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Plant composition and growth of wild *Coffea arabica*: Implications for management and conservation of natural forest resources

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The montane rainforests of Ethiopia are the only places of origin and genetic diversity for *Coffea arabica* species. These natural forest areas with the occurrence of wild coffee gene pools are however under constant threats, largely due to anthropogenic activities. The study aims to determine the variability in plant compositions and growth of wild *Coffea arabica* trees in the natural forests of southeastern and Southwestern Ethiopia. The data were collected at twelve study sites. The dominant plants were broadly classified into three forest canopy strata with varying vegetation coverage among and within the study forests. The average abundance of large shade trees, wild coffee plants and shrubs was highest at Berhane-Kontir, Yayu and Bonga natural forests, respectively. The frequency of the respective plant forms was highest at Birhane-Kontir (61%), Harenna (53%) and Bonga (68%). The occurrence of the semi-domesticated spices crops was higher in the Bonga and Berhane-Kontir forests. The average plant density followed the descending order of Bonga>Yayu>Birhane-Kontir>Harenna forest, largely reflecting anthropogenic impacts. There was negative association between the growth of the coffee trees and the undergrowth shrubs. In contrast, the upper canopy large trees and coffee plants had direct relationships. However, the vegetative and reproductive growth responses of wild coffee plants were impaired, partly due to the multiple stresses in the dense forest ecology. Consequently, more than 70% of the total surface area of coffee trees did not bear crops and altogether coffee yield was low. The highest and lowest reproductive efficiencies were obtained from the Harenna and Yayu wild coffee populations, demonstrating the levels of coffee forest management practices. Overall, our findings indicated great variations in the patterns of plant co-existences and growth natures of wild coffee trees and underlines in multiple benefits of coffee forest environments, among others, as natural coffee gene pools. This depicts the need for multi-site *in situ* conservation and environmental management planning for sustaining biodiversity conservation and maintaining ecosystem goods and services in Ethiopia and worldwide.

Key words: Biodiversity, Ethiopian wild coffee, genetic conservation, natural coffee forest, plant composition.

INTRODUCTION

Coffee belongs to the genus *Coffea*, in the Rubiaceae family. There are about 103 species of genus *Coffea*, all exclusively restricted to the tropical forests of Africa, Madagascar and Islands of the Indian Ocean (Mascarene Islands). Of all the species, only two (*Coffea arabica* L. and *Coffea canephora* Pierre ex Froehn) have commercial value in the world coffee industry. *Coffea arabica* is the only species occurring in Ethiopia and is geographically isolated from the rest of the *Coffea* species. It is naturally restricted to two isolated mountain forests on the western and eastern sides of the Great Rift Valley in Southern Ethiopia (Wrigley, 1988, Wintgens, 2004). Thus, the montane rainforest areas in Ethiopia are

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the only known center of origin and genetic diversity for the highland arabica coffee. In its original forest habitat, coffee occurs in the multi-strata of forest ecosystems and thus it is a shade loving plant. Its response to light has caused it to be traditionally considered a heliophobic plant requiring high, somewhat dense cover in a plantation. Today, the cultivation of coffee in open sun is not uncommon in most coffee producing countries, though its sustainability is questionable. It is known that coffee trees with high productivity potential are capable of high yields when they are cultivated intensively without shade (Chaves et al., 2008).

Although arabica coffee is said to be a shade-loving plant with greater quantum utilization efficiency for photosynthesis, excessive shading or light interception by the upper two to three canopy strata of various tree species would decrease growth and productivity of the crop, as the plant spends much of its photosynthetic activities for maintenance. On the other side, if the light intensity is too high, there will be inadequate reaction centers in the leaves of the crop to accommodate the light energy and convert it into biochemical energy. As a result, the coffee trees excessively photo-respires and eventually most of the stored carbohydrates become depleted. Consequently, the trees may suffer from serious dieback mostly due to excessive fruit load via enhanced flowering in full sunlight compared to shade conditions and coffee production limitations and coffee shade interactions (Beer et al., 1998; DaMatta et al., 2004). Besides, excessive evapo-transpiration and severe drought stress, death of actively growing shoot parts, seasonal crinkling of leaves, frost damage and subsequent yield reduction are common problems observed in unshaded coffee orchards (Franck et al., 2006; Chaves et al., 2008).

Ethiopia has been and still the heartland of the finest quality highland Arabica coffee. But, most coffee farmers have replaced coffee by other high priority monoculture crops and/or there has been a shift in coffee cultivation from productive to marginal sites. Regional climatic change and drought is becoming major problems for the existence of Arabica coffee gene pools. Drought stress at critical growth stages can result in its poor growth and development, aggravating the genetic erosion of local coffee landraces. However, there are still immense diversities among and within the wild and cultivated arabica coffees at each coffee zone of the country. According to Dullo et al. (1998) and Bellachew and Labouisse (2006), there are about 21,407 coffee germplasm in the different field gene banks of some African countries, of which around 89.85% is arabica coffee, which is restricted in Ethiopia. This corroborates with the reports of Surendra (2008), which indicated that Ethiopia alone possesses around 99.8% of the world total arabica's genetic diversity. Up to now, a total of about 11,691 arabica coffee germplasm accessions have been collected from the different areas and conserved *ex-situ* at different field gene banks in Ethiopia (Taye, 2010). In natural coffee forest environments, limitation of single resource is uncommon and coffee plants must simultaneously cope with a range of sub-optimal environmental resources. The inherent growth of coffee is affected by several factors, including drought, temperature, photoperiod, water logging and leaching of nitrates by high rainfall. The major climatic factors include temperature, water, light and wind (Wrigley, 1988).

In Ethiopia, the natural forest areas with the occurrence of precious natural resources, including the wild *C. arabica* gene pools are, however, under serious challenges of loss, largely due to anthropogenic impacts. The destruction of the original forest habitat threatens not only the coffee genetic diversity, but also endangers the exceptional floristic diversity of these forests (Paulos and Demel, 2000). However, there are still diverse wild coffee populations co-occurring with other plants in the natural forest ecosystems by adapting the various biotic and abiotic pressures (Taye, 2006). Hence, it is imperative to conserve the precious natural resources and environments by implementing sustainable conservation, management and utilization of maximum biodiversity, quality environmental goods and services. Cognizant of the importance of coffee, its high genetic erosion in the centers of origin and minimal conservation efforts, Bellachew and Sacko (2009) emphasized the need for immediate conservation measures to safeguard the sustainability of the global coffee industry. For this, knowledge on the adaptation and mitigation mechanisms of wild arabica coffee populations under diverse agro-ecologies is highly required for planning efficient and effective exploitations of coffee diversity (Girma et al., 2008). Hence, information on biophysical features, plant interaction and distribution, description and economic importance of the useful plant species are lacking in the different coffee production systems and coffee zones. This study, therefore, primarily seeks to assess the variations in plant composition and growth characteristics of wild Arabica coffee populations under natural forest environments. This would contribute, *inter alias,* for designing sustainable natural resources management options with a particular focus on the conservation and use of the Ethiopian wild coffee gene pools and its natural forest environments.

MATERIALS AND METHODS

Study area

The study was carried out in 2004/05 at the montane rainforests of southeastern and Southwestern Ethiopia with the occurrence of various plant species, including the wild *C. arabica* genetic resources. The four study forests are among the potential natural forest coffees identified with the primary objective of *in-situ* conservation of the genetic diversity of forest coffee plants in particular and the associated flora and fauna in general (Paulos and Demel, 2000). They are geographically distant and represent the

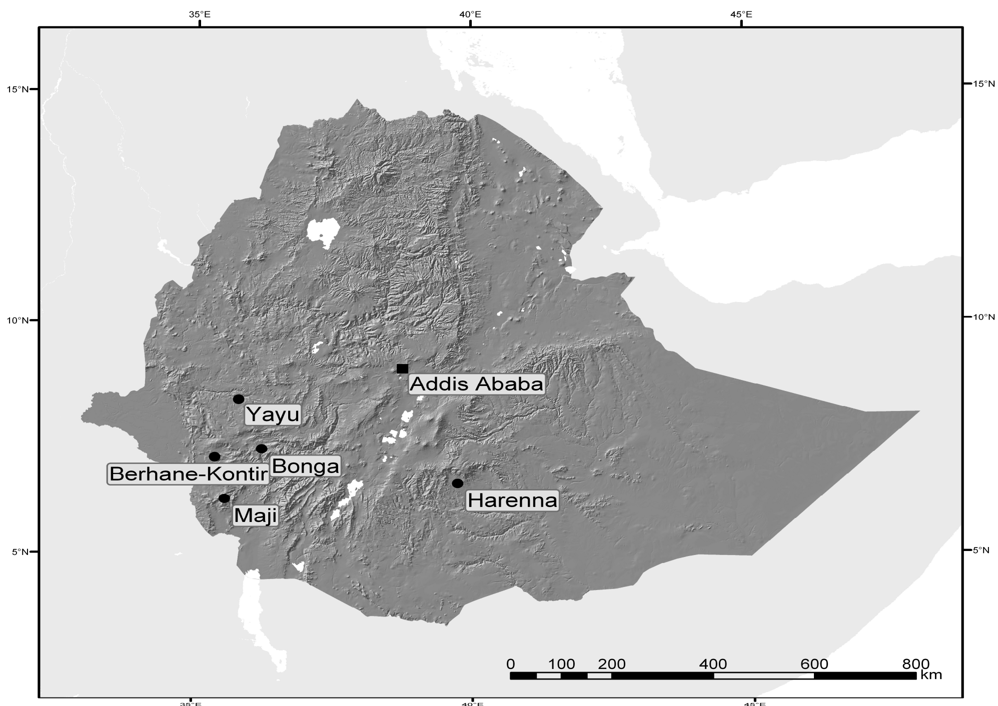

Figure 1. Map of Ethiopia and location of the studied montane rainforests (Harenna, Bonga, Berhane-Kontir and Yayu).

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

Variable	Harenna	Bonga	Berhane-Kontir	Yayu
District	Mena-Angetu	Gimbo	Sheko	Yayu-Hurumu
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^{-1})	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^{-1})	0.93	0.64	0.43	0.35

climate gradients of the remaining fragmented and undisturbed high mountain rainforests of the country with wild coffee populations. The study forest areas include Harenna, Bonga, Berhane-Kontir and Yayu. These forests differ in area coverage (Harenna = 15000 ha, Bonga = 5000 ha, Berhane-Kontir = 1000 ha and Yayu = 1000 ha), agro-ecological zone, physical characteristics and forest vegetation (Paulos and Demel 2000).

They are separated by the Great East African Rift Valley, which dissects the country into southeast and northwest highlands and represents a climate gradient (Figure 1). Except Harenna in the southeastern, the other forests are located in the southwestern Ethiopia. The climate gradient varies from southwest to southeast Ethiopia. The rainfall follow the decreasing order of Berhane-Kontir > Yayu > Bonga > Harenna with the average annual precipitation of 2200, 1800, 1700 and 1000 mm and average air temperatures of 18, 18, 22 and 21°C, respectively (Paulos and Demel, 2000). The dominant soil groups (FAO/UNESCO) are Nitisols, Acrisols and Vertisols, the most common being Nitisols. This is clayey and reddish brown in color with moderate to high CEC (cation exchange capacity), high soil organic matter and total nitrogen content, limited available phosphorus (Murphy, 1968) with medium to strong soil acidity. According to Taye (2006), forest soils were determined to have a clay texture, though Yayu soils had a high proportion of sand. He also described the characteristics (Table 1) of the study montane rainforests.

With regard to conservation of the natural forests, they are accessed and managed by indigenous local communities who have been and still depend on the forest resources for their livelihoods. The local communities living in and around the forest mainly derive their livelihoods from coffee forests which are the source of timber and non-timber forest products like honey, spices, wild food, medicine etc (Feyera, 2006), though human-induced forest losses are still the major threats to forest resources. Beekeeping and hunting are the important activities and cultures of the local people, demonstrating the need to promote sound marketing and ecotourism systems. They are allowed to collect the non-timber forest products including the semi-domesticated wild coffee, spices and other medicinal plants (Baah et al., 2000). The harvesting of wild coffee is carried out at different use intensities by local people who merely harvest coffee fruits with minimum forest disturbance, representing the forest coffee production system. In the semi-forest coffee system, there are more human interventions to systematically remove the dense shading and undergrowth weeds, largely to facilitate coffee harvesting (Workafes and Kassu, 2000).

Data collection

Plant composition

The dominant plants were recorded in each forest site using quadrants of 40 × 40 m for upper canopy big tree layer and of 20 × 20 m for middle strata trees and 5 × 5 m for lower canopy shrubs. The quadrants were nested within each other based on their size and used to determine the variations in plant compositions. In here, plant sampling was systematically carried out in each quadrant that distributed along transects as described by Tadesse (2003). Three quadrants were identified along transects at each natural forest and three plots were placed at each site to determine plant composition within a quadrant. Hence, a total of 36 quadrants and 108 plots were sampled to represent the study forests.

The total plants were broadly grouped into three forest canopy strata: Upper canopy large trees (>15 m height), coffee trees occupying lower to middle canopy strata (5 to 15 m height) and small shrubs (2 to 5 m height), largely the indigenous spices crops at the lower stratum as used by Feyera (2006). The indigenous upper canopy layer involved different big trees species, mostly evergreen, broadleaved and deciduous types. Plant density represents the total number of plants per plot. Additionally, the distance between the wild coffee trees was measured on a plot basis to estimate the patterns of coffee spacing in the dense forest environments.

Growth characteristics of coffee tree

At each site, nine to twelve wild arabica coffee trees were sampled for measurements on morphological and agronomic characters of the wild arabica coffee trees. This was performed by systematically selecting the representative coffee trees with both vegetative and reproductive growths. For this, uniform coffee plants of about six-year- old were used from three replications at each site. The age of coffee trees was estimated by counting the number of nodes on the main stem. Again, six primary branches per coffee tree were selected for data collection on growth parameters as per the standard procedures (Yacob et al., 1996). The studied growth characters include plant height, stem diameter, canopy size, number of primary branches, number of nodes, internode length, leaf and fruit growth. The relative proportions of old, cropping and young growth were determined on the main stem axis of the tree and primary branches.

In addition, healthy and mature leaf samples were collected from the third to fourth nodes on primary branches. Leaf dimensions (maximum length and width) were measured and the intact leaf area was estimated using a coefficient (K = 0.66) developed for Arabica coffee (Yacob et al., 1993). The leaves were oven dried at 70°C for 24 h and the dry weight was measured using a sensitive balance. Then, estimated leaf area to leaf dry matter ratio, specific leaf area (SLA) and its inverse, and specific leaf mass (SLM) were calculated. According to Larcher (2003), water storage is a mechanism for desiccation avoidance and is most effective, when it is coupled with surface reduction and high transpiration resistance of the epidermis. Such a measure of storage capacity is given by the degree of succulence using the formula: Degree of succulence (g cm^{-2}) = water content at saturation per surface area. Besides, hundred seed weight per tree was recorded and thirty green coffee beans per plot were also used to measure seed dimensions (length, width and depth) using a calliper to characterize coffee seed according to Alemseged et al. (1997). The ripe red cherries were harvested from the selected coffee trees per plot and converted into clean coffee yield by multiplying this by 0.166 as described by Yacob et al. (1996).

Data analysis

The frequency of each plant group was computed on each quadrant as the ratio of absolute frequency of a species to the total number of plots multiplied by 100, while abundance represents the number of individual plants. Analysis of variance was computed in a nested design of three replicates to see the variations in the plant parameters considered in the forest ecology. Comparison between means was carried out according to Tukey test at $P = 0.05$, whenever the F-test declared significant differences. Furthermore, regression analysis was performed using the SAS system for Windows-v8 (SAS Institute Inc. Cary NC, USA) to examine the relationships between the major plant growth forms in natural forests and graphs were prepared with SigmaPlot SPW9.0 (SYSTAT Software, Inc.).

RESULTS

Plant composition

The results showed variations in plant composition at the study montane rainforests with three broad canopy strata of upper, middle and lower layer consisting of the large trees, wild coffee plants and shrubs, respectively. The results showed that plant density and coffee spacing were also different across localities. Accordingly, the average abundance value of large trees, wild coffee plants and shrubs was highest at Birhane-Kontir, Yayu and Bonga natural forests, respectively. The frequency of the respective plant forms was highest at Birhane-Kontir (61%), Harenna (53%) and Bonga (68%) forests (Table 2). The frequency of the remnant indigenous upper canopy large trees was higher in the Berhane-Kontir and Herenna forests. In contrary, the lowest (13 %) value was noted at Bonga. The average plant density, however, followed the descending order of Bonga>Yayu>Birhane-Kontir>Harenna forest. At most forest sites, the frequency of the economically valuable upper canopy large coffee shade trees (e.g., *Cordia africana*) was lower than that of others (e.g., *Croton macostachyus*).

The maximum abundance values of wild coffee trees were highest at Harenna, Bonga, Berhane-Kontir and Yayu forests in that order (Table 2). The average value

Table 2. Plant populations and forest structure as well as spacing of wild coffee trees in the montane rainforests of Ethiopia.

Plant parameter	Growth form	Value	Harenna	Bonga	B-Kontir	Yayu
		Min.	7	5	6	11
	Large tree	Max.	10	17	23	14
		Aver.	8	10	17	13
		Min.	7	12	5	13
	Wild coffee	Max.	19	18	15	39
		Aver.	14	15	8	26
Abundance/plot						
		Min.	2	36	0	27
	Shrub	Max.	4	62	7	38
		Aver.	3	53	2	32
		Min.	17	56	11	58
	Plant density	Max.	31	96	38	79
		Aver.	25	78	28	71
		Min.	27	6	55	15
	Large tree	Max.	47	18	66	24
		Aver.	35	13	61	19
		Min.	41	18	14	22
Frequency (%)	Wild coffee	Max.	61	21	45	49
		Aver.	53	19	33	35
		Min.	7	63	0	34
	Shrub	Max.	15	76	20	54
		Aver.	11	68	7	46
		Min.	21	18	19	22
Wild coffee spacing (cm)		Max.	390	315	272	202
		Aver.	317	241	244	174

was lowest at Bonga and highest at Harenna forests (Figure 2). On the other hand, the population of shrubs was lowest in Berhane-Kontir and Harenna as opposed to the Bonga and Yayu forests. The wild coffee trees were irregularly grown with the average intra-spacing ranging from 174 to 317 cm at Yayu and Harenna forests, respectively (Table 2). The vegetation composition also differed from site to site. In contrast to the positive association pattern between the big upper canopy and wild coffee trees, there was a significant indirect relationship between the coffee trees and the shrubs in the less disturbed coffee forest environment (Figure 3).

Growth of wild coffee tree

The results depicted that the growth characteristics of wild coffee trees in shoot system with varying ages was significantly ($P<0.05$) different among the four montane rainforests. The selected coffee plants were relatively younger (ca. 5 to 6 year old) and the results revealed comparable growth response in plant height and relatively tall and short coffee trees were obtained from the Harenna and Berhane-Kontir forests, respectively. The main stem diameter at five centimeters above ground level was high for the Berhane-Kontir (3.35 cm) and Harenna (3.22 cm) as compared to the Bonga and Yayu coffee trees. In addition, stem diameter at a breast height (DBH) ranged from 1.61 to 2.12 cm for Yayu and Harenna wild coffee populations, respectively. Furthermore, the widest canopy spread (206.33 cm) and longest internode length (8.21 cm) was recorded Harenna forests as opposed to the compact Yayu coffee trees with a maximum number of nodes and shortest

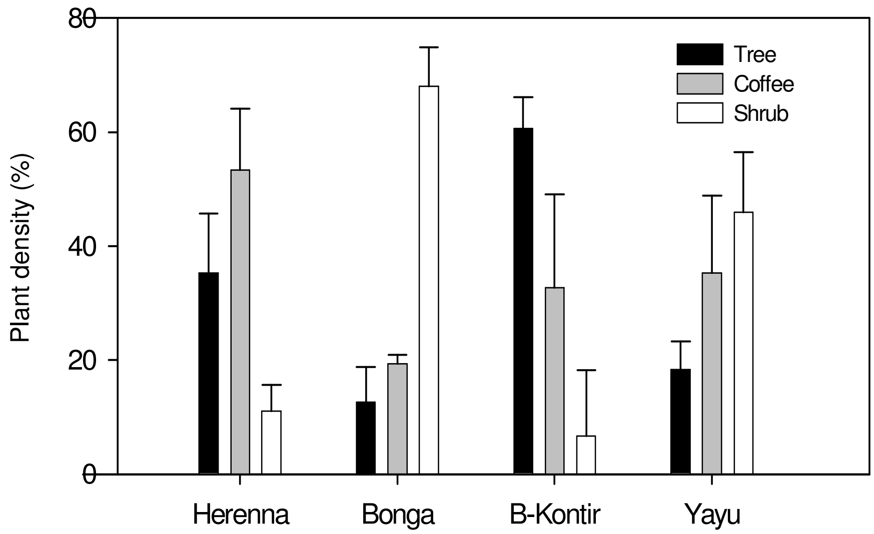

Figure 2. Relative density of the dominant plants in the montane rainforests of Ethiopia (bars represent standard deviations).

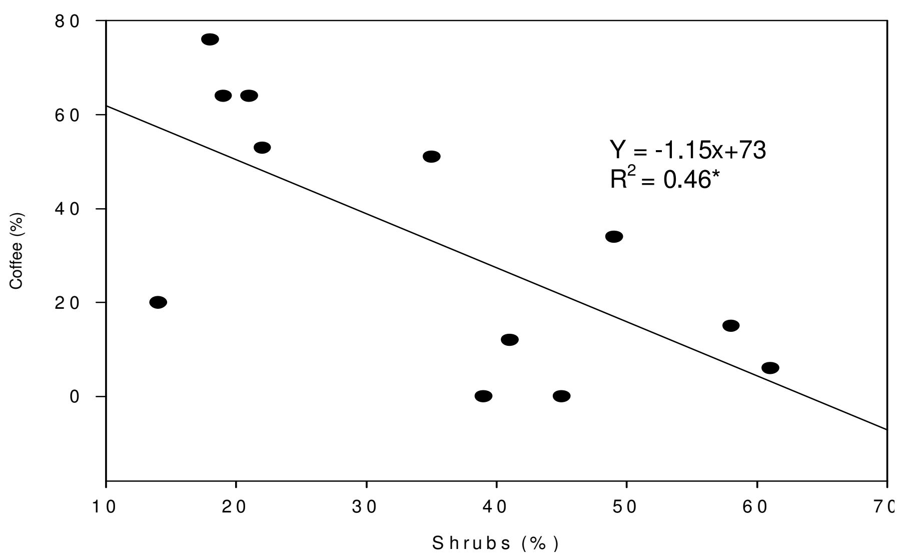

Figure 3. Relationship between the proportion of coffee trees and shrubs in the montane rainforests of Ethiopia (n = 12).

internode growths (Table 3). The reproductive performance of forest coffee trees depicted significant variations ($P<0.05$) among the coffee populations. Consequently, the proportion of crop-bearing surface area was significantly higher in the Harenna and Berhane-Kontir as compared to Yayu and Bonga forests (Figure 4). At Yayu forest, significantly ($P<0.05$) maximum non-productive and old growth was enhanced, primarily due to the adverse effects of deep canopy cover and high plant populations (Table 2). But, insignificant variations were observed in the young branch growth, although it was slightly reduced at the drier Harenna forest areas. With regard to leaf growth, maximum leaf number was recorded under relatively moderate shade levels and wide coffee spacing at all sites. The highest leaf number was obtained at Bonga (Table 4). The intact estimated leaf area was high for Harenna, followed by Berhane-Kontir and Bonga coffee types. In contrast, the smallest leaf area was measured for the Yayu coffees (Table 4).

Moreover, significant ($P<0.05$) difference in the number of fruits and cherry yields were obtained within Bonga sites, though the results did not differ at the other sites. The lowest coffee fruit and leaf number were noticed from

Table 3. Growth characteristics (mean ±SD) of *C. arabica* populations in montane rainforests of Ethiopia.

Growth parameter	Harenna	Bonga	B-Kontir	Yayu	Mean	CV (%)	Pr>F
Plant height (cm)	335.17±35.91	284.33±11.36	275.83±28.02	289.83±19.62	296.29	8.56	Ns
Stem diameter, ground (cm)	3.22±0.30	2.79±0.31	3.35±0.28	2.84±0.08	3.05	9.50	Ns
Stem diameter, DBH (cm)	2.12±0.29	1.94±0.38	1.81±0.11	1.61±0.31	1.87	17.48	Ns
Canopy spread (cm)	206.33±25.32	164.50±13.31	158.83±24.96	166.67±25.87	174.08	14.04	Ns
Number of nodes	41.00±3.28	37.83±5.20	41.17±10.12	45.50±9.12	41.38	17.20	Ns
Internode length (cm)	8.21±0.43	7.66±0.89	6.97±1.28	6.50±1.06	7.34	13.59	Ns
Number of primary branches	34.67±3.06	36.17±5.69	27.00±7.55	29.00±4.50	31.71	19.10	Ns
Old nodes (%)	70.35±9.46	71.00±6.20	72.26±1.56	79.61±9.86	73.31	10.12	Ns
Crop nodes (%)	18.63±5.71a	14.03±2.68ab	16.72±8.66a	2.85±4.93b	13.06	51.51	*
Young nodes (%)	11.03±4.14	14.98±3.54	11.02±9.55	17.55±5.09	13.65	35.80	Ns
Old stem length (%)	74.01±3.86b	74.05±5.83b	79.69±0.73ab	87.30±5.70a	78.76	5.30	*
Crop stems length (%)	18.72±4.81a	14.33±2.87ab	12.76±6.36ab	1.86±3.22b	11.92	43.76	*
Young stem length (%)	7.28±2.49	11.63±3.15	7.56±6.48	10.84±2.75	9.33	33.85	Ns
Old branches (%)	37.83±18.75b	41.21±4.42ab	36.46±5.01b	66.55±4.72a	45.51	20.76	*
Crop branches (%)	42.48±11.43a	33.75±3.66ab	41.19±16.33a	3.70±6.41b	30.28	39.3	*
Young branches (%)	19.69±7.35	25.04±0.81	22.35±19.49	29.76±6.15	24.21	45.36	Ns

Ns = Not significant (P>0.05); * significant at P<0.05 probability level. Mean figures followed by the same letter(s) within a row are not significantly different from each other according to Tukey grouping at P = 0.05.

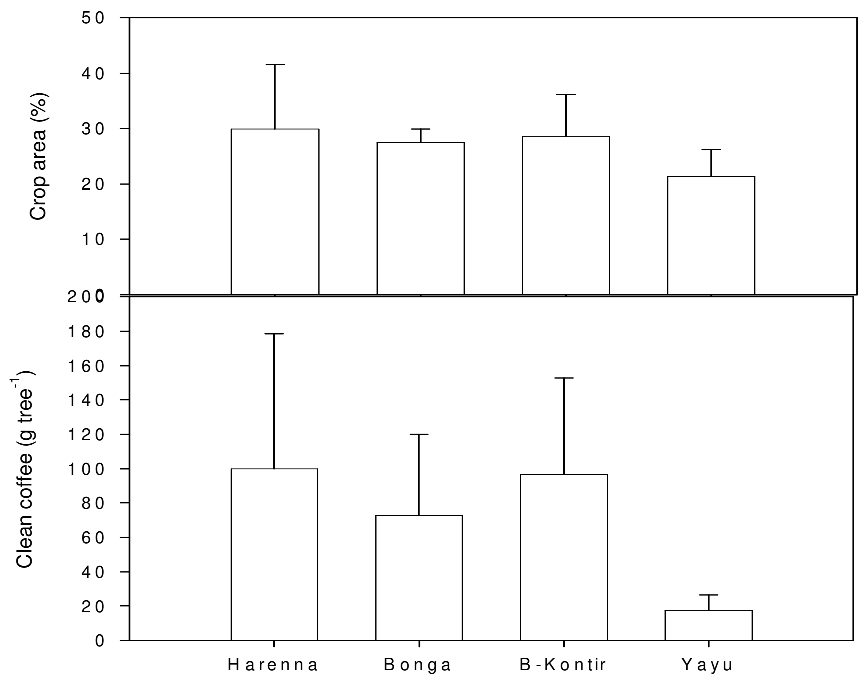

Figure 4. Variations in proportion of crop bearing area on main stem and clean coffee yield of the wild Arabica coffee trees at the four montane rainforests.

coffee trees grown under deep shade conditions. In contrast, the highest average clean coffee yields were obtained at Harenna and Birhane-Kontir, whereas Yayu had the lowest yield performance (Table 5, Figure 4) But, coffee yield levels on hectare bases were low at most sites with increased density of coffee trees and over head shading. On the other hand, maximum average coffee seed weight was recorded for Harenna, Yayu, Bonga and Berhane-Kontir wild coffee populations in that order (Table 5). At all natural forests, growth of unmanageable single stemmed tall coffee trees were favored and more than 70% of the total height did not carry fruits, largely

Table 4. Leaf characteristics of wild *C. arabica* populations in the montane rainforests of Ethiopia.

Parameter	Harenna	Bonga	B-Kontir	Yayu	Mean	CV (%)	Pr>F
LN	12.00±3.33	11.06±0.34	13.83±2.09	16.28±4.26	13.29	24.84	Ns
LL (cm)	11.97±0.54	10.59±1.71	10.79±0.83	9.97±0.43	10.83	6.57	Ns
LW (cm)	5.30±0.34a	4.40±0.78ab	4.19±0.44b	3.99±0.05b	4.47	8.32	*
MLA (cm^2)	42.42±4.61a	31.90±11.06ab	30.32±5.52ab	26.77±0.73b	32.85	14.66	*
TLA (cm^2)	504.17±298.65	347.73±170.07	424.68±222.76	419.45±215.33	424.01	3.47	Ns
LFW (g)	14.22±2.77	10.09±2.44	11.01±2.83	11.92±3.35	11.81	25.06	Ns
LDW (g)	3.57±0.92	2.80±0.72	2.82±0.72	3.02±0.84	3.05	27.30	Ns
LWC (%)	75.18±2.53	72.55±1.35	74.24±0.79	74.89±0.37	74.21	2.2	Ns
SLA (cm^2g^{-1})	150.79±6.55	124.98±9.42	151.78±7.57	140.83±14.30	142.09	7.37	Ns
SLM (g cm^{-2})	0.007±0.001b	0.008±0.001a	0.007±0.01b	0.007±0.001b	0.008	3.85	*
DS (g cm^{-2})	0.35±0.18	0.33±0.11	0.36±0.17	0.46±0.22	0.37	46.54	Ns

Ns: Not significant (P>0.05); *P<0.05. Means followed by the same letter(s) within a row are not significantly different (Tukey test at P = 0.05). Abbreviations: LN, Leaf number; LL, leaf length, LW, leaf width, MLA, mean leaf area, TLA, total leaf area, LFW, leaf fresh weight, LDW, leaf dry weight, LWC, leaf water content, SLA , specific leaf area, SLM, specific leaf mass, DS, degree of succulence.

Table 5. Yield and yield components of forest coffee trees at the study montane rainforests of Ethiopia

Bean character	Harenna	Bonga	B-Kontir	Yayu	Mean	CV (%)	Pr>F
Length (cm)	1.12±0.02a	0.92±0.06b	0.99±0.05ab	1.06±0.02a	1.02	4.39	**
Width (cm)	0.66±0.03	0.63±0.04	0.64±0.02	0.68±0.06	0.65	4.70	Ns
Thickness (cm)	0.43±0.01	0.41±0.02	0.41±0.02	0.43±0.02	0.42	3.89	Ns
Volume (cm^3)	0.32±0.02	0.24±0.04	0.26±0.03	0.31±0.04	0.28	11.21	Ns
Weight (g)	0.20±0.01a	0.16±0.02b	0.15±0.01b	0.18±0.02ab	0.17	7.44	*
Density (g.cm^{-3})	0.61±0.03	0.66±0.04	0.56±0.05	0.56±0.03	0.60	5.51	Ns

Ns: Not significant (P>0.05); * P<0.05; ** P<0.01 significant levels. Means followed by the same letter(s) within a row are not significantly different (Tukey test at P = 0.05).

due to the inhibition effect of climatic stresses including limited light interception. As a result, the lowest (21.4 %) and highest (30.0 %) crop bearing surface area were noted from Yayu and Harenna populations, respectively (Figure 4).

DISCUSSION

The natural forests differed in the pattern of plant associations and compositions. This could come due to the geographical position and the altitude range that can lead to different climate gradients and thus variations in the patterns of vegetation covers. The forests were characterized by broad-leaved forest with dominant upper canopy large tree species. The undergrowths included the wild coffee plants and small shrubs at the middle and lower forest canopy strata. The maximum abundance values of wild coffee trees were highest at Harenna and Bonga as opposed to the Berhane-Kontir and Yayu coffee forests. These represent the semi-forest coffees with varying intensities of human interference in managing the wild coffees in the natural forests as described by Workafes and Kassu (2000).

In addition, the correlation between the most abundant plant forms was significantly different in the four studied forests where the frequency of coffee was negatively correlated with that of shrubs, and thus not compatible. The result showed indirect relationship between the coffee trees and shrubs in natural coffee forests, particularly at Harenna and Berhane-Kontir forests. These differences in the regeneration and adaptation capacities might be explained by the competition effects between forest coffee trees and shrubs with the same plant growth forms in the coffee forest environments. This concurs with the findings of Feyera (2006).

The wild Arabica coffee trees were found to regenerate from the self-sown seeds with little or no care at the early-stages in the less managed forest habitat. The height of coffee trees was noted to be tall and unmanageable in size at all locations. This is quite in line with Feyera (2006) who reports an indirect correlation between the abundance and species richness in the natural forests of Ethiopia. This depicts that the growth response of wild coffee populations could demonstrate their mechanisms of adaptation and practical implication of managing tree architecture vis-à-vis availability of natural resources. Nevertheless, overall growth, yield, quality performances and disease tolerance of the wild and semi-domesticated coffee types under heterogeneous forest environments and agro-ecological coffee zones remain to be investigated.

On the other hand, the number of the shrubs was lowest in Berhane-Kontir and Harenna as compared to the Bonga and Yayu forests. The shrubs represent the semi-domesticated spices crops including *Aframonium corrorima, Curcuma domestica, Zingiber offocinale, Piper capense* and *Piper guineense* are found to co-exist with wild coffee trees in the natural forests, especially in Bonga and Berhane-Kontir (Taye, 2006). The spices were found to co-exist with wild arabica coffee trees, mainly in the Bonga and Berhane-Kontir forests. It was also not uncommon to find *Rhamnus prinoides*, a major ingredient of local drinks (*tela and tej-honey wine*) and other medicinal plants and non-timber forest products in the study forests. In this regard, Vaast et al. (2007) describes the biophysical interactions between timber and coffee trees in ideal agroforestry system. Hence, ecological suitability, farmers' priority and the level of management inputs could be among the possible reasons for the changes in the dominance of different plant species and stand structure in the study areas.

According to other authors (Tadesse, 2003; Feyera, 2006), the vegetation cover declines primarily due to population pressure and expansion of commercial tea and coffee farms around the Bonga and Birhane-Kontir forests. Furthermore, most farmers are also interested in opening up the forest cover for cultivation of food crops, indicating the limited awareness of climate change and loss of genetic resources. Nonetheless, a related study on the analysis of the long- and short-term meteorological records clearly indicates a decreasing trend in rainfall amount and distribution as well as increasing air temperature at the four study areas (Taye, 2006).

In this regard, Tadesse (2003) pointed out the impacts of human use and ecological factors in changing the biodiversity of the Afromontane rainforests. According to Taye (2006), there is a seasonal change in crop and non-crop proportions on coffee trees, where the lowest crop surface area was found during the spring/summer season. This could mainly be due to the varying seasonal availability of the natural resources to favor young vegetative growths across the study sites (Taye, 2006). This is in agreement with other authors (Silva et al., 2004; Chaves et al., 2008) who reported seasonal growth changes in Arabica coffee trees. In Ethiopia, more studies are required on the dynamic functioning of the forest ecosystems and their potential contributions to the coffee sector internationally.

The highest number of lateral branches could be attributed to the low plant density within the forest habitat. This was in contrast to the un-topped long and thin stem coffee trees with little or no cropping branches at the other sites. Because farmers at Berhane-Kontir remove young growing tips to prepare the favorite local drink called '*chemo'*. It is a home-made drink popular among coffee growing communities in the Bench and Sheko districts, Southern Ethiopia. This was noted to modify the inherent growth potentials of coffee trees with short, thick stems, long primary branch and maximum number of crop bearings. Further studies should be made on the influence of topping and other pruning practices on the growth and developments of coffee plants.

The results of the morphological growth indicated that Harenna coffee trees were tall with open crown architectures as opposed to the more compact coffee types in Yayu forest, which supports the report by Taye and Burkhardt (2004a). The coffee trees from Berhane-Kontir and Bonga had intermediate canopy nature. This corroborates with Yacob et al. (1996) who described that arabica coffee germplasm materials are broadly grouped into three broad canopy classes of open, intermediate and compact. Taye et al. (2004b) also reported variations in frequency and adaptation of local coffee landraces along climate gradients in Southern Ethiopia.

The yield of forest coffee tree was altogether low and demonstrated the minimum disturbances of the coffee forests in reducing the dense shade covers, regulating plant density and changing biodiversity as reported by Workafes and Kassu (2000) and Feyera (2006). The lowest number of nodes at Yayu may be attributed to the inherent growth nature or to the dense shade canopy microclimates. The growth and reduced coffee yield with increasing shade levels support the works done by other researchers (Ramalho et al., 1999; Workafes and Kassu, 2000; Franck et al., 2006).

In addition, the results may suggest the variability in growth architectures of wild coffee trees and hence the resistance to the high risks of damage due mainly to wildlife and tree fall in the forest habitats. This underlines the need to manipulate the forest environments in a way to disfavour the major insects and fungal diseases and maximize the light use-efficiency of coffee trees. The results of crop to leaf ratio and seed weight depicted inverse relationships at most sites, which may indicate environmental effects. This may particularly reveal the low light intensity, reduced net photosynthetic rate, and constrained reproductive growth of coffee tree (Vaast et al., 2005).

Leaf growth (retention or initiation) of varying sizes may also indicates the differences in leaf area index to use the natural resources (mainly sun light and carbon dioxide) in the forest environments. Maximum leaf number was recorded under relatively moderate shade levels and wide coffee spacing at all sites with the highest value at Bonga forest. Coffee leaves are thin (high specific leaf area) and may be easily damaged by insects. In contrary, leaf drop was high in Yayu and Berhane-Kontir. The heavy crop loads on the widely spaced coffee trees could promote leaf senescence and subsequent branch dieback (Yacob et al., 1996). Likewise, the enhanced reproductive growth response under reduced over shade conditions may demonstrate the inherent trade-offs between vegetative and reproductive growths. This could underline the possibility to estimate coffee yield performances taking into account these variables as described by many reports (Wrigley, 1988; Yacob et al., 1996). However, stand structure within each production system and hence the extent of competition at the different growth stages may modify these stable and heritable characters, suggesting the need to consider sink-source growth balance in coffee plant. In general, the findings depict morphological diversity of wild coffee populations under reduced light interceptions and other stresses, which is in agreement with that of Robakowski et al. (2003) and Tesfaye et al. (2002).

According to Taye and Burkhardt (2004a), the Ethiopian wild coffee populations differ in morphological characteristics and grouped according to their geographical areas and the most similarities are noticed between and within the south-western areas, particularly between Bonga and Yayu natural forests both of which are identified and approved as UNESCO biosphere reserves in 2010. On the other hand, Bonga and Harenna coffees had the furthest distance (least similarity), reflecting the relatively more humid and drier characteristics of the two forest areas, respectively.

Implication for management and conservation of forest resources

The escalating deforestation rates primarily due to settlement projects, agricultural land-use pressures and fluctuating coffee prices, the regional climatic result of deforestation is becoming one of the major problems for the coffee industry and the existence of wild coffee in the montane rainforests of Ethiopia Paulos and Demel (2000). This will undoubtedly continue unless urgent attentions for sustainable conservation and utilization options of the remaining forest areas are put in place. There are, however, still enormous variations among Arabica coffee populations, demonstrating the long lasting environment-plant relationships. This calls for special attention to systematic investigations in order to tailor site-specific conservation options. Thus, characterization of the diverse coffee types would also allow sustainable, wise exploitation and maintenance of the wealth of wild coffee genetic resources in their original habitats. The present results provide insights into environmental management implications and the need for multi-site *in-situ* conservation and utilization approach of forest genetic resources and environments. This could be a plausible solution to coffee forest threats, largely due to changes in land use through land degradation and disturbance of natural habitats along with maximum biodiversity. It can be concluded that immediate measures are required to identify and design ways of implementing relevant conservation strategies against the possible threats from climate change to coffee ecology and production at country of origin. To this end, implementation of global coffee genetic resources conservation initiatives proposed by Bellachew and Sacko (2009) and other relevant projects could be among the top priority actions to maintain quality environments, conserve and benefit from the unique coffee germplasm base in Africa. However, detail works on the identification and implementation of sustainable (ecological, economical and social) conservation of wild coffee diversity and its natural forest ecosystems are crucial. Moreover, investigations on the levels of forest management, identification of suitable coffee genotypes with desirable traits, including low caffeine, disease resistant, drought tolerant and urgent implementation of sound incentive mechanisms (forest product branding and certification) are of paramount importance to benefit from the potential forest genetic resources and ecosystem services. This need, among others, strong coffee partnerships in both coffee producing and importing countries to coordinate and facilitate sustainability initiatives for the future development of the coffee sector in Africa and globally.

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