

WILD *COFFEA ARABICA* L. IN THE AFROMONTANE RAINFORESTS OF ETHIOPIA: DISTRIBUTION, ECOLOGY AND CONSERVATION

Feyera Senbeta ¹, Manfred Denich ², Hans Juergen Boehmer ³, Tadesse Woldemariam ⁴, Demel Teketay ⁵ and Sebsebe Demissew ⁶

¹ Ethiopian Coffee Forest Forum, Addis Ababa; PO Box 28513, Addis Ababa, Ethiopia.

E-mail: feyeras@yahoo.com

² Centre for Development Research, University of Bonn

³ Department of Geography, University of Bonn, Germany

⁴ Department of Biology Education, Addis Ababa University

⁵ Forest Stewardship Council, African Regional Office, Kumasi, Ghana

⁶ The National Herbarium, Addis Ababa University

ABSTRACT: *Coffea arabica* is native to the Afromontane rainforests of Ethiopia. These rainforests are the last refugia for wild genetic resources of Arabica coffee. To understand the ecological characteristics and the conservation options of wild coffee populations, a study was conducted in Bonga, Harenna, Maji, Berhane-Kontir and Yayu forests. In each forest, quadrats of 20 x 20 m were laid along transects to collect coffee related data. Wild populations of Arabica coffee are distributed over a wide range of geographical regions, but locally have a patchy distribution in the rainforests. The highest abundance of wild coffee plants per plot was recorded in Yayu and the lowest in the Bonga/Berhane-Kontir forests. A low frequency of occurrence was observed in Harenna (71%) and the highest in Maji and Yayu forests (100%). This is related to the major spatial discontinuities caused by factors in edaphic, biotic, microclimatic and topographic features. Wild coffee occurs mostly between 1000 m and 2000 m but its critical altitude is between 1300 m and 1600 m. There is a negative correlation between the abundance of wild coffee and an increase in slope angle. The wild populations of Arabica coffee are also influenced by the structural arrangement of the forest. Slight forest disturbance such as selective tree cutting may create favorable environmental conditions for coffee recruitment. However, serious disturbances such as overgrazing can limit the regeneration capacity of coffee plants in the forest. To conserve the greatest possible amount of wild coffee populations, the rainforests must be maintained and not converted to other types of land use. Nature reserve networks should be established across the Afromontane rainforests of Ethiopia.

Key words/phrases: Distribution patterns, forest coffee, human impacts, wild coffee

INTRODUCTION

Coffea arabica L. is native to the Afromontane rainforests of Ethiopia. Afromontane rainforest is one of the forest vegetation types that occur on the wetter slopes of the higher mountains of the country (White, 1983; Friis, 1992; Friis and Sebsebe Demissew, 2001). Arabica coffee is the only member of the genus *Coffea* that occurs in Ethiopia, and is geographically isolated from all other *Coffea* species. Studies have indicated a high genetic variability of wild Arabica coffee populations in the Afromontane rainforests of Ethiopia (Meyer, 1965; Monaco, 1968; Tewolde-Berhan Gebre-Egziabher, 1990; Tadesse Woldemariam *et al.*, 2002; Esayas Aga *et al.*, 2003). Most of these forests are the major forest fragments in Ethiopia and sources of livelihoods, e.g., for timber and non-timber forest products, for local communities living in and

around the forests. In spite of all this, the wealth of wild coffee genetic resources and its associated habitats are disappearing due to the continuous degradation and loss of Afromontane rainforests (Tadesse Woldemariam *et al.*, 2002; Feyera Senbeta *et al.*, 2005). Adequate attention is not being given to the conservation of the forest with wild coffee populations due to financial constraints (Tewolde-Berhan Gebre-Egziabher, 1990; Demel Teketay, 1999; Paulos Dubale and Demel Teketay, 2000; Tadesse Woldemariam *et al.*, 2002). There is an urgent need to conserve the habitats of wild coffee in order to maintain and prolong its great genetic wealth and the associated forest biodiversity.

Globally, considerable knowledge has been generated on the biology and ecology of cultivated *Coffea arabica* (e.g., Lashermes *et al.*, 1996; Lashermes *et al.*, 2000; Anthony *et al.*, 2001). However, limited information is available

concerning the ecology and distribution patterns of *C. arabica* in its natural habitat (Tadesse Woldemariam, 2003). The relationship between coffee distribution and environmental factors has been studied at a local level in a few sites in Ethiopia (Tewolde-Berhan Gebre-Egziabher, 1978; 1986; Mesfin Tadesse and Lisanework Nigatu, 1996). But the distribution of wild coffee in relation to regional factors is not well documented. To formulate effective conservation approaches, knowledge of ecological and distributional patterns of geographically confined species such as *C. arabica* is essential.

In view of this, the present study was conducted in five Afromontane rainforests of Ethiopia to (1) examine how wild populations of Arabica coffee are distributed in the Afromontane rainforests of Ethiopia, (2) evaluate the relative importance of regional variables such as rainfall, altitude and local variables (*e.g.*, soil characteristics, slope, and canopy cover) on coffee distribution and abundance patterns, and (3) recommend conservation measures/options.

MATERIALS AND METHODS

Study sites

An important feature of the physiography of Ethiopia is the formation of the western and eastern highland plateaus, which are divided by the Great Rift Valley system. The present study was carried out in five rainforests namely Harenna, Bonga, Maji, Yaju and Berhane-Kontir (Fig. 1 and Table 1). Harenna forest is located in SE Highlands, while the other four forests are situated in SW Highlands. The rainforests in the southwest are separated from each other by agricultural landscapes and/or settlements.

The Harenna forest experiences bimodal rainfall patterns from February to April and September to November, with mean annual rainfall of around 1000 mm (Uhlig, 1988; Mesfin Tadesse and Lisanework Nigatu, 1996). The southwestern forests, *i.e.* Bonga, Maji, Berhane-Kontir, and Yaju

receive unimodal rainfall between June and October (Eklundh, 1996), with the mean annual rainfall range of between 1200 mm (Maji) and over 2000 mm (Berhane-Kontir). The minimum and maximum monthly temperatures of some meteorological stations close to the study areas are indicated in Table 2.

Soils of the study areas are characterized as red or reddish-brown, dominated by dystric nitosols (Murphy, 1968; Paulos Dubale and Tesfaye Shimber, 2000).

Coffee and cereal production and livestock rearing are commonly practiced among rural communities in the study areas. The populations in the study areas are increasing and putting immense pressure on the forest and forest resources (Tafese Asres, 1996; Tadesse Woldemariam *et al.*, 2002; Feyera Senbeta *et al.*, 2005). These regions are distinguished for their high population influx because of their high production potential and favorable environment for living. The conversion of undisturbed forest with wild coffee into semi-managed forest coffee system through thinning of understorey trees and shrubs is increasing in order to improve the productivity of wild coffee. Particularly, Maji and Harenna forests are highly influenced by these activities.



Fig. 1. Map of Ethiopia showing the location of study areas and the shaded zone shows the potential areas of wild coffee distribution.

Table 1. Location and some characteristics of five studied Afromontane rainforests in Ethiopia.

Regions	Area (ha)	Number of plot	Elevation (m)	Lat. (N)	Long (E)
Bonga	5000	28	1700-2200	7° 08'	35° 53'
Berhane-Kontir	10000	37	950-1800	7° 00'	35° 00'
Maji	2000	10	1600-1750	6° 00'	36° 00'
Harenna	15000	24	1300-2000	6° 00'	39° 00'
Yaju	10000	48*	1200-2150	8° 05'	35° 06'

*Source: Tadesse Woldemariam (2003).

Table 2. Climatic data for meteorological stations closest to study sites in the rainforest region of Ethiopia.

Station	Alt (m)	Lat.	Long.	Years	P	Tmax	Tmin
Bebeka ¹	1100	6°53'	35°26'	34	1914	29	15
Tepi ¹	1200	7°05'	35°15'	7	-	29	19
Mizan Teferi ¹	1370	6°58'	35°36'	48	2216	27	15
Yayu ²	1630	8°22'	35°50'	20	1586	28	13
Metu ²	1680	8°19'	35°35'	36	1792	27	12
Gore ²	2025	8°10'	35°33'	26	1937	23	13
Bonga ³	1725	7°13'	36°17'	49	1718	26	12
Wushwush ³	1950	7°16'	36°11'	48	1794	25	11
Maji	2310	6°12'	35°36'	23	1638	-	-
Harennna	1400	6°	40°	-	1000	28	10

Source: NMSA (2002); ¹Berhane-Kontir; ²Yayu; ³Bonga; Alt = Altitude, P = Mean annual rainfall (mm), Tmax = Maximum annual mean temperature (°C), Tmin = Minimum annual mean temperature (°C)

Methods

This study was carried out in five Afromontane rainforests in the period between May and June 2003, and from October 2003 to June 2004. In each forest, quadrats of 20 x 20 m were used to collect coffee-related data. The quadrats were placed along transects in each forest. A total of 147 plots were placed in all forests (Table 1). All the data for Yayu forest were taken from Tadesse Woldemariam (2003). In each plot, all woody plants were identified and counted. Coffee plants were categorized into seedlings (height < 0.5 m), saplings (height = 0.5–2 m) and trees (height > 2 m). All woody plants having a height of ≥ 0.5 m and a diameter at breast height (dbh) ≥ 2 cm were measured for height and dbh. The presence of epiphytes, herbs, pteridophytes, grasses and sedges were also noted in each plot.

Additionally, environmental variables such as altitude, slope, aspect and signs of human influences were recorded in each plot. The altitude and UTM co-ordinates were obtained using Garmin GPS-72. The slope and aspect were determined with the help of clinometers and compass, respectively. Data on climatic parameters were obtained from the nearest meteorological stations according to the database provided by the National Meteorological Service Agency of Ethiopia (NMSA). However, the period of data set (1954–2001) differs among the meteorology stations, from 10 to 48 years.

Anthropogenic disturbances were evaluated for each plot on visual scales from 0 to 3 (where 0 represents absence of influence and 3 the highest influence). Disturbance scores were based on visible signs of coffee harvesting, grazing and tree cutting. In addition, plants were grouped into one

of the four vertical strata: forest floor (maximum height < 0.5 m), shrub layer (maximum height = 0.5 to 5 m), small tree layer (maximum height = 5 – 15 m) and tree layer (maximum height > 15 m) and their percentage canopy cover were estimated. Soil samples were also collected from soil pits that were systematically distributed along altitudinal gradients in each forest.

Data analysis

Abundance of coffee plants and other species were summarized on a plot basis. Two-way correlation and linear regression were run to investigate the relationship between coffee abundance and species richness, tree canopy cover, altitude and slope using pooled data of all forests. Although not systematic, casual observations were made in the field and information concerning the potential role of dispersal agents was gathered by interviewing the local people.

Soil samples were analyzed for pH-H₂O, % organic matter, % carbon (C), % total nitrogen (N), available phosphorus (P) (ppm), and exchangeable phosphate (K) (meq/100g). Soil pH was determined in 1:2.5 pH-H₂O using the Beckman Zeromatic-II pH meter. Total organic carbon was determined by oxidation with acid dichromate and spontaneous heating by dilution of sulfuric acid according to (Walkley and Black 1934). Exchangeable K was extracted with 1N ammonium acetate adjusted to pH 7.0 and the amounts were determined with an atomic absorption spectrophotometer (Juo, 1978). Available P was determined by the method of (Bray and Kurtz 1945). Total N was determined with the macro-Kjeldahl method (Jackson, 1958).

RESULTS

Distribution and abundance of wild coffee

Wild populations of *Arabica* coffee occur over a wide range of geographical regions in Ethiopia (Fig. 1). The potential range of wild coffee populations lies between 6° and 8° latitude on the highlands, although the majority of this forest belt is already fragmented and being converted to non-forest land uses. Locally, however, the distribution of wild coffee is patchy. These patches were either very dense and large or thin and sparse. Patches of *C. arabica* occurred very close to each other (less than 20 m distance between the patches), frequently within an area, or there were large areas without *C. arabica* patches (greater than 100 m distance between the patches). The trends were similar in all studied rainforests except in the Yayu forest, where wild coffee was widely distributed across the forest.

In its natural habitat, *Coffea arabica* is exposed to the combined action of different environmental factors and hence the abundance of wild coffee varied across the different study sites/plots (Table 3). The highest abundance of wild coffee plants per plot was recorded in Yayu and the lowest in the Bonga/Berhane-Kontir forests. A low frequency of occurrence was observed in Harena (71%) and

the highest in Maji and Yayu forests (100%). The relationships between abundance of coffee and different environmental factors are discussed in detail in the following sections.

Climatic factors

Wild coffee is adapted to a wide range of climatic parameters. The distribution patterns of mean monthly rainfall and temperature were similar across the different meteorological stations (Fig. 2), although the total mean annual rainfall varied. Harena had the lowest mean annual rainfall and Mizan Teferi (equivalent to Berhane-Kontir) had the highest (Table 2). The lowest mean monthly minimum temperature was found around Bonga and the highest around Mizan Teferi. The mean monthly maximum temperature follows the same trends (Table 2). The distribution and occurrence of wild coffee plants was limited not only by macroclimatic but also by microclimate factors. Due to the effects of canopy cover, the microclimate on the forest floor might differ from the climatic data recorded at stations outside the forest. Thus, direct climate effects led to differences in regional vegetation rather than in coffee occurrence.

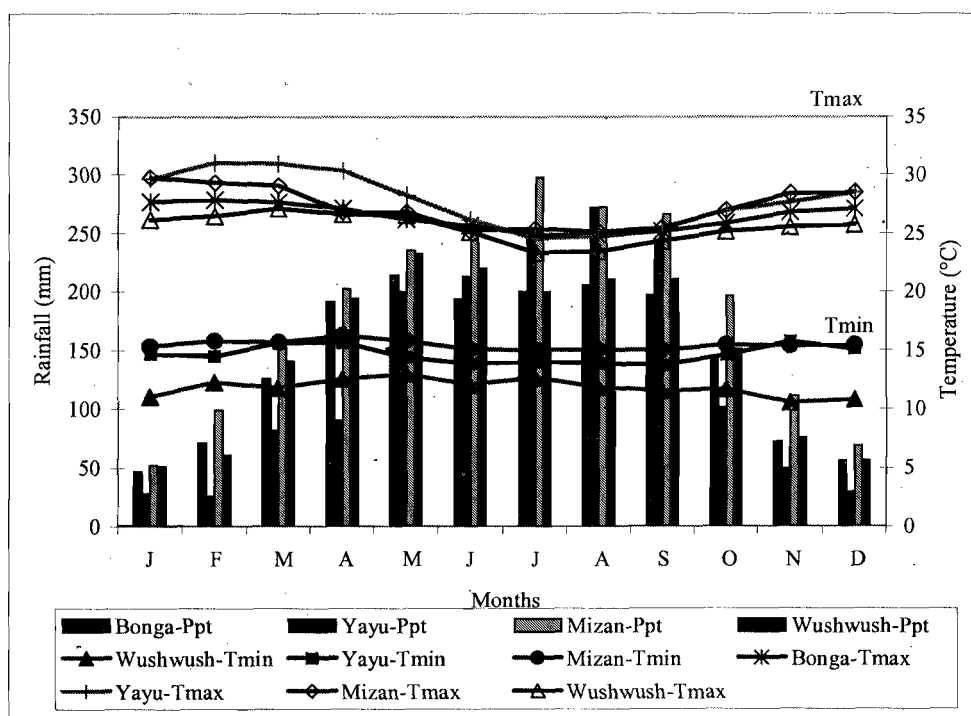


Fig. 2. Annual rainfall and temperature distribution patterns at four meteorological stations near the Bonga, Berhane-Kontir and Yayu forests of Ethiopia (Ppt = Mean monthly precipitation; Tmax = Mean monthly maximum temperature; Tmin = Mean monthly minimum temperature).

Table 3. Abundance and frequency of wild coffee in five studied Afromontane rainforests of Ethiopia.

Characteristics	Bonga	Berhane-kontir	Harena	Maji	Yayu
Abundance of coffee per plot (range)	1-816	1-1007	1-1743	42-1123	117-2020
Median of coffee abundance	51	46	18	385	901
% frequency of coffee	93	91	71	100	100

Topographic factors

The relationship between the abundance of wild coffee and altitude was non-linear (Fig. 3). Along the gradient of altitude, the mean abundance of coffee plants per plot followed a bell-shaped type of distribution (Fig. 3). Coffee was found only between 940 and 2050 m. The lower limit was recorded in the Berhan-Kontir forest and the upper limit in Bonga. The highest densities of coffee plants were recorded between 1300 and 1600 m.

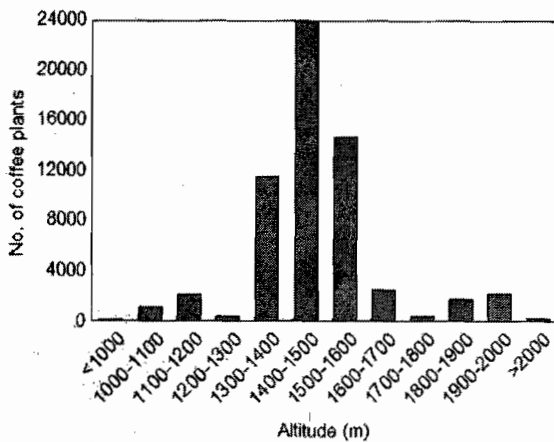


Fig. 3. Mean abundance of wild coffee per plot along the altitudinal gradient in the studied Afromontane rainforests of Ethiopia.

Wild coffee populations were recorded between 0 and 55% slope angle (Fig. 4). The highest mean abundance of coffee per plot was observed between 0 and 25% slope classes. As slope angle increased, abundance of wild coffee plants started to decrease, although this was not statistically significant ($P < 0.71$). This could be associated not only to slope values but also to other related environmental factors (e.g., soil depth, nutrient status of the soil, etc.) and human impact along the slope gradient.

Edaphic factors

The study of soil pits and soil horizons across the different coffee forests revealed the existence of different soil types, namely Nitosols, Regosols, Cambisols, and Acrisols. Results from the soil chemical analyses showed a pH of 4.2 to 6.6. A breakdown of these values showed that 31% of the soils were very strongly acidic (pH = 4.21 to 4.95),

25% strongly acidic (pH = 5 to 5.5), 21% medium acidic (pH = 5.5 to 5.91) and 21% slightly acidic (pH = 6 to 6.6). In all soil pits, pH decreased with increasing soil depth. Available phosphorus was low in most soil samples. Some 67% of the soil samples had less than 1 ppm in total phosphorus and 27% had between 1 and 6.97 ppm; one soil pit (with 3 soil samples) in the Berhane-Kontir forest had 54.9, 55.58 and 63.86 ppm phosphorus. Organic matter in the soils ranged from 0.37% to 9.92% with an average of 3.14%. Total nitrogen ranged from 0.04% to 0.6% with an average of 0.19%. The exchangeable K (meq/100 g) ranged from 0.04 to 2.96 with an average of 0.55. Most soils were reddish-brown to dark reddish-brown, well-drained and clayed in texture. Generally, coffee occurs on acid soils with low available phosphorus.

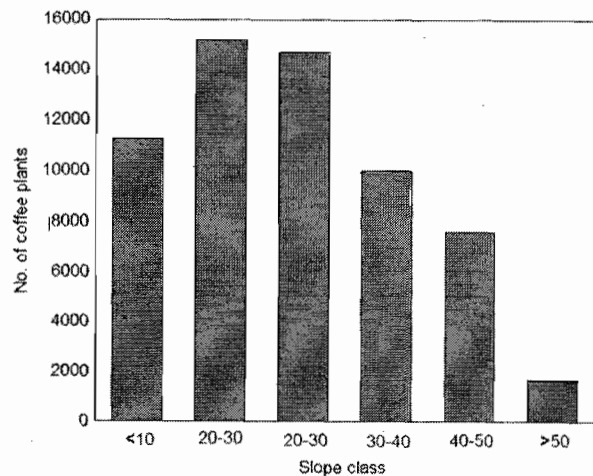


Fig. 4. Mean abundance of wild coffee per plot along slope class in Afromontane rainforests of Ethiopia.

Human impacts and other biotic factors

Little is known about the effect of biotic factors on the distribution patterns of wild *Coffea arabica*. Relevant biotic factors can be human activities, grazing, dispersal agents and competition. It is apparent that human activities can create three scenarios: 1) facilitate seed dispersal from one place to the other, 2) create microenvironments for recruitment and regeneration of coffee by removing the competing undergrowth and herbs

in the forest, and 3) enhance propagation, *e.g.*, establish young plants in the forest. Slight forest disturbance such as selective tree cutting may create favorable environmental conditions for coffee recruitment. However, serious disturbance like overgrazing can limit the regeneration capacity of coffee plants.

Local evidence suggests that baboons and birds (mainly hornbills) are very important dispersal agents for coffee. Coffee fruits have a sweet fleshy pulp that can be used as food by different animals and humans. During the fieldwork, a large number of birds and baboons were observed in the coffee canopy. However, many more animal species are probably involved in the dispersal processes.

In the natural forest, coffee grows under different densities of canopy cover. In Figure 5, a comparison of mean abundance of coffee per plot is made between the > 15 m tall canopy cover and the small-tree canopy cover of between 10 and 15 m height. An analysis showed that, a combination of less than 60% small-tree canopy cover (Fig. 5a)

and greater than 60% higher tree canopy cover (Fig. 5b) were favourable for the abundance of wild coffee populations.

Relationship between coffee abundance and other species

Over 600 plant species representing different growth forms were recorded in the forests where wild coffee populations occur as under story (Feyera Senbeta, 2006). There was a significant negative relationship between species richness and abundance of coffee plants ($P < 0.0001$; $r^2 = 0.11$) (Fig. 6). However, only 11% of the variation in abundance of coffee plants accounted for the variation in species diversity. This is related to disturbance factors and competition. On the other hand, there was a significant positive relationship between the abundance of coffee plants and total abundance of all other plant species ($P < 0.0001$; $r^2 = 0.19$).

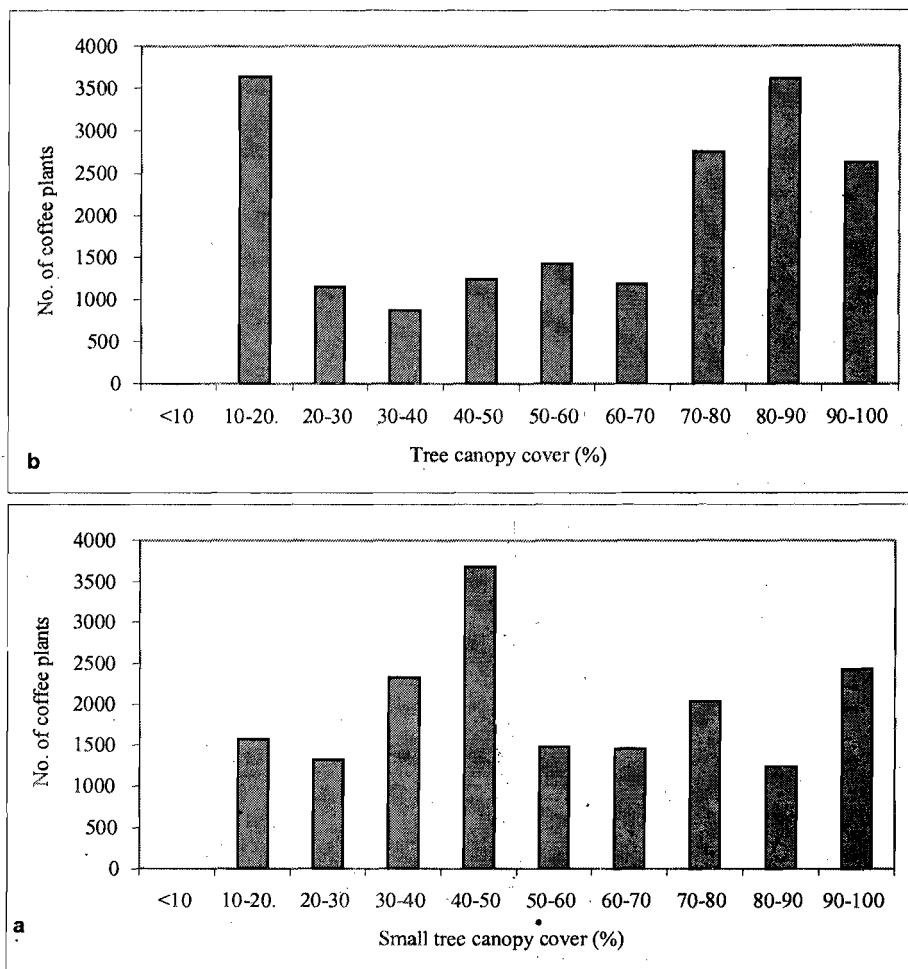


Fig. 5. Relationship between the forest canopy cover (%) and mean abundance of wild coffee per plot in the forest of Harena, Bonga, Maji and Berhane-Kontir, Ethiopia.

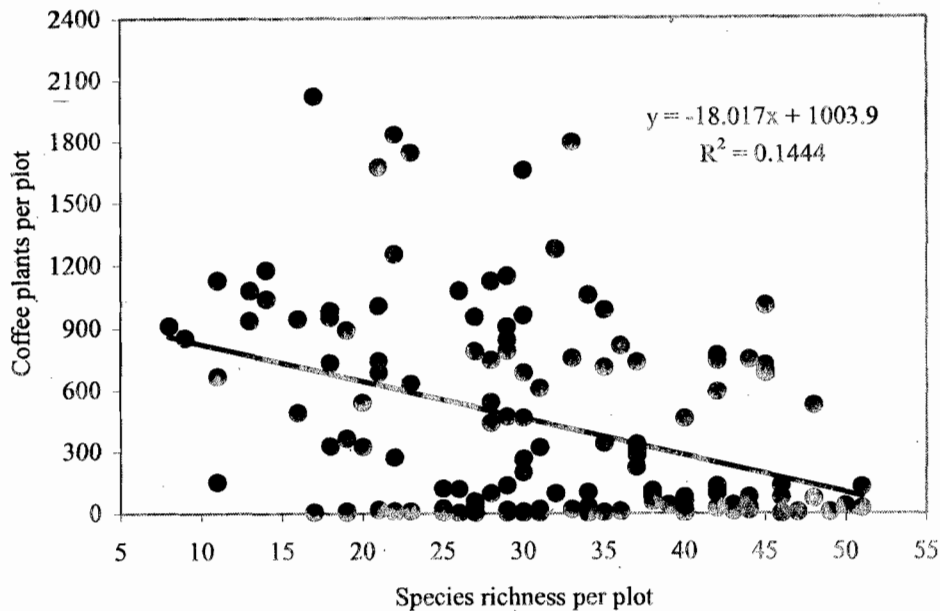


Fig. 6. Relationship between mean abundance of wild coffee per plot and species richness in the Afromontane rainforests of Ethiopia.

The two-way correlation analysis of coffee abundance and abundance of individual species revealed at least two kinds of relationships. The first group of species (e.g., *Paullinia pinnata*, *Diospyros abyssinica*, *Landolphia buchananii*, *Canthium oligocarpum*, *Blighia unijugata*, *Trichilia dregeana*, *Mimusops kummel*, *Ehretia cymosa* and *Cassipourea malosana*) showed a significant positive relationship with coffee abundance. A second group shows a significantly negative relationship (e.g., *Argomuellera macrophylla*, *Psychotria orophila*, *Whitfieldia elongata* and *Baphia abyssinica*).

An analysis of the percentage co-occurrence of some plant species and coffee shows about 14 species with an absolute frequency occurrence of >50%. These species can be considered as "coffee associate species." These include *Landolphia buchananii* (87%), *Diospyros abyssinica* (73%), *Vepris dainellii* (71%), *Dracaena fragrans* (71%), *Maytenus gracilipes* (60%), *Bersama abyssinica* (58%), *Celtis africana* (57%), *Ehretia cymosa* (50%), *Clausena anisata* (53%), *Teclea nobilis* (58%), *Mimusops kummel* (50%), and *Hippocratea africana* (53%). The majority of these species are small-to-medium-sized trees except *Landolphia buchananii* and *Hippocratea africana*, which are climbers. To this end, some plant species are commonly associates to coffee and others are not.

DISCUSSION

Effects of topography and substrate

Many environmental factors (such as soil nutrient status, slope, altitude, and rainfall) that change along the geographic gradient are found to exert an important control on distribution patterns of species (e.g., Coblenz and Riitters, 2004). For instance, the magnitude of topographic changes in forest structure and composition corresponds well with change in nutrient status of the soil (Takyu et al., 2002; Enkoi, 2003; Enkoi and Abe, 2004).

As illustrated in the present study, wild coffee populations occur over wider ranges of temperature and rainfall limits in the rainforests of Ethiopia. Apparently, it is difficult to separate the impact of climate from other environmental factors. Studies (e.g., Friis, 1992; Eilu et al., 2004) showed that tree species distribution is influenced by both local environmental variables (e.g., soil, slope) and regional environmental factors (e.g., rainfall, altitude). This may also hold true for coffee.

The highest mean abundance of coffee individuals per plot were recorded between 1300 and 1600 m suggesting the optimum altitude of wild coffee. (Mesfin Tadesse and Lisanework Nigatu, 1996) report similar results for the Haremma forest. Several other studies (e.g., Hamilton, 1975;

Friis, 1992; Wolf, 1994) have shown the influence of altitudinal gradients on tree species distribution. Friis (1992) argued the existence of critical altitudes for groups of species in northeastern tropical Africa with a separation between Afromontane and lowland species at 1500 m or below. This also holds true for wild populations of coffee which is best established at 1300–1600 m. It appears, however, that the altitudinal range of wild coffee may be increasing to higher altitudes in the Harenna forest and lowland forests in the southwest areas, which might be related to changes in rainfall distribution patterns or recent human interference. Fourteen years ago, the upper altitudinal limit of wild coffee trees were recorded around 1700 m in the Harenna forest (Mesfin Tadesse and Lisanework Nigatu, 1996). In the present study (2003/04), coffee plants were recorded at 1850 m as the upper altitudinal limit in the Harenna forest. Therefore, the lower and upper altitudinal limit of coffee may need further investigation, and may not be constant.

Abundance of wild coffee was not strongly related to slope angle. Tewolde-Berhan Gebre-Egziabher (1978) and Tadesse Woldemariam (2003) reported a negative correlation between slope angle and the abundance of wild coffee in some areas. The negative correlation of the abundance of coffee with the slope angle is due to steeper slopes which have shallower soils more influenced by bedrock, and are, hence, less moist and less acidic (Tewolde-Berhane Gebre-Egziabher, 1978).

In its natural habitat, coffee grows on different soil types. These soils are acidic to slightly acidic and have low available phosphorus. Many studies (e.g., Murphy, 1968; Willson, 1985; Alemayehu Mamo, 1992; Paulos Dubale, 1996; Paulos Dubale and Tesfaye Shimber, 2000) reported the same findings in different rainforests. The coffee plants growing on these soils are able to secure their phosphorus requirements mainly from that released through organic matter decay or weathering. According to (Hall and Swaine, 1976), soil fertility varies with rainfall; forest under high rainfall grows on leached soils with low pH, poor saturation of the cation exchange complex, low total exchangeable bases, and low concentrations of available phosphorus and total nitrogen.

Influences of biotic factors

In the present study, most plots that were affected by human influence were generally found to contain a high number of coffee plants com-

pared to the plots that were located in the inaccessible parts of the forests. In the accessible part of the forests, rural communities collect most of the coffee berries, at the same time modifying micro-sites for new recruitment of coffee plants by removing undergrowth around the mother coffee trees. Several studies have emphasized the influences of human activities on the patterns of wild coffee distribution in the Ethiopian rainforests (Meyer, 1965; Mesfin Tadesse and Lisanework Nigatu, 1996; Tadesse Woldemariam *et al.*, 2002). In the inaccessible parts of the forests, non-human dispersal agents play an important role in governing the pathways of coffee berries and the distribution patterns of the wild coffee populations thus differ according to the dispersal agents. This may lead to the variation in the abundance, growth and survival of new regenerating plants across microsites (Whittaker and Levin, 1977; Peterson and Pickett, 1990), and this in turn influences the spatial distribution of coffee plants across their geographical ranges (Christie and Armesto, 2003). Therefore, the clumped distribution of coffee populations in the inaccessible zone of the forest might be related to competition from other plants, environmental patchiness and dispersal agents.

In most forests, small populations of coffee seedlings were observed occurring patchily even where coffee mother trees were scarce. Here, birds and mammals could have acted as seed dispersal agents leading to coffee plant migration. In most tropical forests, up to 90% of all tree species rely on animals for dispersal of their seeds (Ganzhorn *et al.*, 1999). Hence, one other possible reason for the clumped distribution of coffee populations in the studied rainforests could be habitat preference by dispersal agents (Calvino-cancela, 2002).

Furthermore, the forest canopy structure appears to influence the abundance and distribution of the wild coffee populations. According to Tang *et al.* (1999), the variation in forest canopy structure and foliage height distribution affects understory light availability on the forest floor. The extent of canopy cover by shrubs and small-tree layers might influence the intensity of light reaching the forest floor, which, in turn affects coffee abundance on the forest floor. High canopy cover of small trees and shrubs usually induce competition and reduce recruitment or performance of wild coffee. Figure 5 supported this idea. Therefore, the distribution of wild coffee in the Afromontane rainforests is also affected by the structural arrangement of the forests.

Coffee distribution and species richness

Species distribution patterns reflect the multitude responses that make up the capacity of a species to survive and reproduce under a particular set of conditions (MacArthur, 1972). Although the absence of a species from a site or habitat may not indicate that the species cannot tolerate those conditions, the presence of a species signifies that it can. The locally patchy distribution of wild coffee plants in the rainforests might be due to habitat patchiness, substrate/geology, dispersal limitation, competition or degree of human influence (Vuilleumier and Simberloff, 1980).

The low abundance of coffee corresponding to an increase in species richness might be due to the overwhelming competition from other species. Coffee is highly sensitive to competition from shrubs and small trees (Demel Teketay, 1999). It is because of this physiological issue that farmers usually remove or thin-out the competing trees and shrubs in order to improve the productivity of wild coffee when they exercise forest coffee management. This type of wild coffee management, however, suppresses tree regeneration, reduces tree density and eventually leads to the disappearance of the forest species (Feyera Senbeta, 2006). The losses of species diversity are likely to have negative effects on forest biodiversity and the associated forest ecosystems.

The positive co-existence of some forest species with coffee may indicate their similar ecological requirement or niche. Tewolde-Berhan Gebre-Egziabher (1986) also reported the beneficial co-existence between wild coffee plants and certain forest species. On the other hand, the negative relationship between coffee and other plant species indicates the intolerable competition imposed by some species on coffee plants. The majority of these species are species with a stature comparable to that of coffee (e.g., *Argomuellera macrophylla*, *Psychotria orophila*, and *Chionanthus mildbraedii*). Species with ecological requirements similar to coffee can be regarded as indicator species of the habitat of coffee plants.

Implications for conservation

The wild populations of *Coffea arabica* are restricted to the Afromontane rainforests of Ethiopia. These rainforests contain a high variability of wild coffee populations (Monaco, 1968; Paulos Dubale and Demel Teketay, 2000; Esayas Aga *et al.*, 2003). The existence of this high variability guarantees the availability of large gene pools with the desired characteristics for the future

improvement of coffee through breeding programs. These rainforest fragments are the largest forest ecosystem with wild populations of *Coffea arabica* even globally. Afromontane rainforests also support a high number of economically useful plant species such as *Piper capense*, *P. guineense*, *Dioscorea praehensilis* and *Aframomum corrorima*. Thus, they could be a gene reserve for many useful forest species beside the wild coffee populations. Notwithstanding, most of these Afromontane rainforests have not been a focus of the conservation agenda in the past (Tewolde-Berhan Gebre-Egziabher, 1990; Tadesse Woldemariam *et al.*, 2002). Only very recently, the Afromontane region of Ethiopia has been recognized as the "Eastern Afromontane Hotspot," which is one of the globally important regions for biodiversity conservation. As a result, the rainforest fragments are unsustainably exploited and partly converted into semi-managed forest coffee systems while the remaining forests are inadequately conserved. Wild coffee conservation in the rainforests should be considered as continuing the existence of evolutionary processes and promoting the availability of wild relatives of the coffee genes in the future. Hence, wild coffee populations in the Afromontane rainforests need conservation. Conversely, the natural habitat of wild coffee, *i.e.* the Afromontane rainforest fragments also need conservation.

The empirical analyses in the present study revealed that the occurrence and abundance of wild coffee populations differ among the Yayu, Bonga, Berhane-Kontir, Harenna and Maji forest fragments. Underlying factors are the variations in human influence and environmental factors. For instance, the highest abundance of wild coffee plants was observed between 1300 and 1600 m altitudes (critical zone of wild coffee) and on flat to gentle slopes. The distribution patterns of wild coffee populations in the rainforests can assist in prioritizing the studied rainforests for conservation. In the present study, the Yayu, Harenna and Berhane-Kontir forests contain large tracks of forests with the critical zone of wild coffee occurrence. On the other hand, the Bonga forest is located close to the upper altitudinal limit of wild coffee occurrences, and hence the abundance of wild coffee plants was not comparable to that in the Harenna and Berhane-Kontir forests. Furthermore, a greater proportion of the Maji forest is highly manipulated by human interference. As a result, the Bonga and Maji forests have a lower priority for conservation of wild coffee

populations than the Harena, Yayu and Berhane-Kontir forests.

Tadesse Woldemariam (2003) indicated the importance of Yayu forest for conservation of wild coffee populations. A comparison of his data with the present findings also showed that the Yayu forest has the highest abundance of wild coffee plants compared with Harena and Berhane-Kontir forests. Because of the status of the wild coffee populations and habitat suitability, the Yayu forest should deserve a high priority for conservation. The Berhane-Kontir forest also has large areas with wild coffee populations under intact conditions, while the Harena forest is relatively influenced by human interference.

Importantly, the study of genetic variability within and between wild populations of Arabica coffee in the different Afromontane rainforest fragments can provide more evidence as to which site to select for conservation of the wild coffee populations. To conserve the greatest possible amount of wild coffee populations, the rainforests must be maintained and not converted to other types of land use. Nature reserve networks should be established across the Afromontane rainforests of Ethiopia. Finally, further research is required to understand better the reproductive biology, dispersal and germination ecology of wild coffee populations in the different rainforests.

ACKNOWLEDGEMENTS

The first author is very grateful to the Center for Development Research (ZEF), University of Bonn and the German Federal Ministry for Education and Research (BMBF) for financing the scholarship and the study. We are also grateful to the Ethiopian Agricultural Research Organization (EARO) and the National Herbarium (ETH), Addis Ababa University, for logistic and herbarium services. Special thanks also go to Dr. Sileshi Nemomissa for his valuable comments on the manuscript. I am grateful to Mr. Georg Lieth for mapping coffee growing regions.

REFERENCES

1. Alemayehu Mamo (1992). Nutritional status of coffee soils of Keffa and Illubabor Administrative Regions in south western Ethiopia. *Inaugural-Dissertation*, University of Giessen, 78 pp.
2. Anthony, F., Bertrand, B., Quiros, O., Wilches, A., Lashermes, P., Berthaud, J. and Charrier, A. (2001). Genetic diversity of wild coffee (*Coffea arabica* L.) using molecular markers. *Euphytica* 118:53-65.
3. Bray, R.H. and Kurtz, L.T. (1945). Determination of total organic and available forms of phosphorous in soils. *Soil Science* 59:39-45.
4. Calvino-cancela, M. (2002). Spatial patterns of seed dispersal and seedling recruitment in *Corema album* (Empetraceae): the importance of unspecialized dispersers for regeneration. *J. Ecol.* 90:775-784.
5. Christie, D.A. and Armesto, J.J. (2003). Regeneration microsites and tree species coexistence in temperate rainforests of Chiloe Island, Chile. *J. Ecol.* 91:776-784.
6. Coblenz, D.D. and Riitters, K.H. (2004). Topographic controls on the regional-scale biodiversity of the south-western USA. *J. Biogeogr.* 31:1125-1138.
7. Demel Teketay (1999). History, botany and ecological requirements of coffee. *Walia* 20:28-50.
8. Eilu, G., Hafashimana, D.L.N. and Kasenene, J.M. (2004). Density and species diversity of trees in four tropical forests of the Albertine Rift, Western Uganda. *Diversity Distrib.* 10:303-312.
9. Eklundh, L. (1996). AVHRR NDVI for monitoring and mapping of vegetation and drought in East African environments. Doctoral Dissertation, Lund Univ. Press, Lund.
10. Enkoi, T. (2003). Micro-topography and distribution of canopy trees in a subtropical evergreen broad-leaved forest in the northern part of Okinawa Island. *Jap. Ecol. Res.* 18:103-113.
11. Enkoi, T. and Abe, A. (2004). Saplings distribution in relation to topography and canopy openness in an evergreen broad-leaved forest. *Plant Ecol* 173:283-291.
12. Esayas Aga, Bryngelsson, T., Endshaw Bekele and Salamon, B. (2003). Genetic diversity of forest coffee (*Coffea arabica* L.) in Ethiopia as revealed by random amplified polymorphic DNA (RAPD) analysis. *Hereditas* 138:36-46.
13. Feyera Senbeta (2006). Biodiversity and ecology of Afromontane rainforests with wild *Coffea arabica* L. populations in Ethiopia. *Ecology and Development Series* 38, ZEF, University of Bonn.
14. Feyera Senbeta, Schmitt, C., Denich, M., Sebsebe Demissew, Velk, P.L., Preisinger, H., Tadesse Woldemariam and Demel Teketay (2005). The diversity and distribution of lianas in the Afromontane rainforests of Ethiopia. *Diversity Distrib* 11:443-452.
15. Friis, I. (1992). Forests and forest trees of North East Tropical Africa. *Kew Bulletin Additional Series* 15, London.

16. Friis, I. and Sebsebe Demissew (2001). Vegetation maps of Ethiopia and Eritrea. A review of existing maps and the need for a new map for the flora of Ethiopia and Eritrea. *Biol. Skr.* 54:399-439.
17. Ganzhorn, J.U., Fietz, J., Rakotovo, E., Schwab, D. and Zinner, D. (1999). Lemurs and the regeneration of dry deciduous forest in Madagascar. *Conserv. Biol.* 13(4):794-804.
18. Hall, J.B. and Swaine, M.D. (1976). Classification and ecology of closed-canopy forest in Ghana. *J. Ecol.* 64:913-951.
19. Hamilton, A.C. (1975). A quantitative analysis of altitudinal zonation in Uganda forests. *Vegetatio* 30:99-106.
20. Jackson, M.L. (1958). *Soil Chemical Analysis*. Prentice-Hall, Ind. Englewood Cliffs, New Jersey.
21. Juo, A.S.R. (1978). *Selected Methods for Soil and Plant Analysis*. Manual series No. 1, International Institute of Tropical Agriculture. Ibadan, Nigeria.
22. Lashermes, P., Andrzejewski, S., Bertrand, B., Combes, M.C., Dussert, S., Graziosi, G., Trouslot, P. and Anthony, F. (2000). Molecular analysis of introgressive breeding in coffee (*Coffea arabica* L.). *Theor. Appl. Genet.* 100:139-146.
23. Lashermes, P., Trouslot, P., Anthony, F., Comes, M.C. and Charrier, A. (1996). Genetic diversity for RAPD markers between cultivated and wild accessions of *Coffea arabica*. *Euphytica* 87:59-64.
24. MacArthur, R.H. (1972). *Geographical Ecology*. Harper & Row, New York.
25. Mesfin Tadesse and Lisanework Nigatu (1996). An ecological and ethnobotanical study of wild or spontaneous coffee, *Coffea arabica* in Ethiopia. In: *The Biodiversity of African Plants*, pp. 277-294, (Van der Maesen, L.J.G., van der Burgt, X.M., and van Medenbach de Rooy, J.M., eds). Academic Publishers, Dordrecht.
26. Meyer, F.G. (1965). Notes on wild *Coffea arabica* from Southwestern Ethiopia, with some historical considerations. *Econ. Bot.* 19:136-151.
27. Monaco, L.C. (1968). Considerations on the genetic variability of *Coffea arabica* populations in Ethiopia. In: *FAO Coffee Mission to Ethiopia 1964-65*. Rome, Italy, pp. 49-69.
28. Murphy, H.E. (1968). A report on the fertility status and other data on some soils of Ethiopia. College of Agriculture, Haile Sellassie I University.
29. NMSA (2002). Climatic data. National Meteorological Service Agency. Addis Ababa, Ethiopia.
30. Paulos Dubale (1996). Availability of phosphorous in the coffee soils of southwest Ethiopia. In: *Proceedings of the Third Conference of the Ethiopian Society of Soil Science*, pp. 119-127, (Teshome Yizengaw, Eyasu Mekonnen and Mintesinot Behailu, eds). Addis Ababa, Ethiopia.
31. Paulos Dubale and Demel Teketay (2000). The need for forest coffee Germplasm conservation in Ethiopia and its significance in the control of coffee diseases. In: *Proceedings of Coffee Berry Disease Workshop*. Addis Ababa, Ethiopia, pp. 125-135.
32. Paulos Dubale and Tesfaye Shimber (2000). Some ecological parameters occurring in the major coffee growing areas of south western and southern Ethiopia. In: *Proceedings of Coffee Berry Disease Workshop*. Addis Ababa, Ethiopia, pp. 107-124.
33. Peterson, C.J. and Pickett, S.T.A. (1990). Micro site and elevational influences on early forest regeneration after catastrophic wind throw. *J. Veget. Sci.* 1:657-662.
34. Tadesse Woldemariam, Denich M., Demel Teketay and Vlek, P.L. (2002). Human impacts on *Coffea arabica* genetic pools in Ethiopia and the need for its *in-situ* conservation. In: *Managing plant genetic diversity*, pp. 237-247, (Engels, J.M., Rao, V.R., Brown, A.H.D. and Jackson, M.J., eds). CABI Publishing, Wallingford, UK.
35. Tadesse Woldemariam (2003). Vegetation of the Yayu forest in SW Ethiopia: impacts of human use and implications for *in situ* conservation of wild *Coffea arabica* L. populations. Doctoral dissertation, Center for Development Research, University of Bonn.
36. Tafese Asres (1996). Agroecological Zones of Southwest Ethiopia. Doctoral dissertation, University of Trier.
37. Takyu, M., Aiba, S. and Kitayama, K. (2002). Effects of topography on tropical lower montane forests under different geological conditions on Mount Kinabalu, Borneo. *Plant Ecol.* 159:35-49.
38. Tang, Y., Kachi, N., Furukawa, A. and Awang, M.B. (1999). Heterogeneity of light availability and its effects on simulated carbon gain of tree leaves in a small gap and the understory in a tropical rain forest. *Biotropica* 31:268-278.
39. Tewolde-Berhan Gebre-Egziabher (1978). Some vegetative parameters of coffee, *Coffea arabica* L., proportional to yield. *SINET: Ethiop. J. Sci.* 1:51-57.
40. Tewolde-Berhan Gebre-Egziabher (1986). Preliminary studies on the ecology of a natural coffee (*Coffea arabica*) forest with emphasis on coffee. *Symb. Bot. Ups.* 26(2):146-156.

41. Tewolde-Berhan Gebre-Egziabher (1990). The importance of Ethiopian forests in conservation of Arabica coffee gene pools. In: *Proceedings of the 12th Plenary Meeting of AETFAT*, pp. 65-72, (Ihlenfeldt, H.D., ed), Hamburg, Germany.
42. Uhlig, S.K. (1988). Mountains forests and the upper tree limit on the southeastern plateau of Ethiopia: Africa Mountains and Highlands. *Mount. Res. Develop.* 8(2/3):227-234.
43. Vuilleumier, F. and Simberloff D. (1980). Ecology versus history as determinants of patchy and insular distribution in high Andean birds. *Evol. Biol.* 12:235-379.
44. Walkley, A. and Black, I.A. (1934). An experimentation of degtiareff method or determining soil organic matter and proposed modification of the chromic acid titration methods. *Soil Sci.* 37:29-38.
45. White F. (1983). *The Vegetation of Africa*. A Descriptive Memoir to Accompany the Unesco/AETFAT/UNSO Vegetation Map of Africa. UNESCO, Paris.
46. Whittaker, R.H. and Levin, S.A. (1977). The role of mosaic phenomena in natural communities. *Theor. Popul. Biol.* 12:117-139.
47. Willson, K.C. (1985). Climate and soil. In: *Coffee: Botany, Biochemistry and Production of Beans and Beverage*, pp. 97-107, (Clifford, M.N. and Willson, K.C., eds). Croom Helm, London.
48. Wolf, J.H.D. (1994). Factors controlling the distribution of vascular and non-vascular epiphytes in the northern Andes. *Vegetatio* 112:15-28.