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Research Paper

Studies on root growth of *Coffea arabica* populations and its implication for sustainable management of natural forests

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Abstract. The study was carried out with the objective to compare the variations in root growth characteristics of wild *Coffea arabica* populations in Ethiopia. A total of 24 wild coffee trees were used for *in-situ* root growth measurements under four natural coffee forests, viz., Harenna, Bonga, Birhane-Kontir and Yayu. Analysis of variance was performed to compare the variability among and within wild coffee population in root growth parameters. The results depicted significant variations among the wild coffee populations in the size and length of larger lateral roots ($p < 0.01$), taproot fresh and dry weights as well as taproot volume ($p < 0.05$). The populations also exhibited significant differences ($p < 0.05$) in total root fresh and dry weights. There were also significant site variations in the number of large and fine laterals as well as in the length of medium laterals. The frequency of small laterals varied significantly among sub-sites. In addition, sites significantly differed in the moisture contents of taproot ($p < 0.05$) and total root growth ($p < 0.01$). Meanwhile, significantly ($p < 0.05$) high proportions of coarse laterals were found in Bonga and Berhane-Kontir, whilst the proportions of fine and medium laterals were high in the Yayu and Harenna populations. In addition, the surface plate laterals were significantly ($p < 0.01$) thick and longest at Harenna and the next longest recorded at Berhane-Kontir. The significantly ($p < 0.05$) longest fine lateral roots was from the Berhane-Kontir population. Similarly, both lateral root fresh and dry weights were maximum at Berhane-Kontir and lowest at Yayu, intermediate at Herenna and Bonga forests. The results also depicted root variations within sites, largely due to the possible effects of varying intensities of human disturbance on site factors and plant growth response. The extent of variations in root growth also varied across geographical areas, demonstrating the strong link between coffee genetic and climatic factors. Hence, the present findings imply the need to consider root traits in developing coffee technologies and to support sustainable management of natural forest environments.

Keywords: Ethiopian coffee diversity, coffee forest ecology, conservation and management, moisture gradients, root growth characteristics.

INTRODUCTION

The montane rainforests of Ethiopia are the known center of origin and genetic diversity for the highland arabica coffee (*Coffea arabica* L.). Arabica coffee is thus a shade adapted plant in the natural multi-strata forest ecosystems with the occurrence of wild Arabica coffee populations (Wrigley, 1988). Ethiopia is endowed with wide ecological suitability and genetic potentials for sustainable production and export of fine quality specialty coffees, while conserving healthy environments. However, the fragmented Ethiopian coffee forest area is shrinking from time to time, largely due to increasing population, land use conflict, high deforestation, expansion of large-scale coffee and tea farms, other agricultural practices and fluctuating international coffee prices (Dubale and Teketay, 2000; Gole, 2003). As a result, the known coffee types and brands are either replaced by other more profitable crops or their cultivation is expanding into less suitable areas. Bellachew and Sacko (2009) indicated that coffee genetic resources are under severe threat from genetic erosion in the centres of origin and diversity. These coupled with the increasing patterns of climate change are threatening the natural coffee gene pools (Kufa, 2010), requiring urgent measures for preserving environmental sustainability and coffee biodiversity at their country of origin and genetic diversity in Africa.

Root is the hidden growth part that is equally important to the above ground growth in the characterization and adaptation of plant species, though little used in coffee diversity. The typical root system of a mature Arabica coffee tree consists of a taproot, axial vertical roots, lateral roots, some of which are more or less parallel to the soil surface (surface plate roots) and other deeper roots that ramify evenly in the soil and sometimes become vertical, feeder bearers evenly distributed, and feeder-borne roots at all depths. The horizontal and vertical growth of coffee roots can be influenced by plant, environmental and soil factors (Wrigley, 1988; Wintgens, 2004). The soil conditions include soil texture, depth, reaction and soil moisture, corroborating with the findings of Nabati et al. (2008), which indicated decreased root length with soil moisture level. This characteristic enables it to exploit a considerable volume of land and to thus offset a relative lack of soil fertility condition. In this regard, other findings also pointed out the roles of plant nutrients on root growth characteristics in rice (Jamalomidi et al., 2006) and in tall fescue ecotypes (Rahman and Saiga, 2007). Coffee plant requires an effective depth of greater than 150 cm. Coffee trees can root deeply in a normal soil, although about 90% of the roots develop in the upper 30 cm layer. This is similar to the ristricted root depth and effect of tillage found in rice (Alam and Matin, 2002). These roots are sensitive to climatic variations (temperature, drought and moisture), but can be protected by shade and mulch (Wrigley, 1988). In Ethiopia, there are still immense genetic potentials among and within the wild types, local landraces and released arabica coffee varieties with great diversity for any desirable traits (yield, quality, disease resistance, drought tolerance, low caffeine content, etc) and wider ecological conditions. Based on the interdisciplinary research findings and recommendations of the project on the conservation and utilization of wild *Coffea arabica* populations in the montane rainforests of Ethiopia, CoCE (www.coffee.uni-bonn.de), the Yayu, Kafa and Sheka forest sites were identified and approved as UNESCO Coffee Forest Biospheres. In this regard, effectve and efficient coffee production demands the need for considering genotype by environment interactions as pointed out by Bellachew and Labouisse (2006) in the local landrace coffee variety development program. Further, the major findings, potentials, constraints and recommendations of Arabica coffee germplasm conservation were synthesized and reported by Girma et al. (2008).

The previous attempts on the characterization of arabica coffee genotypes focused on *ex-situ* assessement of the collections, mainly using yield and yield components, disease resistance and quality attributes. Again, the effect of changing climatic and soil conditions on the growth performances of arabica coffee trees, particularly on root growth is little understood under the various agro-ecologies and production systems of Ethiopia, its birth place where there are still immense coffee genetic diversity with desirable traits (yield performance, resistance to diseases and insects, unique quality standards of low caffeine conent and tolerance to drought stress). However, knowledge of below ground root growth is equally important in characterization, evaluation and identification of suitable coffee cultivars for specific geographical area. This helps in understanding the best genotype-environment relationships and targeting recomendations on management practices as implications on sustainable use and conservation of coffee genetic resources. In this study, arabica coffee trees were studied under field conditions with the objectives of comparing the variations in root growth characteristics among and within wild arabica coffee populations in the montane rainforests of Ethiopia.

MATERIALS AND METHODS

Study area

The wild arabica coffee populations in four montane rainforests, namely, Harenna, Bonga, Berhane-Kontir and Yayu, were studied between August and September 2005. These were abbreviated as: Harenna (PI), Bonga (PII), Berhane-Kontir (PIII) and Yayu (PIV). From which again, three sub-sites were selected for *in-situ* characterization of coffee root growth systems. Except Harenna in the southeast, the other coffee forest units are located in the southwestern part of Ethiopia. These are separated by the Great East African Rift Valley, which dissects the country into southeast and northwest highlands. According to Dubale and Teketay (2000), these coffee forests differ in area coverage (Harenna 15,000 ha, Bonga 5,000 ha, Berhane- Kontir 1,000 ha and Yayu 1,000 ha), physical characteristics and forest vegetation. According to Dubale and Teketay (2000), the mean annual rainfall gradients followed the decreasing order of Berhane-Kontir > Yayu > Bonga > Harenna. The

Table 1. Characteristics of the study montane rainforests in Ethiopia.

Variable	Harenna	Bonga	Berhane-Kontir	Yayu
Wereda/district	Mena-Angetu	Gimbo	Sheko	Yayu-Hurumu
Site code/symbol	PI	PII	PIII	PIV
Area coverage (ha)	15000	5000	1000	1000
Latitude (N)	6°23′ - 6°29′	7°17′ - 7°19′	7°04′ - 7°07′	8°23′
Longitude (E)	39°44′ - 39°45′	36°03′ - 36°13′	35°25′ - 35°26′	35°47′
Altitude (m a.s.l)	1420 - 1490	1520 - 1780	1040 - 1180	1400
Slope (%)	2 - 3	3 - 6	4 - 18	1 - 8
Rainfall (mm/year)	950	1700	2100	1900
Max temperature (°C)	34.4	29.9	31.4	34.7
Min temperature (°C)	10.4	8.7	13.8	7.6
Mean temperature (°C)	22.2	18.2	20.3	19.7
Minimum RH (%)	37.9	45.0	50.8	41.8
Maximum RH (%)	84.3	95.2	85.4	98.5
Mean RH (%)	63.2	80.4	68.9	80.9
Wind speed (m/h)	0.93	0.64	0.43	0.35

characteristics of the study montane rainforests were also described and they differed in climate factors and soil properties (Table 1).

The study forests are accessed and managed by indigenous communities who have been and still depend on forest resources for their livelihoods. The forest zone is often characterized by steep to gentle slopes. Beekeeping and hunting are the important activities and cultures of the local community. They are allowed to collect the non-timber forest products including the semi-domesticated wild coffee types, spices and other medicinal plants (Baah et al., 2000). The management and harvesting of wild coffee tree is carried out at different use intensities by local people who merely harvest coffee fruits with minimum forest disturbance, promoting sustainable coffee landscape and production of high quality coffees in the country (Wolde-Tsadik and Kebede, 2000).

Root measurements

From each plot, six representative mature wild coffee trees (ca. 6-year- old) were used at each forest coffee area for the *in situ* data collections on root growth parameters. Hence, a total of 24 coffee trees were sampled to characterize root growth charcateristics of the wild arabica coffee popuations in four montane rain forests of Ethiopia. In this case, the roots were carefully uprooted and intact soil removed for root growth measurements. The parameters include root fresh and dry weights, number of lateral roots, root diameter, root length and root volume were recorded for the taproot and lateral roots. Based on root thickness, the lateral roots were grouped into three broad classes of fine/small (<0.10 cm), medium (0.10 to 0.30 cm) and coarse/large (>0.30 cm) and their relative proportion was estimated from the total root growth. Finally, root fresh density was calculated from the mass and volume data. Oven-dried root samples (105°C for 24 h) were weighed using a sensetive balance and root moisture content (% vol.) was determined for the wild arabica coffee trees and populations under natural forest conditins.

Data analysis

Analysis of variance (ANOVA) in a nested design was performed to compare the variability among and within wild coffee population in root growth parameters. In this case, the average results of the four wild coffee populations, three sub-sites and coffee trees were accordingly nested under each other in that order. Moreover, one-way ANOVA in a randomized complete block design with three replications was used to examine the root growth system of coffee trees at each site. Comparison between means was carried out according to Turkey's test at $P < 0.05$, whenever the F-test declared significant differences. The data were analyzed using the default SAS system for Windows-v8 (SAS Institute Inc. Cary NC, USA), and graphs were prepared with Sigma Plot SPW9.0 (SYSTAT Software, Inc.).

RESULTS

Root growth of the spontaneously grown forest coffee trees depicted significant variations in the size and length of large/coarse lateral roots ($p < 0.01$), taproot fresh and dry weights as well as taproot volume ($p < 0.05$). The populations also exhibited significant differences ($p < 0.05$) in total root fresh and dry weights.

Table 2. Root growth parameters (mean ± SD) in wild Arabica coffee trees at the study sub-sites within each montane rainforest.

Location	Number of lateral roots				Diameter of lateral root (cm)			Length of lateral root (cm)			
	Large	Medium	Small	Total	Large	Medium	Small	Large	Medium	Small	Taproot
Harenna	NS	NS	*	NS	NS	NS	NS	NS	*	NS	NS
PIS1	9.50±0.71	14.00±4.24	33.00±2.83a	56.50±6.36	0.79±0.01	0.23±0.01	0.09±0.01	113.39±33.43	33.24± 3.53b	23.53±13.05	83.25±25.81
PIS2	8.50±3.54	11.00±4.24	20.50±0.71b	40.00±7.07	0.90±0.25	0.31±0.06	0.11±0.01	109.15±15.55	46.69± 6.30b	12.70± 1.46	85.25±16.62
PIS3	5.50±3.54	19.50±4.95	25.50±0.71b	50.50±2.12	0.72±0.06	0.32±0.03	0.11±0.01	125.57±53.12	86.98±14.44a	24.30± 0.03	114.50±10.61
Bonga	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
PIIS1	13.00±0.00	9.50±7.78	23.50±21.92	46.00±29.70	0.35±0.13	0.22±0.04	0.11±0.00	67.52±30.21	47.31±8.92	29.04±2.50	69.33±16.02
PIIS2	12.00±5.66	9.00±2.83	3.50±4.95	24.50±13.44	0.63±0.22	0.23±0.01	0.06±0.08	85.44±12.46	76.19±32.07	14.52±20.53	64.20±15.98
PIIS3	19.00±2.83	5.00±2.83	6.50±2.12	30.50±3.54	0.48±0.01	0.22±0.00	0.12±0.01	71.59±5.20	52.19±2.15	28.56±4.41	71.25±1.77
B-Kontir	*	NS	NS	NS	NS	NS	NS	NS	**	NS	NS
PIIIS1	16.00±0.00[a]	10.00±7.71	9.50±2.12	35.50±4.95	0.51±0.11	0.21±0.01	0.11±0.00	100.59±18.98	51.52±5.72[b]	31.78±4.58	70.73±3.63
PIIIS2	11.00±1.41[b]	6.50±2.12	22.50±10.61	40.00±14.14	0.52±0.08	0.23±0.04	0.13±0.02	69.17±11.43	69.68±6.39[a]	29.52±0.01	95.05±24.11
PIIIS3	13.50±0.71[ab]	8.00±7.07	10.50±10.61	32.00±16.97	0.59±0.04	0.26±0.01	0.12±0.03	91.68±9.69	70.42±8.62[a]	34.81±1.60	92.95±2.76
Yayu	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
PIVS1	11.50±2.12[ab]	15.50±4.95	48.50±12.02	75.50±14.85	0.46±0.01	0.25±0.04	0.11±0.01	80.72±13.71	54.43±6.64	27.71±0.32	129.32±100.67
PIVS2	15.00±0.00[a]	11.00±0.00	22.50±0.71	48.50±0.71	0.45±0.11	0.23±0.04	0.12±0.02	76.98±13.34	49.69±7.81	21.37±8.17	91.00±28.28
PIVS3	8.50±0.71[b]	11.00±1.41	20.00±2.83	39.50±2.12	0.42±0.06	0.20±0.03	0.11±0.02	74.35±11.73	52.34±7.87	23.79±2.13	93.60±22.49

NS = Not significant, *, ** = significant at P < 0.05 and P < 0.01, respectively. Means with the same letter(s) within a column are not significantly different from each other according to Tukey mean grouping at P = 0.05.

Again, there were significant site variations in the number of large and fine/small laterals as well as in the length of medium laterals (Table 2). The frequency of small laterals varied significantly among sub-sites. In addition, sites significantly differed in the moisture contents of taproot ($p < 0.05$) and total root ($p < 0.01$). However, the other root characteristics did not reveal significant variations among populations and sub-sites.

The coffee trees of natural forests were found to produce few axial roots that grew from the taproot downwards in all directions. These roots were restricted and predominant in the upper 20-cm soil layer and were few in number.

Within sites, no significant variations were detected in the diameter of lateral roots. There were, however, significant site variations ($p < 0.05$) in the number of large and small laterals as well as in the length of medium lateral root growth within Harenna ($p < 0.05$) and Birnahe-Kontir ($p < 0.01$) coffee trees. The results of the large lateral root count show variations among the Berhane-Kontir sites, where more average values were obtained at PIIIS1, compared to PIIIS2. At Harenna, significantly ($p < 0.05$) more fine/small roots were recorded at PIS1 (33.00 ± 2.83) as compared to the other sites (Table 2).

Although not significant, these root numbers were higher at PIVS1, where maximum growth of total laterals was also measured. No significant variations were recorded within all sites in the diameter of lateral roots for the three root growth groups (coarse, medium and fine). However, the magnitude of variation in root growth varied from location to location. Accordingly, the average values of coarse and fine laterals ranged between 0.90 ± 0.25 and 0.09 ± 0.01, 0.63 ± 0.22 and 0.22 ± 0.04, 0.59 ± 0.04 and 0.21 ± 0.01, and 0.46 ± 0.01 and 0.11 ± 0.02 cm in Harenna, Bonga, Berhane-Kontir and Yayu, respectively.

Significantly ($p < 0.05$) high frequency of coarse laterals were found in Bonga (49.4%) and

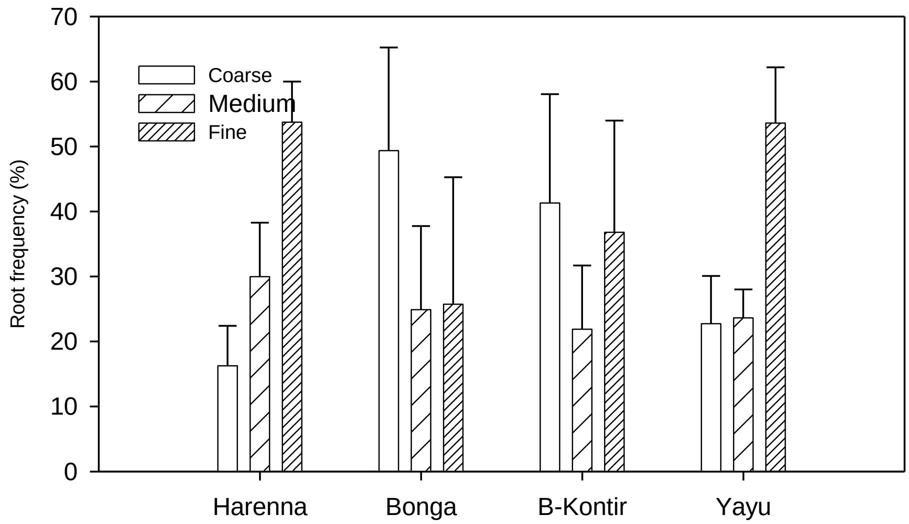

Figure 1. Frequency of coarse, medium and fine lateral roots in the wild Arabica coffee populations at the study montane rainforests of Ethiopia.

Berhane-Kontir (41.3%), whilst the proportions of fine and medium laterals were high in the Yayu and Harenna forests (Figure 1). Hence, the overall average revealed pronounced growth of lateral roots in the same coffee populations. In addition, the surface plate laterals were significantly ($p < 0.01$) thick (0.80 ± 0.09 cm) and longest (116.03 ± 8.52 cm) at Harenna and next longest (87.15 ± 16.19 cm) at Berhane-Kontir site. On the other hand, significantly ($p < 0.05$) the longest fine lateral roots (32.04 ± 2.65 cm) were measured for Berhane-Kontir as compared to others, particularly at Harenna (20.18 ± 6.49 cm) (Table 3).

Furthermore, coffee trees varied in the growth of the taproot system, which grew straight downward and produced many branches in the Berhane-Kontir forest. Accordingly, the average taproot lengths ranged from 68.26 ± 3.64 cm to 104.64 ± 21.41 cm for the Bonga and Yayu coffee trees, respectively. The next longest taproots were obtained from Harenna (94.33 ± 17.49 cm) and Berhane-Kontir (86.24 ± 13.48 cm). Consequently, these coffee trees had significantly ($p < 0.05$) high and low fresh and dry weight taproot, total roots and volume of taproots, respectively. Although insignificant, the density of laterals, taproot and total roots were high in the Harenna and low in the Bonga forest (Table 3). The frequency of small laterals varied significantly within sites. In addition, significant variations in the moisture contents of taproots were detected within the Harenna ($p < 0.05$) and Yayu ($p < 0.01$) sites (Table 4), though the other root parameters were comparable among and within coffee populations. Taproot moisture content was significant within Harenna ($p < 0.05$) and Yayu ($p < 0.01$) populations. The highest average values were recorded at PIS3 (46.19%) and PIVS1 (48.63%). Further, both lateral root fresh and dry weights were maximum at Berhane-Kontir and lowest at Yayu. And the values at Herenna and Bonga were intermediate (Figure 2).

DISCUSSION

The study showed significant variations in root growth natures among and within the wild coffee coffee populations in the natural forests of Ethiopia. There were significant within site variations in the number of large and small laterals as well as in the length of medium lateral root growth. The results of the large lateral root count showed variations within the Berhane-Kontir forest. In additions, there were significant variations between the surface and sub-surface layers and most root parameters were impaired with increased soil depth at each forest site. This may largely be associated to variations in site features (plant density, vegetation cover, soil properties and moisture gradients), genetic, climate and soil factors (Wrigley, 1988; Wintgens, 2004).

According to Edjamo et al. (1996), the diverse arabica coffee materials can be grouped into three broad canopy classes of open, intermediate and compact types with varying shoot and root growth characteristics. The uptake of water and thus the optimal soil temperature for arabica coffee was found to be between 20 and 28°C. This temperature range can be extended where mulching, irrigation and shading are practiced, because they can reduce temperature variations (Kumar, 1979). Optimum temperature of soil for root development and effective functioning of the rooting system are around 26 °C during the day and not less than 20°C during the night (Wintgens, 2004).

Furthermore, coffee trees varied in the growth of the taproot system, which grew straight downward and produced many branches in the Berhane-Kontir forest, perhaps reflecting the long-lasting imprints of site-

Table 3. Root growth characteristics (mean ± SD) of the wild Arabica coffee populations at the study montane rainforests.

Root character	Harenna	Bonga	B-Kontir	Yayu	Mean	CV (%)	ANOVA
Number of laterals							
Large/coarse	7.83±2.08	14.67±3.79	13.50±2.50	11.67±3.25	11.92	28.45	NS
Medium	14.83±4.31	7.83±2.47	8.17±1.76	12.50±2.60	10.83	27.29	NS
Small/fine	26.33±6.29	11.17±10.79	14.17±7.23	30.33±15.78	20.50	45.12	NS
Total	49.00±8.35	33.67±11.09	35.83±4.01	54.67±18.73	43.25	21.21	NS
Girth of lateral root (cm)							
Large	0.80±0.09[a]	0.48±0.14[b]	0.54±0.04[b]	0.44±0.02[b]	0.57	14.35	**
Medium	0.28±0.05	0.22±0.01	0.23±0.03	0.23±0.03	0.24	13.17	NS
Small	0.10±0.01	0.10±0.03	0.12±0.01	0.11±0.01	0.11	18.20	NS
Root length (cm)							
Large lateral	116.03±8.52[a]	74.85±9.39[b]	87.15±16.19[ab]	77.35±3.20[b]	88.85	12.88	**
Medium lateral	55.63±27.96	58.56±15.46	63.87±10.70	52.15±2.38	57.55	27.63	NS
Small lateral	20.18±6.49[b]	24.04±8.25[ab]	32.04±2.65[a]	24.29±3.20[ab]	25.13	13.20	*
Taproot	94.33±17.49	68.26±3.64	86.24±13.48	104.64±21.41	88.37	19.32	NS
Root weight (g)							
Fresh lateral	130.02±9.75	100.76±37.97	163.02±84.67	81.33±24.76	118.78	43.47	NS
Fresh taproot	396.26±89.84[ab]	244.50±46.01[b]	459.44±91.31[a]	262.25±49.56b	340.61	23.03	*
Total fresh root	526.27±99.60[b]	345.25±83.30[b]	622.46±173.46[a]	343.57±74.18[b]	459.39	26.78	*
Dry lateral root	62.03±9.87	41.26±13.19	71.64±38.90	34.58±11.37	52.38	42.83	NS
Dry taproot	223.58±57.85[ab]	126.91±11.61[b]	257.57±44.91[a]	144.25±23.83[ab]	188.08	21.40	*
Total dry root	285.61±66.40[ab]	168.17±24.76[b]	329.21±82.56[a]	178.83±35.16[ab]	240.45	24.19	*
Root volume (cm^3)							
Lateral roots	134.67±11.30	105.00±15.00	176.67±88.08	95.00±35.00	127.83	40.95	NS
Taproot	334.17±62.64[ab]	220.17±50.70[b]	386.67±77.84[a]	231.67±51.32[ab]	293.17	22.87	*
Total root	468.88±72.89	325.17±65.54	563.33±163.27	326.67±85.78	421.01	27.03	NS
Root density (g cm^{-3})							
Lateral root	0.97±0.05	0.92±0.29	0.920.03	0.86±0.080	0.92	17.64	NS
Taproot	1.21±0.11	1.13±0.02	1.19±0.01	1.15±0.04	1.17	5.44	NS
Total root	1.13±0.09	1.04±0.08	1.10±0.02	1.06±0.06	1.09	6.22	NS
Moisture content (%)							
Lateral roots	52.42±5.50	58.15±2.69	56.11±0.98	56.90±2.30	55.90	6.04	NS
Taproot	43.88±4.30	46.48±3.69	43.54±1.34	44.70±3.62	44.65	7.72	NS
Total root	46.04±4.83	50.03±4.64	46.67±1.54	47.53±3.12	47.57	8.25	NS

NS = Not significant, *, ** = significant at $P < 0.05$ and $P < 0.01$, respectively. Means with the same letter(s) within a row are not significantly different from each other according to Tukey mean grouping at P = 0.05.

specific stresses during the establishment stages. Likewise, significant variations in the moisture contents of taproots ($p < 0.05$) were detected within the Harenna and Yayu sites, reflecting the effect of site conditions largely due to the varying magnitude of management practices by the local community in manipulating the forest ecology for their livelihoods. The root hairs are found at all depths, but are most numerous near the surface of the soil and may be the main providers of mineral nutrition to the coffee plant. Similarly, the surface roots are concentrated mostly in the upper layers, while there are fewer such roots in dry and full sun-exposed coffee soils in humid heavy soils (Wintgens, 2004). In this case, root growth is to great extent influenced by climatic conditions (wind spread, temperature, humidity and turbulence) and solar radiation (Salisbury and Ross, 1992). Most of the active roots are found to be close to the trunk (within a radius of 83 to 120 cm) and at a depth of 45 to 75 cm. Studies on the seasonal distribution of functional roots of coffee also indicated that regrown

Table 4. Moisture content (% dry weight), root volume (cm^3) and dry mass (g) of lateral roots (mean ± SD) for the wild arabica coffee populations and within each montane rainforest of Ethiopia.

Population/sub-site	TRV	LRV	LRDW	TRDW	LRD	TRD	LRMC	TRMC
Harenna	Ns	Ns	Ns	Ns	Ns	Ns	Ns	*
PIS1	262.50±88.39	124.00±26.87	54.10± 11.26	158.65±57.64	0.96±0.05	1.12±0.01	54.10±2.79	46.19±2.24[a]
PIS2	361.50±210.01	133.50±9.19	58.92±0.77	242.47±97.15	1.03±0.05	1.33±0.25	56.88±0.35	46.53±0.81[a]
PIS3	378.50±51.62	146.50±65.76	73.08±33.18	269.63±35.01	0.93±0.04	1.17±0.02	46.28±2.75	38.92±0.72[b]
Bonga	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns
PIIS1	175.00±91.92	90.00±28.28	27.10±25.80	115.11±64.66	0.61±0.44	1.15±0.08	55.94±0.86	43.03±1.32
PIIS2	275.00±190.92	120.00±42.43	53.20±11.51	138.31±61.86	1.17±0.20	1.12±0.13	61.15±1.01	50.37±8.74
PIIS3	210.50±14.85	105.00±35.36	43.49±9.91	127.31±1.56	0.99±0.03	1.13±0.08	57.37±6.14	46.03±0.54
B-Kontir	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns
PIIIS1	395.00±63.64	150.00±70.71	58.70±24.89	260.42±32.94	0.92±0.00	1.19±0.01	56.95±2.12	44.24±1.34
PIIIS2	305.00±7.07	105.00±35.36	40.85±14.07	211.30±11.99	0.89±0.01	1.20±0.04	56.36±0.28	42.00±0.40
PIIIS3	460.00±183.85	275.00±120.21	115.36±51.31	300.99±118.24	0.94±0.02	1.18±0.02	55.03±0.70	44.39±2.36
Yayu	Ns	Ns	Ns	Ns	Ns	Ns	Ns	**
PIVS1	245.00±21.21	95.00±7.07	36.54±3.18	145.27±15.43	0.93±0.05	1.15±0.01	58.43±4.39	48.63±0.33[a]
PIVS2	275.00±120.21	130.00±70.71	44.85±23.49	167.55±60.85	0.77±0.08	1.11±0.11	54.25±5.77	43.97±0.74[b]
PIVS3	175.00±63.64	60.00±14.14	22.36±6.74	119.92±41.34	0.89±0.12	1.18±0.00	58.02±2.84	41.51±1.13[c]

Ns = Not significant; *P < 0.05; **P < 0.01 significance levels. Means with the same letter(s) within a column are not significantly different according to Tukey grouping at P = 0.05. Abbreviations: TRV= taproot volume, LRV = lateral root volume, LRFW = lateral root fresh weight, TRFW = tap toot fresh weight, LRDW = lateral root dry weight, TRDW = taproot dry weight, LRD = lateral root density, TRD = taproot density, LRMC and TRMC = lateral and taproot moisture content, respectively.

roots were found be to healthy and consisted of feeders, feeder-bearers and laterals (Kumar, 1979). Coffee tree can root deeply in a normal soil although about 90% of their roots develop in the upper 30 cm layer and sensitive to climatic variations. In dry sun-exposed soils, the root system is less superficial unless appropriate field management operations, including mulching are applied (Wintgens, 2004).

The growth of high proportions of fine roots at Harenna and Yayu could be due to the limited availability of soil moisture. And, the high proportion of coarse root growth at Bonga and Berhane-Kontir could be related to high rainfall and sufficient soil moisture. In addition, the high mass of lateral roots at Harenna could be an avoidance strategy to cope with drier conditions. The proportion of lateral roots of varying size followed annual precipitation gradients as described in Table 1.

Root growth was observed to occur in fruiting and non-fruiting, irrigated and non-irrigated coffee trees from the long rains to the beginning of the short rains, after which extension growth was at a slow rate (Kumar, 1979). Tips of functional roots on coffee trees with a crop had a higher uptake than those on trees without a crop, suggesting that fruiting load may stimulate the activity of roots (Wrigley, 1988). The movement of water from the soil into the roots is mainly affected by the extent to which the roots spread. The coffee tree has a limited surface area but widely spreading surface roots, and therefore has generally low rates of water uptake. This indicates that root growth response might be controlled by the soil fertility conditions and moisture regimes in the soil-plant-atmosphere continuum. This corroborates with the shoot growth of Arabica coffee materials in Ethiopia

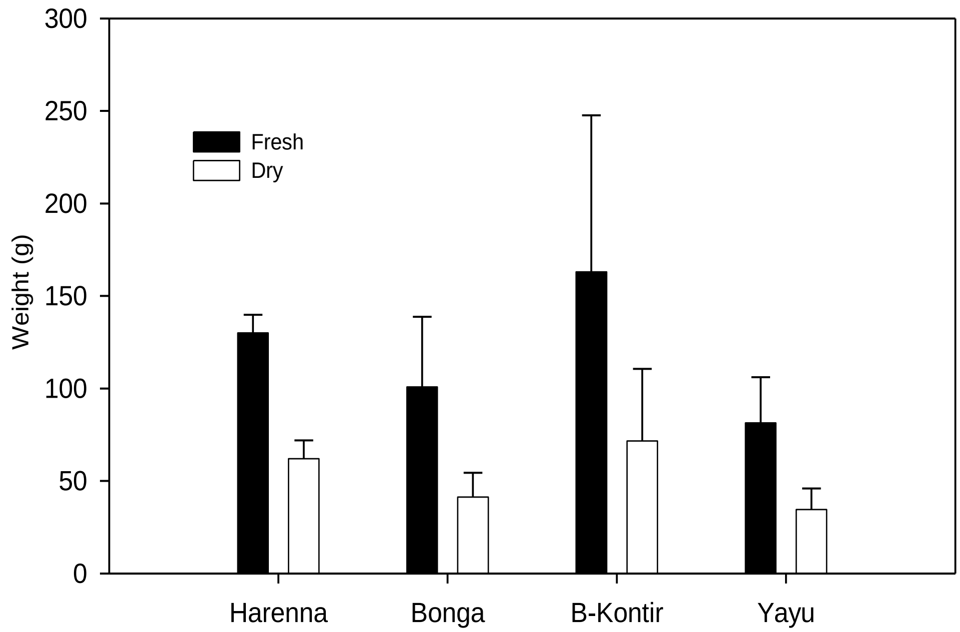

Figure 2. Fresh and dry mass of lateral roots for coffee trees of the wild Arabica coffee populations in the four montane rainforests of Ethiopia.

(Edjamo et al., 1996; Kufa et al., 2004b).

The present findings on root growth natures are in agreement with the variations in forest soil properties, notablty in the distribution of silt and soil bulk density as well as permanent wilting points and available water holding capacity. To this effect, climatic variables and soil moisture gradients were found to influence the adaptation of coffee local landraces (Kufa et al., 2004a). According to this report, the compact coffee trees have an extensive but shallow root system that gives access to the upper soil water; these trees were limited to favorable sites. In effect, root characteristics are considered to play an important role with regard to survival and better performance of coffee plant. Therefore, identification of suitable coffee types with respect to ideal root traits is essential at each specific locality. Drought-adapted plants are often characterized by deep and vigorous root systems (Wintgens, 2004). According to Daniel et al. (2004), total transpiration was high in coffee genotypes with relatively high root biomass.

The results depicted highly significant variations in the size and length of coarse lateral roots among the wild coffee populations: a high proportion of coarse lateral roots were determined in Bonga and Berhane-Kontir, while the fine and medium lateral roots were high for the coffee trees in Yayu and Harenna. Consequently, the Harenna and Yayu populations had a higher proportion of fine lateral roots than those at Bonga and Berhane-Kontir. This could serve as a drought-stress avoidance mechanism in the drier Harenna areas as reported by Burkhardt et al. (2006). The wild coffee trees were comparable in the density of laterals, taproot and total roots, though the results were high in the Harenna and low in the Bonga populations. The root moisture content, however, depicted a reverse pattern, illustrating the increased root volume mainly due to more numerous feeder bearers and feeder roots, which are responsible for water absorption. In this case, soil texture and depth of the soil are extremely important factors that affect root system considerably (Wintgens, 2004). This supports our previous results on high hydraulic conductance in Harenna coffee populations under field (Kufa and Burkhardt, 2010) and their better root growth characteristics under controlled nursery conditions (Taye and Alemseged, 2013). Hence, they can be selected as root stocks for grafting or breeding for developing drought resistance coffee cultivars.

In general, forest grown coffee trees were found to produce few axial roots that grew from the taproot downwards in all directions. These roots were few in number and restricted in the upper forest soil layer.

Likewise, significant variations were noted between the surface and sub-surface soils of the four forests. Similarly, the plant density followed the descending order of Bonga > Yayu > Birhane-Kontir > Harenna forest, largely reflecting the variations in vegetation cover due to management levels as elaborated by Gole (2003). This could also be explained in terms of the adequate availability of soil moisture and plant nutrients in the forest ecosystem, indicating their high vulnerability to anthropogenic impacts, coupled with the possible adverse impacts of climate change and variability (Taye and Burkardt, 2011). Nonetheless, environmental, social and economical sustainability aspects of the remaining fragmented natural wild coffee forests in Ethiopia need to be studied. In this regard, Bellachew and Sacko (2009) and Kufa (2010) also emphasized on the severity of human disturbance threats and underlined the need for urgent characterization and conservation measures of coffee genetic resources for future development of the coffee sector worldwide.

CONCLUSION AND IMPLICATIONS

The study still indicates the strong relationships between coffee genetic and environmental factors in detecting root growth in shade grown mature coffee trees. It provides insight into the use of the hidden root growth part in characterizing and identifying ideal genotype environment interactions. The findings shade a light, at a small measure, in understanding the underlying adaptation and mitigation mechanisms and identifying suitable coffee genotypes and appropriate management options. In light of the disturbance of natural coffee forest habitats due to human induced factors and aggravated changing climate conditions, the study would contribute towards promoting sustainable preservation of natural coffee habitats. The findings also demonstrate the practical implications for a multi-site *in-situ* management and utilization of Arabica coffee genetic resources at their place of origin in natural rainforests for global benefits. It is, however, imperative to generate information, among others, on ecological, physiological and molecular attributes and applying appropriate field management operations, including shade regulation, soil conservation and irrigation schemes as well as developing drought tolerant Arabica coffee genotypes in the present local landrace coffee technology development strategy in Ethiopia.

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