrient availability, which is characterized by higher carbon-to-nutrient ratios, such as C:N, C:P, etc. (Wilcke et al., 2003, 2008). In the present study, C:P and C:N ratios were significantly higher at higher elevations than at lower elevations (data not shown). Thus, decreasing nutrient availability at higher elevations might be the probable reason for decreasing bean size after an elevation gradient of 1600 m.

As shown in Figure 5, coffee bean weight was significantly varied across the elevation ranges, being highest in the elevation range 1300-1600 m above sea level (asl). Values of 100 bean weight varied from 13.53 to 18.79 g (mean 15.62 g) in the elevation range <1300 m asl, from 14.52 to 20.51 g (17.28 g) in the elevation range 1300-1600 m asl, and from 14.43 to 19.57 g (mean 16.47 g) in the elevation range >1600 m asl.

As a general trend, bean size showed a hump-shaped relationship with elevation; that is, it increased with increase in elevation at low elevation levels, reached a peak at intermediate elevation levels, but declined at high elevation levels. This may be because increase in

elevation in already a highland area and to higher ranges may lead to decrease in temperature below the optimal range for coffee. The optimum temperature for Arabica coffee is between 15-24°C year round, and photosynthesis is reduced above these temperatures (Willson, 1999; CRI, 2001). And this also leads to decrease in decomposition rate and subsequent accumulation of soil organic matter. Temperature has a significant impact on coffee trees (Descroix and Snoeck, 2004), and it is generally agreed that every 100 m of elevation corresponds to a decrease in temperature of 0.6°C (Wintgens, 2004b; CRI, 2001).

Influence of topographic aspect

The effect of topographic aspect was rather more important than elevation for coffee quality in the natural coffee forests. Generally, beans on the southern and western facing aspects were bolder in size as opposed to those on the northern and eastern aspects (Figure 6). This could be due to difference in environmental factors, especially soil properties, which is evidenced by higher soil organic matter and nutrients on the south-and west-facing aspects as compared to the north- and east-facing

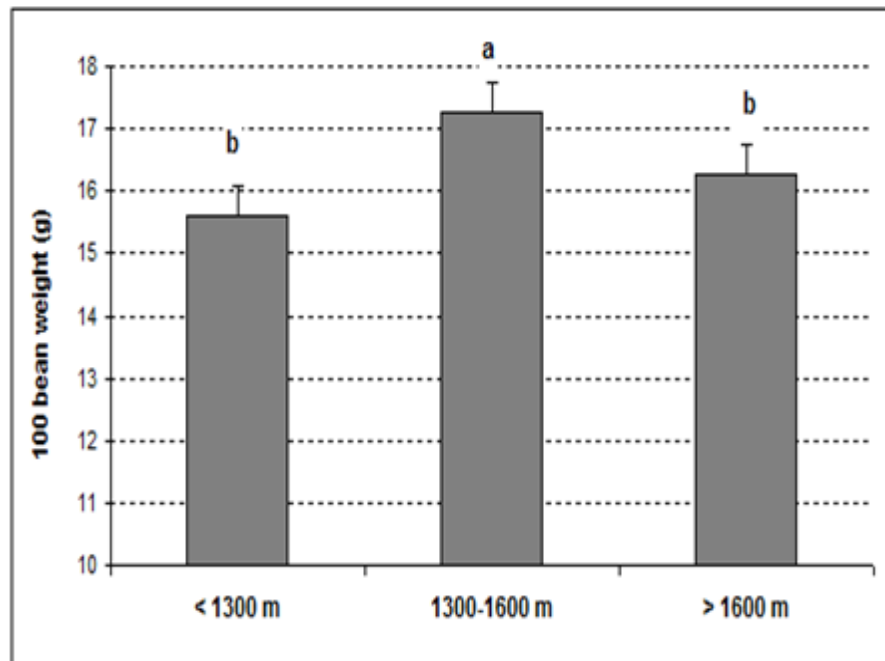


Figure 5. Hundred bean weight across the elevation gradient in the natural coffee forests of Ethiopia; mean values followed by similar letters are not significantly different by Tukey's significant test.

aspects. The reason why coffee beans from the south- and west-facing aspects are bolder than those from the north- and east-facing aspects could be due to variability in environmental factors like soil characteristics. This argument was supported by significantly higher soil organic matter, pH, and nutrients (e.g. Mn, Ca, Na, etc.) on the south- and west-facing aspects as compared to the north- and east-facing aspects, as shown in Figure 7. Soil Mn (important soil parameter for bean size) was 339.07, 258.29, 251.12 and 84.07 ppm, under west, south, east and north facing aspects, respectively. A study in China also revealed that high fertility plots often exist on south-facing slopes and soil organic matter is an important indicator to soil fertility (Fu et al., 2004). Variation in coffee quality with respect slope aspect may be related to differences in availability of light, moisture, etc. Slopes facing the equator (south-facing slopes in the northern hemisphere and north-facing slopes in the southern hemisphere) receive more radiation than opposing slopes and thus have warmer and drier conditions (Chapin et al., 2002). A study by Avelino et al. (2005) in Costa Rica showed that coffees from east-facing slopes had better quality.

Influence of geographical location

Latitude was inversely correlated with bean size; that is, as one moves from north-south gradient within the study

sites (decrease in latitude), the proportion of larger/bolder beans increased, and vice versa. But for the case of longitude, the opposite trend was observed. Generally, samples that were collected from plots with higher longitude readings had relatively higher proportions of larger/bolder beans. This means the proportion of larger beans decreased from east-west gradient (decrease in longitude).

In general, the proportion of bold beans decreased as latitude increased, but it increased as longitude increases, and vice versa. The relationship is shown as follows:

The proportion of bold beans (% of beans retained on screen 17) = -3.042 latitude readings (in decimal degrees) + 3.064 longitude readings (in decimal degrees) – 69.788

From geographical location point of view, coffee beans from the SE Afromontane rainforests were bolder in size as compared to those from the SW Afromontane rainforests. This is because soil organic matter, pH, Mn and sand in the SE were higher than in the SW, and also their distribution followed an increasing trend along the west-east longitudinal gradient in the study sites. This variation in soil characteristics imparts variability in coffee quality. The soils in the southeast are more sandy and less weathered (Yimer et al., 2006) compared to the more clay dominated and highly weathered soils in the

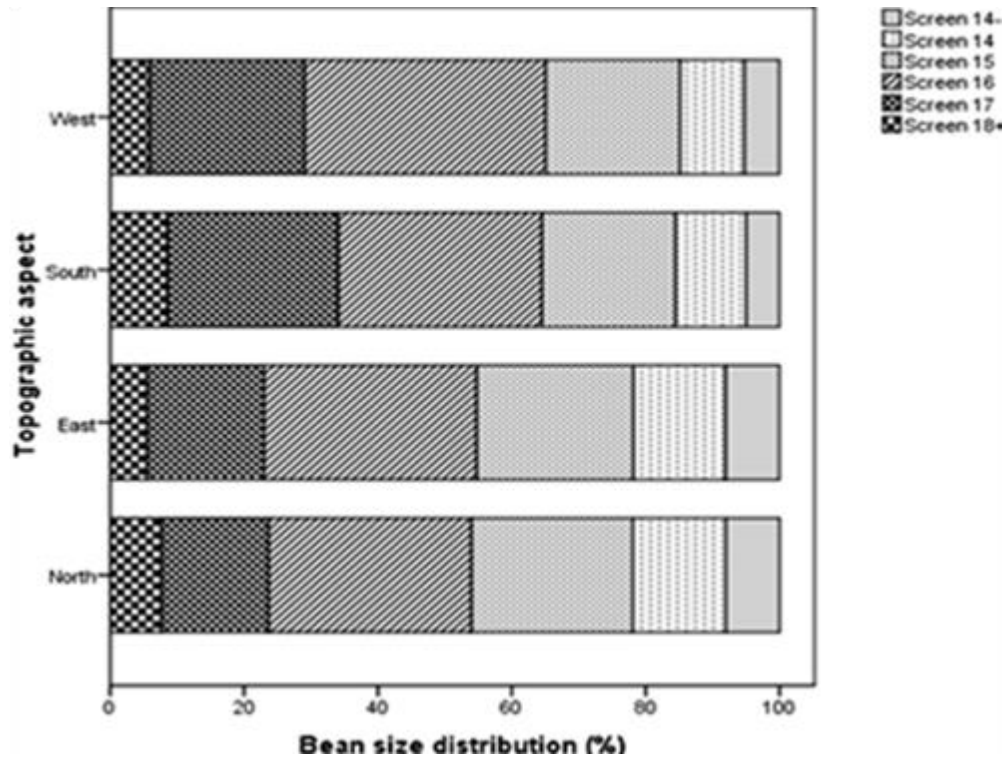


Figure 6. Bean size distribution as influenced by topographic aspect in the natural coffee forests of Ethiopia.

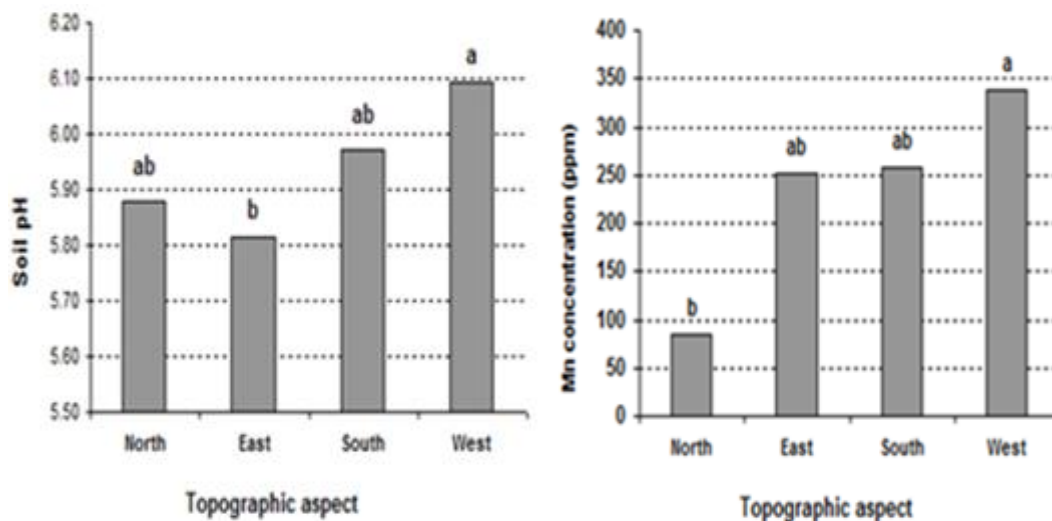


Figure 7. Soil pH and Mn concentrations across the different topographic aspects in the Afromontane rainforests of Ethiopia.

southwest (Dubale and Mikiru, 1994). As latitude increases, temperature decreases. Latitude influences the climate by influencing the amount of solar radiation received (MacMahon et al., 2007). Areas near the equator receive more incoming solar radiation than areas

near the poles. At the equator, the sun's rays are almost perpendicular to the surface at solar noon. At lower sun angles experienced at high latitudes, the sun's rays are spread over a larger surface area, resulting in less radiation received per unit ground area (Chapin et al.,

Table 2. Pearson correlation coefficients showing the relationship between climate and coffee quality traits; climatic data from mobile weather station was used.

Traits	Rainfall	Tmin	Tmax
Sensory characteristics			
Fragrance	0.227*	0.348**	-0.267**
Aroma	0.116	0.262**	-0.100
Acidity	-0.071	0.024	0.103
Flavor	-0.009	0.135	0.028
Body	0.071	0.158	-0.032
Aftertaste	0.093	0.234*	-0.091
Bean characteristics			
Screen 18 ⁺	-0.077	-0.091	0.175
Screen 17	-0.584**	-0.446**	0.623**
Screen 16	-0.240*	-0.144	0.186
Screen 15	0.484*	0.365*	-0.559**
Screen 14	0.527**	0.406**	-0.533**
Screen 14 ⁻	0.475**	0.335**	-0.460**
100 bean weight	-0.404**	-0.421**	0.502**
Bean length	-0.361**	-0.397**	0.309**
Bean width	-0.080	0.046	0.254**
Bean thickness	0.109	0.015	-0.085
Bean shape index	-0.313**	-0.385**	0.207*

Tmin = minimum temperature, Tmax = maximum temperature.

2002; Raven et al., 2010). For each degree of latitude away from the equator, the corresponding reduction in temperature is estimated at 0.5 °C (Descroix and Wintgens, 2004).

Influence of climate

There was a positive and significant relationship between minimum temperature and coffee aroma (Table 2). This may be because climate is an important factor with considerable effect on soil properties and thus important factor for coffee quality. It affects the rate of soil formation especially temperature and rainfall and the type of soil that is ultimately formed by influencing weathering processes.

The climate also affects the type of vegetation it supports by influencing the physiology of plants such as photosynthesis, flowering, maturity, etc., which has implications on coffee quality. This is very interesting in the context of current global climate change. The influence of rainfall on cup quality was not as apparent as that of its effect on bean size distribution. In general, the higher the rainfall, the higher the proportion of smaller beans and vice versa (Table 2). High temperature accelerates fruit maturation in coffee (Descroix and Snoeck, 2004). But at lower temperature coffee fruits undergo a slower maturation process, allowing the full manifestation of all biochemical steps necessary for the

development of beverage quality (da Silva et al., 2005). A study by Camargo et al. (1992), cited in da Silva et al. (2005) also suggested that regions with a relatively high temperature tend to produce low quality coffee.

Influence of forest management on coffee quality

Anthropogenic factors (human activities) are one of the causes for spatial heterogeneity of ecosystems. According to the present study, the level of forest management influenced both the cup quality and the bean physical characteristics of wild Arabica coffee, but not the biochemical contents. The level of forest management (level of human interference) considerably influenced the bean size distribution and cup quality traits. When the level of human interference was relatively higher, the cup quality of coffee was better, the proportion of larger beans increased, and available phosphorus increased but soil organic matter decreased. 'Managed (slashed) plots had relatively better cup quality and higher proportion of larger beans. This could be due to improved micro-environmental conditions such as light/temperature and subsequent decomposition and soil mineralization and reduction of weed competition (Table 3).

Forest coffee management modifies the forest ecosystem by changing the microclimate (e.g. light, soil, etc.) and the forest conditions (e.g. species composition,

Table 3. Cup quality and bean size distribution of wild Arabica coffee as influenced by forest management in the natural coffee forests of Ethiopia.

Level of forest management	Cup quality traits						
	Fragrance	Aroma	Acidity	Flavour	Body	Aftertaste	Overall
Little	5.54 ^b	5.22 ^b	5.48 ^b	4.75 ^b	5.53	4.64 ^b	5.20 ^b
Medium	5.93 ^{ab}	5.79 ^a	6.00 ^a	5.58 ^a	6.04	5.37 ^a	6.02 ^a
High	6.09 ^a	5.94 ^a	5.96 ^{ab}	5.51 ^a	6.06	5.33 ^a	5.96 ^a
P value	0.025	0.013	0.049	0.003	NS	0.018	0.004

	Bean size distribution (%)					
	Screen 18+	Screen 17	Screen 16	Screen 15	Screen 14	Screen 14-
Little	5.12 ^b	17.31 ^b	32.93	24.45 ^a	12.65	7.56
Medium	5.62 ^b	17.81 ^{ab}	32.56	23.47 ^a	13.21	7.34
High	9.40 ^a	23.03 ^a	30.72	19.61 ^b	11.14	6.11
P value	0.000	0.028	NS	0.005	NS	NS

Means followed by similar letters are not significantly different by Tukey's significant test.



Figure 8. Theft affects coffee quality by affecting cherry harvesting quality. Source: Photo by Abebe Yadessa.

vegetation structure, space availability, etc.), due to tree thinning and slashing of undergrowth (Senbeta and Denich, 2006; Hundera et al., 2013). Forest management also influences soil nutrient ratios, which impart variations in coffee quality (Yadessa et al., 2019). But in contrast to the present findings, a study by Geeraert et al. (2019) reported a decreasing trend in cup quality of Arabica coffee with increasing intensity of coffee forest management.

Other important factors affecting coffee quality

Theft problem

The effect of theft on coffee quality is indirect. Because of

the problem of cherry thievery in the field during harvesting, farmers in some coffee growing areas are forced to pick green and red cherries together (that is, early harvest) as an escape strategy, and this has a considerable impact on coffee quality (Figure 8a, b). Harvesting quality is essential for better cup quality of coffee (Perroit et al., 2006). The problem of coffee cherry theft during harvesting is also reported by Schmitt (2006), which is in agreement with the present findings. But this forced early harvest due to thievery should not be confused with the early harvest of red cherries, which may give even better cup quality. For instance, Läderach (2007) reported relatively better beverage quality for early harvest as compared to late harvest. Unintentional or intentional harvesting of cherries at several stages of maturation may have adverse impacts on coffee quality if

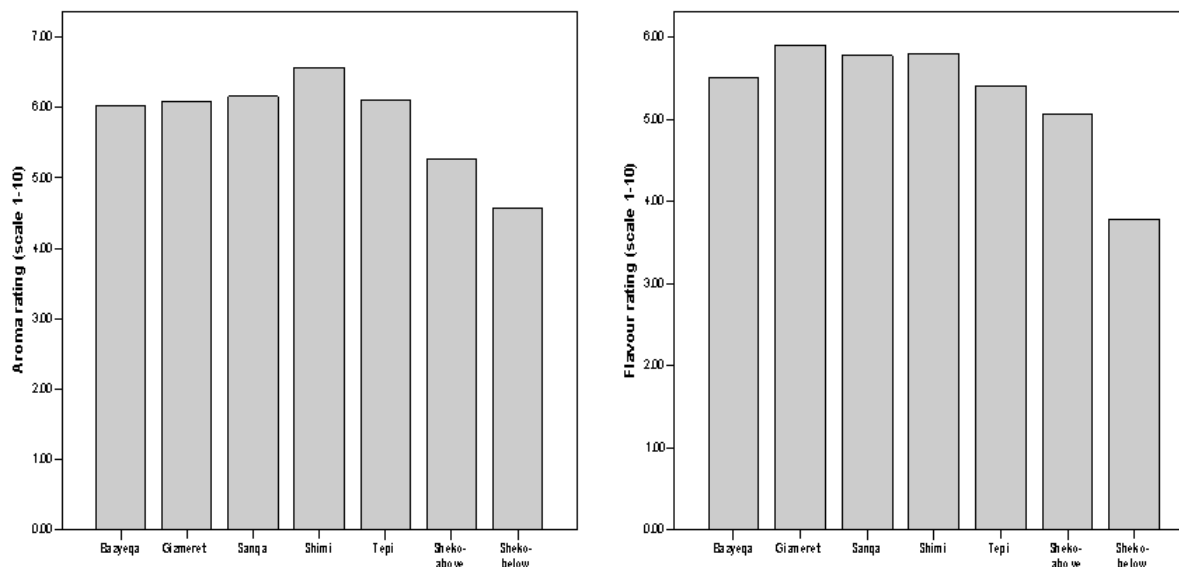


Figure 9. Selected cup quality traits of wild Arabica coffee collected from below the trees as compared to hand-picked coffees in Sheko coffee forest site. Sheko-above refers to coffee samples from farmers but collected from the coffee trees (not from the ground), whereas Sheko-below refers to coffee samples from farmers with coffees collected from below the trees (fallen berries from the ground floor).

these materials are processed together (Brando, 2004). Thus, coffee quality, especially its cup quality is directly correlated with optimal cherry maturity, and theft thus plays a considerable role in coffee quality by influencing cherry harvesting quality.

Heavy rainfall during peak harvesting period

Rainfall influences coffee quality in both direct and indirect ways. On one hand, heavy rainfall can lead to falling (drop) of cherries from coffee trees to the ground before harvest. Fallen cherries from the ground (below coffee trees) can be a major constraint to coffee quality unless care is taken (Figure 9). On the other hand, heavy rainfall during harvesting and/or processing can lead to mould development due to inappropriate drying. Coffee quality is highly dependent on post-harvest processing (Menon, 1992; Perroit et al., 2006). Because of heavy rainfall during cherry maturity or during post-harvest processing, coffee cherries and/or beans can be contaminated by soil when dropped to the ground giving earthy or moldy taste. A study by Tagliaferro et al. (2007) also showed that the impurities from the soil can reach the cup and spoil the beverage quality, and this supports the present findings. Falling of cherries from the coffee trees to the ground due to heavy rainfall was more apparent in Sheko area as compared to other forest coffee sites, due to heavy rainfall and local tradition of cherry handling prevalent in the area. Therefore, harvesting of green cherries, over-ripe cherries, and

picking of fallen cherries from the ground are the major harvesting-related factors influencing coffee quality in the study sites.

Lack of differential price for coffees of different quality

Traders usually pay the same price for coffees of different quality, and bulking of coffees of different qualities or origins is not uncommon practice in the study areas and elsewhere as well with no consideration for quality harvesting and processing (Figure 10). And payment is effected on the basis of quantity, not on quality; that is, there is no market segmentation according to coffee quality. This inevitably leads to reluctance by producers for the coffee quality if this problem is not taken into consideration in the future. This is almost common in most of the study sites or elsewhere. A study by Kodama (2007) also showed that farmers sell a better quality coffee to cooperatives as they expect dividends, but they are less concerned about the quality of coffee for private traders. A study in Jimma zone by Tolessa et al. (2018) revealed that coffee beans managed by cooperatives had better quality scores than those managed by private traders. A study by Bacha (2007) in Bonga (Kaffa zone), for instance, showed that the share of forest coffee producers is only 3% of the retail price.

The lack of differential price has two negative effects, namely: (i) discourages farmers to invest in coffee quality improvement (resources like money, labor, time, etc.),



Figure 10. Coffees of different quality, but sold with the same price; (a) well dried coffee, and (b) mould developed coffee.

Source: Photo by Abebe Yadessa.

better quality scores than those managed by private traders. A study by Bacha (2007) in Bonga (Kaffa zone), for instance, showed that the share of forest coffee producers is only 3% of the retail price.

The lack of differential price has two negative effects, namely: (i) discourages farmers to invest in coffee quality improvement (resources like money, labor, time, etc.), and (ii) bulking of coffees of different quality (sources) considerably influences coffee quality. Generally, if there is no or little difference in the price of a high and a low quality coffee, farmers will show reluctance for investing in coffee quality improvement activities because such investment cannot justify the incurred cost.

Poor share-harvesting arrangements

The use of hired labour from the neighbouring non-coffee growing areas (e.g. Adaba, Ganale, Bidire, etc.) is also an important factor of coffee quality since payment for labourers is based on the quantity harvested, not on the quality of coffee harvested. One third of the harvest is usually for the collector and two third is for the owner, without due consideration to the quality of cherry harvested. This problem is more common in Harena area (Yadessa et al., 2008b). It is also a problem in Sheko area.

Bulking of coffees from different sources

In many coffee producing areas, coffees from different

sources, from forest or plantation, red or green harvested, well dried or mould developed, etc., are sold with the same price. There is usually little or no market differentiation, if any, for coffees of different quality, which leads to reluctance of farmers to give more attention to quality. High quality coffee requires special care and thus coffees with better quality represents good differentials of product price (Pereira et al., 2010).

Limited research capacity

Although Ethiopia is the birthplace of Arabica coffee, factors influencing coffee quality are less studied in the country as compared to other Arabica coffee producing countries. Limited trained manpower and institutional capacity are the major bottlenecks in the country. But this is not the case at the present time, and this should be given due attention in the future.

Poor cooperation between the coffee stakeholders in quality control

Collectors/traders in most cases buy coffees without due consideration to quality, no differential price for different quality coffees. They also buy coffees from anybody, including thieves. In the case of cooperatives, on-farm supervision is a common practice, and production, harvesting and processing are usually supervised with the technical staff of the cooperatives. They also participate in development works such as schools, clinics,



Figure 11. Schematic presentation of the major factors influencing coffee quality and their interactions in Ethiopia.

feeder roads, etc. But in the case of traders, participation in development activities are less experienced. But traders in some cases slightly increase some cents for coffee price to relieve from the competition with cooperatives or farmers, but still these are not as such significant. Apart from the price, handling coffee lots from different sources or farmers differently is not an easy task as well, which is one constraint for coffee quality improvement.

In Ethiopia, coffee cooperatives have brought benefits to coffee farmers by providing a new marketing channel. The dividends are being appreciated by farmers and have encouraged farmers to improve the quality of their coffees. Although the actual volume purchased by cooperatives is limited due to financial constraints, the existence of cooperatives in the coffee market has improved the purchasing price offered by private traders because of competition with the cooperatives. Since the late 1990s, in Ethiopia cooperative activities have been encouraged again, despite bad experiences during the socialist regime (Kodama, 2007). Cooperatives are being appreciated or recognized as business and marketing organization in Ethiopia and as one means of protecting farmers as opposed to its past notion. This is because, in union there is strength. Thus, different stakeholders in coffee sector better promote quality and the sustainability of coffee production rather than competing with each

other. Therefore, the role of agricultural marketing cooperatives is very crucial for smallholder farmers.

Poverty and illiteracy

Apart from the above factors, one of the main challenges facing small-scale coffee producers is their lack of access to physical, economic, and educational resources. Many farmers lack the knowledge and resources (financial or material) to ensure efficient and high quality coffee production. Moreover, traders or suppliers should also be experts in coffee quality themselves to alleviate these problems. Another problem is that those who have information often lack the resources for quality improvement (ITC, 2011a).

In general, coffee quality is the result of interaction of both natural/environmental (soil, climate, elevation, aspect, latitude, longitude) and human (coffee management, theft, harvesting, processing) factors, as summarized in Figure 11. For any system to function properly, there are naturally interactions between the different components of the system. One element of the system can't exist on its own (Yadessa et al., 1999). Similarly, there is an inevitable interdependence and interrelationships among the different factors affecting coffee quality in one way or another. As presented in

As presented in Figure 11, different factors affect coffee quality:

- i) Environmental factors (soil, topography, climate, geography),
- ii) Management factors (cherry harvesting and processing, slashing/forest management),
- iii) Socio-economic factors (theft problem, poor-share arrangement, lack of differential price, poverty and illiteracy etc.),
- iv) Institutional factors (cooperatives, traders, etc.).

As to the genetic factors, the study was conducted in natural coffee forest ecosystem (the gene pool for other Arabica coffee varieties) and Robusta coffee is not common in Ethiopia, and hence the issue of coffee species/variety in natural coffee forests harbouring wild coffee Arabica populations is less relevant here. Of course, the genetic factor might have contributed to the quality of wild Arabica coffee in its natural habitat of southwest and southeast Afromontane rainforests of Ethiopia, but further study on genotype and environment (G*E) interaction is required.

As the importance of quality and origin is increasing in coffee market, the research that deals with factors that influence coffee quality should be a priority in coffee research. Generally, high-quality coffee arises from maintaining close control over a multitude of factors in the field, in the plant and in the cup across the value chain (Prodolliet, 2004; Perroit et al., 2006).

Conclusion

The study demonstrated that the quality of wild Arabica coffee was influenced by different factors -environmental factors (soil, topography, climate, geography), management factors (cherry harvesting and processing, slashing/forest management), socio-economic factors (theft problem, poor-share arrangement, lack of differential price, poverty and illiteracy etc.), institutional factors (cooperatives, traders, etc.) and others. Coffee quality was influenced by complex interactions of different factors. In Ethiopia, wide range of climatic conditions, soil characteristics, topographic features, geographic locations, socio-economic factors, etc. inevitably have led to high diversity of coffee production systems managed with different intensities, which impart diversity in coffees with diverse quality attributes. Consequently, coffee quality is the product of many environmental and anthropogenic factors acting together and hence yielding coffees of different quality with their own unique characteristics. The study tested the traditional theory that states coffee quality is affected by different factors. The results presented here under different sections in this article were highlighted to support the framework outlined in Figure 11 (factors influencing coffee quality), which is

the nucleus or focus of the current study.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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REFERENCES

- Alpizar E, Bertrand B (2004). Incidence of elevation on chemical composition and beverage quality of coffee in Central America. In: 20th International Conference on Coffee Science (ASIC), 11-15 October, 2004, Bangalore, India, pp. 322-327.
- Austin MP, Cunningham RB, Fleming PM (1984). New approaches to direct gradient analysis using environmental scalars and statistical curve-fitting procedures. *Vegetatio* 55: 11-27.
- Avelino J, Bernardo B, Araya JC, Fonseca C, Davrieux F, Guyot B, Cilas C (2005). Effects of slope exposure, altitude and yield on coffee quality in two altitude terroirs of Costa Rica, Orosi and Santa Maria de Dota. *Journal of the Science of Food and Agriculture* 85:1869-1876.
- Bacha DM (2007). Assessment of forest coffee value chains in Ethiopia: A case study in Kaffa zone, Gimbo district. MSc Thesis from Rheinische Friedrich-Wilhelms-Universität zu Bonn, Bonn, Germany.
- Barbosa JN, Borém FM, Cirillo MÂ, Malta MR, Alvarenga AA, Alves HMR (2012). Coffee quality and its interactions with environmental factors in Minas Gerais, Brazil. *Journal of Agricultural Science* 4:181-190.
- Barker AV, Pilbeam DV (2007). Introduction. In: Allen VB, David JP (eds.), *Handbook of Plant Nutrition*, CRC Press, USA, pp. 3-18.
- Beining AM (2007). Ecophysiological diversity of wild *Coffea arabica* populations in Ethiopia: Drought adaptation mechanisms. Institut für Nutzpflanzenwissenschaften und Ressourcenschutz - Fachbereich Pflanzenernährung - der Rheinischen Friedrich-Wilhelms-Universität Bonn. Bonn, Germany.
- Brando J (2004). Harvesting and green coffee processing. In: Witngens JN (ed.), *Coffee: Growing, processing, sustainable production. A guidebook for growers, processors, traders and researchers*. Wiley-VCH Verlag GmbH & Co. KGaA, pp. 604-717.
- Bray RH, Kurtz LT (1945). Determination of total, organic and available forms of phosphorus in soils. *Soil Science* 59:39-45.
- Cannell MGR (1985). Physiology of the coffee crop. In: N. M. Clifford and K. C. Willson (eds.), *Coffee: Botany, biochemistry and production of beans and beverage*, Croom Helm, London, pp. 108-134.

- Caplan RH (1978). A practical approach to quality control. Third edition. Business Books Limited, London.
- Chapin III FS, Matson PA, Mooney HA (2002). Principles of terrestrial ecosystem ecology. Springer-Verlag New York, Inc.
- Costell E (2002). A comparison of sensory methods in quality control. *Food Quality and Preference* 13: 341-353.
- CRI (Coffee Research Institute) (2001). Coffee quality and environmental conditions. *Coffee Research Newsletter* 1(3):4-6. <http://www.coffeeresearch.org/Newsletters/newsletter%203.pdf>
- Da Silva EA, Mazzafera P, Brunini O, Sakai E, Arruda FB, Mattoso LH, Carvalho CRL, Pires CM (2005). The influence of water management and environmental conditions on the chemical composition and beverage quality of coffee beans. *Brazilian Journal of Plant Physiology* 17: 229-238.
- Day PR (1965). Hydrometer method of particle size analysis, pp. 562-563. In: C.A. Black (ed.) *Methods of soil analysis*. American Society of Agronomy, Madison, Wisconsin.
- De Groot CC, Marcelis LFM, van den Boogaard R, Kaiser WM, Lambers H (2003). Interaction of nitrogen and phosphorus nutrition in determining growth. *Plant and Soil* 248:257-268.
- Decazy F, Avelino J, Guyot B, Perriot JJ, Pineda C, Cilas C (2003). Quality of different Honduran coffees in relation to several environments. *Journal of Food Science* 68:2356-2361.
- Descroix F, Snoeck J (2004). Environmental factors suitable for coffee cultivation. In: Wintgens JN (ed.). *Coffee: Growing, processing, sustainable production. A guidebook for growers, processors, traders and researchers*. Wiley-VCH Verlag GmbH & Co. KGaA, pp. 164-177.
- Descroix F, Wintgens JN (2004). Establishing a coffee plantation, In: Wintgens, J.N. (ed.), *Coffee: Growing, processing, sustainable production. A guidebook for growers, processors, traders and researchers*. Wiley-VCH Verlag GmbH & Co. KGaA, pp. 178-245.
- Dray S (2008). On the number of principal components: a set of dimensionality based on measurements of similarity between matrices. *Computational Statistics and Data Analysis* 52:2228-2237.
- Dubale P, Mikru Z (1994). Ecology and soils of major coffee growing regions of Ethiopia. In: Paulos Dubale (ed.), *Mineral fertilization of coffee in Ethiopia*. Institute of Agricultural Research, Addis Ababa, Ethiopia.
- Fageria NK (2009). *The use of nutrients in crop plants*. CRC Press, New York, USA.
- Feria-Morales AM (2002). Examining the case of green coffee to illustrate the limitations of grading systems/expert tasters in sensory evaluation for quality control. *Food Quality and Preference* 13: 355-367.
- Fisken D (1990). Sensory quality and the consumer: viewpoints and directions. *Journal Sensory Studies* 5:203-209.
- Friis I (1986). Zonation of forest vegetation on the south slopes of Bale Mountains, South Ethiopia. *SINET: Ethiopian Journal of Science* 9:29-44.
- Fu BJ, Liu, Ma KM, Zhu YG (2004). Relationships between soil characteristics, topography and plant diversity in a heterogeneous deciduous broad-leaved forest near Beijing, China. *Plant and Soil* 261:47-54.
- Geeraert L, Berecha G, Honnay O, Aerts R (2019). Organoleptic quality of Ethiopian Arabica coffee deteriorates with increasing intensity of coffee forest management. *Journal of Environmental Management* 231:282-288.
- Gichimu BM, Gichuru EK, Mamati GE, Nyende AB (2012). Selection of Ruiru 11 hybrid sibs on raw coffee quality. *African Journal of Horticultural Science* 6:72-82.
- Guoqing L, Xiaon W, Hua G, Zhihong Z (2008). Effects of ecological factors on plant communities of Ziuling Mountain, Shaanxi Province, China. *Acta Ecologica Sinica* 28:2463-2471.
- Hay RKM, Porter JR (2006). *The physiology of crop yield*. Second edition. Blackwell Publishing Ltd., Singapore.
- Hillan J (1988). The Bale Mountains National Park area, southeast of Ethiopia and its management. *Mountain Research and Development* 8:253-288.
- Hawkesford M, Horst W, Kichey T, Lambers H, Schjoerring J, Møller IS, White P (2012). Functions of macronutrients. In: Marschner P (ed.), *Marschner's Mineral Nutrition of Higher Plants*. 3rd edition. Elsevier Ltd., USA.
- Hopkins WG, Hüner NPA (2009). *Introduction to plant physiology*. Fourth edition. John Wiley & Sons, Inc. USA.
- Hundera K, Aerts R, Fontaine A, Van Mechelen M, Gijbels P, Honnay O, Muys B (2013). Effects of coffee management intensity on composition, structure, and regeneration status of Ethiopian moist evergreen Afromontane forests. *Environmental Management* 51:801-809.
- ISO (2000) International Standard ISO 9000: 2000. *Quality management systems - Fundamentals and vocabulary*, 29 pp.
- ITC (International Trade Centre) (2011a). Ethiopian coffee quality improvement project. 2011 AID for trade global review: Case study. International Trade Centre (ITC), Geneva, Switzerland.
- ITC (International Trade Centre) (2011b). *The coffee exporter's guide - Third edition*. Geneva, Switzerland, xvi, 247p.
- Jackson ML (1958). *Soil chemical analysis*. Prentice Hall, Inc. New Jersey.
- James FC, McCulloch CE (1990). Multivariate analysis in ecology and systematics: Panacea or Pandora's box? *Annual Review of Ecology and Systematics* 21:129-66.
- Jongman RHG, terBraak CJF, van Tongeren OFR (1987). *Data analysis and community and landscape ecology*. Pudoc Wageningen, The Netherlands.
- Kilambo D, Mlilo B, Mtenga D, Maro G (2015). Effect of soils properties on the quality of compact Arabica hybrids in Tanzania. *American Journal of Research Communication* 3:15-19.
- Knopp S, Bytof G, Selmar D (2006). Influence of processing on the content of sugars in green Arabica coffee beans. *European Food Research and Technology* 223:195-201.
- Kodama Y (2007). New role of cooperatives in Ethiopia: the case of Ethiopian coffee farmers' cooperatives. *African Study Monographs, Supplementary* 35:87-108.
- Krug CA, de Poerck RA (1968). *World coffee survey*. Food and Agriculture Organization of the United States, Rome, Italy.
- Kufa T (2006). Ecophysiological diversity of wild Arabica coffee populations in Ethiopia: Growth, water relations and hydraulic characteristics along a climatic gradient. *Ecology and Development Series No. 46*.
- Läderach P (2007). *Management of intrinsic quality characteristics for high-value specialty coffees of heterogeneous hillside landscapes* PhD dissertation from Rheinischen-Wilhelms-Universität zu Bonn, Germany.
- Läderach P, Oberthür, Cook S, Fujisaka S, Estrada Iza M, Pohlen JA (2006). Systematic agronomic farm management for improved coffee quality. http://gisweb.ciat.cgiar.org/sig/download/Annual_Report_2006.pdf#page=34
- Lepš J, Šmilauer P (2003). *Multivariate analysis of ecological data using CANOCO*. Cambridge University Press, Cambridge.
- Leroy T, Ribeyre F, Bertrand B, Charmetant P, Dufour M, Montagnon C, Marraccini P, Pot D (2006). Genetics of coffee quality. *Brazilian Journal of Plant Physiology* 18:229-242.
- Liebold AM, Gurevitch J (2002). Integrating the statistical analysis of spatial data in ecology. *Ecography* 25:553-557.
- Lindsay WL, Norvell WA (1978). Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal* 42: 421-428.
- Lochner RH, Mater JE (1990). *Designing for quality: an introduction to the best of Taguchi and Western methods of statistical experimental design*. Springer, Netherland.
- MacMahon MJ, Kofranek AM, Rubatzky VE (2007). *Hartmann's plant science: Growth, development and utilization of cultivated plants*. Fourth edition. Pearson Education, Inc., USA.
- Mazzafera P (1999). Mineral nutrition and caffeine content in coffee leaves. *Bragantia* 58:387-391.
- Menon SN (1992). Interconnection between postharvest processing and the intrinsic quality of coffee. In: ASIC (Colloque Scientifique International sur le Café), San Francisco, USA.
- Mintesnot A, Dechassa N, Mohammed A (2015). Association of Arabica coffee quality attributes with selected soil chemical properties. *East African Journal of Sciences* 9:73-84.
- Muschler RG (2001). Shade improves coffee quality in a sub-optimal coffee-zone of Costa Rica. *Agroforestry Systems* 85:131-139.
- Neilson J (2007). Institutions, the governance of quality and on-farm value retention for Indonesian specialty coffee. *Singapore Journal of*

- Tropical Geography 28:188-204.
- Ngugi K, Aluka P, Maina D (2016). Variation of mineral micronutrient elements in Robusta Coffee (*Coffea canephora* Pierre ex A.Froehner) as measured by energy dispersive X-ray Fluorescence. Annual Research and Review in Biology 9: 1-13.
- Pallardy SG (2008). Physiology of woody plants, third edition, Elsevier Inc., USA.
- Peres-Neto PR, Legendre P, Dray SP, Borcard D (2006). Variation partitioning of species data matrices: estimation and comparison of fractions. Ecology 87:2614-2625.
- Perroit JJ, Ribeyre F, Montagnon C (2006). The qualities of the coffee. In: Christophe Montagnon (ed.), *Coffee: terroirs and qualities*. Editions Quæ, France, pp. 11-20.
- Pereira MC, Chalfoun SM, de Carvalho GR, Savian TV (2010). Multivariate analysis of sensory characteristics of coffee grains (*Coffea arabica* L.) in the region of upper Paranaíba. Acta Scientiarum. Agronomy, Maringá 32:635-641.
- Prodoliet J (2004). Coffee quality assurance: Current tools and perspectives, In: 20th ASIC (International Conference on Coffee Science), 11-15 October, Bangalore, India, pp. 120-145.
- Raven PH, Berg LR, Hassenzahl DH (2010). Environment. John Wiley & Sons, Inc., USA.
- Roy RN, Finck A, Blair GJ, Tandon HLS (2006). Plant nutrition for food security. A guide for integrated nutrient management. Fertilizer and Plant Nutrition Bulletin No. 16. Food and Agriculture Organization of the United Nations, Rome, Italy.
- Sanchez CA (2007). Phosphorus. In: Allen V. Barker and David J. Pilbeam (eds.), Handbook of Plant Nutrition, CRC Press, USA, pp. 51-90.
- Schmitt C (2006). Montane rainforest with wild *Coffea arabica* in the Bonga region (SW Ethiopia): plant diversity, wild coffee management and implications for conservation. Ecology and Development Series, No. 47.
- Senbeta F (2006). Biodiversity and ecology of Afromontane rainforests with wild *Coffea Arabica* L. populations in Ethiopia. Ecology and Development Series No. 38.
- Senbeta F, Denich M (2006). Effects of wild coffee management on species diversity in the Afromontane rainforests of Ethiopia. Forest Ecology and Management 232:68-74.
- Sokal RF, Rohlf FHJ (1995). Biometry, 3rd ed. W.H. Freeman, San Francisco, p. 887.
- Tafesse A (1996). Agro-ecological zones of southwest Ethiopia. Matreialien Zur Ostafrika-Forschung, 13.
- Tagliaferro FS, De Nadai Fernandes EA, Bacchi MA, Bode P, Joacir De França E (2007). Can impurities from soil-contaminated coffees reach the cup? Journal of Radio Analytical and Nuclear Chemistry 271:371-375.
- Taiz L, Zeiger E (2002). Plant Physiology, third edition. Sinauer Associates, Sunderland, p. 623.
- terBraak CJF, Smilauer P (2002). CONOCO for Windows Version 4.5, 1997-2002. Biometris - Plant Research International. Wageningen, The Netherlands.
- Tolessa K, Duchateau L, Boeckx P (2018). Analysis of coffee quality along the coffee value chain in Jimma zone, Ethiopia. African Journal of Agricultural Research 13:1468-1475.
- Vaclavik VA, Christian EW (2008). Essentials of food science. Springer Science and Business Media, LLC., New York, USA.
- van der Wollenberg AL (1977). Redundancy analysis. An alternative for canonical correlation. Psychometrika 42:207-219.
- Walkley A, Black CA (1934). An examination of Degtjareff method for determining soil organic matter and proposed modification of the chromic acid titration method. Soil Science 37:29-38.
- Wilcke W, Oelmann Y, Schmit A, Valarezo C, Zech W, Homeier J (2008). Soil properties and tree growth along an altitudinal transect in Ecuadorian tropical montane forest. Journal of Plant Nutrition and Soil Science 171:220-230.
- Wilcke W, Valladarez H, Stoyan R, Yasin S, Valarezo C, Zech W (2003). Soil characteristics on a chronosequence of landslides in montane rainforest, Ecuador. Catena 53:79-95.
- Willson KC (1999). Coffee, cocoa, and tea. CABI International, UK.
- Wintgens JN (2004a). Factors influencing the quality of green coffee, In: Wintgens JN (ed.), Coffee: Growing, processing, sustainable production. A guidebook for growers, processors, traders and researchers. Wiley-VCH Verlag GmbH & Co. KgaA, pp. 789-809.
- Wintgens JN (2004b). Coffee bean quality assessment, In: Wintgens, J.N. (ed.), Coffee: Growing, processing, sustainable production. A guidebook for growers, processors, traders and researchers. Wiley-VCH Verlag GmbH & Co. KgaA, pp. 810-819.
- Yadessa A, Burkhardt J, Bekele E, Hundera K, Goldbach H (2019). 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. African Journal of Agricultural Research 14:2090-2103.
- Yadessa A, Burkhardt J, Denich M, Gole TW, Bekele E, Goldbach H (2008a). Influence of soil properties on cup quality of wild Arabica coffee in coffee forest ecosystem of SW Ethiopia. In: 22nd International Conference on Coffee Science (ASIC), held between 14-19 September 2008, Campinas, SP Brazil, pp. 1066-1075.
- Yadessa A, Burkhardt J, Denich M, Gole TW, Bekele E, Goldbach H (2008b). Sensory and bean characteristics of wild Arabica coffee from southeast Afromontane rainforests in Ethiopia. In: 22nd International Conference on Coffee Science (ASIC), held between 14-19 September 2008, Campinas, SP, Brazil, pp. 617-624.
- Yadessa A, Itanna F, Olsson M (2001). Contribution of indigenous trees to soil properties: The case of scattered trees of *Cordia africana* Lam. in croplands of western Oromia. Ethiopian Journal of Natural Resources 3:245-270.
- Yadessa A, Lakew B, Mulat E, Atlabatchew W, Anbessa Y (1999). Management of the declining soil fertility in the mixed farming system of Adaa Bargaa district, Oromia National Regional State, Ethiopia. Ethiopian Agricultural Research Organization (EARO) and International Centre for development-oriented Research in Agriculture (ICRA), Saint George Printing Press, Addis Ababa, Ethiopia, pp. x+109.
- Yadessa A, Itanna F, Olsson M (2009). Scattered trees as modifiers of agricultural landscapes: the role of *waddeessa* (*Cordia africana* Lam.) trees in Bako area, Oromia, Ethiopia. African Journal of Ecology 47(Suppl. 1):78-83.
- Yimer F, Ledin S, Abdulkadir A (2006). Soil property variations in relation to topographic aspect and vegetation community in the south-eastern highlands of Ethiopia. Forest Ecology and Management 232:90-99.
- Zhang J, Oxley RRB (1994). A comparison of three methods of multivariate analysis of upland grasslands in North Wales. Journal of Vegetation Science 5:71-76.

APPENDIX

Table 1. Mean values (\pm standard deviation) for the considered soil parameters from the four Afromontane rainforests in the SW and SE Ethiopia.

Statistic	SW soils			SE soils	P value
	B. Kontir (n=41)	Bonga (n=16)	Yayu (n=34)	Harena (n=20)	
SOM (% DM)	4.64 \pm 1.34 ^c	6.52 \pm 1.25 ^b	7.21 \pm 2.20 ^b	8.49 \pm 1.00 ^a	0.000
Total N (% DM)	0.32 \pm 0.07 ^c	0.41 \pm 0.05 ^b	0.41 \pm 0.13 ^b	0.52 \pm 0.005 ^a	0.000
Avail. P (ppm)	39.99 \pm 34.48 ^a	3.44 \pm 7.52 ^b	11.22 \pm 12.56 ^b	1.94 \pm 2.09 ^b	0.000
Na (meq/100 g)	0.05 \pm 0.06 ^c	0.10 \pm 0.06 ^b	0.04 \pm 0.02	0.16 \pm 0.07 ^a	0.000
K (meq/100 g)	1.23 \pm 0.68 ^a	1.34 \pm 0.80 ^a	1.07 \pm 0.74 ^a	0.56 \pm 0.40 ^b	0.002
Ca (meq/100 g)	11.88 \pm 4.87 ^{bc}	9.40 \pm 3.52 ^c	13.15 \pm 5.74 ^b	19.18 \pm 3.89 ^a	0.000
Mg (meq/100 g)	3.70 \pm 1.77	2.91 \pm 1.09	3.04 \pm 1.56	3.73 \pm 0.58	NS
CEC (meq/100 g)	29.08 \pm 7.39 ^b	34.96 \pm 5.05 ^b	32.22 \pm 12.33 ^b	43.77 \pm 4.69 ^a	0.000
BS (%)	56.58 \pm 12.57 ^a	39.01 \pm 13.68 ^b	53.89 \pm 11.83 ^a	54.44 \pm 10.23 ^a	0.000
pH	5.90 \pm 0.24 ^b	5.47 \pm 0.43 ^c	5.82 \pm 0.22 ^b	6.42 \pm 0.18 ^a	0.000
Sand (% DM)	20.18 \pm 9.07 ^c	29.13 \pm 6.37 ^b	43.82 \pm 11.14 ^a	46.70 \pm 5.92 ^a	0.000
Silt (% DM)	37.76 \pm 4.76 ^a	34.57 \pm 3.37 ^a	28.88 \pm 7.76 ^b	27.86 \pm 2.70 ^b	0.000
Clay (% DM)	42.06 \pm 8.02 ^a	36.31 \pm 5.49 ^b	27.30 \pm 4.69 ^c	25.44 \pm 5.95 ^c	0.000
Fe (ppm)	57.39 \pm 34.98 ^b	246.36 \pm 313.99 ^a	50.93 \pm 40.78 ^b	82.61 \pm 50.44 ^b	0.000
Mn (ppm)	136.91 \pm 45.96 ^{ab}	212.10 \pm 158.79 ^b	66.29 \pm 28.11 ^b	738.74 \pm 179.06 ^a	0.000
Zn (ppm)	2.97 \pm 1.72 ^a	3.26 \pm 0.85 ^a	1.41 \pm 0.60 ^b	2.38 \pm 0.55 ^{ab}	0.000

Means followed by similar letters within a row are not significantly different, DM = dry matter, BS= base saturation, SOM = soil organic matter, 1 ppm=mg/L (liquid substance) or 1 mg/kg (solid substance). In terms of percents, 1 ppm equals 0.0001 percent. Source: Yadessa et al. (2019).

Table 2. Leaf nutrient content in the Afromontane rainforests of southwest and southeast Ethiopia harbouring wild *C. crabica* populations.

Nutrient	Harena	Bonga	Yayu	B.-Kontir
P (%)	0.07 ^c	0.12 ^b	0.11 ^c	0.15 ^a
K (%)	1.80 ^c	2.2 ^b	2.1 ^b	2.7 ^a
Ca (%)	1.60 ^a	1.2 ^b	0.33 ^c	0.02 ^c
Mg (%)	0.35 ^a	0.33 ^b	0.26 ^{bc}	0.28 ^{ac}
Zn (ppm)	13.9 ^b	11.5 ^b	9.7 ^c	11.1 ^b
Mn (ppm)	61.0 ^b	67 ^b	59 ^b	98 ^a

Means followed by similar letters within a row are not significantly different. Source: Beining (2007).

Table 3. Screen sizes and descriptions.

Screen no.	Screen diameter (mm)	ISO norm	Bean size description
20	7.94	8.00	Very large
19	7.54	7.50	Extra large
18	7.14	7.10	Large
17	6.75	6.70	Bold
16	6.35	6.30	Good
15	5.95	6.0	Medium
14	5.55	5.6	Small
13	5.16	5.0	
12	4.76	4.75	

Source: Wintgens (2004b).