

Measuring Extent of Restoration Using Coffee (Coffea arabica L.) as a Bioassay Plant Species

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Abstract
This study was undertaken as part of the ongoing biological restoration with the objective of measuring extent of restoration over a degraded landscape using coffee plants (*Coffea arabica* L.) as bioassay organisms. The coffee plants were established beneath *Acacia abyssinica* Hochst.ex.Benth., *Croton macrostachyus* Hochst. ex Del. and *Euclea divinorum* Hiern. stands which were established 9-11 years ago in a degraded landscape. All the vegetative and reproductive data were collected on randomly selected 3- to 5-year-old coffee plants. The results showed that mean number of lateral stem branch, leaves, leaf area and internodal lengths were significantly ($P<0.05$) greater for those established beneath the shades of *E. divinorum* for 3-4 years, compared to those beneath the *C. macrostachyus* and *A. abyssinica* shades. Further, key biological indices such as mean number of fruiting nodes, berries per node, mature red berries harvested per plant, fresh weight of berries, size and weight of beans, bean to berry weight ratio, weight per 1000 beans and coffee bean yield (g/tree) were all significantly ($P<0.05$) higher for coffee plants established under the shade of *A. abyssinica* than those established under the shades of *C. macrostachyus* and *E. divinorum*, and on less-restored area. The levels of available phosphorous, total nitrogen and organic carbon were significantly ($P<0.05$) 54, 39 and 56 % higher, respectively, in the sites that were in the process of restoration than adjacent, non-restoring sites. This study showed that restoring native plants over degraded landscapes restores essential nutrient elements and favorable environmental conditions for the successful development productivity of economically useful crops such as *C. arabica*.
Keywords: coffee reproductive traits, degraded landscapes, Ethiopia, indigenous trees, restoration bioassay

1. Introduction

Deforestation has been a major problem in Ethiopia for quite a long time with serious environmental, economic and social consequences. These include degradation of keystone natural resources (e.g., soils, water) loss of biodiversity and disappearance of livelihoods, as well as negative impacts on the local, regional and global climatic conditions (Eshetu Yirdaw 2002; Legesse Negash 2010; Kibebew Wakjira and Legesse Negash 2013; Legesse Negash and Birhanu Kagnew 2013; Millet *et al*. 2013).

There have been various responses to the losses of keystone natural resources including attempts to restore soils, water, and biodiversity. Conventional restoration is a process that attempts to regain ecological integrity and enhance human *well*-being in degraded landscapes (Berger 1993; Hobbs and Norton 1996; Lamb 1998; Millet *et al*. 2013; Tina *et al*. 2013). In the restoration process, natural succession is a key factor and the ecological principles have been used to restore degraded sites (Bradshaw and Chadwick 1980; MacMahon 1997; Elliott *et al*. 2000; Tina *et al*. 2013).

A novel approach that employs a judicious selection of native trees with distinctive biological attributes (including nitrogen fixation, deciduousness, temperature modulation through shade provision, soil fertility enhancement, suitability for wildlife, etc.) has been applied at our "*Center for Native Trees Propagation and Biodiversity Development in Ethiopia* (**CNTPBDE**)" (Legesse Negash 2010; Legesse Negash and Berhanu Kagnew 2013). Additional tree biological traits include tolerance to poor soils and water stress (e.g. *A. abyssinica* Hochst.ex.Benth.) with its retreat-advance growth strategy); easily dispersing seeds (e.g. *Vernonia amygdalina* Del. in Caill.); species forming beneficial relationships with animals (e.g. *Olea europaea* subsp. *Cuspidate* (Wall. ex DC.)); fast-growing species (e.g. *A. abyssinica, Millettia ferruginea* (Hochst.) Bak); nitrogen-fixing species (e.g., *A. Abyssinica*) and species attractive to frugivores (e.g., *Syzigium guinineese*). Besides, trees capable of restoring soil fertility through rapid litter decomposition and nutrient recycling (e.g. *C. macrostachyus* Hochst. ex Del.), and/or water conservation (e.g. *Ficus sur* Forssk.; *F. sycomorus* L. subsp. *gnaphalocarpa* (Miq.) C.C. Berg*; F. vasta* Forssk.) are essential.

The extent, stability and success of restoration in a site which is being restored could be measured using different criteria such as: plant structural elements (plant cover, the heights, diameters, areas, growth rate, etc.); composition of the community; temporal variations in biological stock of a given landscape (Bradshaw and Chadwick 1980; Hobbs and Norton 1996; Lamb 1998; Elliott *et al*. 2000; Lamb and Gilmour 2003); periodic analyses of restored nutrient elements in the soil; and temporal increases in intensity and volume of stream and/or river discharges; and program efficiency and flexibility (Bradshaw and Chadwick 1980; Legesse Negash 2010).

At **CNTPBDE**, we have coined a phrase '**Restoration Bioassay**' in which we asses extent of restoration through use of coffee plants (*C. arabica* L.). Coffee plants are selected because of their sensitivity to direct electromagnetic radiation (i.e., are photoinhibited, and therefore require shade from suitable native trees such as *M. ferruginea*, *C. macrostachyus*, *Cordia africana* Lam., *A. abyssinica* or *F. vasta*). They are also highly sensitive to moisture and nutrient deficits in the soil, temperature differentials of the air and the soil environment, as well as to soil micro-fauna and flora. On top of this, coffee's contribution to the economic development of Ethiopia is critical.

The objective of this study was, therefore, to use our new "**Restoration Bioassay"** approach and measure the extent of restoration of previously degraded landscape using the biological performance of *C. arabica* (e.g., extent of vegetative growth and fruiting efficiency) along with climatic factors (temperature and photosynthetic active radiation-PAR) and key soil parameters.

2. Materials and methods

2.1. Study site

The study was conducted at the CNTPBDE. Established in a degraded landscape on 10 July 2004, the CNTPBDE is located in a locality called Tulu-Korma (Ejéré Wereda, West Shewa Zone, Oromia Regional Government: 09°01'188" N; 038°21'566" E, 2,176m a.s.l. and 51-55 Km west of Addis Ababa: for almost 15 years before 2004, the area was extensively degraded due to various activities but the most common once were animal grazing and tree cutting for fuel). The rainfall pattern of the area is bimodal, with the 'little' and 'big' rainy seasons being prevalent during February to April and June to September, respectively, but this 'normal' rainfall pattern is now being increasingly upset due to climate change. The mean annual rainfall, and annual minimum/maximum temperatures of the area are 1140 mm and 8/26 º C, respectively. The soil type is vertisol on the lower slope and nitosol on the upper slope of the area.

Before the start of restoration activities back in 2004, the area was degraded, with much of the vegetation removed and the soil impoverished. But soon after the establishment of the CNTPBDE, native trees such as *Juniperus procera* Endl., *Podocarpus falcatus* (Thunb.) Mirb., *Allophyllus abyssinicus* (Hochst.) Radlk., *Dovyalis abyssinica* (A. Rich) Warb., *Albizia schimperiana* Oliv., *Prunus Africana* (Hook.f.) Kalkm. as well as other less charismatic tree and shrub species were planted and successfully established. Also, keystone tree species such as *F. vasta* and *F. sur* were established. Natural regeneration of native shrubs such as *Carissa spinarum* and *Rumex nervosus* Jacq., as well as diverse number of herb species including *Achyranthes aspera* L. and *Scadoxus multiflorus* (Martyn) Raf. occurred following establishment of native trees and protection of the area. Grass species such as *Andropogon schirenis* Hochst.ex.A.Rich. and *Arthraxon micans* (Nees) Hochst. were also the plant biodiversity that is being restored. As direct consequences of improved biological and physical conditions, establishment of *C. arabica* became evident, not only in a previously degraded landscape, but also in an ecosystem where coffee plants never used to grow naturally.

2.2. Plant material and experimental design

The coffee seeds of the same cultivar were collected from an ancient Ethiopian garden coffee growing region-Harerge, Oromia Regional State, Eastern Ethiopia; where the seeds were proven in providing high yield/tree and best caffeine contents (Yigzaw *et a*l. 2008). At the beginning of the restoration process back in 2004, various native plan species were systematically planted. In addition, for a research purpose, a specific site (with total area of 500 m^2) was identified, and an area covering 375 m^2 were planted with *C. Macrostachyus*, *A. abyssinica* and *E. divinorum* each with 125 m^2, and 125 m^2 were left open/non-shaded, for the purpose of comparative study where it is still degraded. In 2012/13, the site was categorized into four blocks depending on the extent of shade afforded by: *C. macrostachyus* (Block I, with photon flux density of 374 ± 19 $\mu mol\ m^{-2}s^{-1}$); *A. abyssinica* (Block II; mean photon flux density of 117 ± 11 $\mu mol\ m^{-2}s^{-1}$); and *E. divinorum* (Block III; mean photon flux density of 107± 9 $\mu mol\ m^{-2}s^{-1}$). Block IV (mean photon flux density of 840 ± 25 $\mu mol\ m^{-2}s^{-1}$) was the block with no shade afforded by any of the above plant species, with. Compared to the non-shading plots (which received 840 $\mu mol\ m^{-2}s^{-1}$), photon flux densities beneath *C. macrostachyus*, *E. divinorum* and *A. abyssinica* and at the top of the coffee plants were 374, 107 and 117 $\mu mol\ m^{-2}s^{-1}$, respectively. These values represent 45, 13 and 14 % respectively of shades afforded by the two shade trees and the shrub/tree.

Fig. 1 here

After progressive restoration process in 2008 and 2010, the coffee seeds were propagated under green house conditions, the seedlings hardened and planted under the shades of each plant (planted 50-60 cm away from the shade to each other) and non shade area (planted 1m away from each other). The study was conducted during the months of October to March 2012/13 with five and three-year-old plants of *C. arabica*. During the study period, based on the respective ages, the coffee plants were grouped into two, i.e., three-year-old (**3Ca; Ca** = *C. arabica*) and five-year-old (**5Ca**) coffee plants.

A total of 78 three-year-old *C. arabica* plants were randomly selected and 24 of these were systematically selected for measuring vegetative growth under the three shade levels afforded by *C. macrostachyus*, *A. abyssinica*, and *E. divinorum*. The selected plants from 3Ca were then tagged for monthly measurements starting from October 2012 to March 2013. In total, 74 5Ca coffee plants were selected and 32 of these were systematically selected from coffee plants grown in the three shade levels afforded by *C. macrostachyus*, *A. abyssinica*, and *E. divinorum* and from those grown in open-sun light conditions. These plants were permanently tagged for use in during the study period.

In addition, the 3Ca plants were grown under three different shade regimes, namely, shades of *C. macrostachyus*, *A. abyssinica*, and *E. divinorum* shade from which 24 plants (eight replicate per treatment) were randomly selected for vegetative data collection on growth performances of coffee plants grown under the tree shade regimes. Similarly, the 32 randomly selected 5Ca plants were subjected to four treatments (i.e., were grown under the shades of *C. macrostachyus*, *A. abyssinica*, or *E. divinorum*, as well as under full sun light conditions). In this set of experiments, eight replicates per treatment were used for assessing extent of coffee plant productivity as manifested through successful berry setting and bean production.

2.3. Air temperature (T_{air}) and photosynthetically active radiation (PAR)

Air temperature (T_{air}) was recorded with a minimum-maximum thermometer permanently located in the study area. The daily T_{air} of the study site was recorded for five consecutive months, and the mean monthly minimum, maximum and average T_{air} were calculated from data on daily measurements. The data on the air temperature was not designed to record at each shade canopy but was designed to determine the overall impact of under canopy tree shades through comparing the nearby air temperature of the degraded landscape.

Similarly, photosynthetically active radiation was measured using a PAR sensor (Li-Cor; Li-189; USA) over the same period of time, and the mean PAR (µmol m^{-2} s^{-1}) values were calculated. The measurements were taken on the open sun, under the canopies of *C. macrostachyus*, *A. abyssinica* and *E. divinorum*, and beneath the canopies of young coffee plants. Light measurements were taken monthly during the months of October to March (typical dry season in Ethiopia), and the day time of 9 AM, 12 PM and 3 PM.

2.4. Soil samples

Similar with the air temperature, the soil study were designed to investigate and compare the overall impact of the selected shade trees in the soil restoration process from the nearby non-restoring site. The Soil samples were collected from the restoring Sites, as well as from the non-restoring study sites located outside the CNTPBDE. Sample collections took place during February, one of the dry seasons on the study site. Soil sampling followed the zigzag method, and random sampling procedures were used to collect the samples from both the restoring and non-restoring sites. Samples were collected using 1 kg plastic pot from the soil profiles of 0-15 cm and 16-30 cm. A total of 72 samples (36 from the restoring where 18 from the soil profiles of 0-15 cm and 16-30 cm, each and 36 from the non-restoring where 18 from the soil profiles of 0-15 cm and 16-30 cm, each) were collected carefully and each were mixed to form a representative sub-samples for both sites and soil profile. Each sub-sample was labelled and marked properly, and delivered to JIJE Analytical Testing Service Laboratory for key soil measurements related with restoration. This are Soil Moisture (%), Exchangeable Bases (Ca, Na, Mg and K) (cmol(+)/Kg), Phosphorous-P (mg/Kg),Total Nitrogen-TN (%), Organic Carbon-OC (%), Micro Nutrient (Mn, Fe, cu and Zn) (cmol(+)/Kg)) analyses.

2.5. Data collection

2.5.1. Growth measurements

Vegetative development of the three-year-old coffee plants was evaluated on the four plagiotropic branches of the plant. The branches were selected from the middle region of the plants, and were oriented to the north, south, east and west directions. On these branches, the total numbers of nodes and leaves were counted. Measurements on inter-nodal and leaf lengths, as well as leaf area were made following the selection of appropriate plant branches and leaves. Leaf areas of the respective treatments were then calculated following the steps developed by Tavares-Junior *et al.* (2002) and Catalina *et al.* (2010). Total leaf area of the leaves per branch was determined by multiplying the average leaf area by the number of leaves per branch. Leaf area was calculated from the area of the rectangle determined by the leaf dimensions, adjusted by the equation:

$$c = Y/X; \text{ (Y= actual leaf area (cm}^2\text{) and X= estimated leaf area (cm}^2\text{))}$$

$$\text{Leaf area (Y)} = 0.668\,X$$

2.5.2. Berry and bean data collection

Number of red berries per plant, aborted red berries per plant, fruiting node per plant and number of berries per node were determined every month. Counting and harvesting of fully mature red berries were performed at weekly intervals, soon after assessing extent of maturity and level of berry redness (both of which occurred sporadically at the beginning). Red berries were selectively picked by hand, just after these had turned completely red and before they had started to dry. The red berries were collected in perforated plastic bags and placed in ice for transport to the Plant Propagation Laboratory at the Department of Plant Biology and Biodiversity Management (College of Natural and Computational Sciences, Addis Ababa University). Fresh weight of red berries per plant was recorded after removing any surface moisture using blotting paper. The beans were then extracted one by one, dried for two weeks at room temperature (*ca* 23/12 °C, day/night) until constant weights of beans from each of the treatments were obtained. The beans were then separated from the respective parchments (i.e., the thin coverings of the bean proper) by rubbing these between hands before the final weights of the clean beans obtained from the different treatments were recorded. As well as weights, number of viable and aborted beans, length of the dry and clean beans was measured using vernier caliper. From the above primary data, weight of beans per berry (=weight per fruit*bean/fruit weight ratio), bean-berry weight ratio, 1000 beans weight (g/1000 beans), as well as coffee yield per plant (kg/tree) (=number of fruits per tree*weight of beans per fruit) were calculated.

2.6. Statistical analyses

The mean vegetative growth, flowering and fruiting performance of *C. arabica* grown under the shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and those coffee plants growing on the less restored site under a more open sunlight conditions were analyzed using ANOVA (Sigma Plot 8.0, Systat Software, Inc.). Pair-wise T-tests were performed for comparing means of monthly measurements the different treatments, and differences were considered significant at $P \leq 0.05$.

3. Results

3.1. Environmental variables

The mean minimum and maximum T_{air} recorded from under the restoring shades (*C. macrostachyus*, *E. divinorum* and *A. abyssinica*) were significantly (P<0.001) different on monthly and annual bases. Furthermore, the mean annual maximum and minimum T_{air} of the restoring under canopy site (26.5±0.88° C and 8.37±0.38° C) were significantly (P<0.001) lower than the nearby non-restoring/shading sites (32.4±0.88° C and 14.78±0.38° C).

Photosynthetic active radiation (PAR) over the study period (among AM, MM and PM), under the restoring shades and bottom of the respective coffee plants showed a significant (P<0.001) difference. Compared to the non-shading sites, which were significantly (P<0.001) higher than the restoring sites and received 840 µmol $m^{-2}s^{-1}$; the annual average photon flux densities beneath *C. macrostachyus*, *A. abyssinica* and *E. divinorum*, were 374, 117 and 107 µmol $m^{-2}s^{-1}$, and represented 45, 14 and 13 % respectively of shades afforded by the tree shade trees. The amount of photon flux densities at the bottom of the coffee plants grown beneath *C. macrostachyus*, *E. divinorum* and *A. abyssinica* were 309, 33 and 30 µmol $m^{-2}s^{-1}$, and represented light absorption of 17, 69 and 74 % by coffee plants.

Table 1 here

The highest mean levels of soil moisture content (15.52 %), organic carbon (3.16 %), total nitrogen (0.25 %), available phosphorus (12.5 mg/kg) and electrical conductivity (EC: 0.18 mS/cm) analyzed from soil samples collected, at the soil profiles of 0-15 cm and 16-30 cm, from the restoring sites, were significantly (P<0.05) higher than the non-restoring sites (fig. 3). With the exception of Magnesium (Mg^{2+}: 14.65 cmol(+)/Kg) and Sodium (Na^{+})) (0.45 cmol(+)/Kg) ions, the mean (0–15 and 16–30 cm soil) levels of the soil exchangeable cations (Potassium (K^{+}) (1.72 cmol(+)/Kg) and (Calcium (Ca^{2+}) (31.1 cmol(+)/Kg) ions), and micronutrients [(Fe (123.12 cmol(+)/Kg), Mn (95.82 cmol(+)/Kg), Zn (2.67 cmol(+)/Kg) and Cu (4.56 cmol(+)/Kg))] were significantly (P<0.05) higher on the restoring sites than the non-restoring sites (table 2).

Table 2 here

3.2. Vegetative responses of plants

The study identified that, at the end of the measurements, the mean coffee stem height (SH) that were grown under the restoring shade of *C. macrostachyus* (39.2±0.7 cm), *E. divinorum* (40.36±2.1 cm) and *A. abyssinica* (41.3±2.1 cm) showed no significant (P>0.05) differences; however, the mean number of lateral branches (LB) development showed that, there was a significant higher value and a positive correlation (r) with PAR (P<0.05; r_{LB}= 0.84) under the restoring shades of *E. divinorum* (18.20±0.81) than coffees of *C. macrostachyus* (12.79±0.63) and *A. abyssinica* (15.04±1.01) (fig. 4).

Fig. 2 here

The mean number of nodes (NN) growing under the shade of *C. macrostachyus* (3.66±0.06) were significantly (P<0.05) higher than those under *E. divinorum* (3.23±0.10) and *A. abyssinica* (3.48±0.15). But the mean inter-node length (IL) under the restoring shade of *E. divinorum* (35.34±1.05 cm) was significantly higher and positively correlate (r) with PAR (P<0.05; r_{IL}= 0.83), than *A. abyssinica* (31.51±0.64 cm) and *C. macrostachyus* (30.48±0.48 cm) throughout the study period (fig. 5).

Fig. 3 here

Furthermore, the mean monthly number of leaves (NL) and branch leaf area (BLA) under the restoring shades of *E. divinorum* (5.43±0.20 and 85.82±1.77 cm^2) were significantly higher and positively correlate (r) with PAR ($P < 0.05$; r_{NL}= 0.83 and r_{BLA}= 0.84, respectively) than coffee plants of *A. abyssinica* (4.98±0.11 and 79.33±2.56 cm^2) and *C. macrostachyus* (4.24±0.10 and77.21±1.65 cm^2) (fig. 6).

Fig. 4 here

3.3. Berry and bean responses

A significant (P<0.05) highest mean number of red berries per plant were harvested in those coffee plants growing under the shade of *A. abyssinica* (126.37±37.5), *C. macrostachyus* (70.64±37.1) and *E. divinorum* (61.75±17.5) than coffees on less restored site (0.87±0.5). The amount of aborted mean red berries per plant showed significantly (P<0.05) highest, even collectively, in those coffees growing under the three shades (13.63±6.07) than those on non-restored area (fig. 7).

Fig. 5 here

The mean number of fruiting nodes per plant identified that, under the shade of *E. divinorum* (25.2±6.5), *A. abyssinica* (21.38±4.3) and *C. Macrostachyus* (16.67±4.5) were significantly (P<0.01) different than on degraded landscape coffees (3.5±0.2) growing coffee plants. Likewise, the mean number of berries per node were significantly (P<0.001) different and highest on coffees of the restoring shades, i.e., *A. abyssinica* (4.75±0.92) than *C. macrostachyus* (3±0.85) and *E. divinorum* (2.38±0.32), than coffee populations of the less restored site (0.25±0.1) (fig. 8).

Fig. 6 here

The mean weight of fresh berry were significantly (P<0.001) highest under the restoring shade of *A. abyssinica* (1.42±0.02 g), *E. divinorum* (1.14±0.09 g) and *C. macrostachyus* (0.94±0.6 g) than on less restored site (0.12±0.09 g). The mean number of viable beans were significantly (P<0.05) higher on the restoring shade of *A. abyssinica* (169.1±50.3), *C. macrostachyus* (106.4±54) and *E. divinorum* (95.2±31) than on less restored site (1±0.6). However, the mean the number of aborted beans were significantly (P<0.05) highest under the restoring shade of *A. abyssinica* (49.2±16.3), than coffees under the shade of *E. divinorum* (22.5±7.9), *C. macrostachyus* (20.25±11.4) and on less restored site (0.37±0.2). The mean dry weight of beans under the restoring shades of *A. abyssinica* (0.27±0.02 g), *C. macrostachyus* (0.13±0.02 g) and *E. divinorum* (0.19±0.02 g) showed a significant (P<0.05) difference than coffees on degraded landscapes (0.01±0.01g). The mean bean length obtained from coffee trees under the restoring shades shade were significantly higher *A. abyssinica* (1.16±0.05 cm), *E. divinorum* (0.82±0.02 cm), and *C. macrostachyus* (0.66±0.02 cm), than those growing on less restored site (0.44±0.02 cm). The mean coffee bean weight per thousand beans (g/1000 beans) were significantly (P<0.001) highest on the restoring shades where 276.1g from *A. abyssinica*, 192.3g *E. divinorum*, and 137.1g *C. macrostachyus*, than on less restored site with 10g. There was also considerable significant (P<0.001) higher value in the bean/berry ratios obtained from those coffee plants beneath the restoring shades of *A. abyssinica* (0.38) than *C. macrostachyus* (0.20), *E. divinorum* (0.26) and less restored site (0.01). Besides, the mean weight of beans per berry was significantly (P<0.001) highest in the restoring shade of *A. abyssinica* (0.55g), *E. divinorum* (0.3g), *C. macrostachyus* (0.19g), than coffee plants growing on less restored site (0.003g) (table 3).

Table 3 here

The overall mean yield results depict that coffee trees planted under the restoring shade of *A. abyssinica* (69.7±20g/tree) were significantly (P<0.01) different than those coffee plants growing the shade of *E. divinorum* (17.8±5.2 g/tree), *C. macrostachyus* (17.6±11 g/tree) and less restored site (0.01±0.008 g/tree) (Fig.). In addition, correlation (r) coefficients between bean yield and number of fruits per tree, on the four treatments, were all significantly (r_C=0.988/p<0.001, r_E=0.950/p<0.001, r_A=1.000/p<0.001 and r_F=0.925/p<0.01) positive and highest (fig. 9).

Fig. 7 here

4. Discussion

4.1. Environmental responses

C. arabica, occurs naturally in the undergrowth of montane rainforests of Ethiopia at altitudes of 1600-2800 m (DaMatta 2004; DaMatta *et al*. 2007; Mohammed Worku and Teklu Astatkie 2010; Taye Kufa 2012; Alemu 2015; Worku *et al*. 2015). In natural environments, limitation of single resource is uncommon and plants must simultaneously cope with a range of suboptimal resources. Understanding the response of coffee plants to the environment is imperative to circumvent environmental stresses and to target future corrective management alternatives, because coffee trees cannot grow if certain limits of these conditions are not met or if the coffee trees are more sensitive to the prevailing limiting climatic conditions (DaMatta 2004; Campanha *et al*. 2005; Morais *et al*. 2006; Daniel *et al*. 2011; Baliza *et al*. 2012; Lopez-Bravo *et al*. 2012; Millet *et al*. 2013; Tina *et al*. 2013; Nguyen *et al*. 2015). As to the ecological requirements, climate (include temperature, water, light and wind) and soil are ecological factors affecting coffee cultivation (DaMatta 2004; Campanha *et al*. 2005;Baliza *et* *al*. 2012; Mayoli and Gitau 2012; Nguyen *et al*. 2015).

Sequentially, to create an ambient micro- climate condition, shade trees have a pivotal role for coffee plantations in particular and for the integral ecological system of the coffee tracts in general (Lopez-Bravo *et al*. 2012; Millet *et al*. 2013; Tina *et al*. 2013; Nguyen *et al*. 2015). Tree shades basically help to reduce the amount of heat reaching the coffee plant during the day time and protects the coffee plants from the evening and night low temperatures as the trees will serve as a cover and protection, hence contribute for the creation of ambient micro-climate which suits well for the growth and development of coffee bushes (John 1997; Beer *et al*. 1998; Siebert 2002; DaMatta 2004; Campanha *et al*. 2005; Morais *et al*. 2006; Alemu 2015).

According to study of Millet *et al*. (2013) and Tina *et al*. (2013), the role of native species to restore the lost soil fertility, regulate the climatic conditions (T_{air} and PAR) and boost the biodiversity when planted on degraded landscapes is a well known proven fact. Research findings performed on those coffee plants growing under the canopy of natural forests or garden plantations in Ethiopia and the world indicated that, the presence of a mean T_{air} ranging between 18-22 º C was found out to be suitable for the growth and production of coffee plants (Alegre 1959; Beer *et al*. 1998; Demel Teketay 1999; DaMatta 2004; Baliza *et al*. 2012; Lopez-Bravo *et al*. 2012; Nguyen *et al*. 2015). In the case of this study; the presence of the shading trees (after 14 years) for the itinerary of restoration lead to the establishment of suitable coffee growing monthly and annual mean T_{air} (8-26 ° C) which were comparable with the natural forest habitat of Ethiopia (Alemu 2015; Worku *et al*. 2015). Therefore, the use of shading trees for restoration facilitate to: buffer the previous extreme temperature (John 1997; Beer *et al*. 1998; Siebert 2002; DaMatta 2004; Campanha *et al*. 2005; Morais *et al*. 2006; Legesse Negash 2010; Daniel *et al*. 2011; Baliza *et al*. 2012; Lopez-Bravo *et al*. 2012; Millet *et al*. 2013; Tina *et al*. 2013; Nguyen *et al*. 2015), oscillate under canopy status i.e., during the day the vegetation protects the soil surface against radiation that causes excessive heating, and during the night it minimizes thermal radiation loss (Larcher 2000; Kenich *et al*. 2006; Millet *et al*. 2013; Tina *et al*. 2013) and develop coffee plants like those growing under the natural coffee habitat (Beer *et al*. 1998; DaMatta 2004; Mouen *et al*. 2008; Baliza *et al*. 2012; Lopez-Bravo *et al*. 2012; Mayoli and Gitau 2012; Millet *et al*. 2013; Tina *et al*. 2013; Molla Mekonnen 2015).

Similar with the role of natural forests canopy to minimizing solar radiation for effective coffee growth, the restoring shade trees of the study provided a suitable shade for the under canopy coffee plants through reduction of the excessive light radiation (in our study by 75 %) and helps the photo-inhibited plant (*C. arabica*) to obtain suitable photon flux radiation (PAR) (Fahl *et al*. 1994; Beer *et al*. 1998; Elliott *et al*. 2000; DaMatta 2004; Campanha *et al*. 2005; Mouen *et al*. 2008; Pompelli *et al*. 2010; Daniel *et al*. 2011; Baliza *et al*. 2012; Mayoli and Gitau 2012; Nguyen *et al*. 2015). With the considerable canopy of the restoring shading trees, compared to the non-shading plots (which received 840 µmol $m^{-2}s^{-1}$), photon flux densities beneath *C. macrostachyus*, *A. abyssinica* and *E. divinorum* were 374, 117and 107 µmol $m^{-2}s^{-1}$, respectively. These values represent 45, 14 and 13 % respectively of shades afforded by the shade trees. Furthermore, such decreased shade level conditions reported by various researches indicated the development of certain morphological modifications and physiological adaptations of coffee plants, leads their leaves to absorb more of the energy contained in the wavelengths between 400 and 700 nm and develop high chloroplast pigments (John 1997; Fahl *et al*. 1994; Beer *et al*. 1998; Muschler 2001; Campanha *et al*. 2005; Taiz and Zeiger 2006; Mouen *et al*. 2008; Pompelli *et al*. 2010; Baliza *et al*. 2012; Mayoli and Gitau 2012).

Coffee does not appear to have very specific soil requirements (DaMatta 2004; DaMatta *et al*. 2007). Considering the key soil nutrients, the restoring sites had the higher mean organic carbon, total nitrogen, available phosphorus e*xchangeable cations* and *micronutrients* which were comparably near to the demands provided by the natural coffee forests of Ethiopia. According to soil fertility scale by Landon (1991), the total N and available phosphorus belongs to *high* (0.25 %) and *very high* (12.5 mg/kg) level, respectively; and it indicated the presence of suitable growing conditions under the restoring shades like the natural coffee forest soil fertility. In line with our results, a study performed by Legesse Negash and Birhanu Kaghew (2013) on similar site indicated that the presence of considerable quantity of available P and total N in the restoring shades of the study site are due to appropriate native trees like *A. abyssinica* and other key plant species; where they do not only 'pump' nutrients from the soil subsurface to the surface but also fix nitrogen and attract fauna and avifauna that contribute to the soil N and P level through their excreta and dead bodies. In addition, when such a native plants die, shade their leaves and/or loss the outer bark components, secondary branches, leaflets, flowers, pods, and seeds in to the soil, decomposing organisms excrete a variety of enzymes and breakdown the necromass/litters and release various macro and micro-nutrients to the soil (Nelson and Sommers 1982; Lavelle *et al*. 1993; Fahl *et al*. 1994; Myers *et al*. 1994; Marschner 1995; Raymond and Roy 1995; Cadish and Giller 1997; Beer *et al*. 1998; Bot and Benites 2005; Tesfay Teklay 2005; Mouen *et al*. 2008; Sylvana *et al*. 2008; Legesse Negash 2010; Mayoli and Gitau 2012; Legesse Negash and Birhanu Kaghew 2013; Nguyen *et al*. 2015). Moreover, the presence of key nutrients on the restoring site like the natural coffee growing forests of Ethiopia encouraged the vegetative and fruiting performances of the study coffees (Hobbs and Norton 1996; Elliott *et al*. 2000; Lara and Vaast 2007; Catalina *et al*. 2010; Baliza *et al*. 2012; Alemu 2015; Nguyen *et al*. 2015; Worku *et* *al*. 2015).

4.2. Vegetative measurements

Traditionally, all coffee plants were shade grown and most varieties are naturally intolerant of direct sunlight, and prefer a canopy of sun-filtering shade trees (DaMatta *et al*. 2007; Mohammed Worku and Teklu Astatkie 2010; Baliza *et al*. 2012; Adugna and Paul 2010). The trees not only protect coffee from direct sun light, they also mulch the soil with their fallen leaves which helps to protect the soil from excessive temperature and retain soil moisture thereof reducing evaporation (Pompelli *et al*. 2010; Daniel *et al*. 2011; Baliza *et al*. 2012; Jose 2012; Lopez-Bravo *et al*. 2012; Joel 2014).

Regarding the growth evaluations, for all the analyzed variables, it was observed that with the exception of the mean stem height and inter-node length (which is high under the shade of *C. macrostachyus*); the mean lateral branch growth, branch node number, number of leaves and branch leaf area showed relatively higher on the shade of *E. divinorum* than *A. abyssinica* and *C. macrostachyus*. The mean lateral branch growth and number of nodes became increased with decreased shade level, i.e. from *C. macrostachyus*, *A. abyssinica* to *E. divinorum*. Here, the works of Cannell (1971), DaMatta *et al*. (2007), Ronchi *et al*. (2007), Catalina *et al*. (2010), Mohammed Worku and Teklu Astatkie (2010), Baliza *et al*. (2012), Adugna and Paul (2010), Daniel *et al*. (2011), Taye Kufa (2012), Mayoli and Gitau (2012) and Nguyen *et al*. (2015) confirmed that shade on top of the coffee plants, when the level of the PAR become increases, directly influence in enhancing growth of more branches and nodes with short inter-node length. The less shaded plants, in this study *C. macrostachyus*, had more nodes with fruit, and small inter-node length where these components are directly related to the low production. Fahl *et al*. (1994) also reported a reduction of PAR, in a coffee plantation shaded, with beneficial effects to the coffee enlargement of inter-nodal length while a relative increment of PAR under the shade causes only number of branch nodes. Here, the vegetative growth responses of the coffee plants were similar with those growing under the canopy of natural forests and properly managed plantations (Mohammed Worku and Teklu Astatkie 2010; Taye Kufa 2012; Alemu 2015; Worku *et al*. 2015). On the same restoration approach, the findings of Tina *et al*. (2013) showed, native tree species therefore merit improving the survival and vegetative growth performance of not only coffee plants but also other under canopy plant species. Similarly, the impact of shades and restoration on the positive vegetative growth response of various plant species were reported in the work of Kenich *et al*. (2006), Sales-Come and Holscher (2010), Millet *et al*. (2013) and Tina *et al*. (2013).

Consequently, the mean number of leaves and branch leaf areas, the highest value were obtained from coffee plants grown under the shade of *E. divinorum*, which correlated with the lowest PAR level, than coffees under the shade of *A. abyssinica* and *C. macrostachyus*. Shading, *E. divinorum*, reduced the mean air and leaf temperatures, similar with the natural coffee forest canopies due to the dense vegetative covering established over the coffee plants. A reduction of PAR and high temperatures can be favorable for *C. arabica* leaf number and areas development (Fahl *et al*. 1994; Morais *et al*. 2006; Pompelli *et al*. 2010). In order for calculating the branch leaf area, the study primarily developed the leaf area equation (LA_Y=0.668X), which is similar with the works of Tavares-Junior *et al*. (2002) and Catalina *et al*. (2010) where LA_Y =0.667 X and LA_Y = 0.667 X, respectively. Such vegetative response is directly related with the availability of PAR responsible for photosynthesis, and it is an indication of maximizing chlorophyll content for increasing absorption of light-PAR (Friend 1984; Fahl *et al*. 1994; DaMatta *et al*. 2007; Adel and Travis 2010; Adugna and Paul 2010; Catalina *et al*. 2010; Pompelli *et al*. 2010; Daniel *et al*. 2011; Baliza *et al*. 2012; Lopez-Bravo *et al*. 2012). The result of this study is also in accord with Robakowski *et al*. (2003), Brenda (2009) and Lara and Vaast (2007) which concluded that branch leaf areas increases as light intensity decreases. It is likely that the increased branch leaf area under the restoring shaded coffee plants partly contributed for the higher rate of photosynthesis observed under this condition (Tavares-Junior *et al*. 2002; Ronchi *et al*. 2006; Taiz and Zeiger 2006; DaMatta *et al*. 2007; Lara and Vaast 2007; Catalina *et al*. 2010; Baliza *et al*. 2012). Photosynthetic rate of coffee plants grown on open sun, on the other hand, was limited by stomata closure, high leaf temperature and low internal carbon dioxide concentration (Lara and Vaast 2007; Brenda 2009; Adel and Travis 2010; Catalina *et al*. 2010; Pompelli *et al*. 2010; Daniel *et al*. 2011; Baliza *et al*. 2012). Similar results were obtained by DaMatta (2004) and Mayoli and Gitau (2012) in which the coffee plants grown under 50% shading showed higher branch leaf area and photosynthetic rate values compared to plants grown under full sun. On the contrary, it is reported that visible symptoms of vegetative damage and lack of leaf growth are caused and observed by over-heating and excess radiation intensity (Morais *et al*. 2006; Clara *et al*. 2008). Furthermore; the result of this study is in agreement with the restoration work of Millet *et al*. (2013) and Tina *et al*. (2013) where the highest leaf growth performance (number and area) were obtained on those species growing under the restoring shades of *different plants* of degraded landscape.

4.3. Fruiting measurements

According to Kenich *et al*. (2006), Shono *et al*. (2007), Millet *et al*. (2013) and Tina *et al*. (2013), restoring environmental resources, such as soil fertility, with the involvement of native trees also improved the yield of various fruit trees. In our study, the 5-year *C. arabica*'s growing under the restoring shade trees showed significant response in fruiting data than those on less-restored area; where the result indicated similarity with coffee plants of the natural forest coffee of Ethiopia (Mohammed Worku and Teklu Astatkie 2010; Taye Kufa 2012; Alemu 2015; Worku *et al*. 2015). The overall mean results on the number of green berries per plant harvested during the study period depict that coffee trees planted under the restoring moderate shade of *A. abyssinica* resulted in highest number of coffee berries unlike coffees of the other shades and less-restored area, showing the moderate radiation environment provided by shade improves viability and maturation (DaMatta 2004; Vaast *et al*. 2005; Clara *et al*. 2008; Baliza *et al*. 2012). Other studies have also shown that shading extends and improves fruit maturation to higher quality, since there is an increase on the accumulation of sugar and soluble solids. Cambrony (1992), Cadish and Giller (1997), Muschler (2001), DaMatta (2004), Campanha *et al*. (2005), DaMatta *et al*. (2007), DaMatta *et al*. (2008), Adel and Travis (2010), Catalina *et al*. (2010) and Adugna and Paul (2011), showed that shading enhances coffee quality, in terms of biochemical composition, including the contents of caffeine, oil and chlorogenic acid. The main reason according to work of DaMatta *et al*. (2008), Adel and Travis (2010), Legesse Negash (2010) and Legesse Negash and Birhanu Kaghew (2013), were due to the presence of favorable PAR level, temperature and the highest litter decomposition that leads to favorable soil nutrients (such as organic carbon, total nitrogen and available phosphorous) under the restoring shades of *A. abyssinica*. Due to this, the under canopy of *A. abyssinica* create a positive impact on the environment which is high as compared to the other shades and less-restored area and plays a vital role for those coffee plants growing. Furthermore, the result was in contrast to the harvest obtained from coffee plants growing on the open sun or less restored site, indicating that it was not amongst the suitable coffee growing sites (Vaast *et al*. 2005; Vaast *et al*. 2006; DaMatta *et al*. 2007; DaMatta *et al*. 2008; Adugna and Paul 2011; Lopez-Bravo *et al*. 2012; Mayoli and Gitau, 2012). Nonetheless, the most unstable number of red berries per plant and high mean rate of berries and beans abortion were noted from coffee plants on the less-restoring sites, and it is clearly associated with the exposure to adverse photon flux. As a result of this, the growth and development of berries became affected and produced unequal sized and low number of mature red berries (Vaast *et al*. 2005; Morais *et al*. 2006; Vaast *et al*. 2006; DaMatta *et al*. 2007; Adugna and Paul 2011).

In addition, even if the mean number of berries per node is higher on those coffee plants under the restoring shade of *A. abyssinica*, the highest mean fruiting nodes per plant occurred on coffee plants growing under the restoring shade of *E. divinorum*. For these, the main causes are due to the presence of higher shade level under the canopy of Euclea that promotes vegetative nodal growth, reduces the flowering and berries per node, keeping the number of fruiting nodes high (DaMatta 2004; Campanha *et al*. 2005; Vaast *et al*. 2005; DaMatta *et al*. 2007; DaMatta *et al*. 2008; Adel and Travis 2010; Catalina *et al*. 2010). Furthermore, similar with the findings of DaMatta *et al*. (2007), Adel and Travis (2010), Adugna and Paul 2010; Catalina *et al*. 2010; Mohammed Worku and Teklu Astatkie (2010), Taye Kufa (2012), Alemu (2015), Worku *et al*. (2015) the mean fresh weight of berry and beans, number of viable beans, bean length, coffee bean weight per thousand beans (g/1000 beans), bean/berry ratios and weight of beans per berry from the harvested berries indicated that berry/beans developed under the restoring shade of *A. abyssinica* displayed a significant higher value than those coffee trees grown on the other shades and less-restored site. The fact that the restoring *A. abyssinica* shaded coffees had larger berry and grain size, high bean weight per thousand beans (g/1000 beans), high bean/berry ratios and weight of beans per berry were mainly caused by the under canopy suitable shade effects on temperature, humidity and soil fertility which improves and controls the effectiveness of the berry ripening physiology (Barros *et al*. 1999; Amaral *et al*. 2001; Bot and Benites 2005; Campanha *et al*. 2005; DaMatta *et al*. 2007; Adel and Travis 2010; Animm and Boamah 2010; Catalina *et al*. 2010; Adugna and Paul 2011). Coste (1992), Muschler (2001), Catalina *et al*. (2010), Baliza *et al*. (2012), and Clara *et al*. (2008), who found comparable results, indicated that larger berry and grain weight and size, is a favorable characteristic that enhances market value of coffee. These results are in accordance with Morais *et al*. (2006), who also demonstrated that forest shade enhances coffee grain weight and size.

The difference in coffee yield per plant between treatments was notable. The shade of *A. abysinica* produced more coffee berries per plant during the final harvest, than coffees of the other shades and less-restored area. Coffee yields may decrease with excessive shading because of: lower whole-tree carbon assimilation under excessive shading, greater stimulus to vegetative rather than flower buds, and fewer nodes formed per branch and flower buds at existing nodes (DaMatta *et al*. 2007; Morais *et al*. 2008; Clara *et al*. 2008; Adugna and Paul 2010; Pompelli *et al*. 2010; Baliza *et al*. 2012; Nguyen *et al*. 2015). If the number of nodes is the key component of coffee production, yields should then decline with increased shading. On the other hand, when coffee plants are exposed to full solar radiation, the yield directly decline due to the fact that *C. arabica* plants are sensitive to high electromagnetic radiation that leads to physiological disease incidence, abortion of flower buds and flowering (Campanha *et al*. 2005; DaMatta *et al*. 2007; Baliza *et al*. 2012; Nguyen *et al*. 2015). However, there are other researches that like Vaast *et al*. (2006), Jose (2012), Joel (2014), RBG (2016) and WCR (2014) which indicated un-shaded grown coffee gave higher yields than coffee in the open sun with considering the coffee variety adaptation. However, the result of this study is in agreement with Perfecto *et al*. (2002), Dussi *et al*. (2005), Adugna and Paul (2011) and Baliza *et al*. (2012) since the highest yields were obtained from those coffee plants growing under the restoring shades of *A. abyssinica* than from coffee plants *C. macrostachyus*, *E. divinorum* and the less-restored site.

The finding of this study, comparable with the restoration measuring works of Mangaoang and Pasa (2003), Kenich *et al*. (2006), Millet *et al*. (2013) and Tina *et al*. (2013) showed that the shaded sites with the use of native trees enhance coffee development and production than those growing on less-restored site. Therefore, coffee under shading or full sunlight account for almost all the world's production, were originally considered shade-obligatory (Catalina *et al*. 2010; Baliza *et al*. 2012). Research findings like Perfecto *et al*. (2002), Dussi *et al*. (2005), Baliza *et al*. (2012), Jose (2012), Joel (2014) and Nguyen *et al*. (2015) have shown that dense shading and excessive radiation negatively affected coffee and other fruits production. Furthermore, it is important to highlight that it is very difficult to compare productivities obtained in different shading conditions, because the results are influenced by several factors including tree species used, tree planting density, soil and climatic conditions, coffee genotype, crop spacing and the incidence of pests, diseases and weeds (DaMatta *et al*. 2008; Adel and Travis 2010; Catalina *et al*. 2010; Baliza *et al*. 2012). As a rule, the benefits and needs of shading via restoration increase as the environment becomes less favorable and degraded for agricultural cultivation (Marschner 1995; Cadish and Giller 1997; Beer *et al*. 1998; Mouen *et al*. 2008; Sylvana *et al*. 2008; Legesse Negash 2010; Legesse Negash and Birhanu Kaghew 2013; Millet *et al*. 2013; Tina *et al*. 2013). This should reduce exhaustion of the coffee tree, and allow it to satisfactorily produce for longer, and will promote sensitive plants to grow and indicates the success of restoration (Perfecto *et al*. 2002; Dussi *et al*. 2005; Kenich *et al*. 2006; Baliza *et al*. 2012; Tina *et al*. 2013; Nguyen *et al*. 2015).

5. Conclusions

This study has shown that: through use of appropriate native trees, a degraded landscape can be restored to the extent of supporting the growth, development and reproductive processes of sensitive plants such as *C. arabica*, serving as a bioassay plant; and, the extent of restoration success can be quantified through measuring vegetative and fruiting characteristics of *C. arabica*. In addition, it is concluded in our study that coffee plants grown in the restoring shade of *E. divinorum*, *A. abyssinica* and *C. macrostachyus* had analogous vegetative growth performances; and, coffee plants grown under shady and relatively restored soil conditions produced larger and heavier beans, and provided highest coffee yield performances, compared to those grown in an exposed and relatively less restored site of the study area like those coffee plants growing under the conducive environment's of the world and Ethiopian highland forests, controlled plantations and home gardens.

Generally, the response of coffee plants grown over a previously degraded landscape and, after such restoration period has been favourable; and since coffee is Ethiopia`s major foreign exchange earner, restoring critical watersheds and establishing coffee plants in a sustainable manner shall provide significant boosts to the country not only in terms of successful restoration, but also in restoring nation`s economic, food and livelihood security.

Acknowledgements

We acknowledge the use of facilities in the Plant Propagation Laboratory and nursery at the Department of Plant Biology and Biodiversity Management (College of Natural and computational Sciences, Addis Ababa University). Thanks are due also to Addis Ababa University and ''Center for Native Trees Propagation and Biodiversity Development in Ethiopia'' for providing financial support and additional grant, respectively.

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Tables

Table 1: Extent of shading afforded by *C. macrostachyus*, *E. divinorum* and *A. abyssinica* to coffee plants grown beneath these trees. Also, quantum flux densities in non-shading coffee plants. Within a row, means followed by different letters are significantly different. Data (PAR: photosynthetic active radiation; units: µmol $m^{-2}s^{-1}$) were derived from site from the four shade treatments at CNTPBME. Light measurements were taken monthly during the months of October to March (typical dry season in Ethiopia), and the day time of 9 AM, 12 PM and 3 PM. Standard errors of means (SEs) are indicated in parenthesis. Different letters within the same row indicate significant differences between means of the three substrates after Pair-wise-T test.

Variables: Shading (PAR) extent	**Treatments**				**P-value**
	C. macrostachyus	***E. divinorum***	***A. abyssinica***	**Non-shaded**	
Above shade trees	840^{a} (36.6)	840^{a} (36.6)	840^{a} (36.6)	840^{a} (36.6)	ns
Top of coffee/ under shade trees	374^{a} (123.8)	107^{b} (13.2)	117^{c} (13.3)	840^{d} (28.6)	*
Bottom of coffee	309^{a} (117.4)	33^{b} (5.3)	30^{c} (4.5)	794^{d} (28.6)	*
PAR difference between top and bottom of coffee	65^{a} (8.2)	74^{b} (9.5)	87^{c} (9.1)	46^{d} (9.0)	*

ns: not significantly different and (*) significantly different (P<0.001)

Table 2: The mean soil physico-chemical measurements at the restoring sites and non-restoring sites (control) of the study site. Soil samples were collected from depths of 0–15 and 16–30 cm soil profile, and each data point summarizes analytical results from a composite soil sample of at least 30 individual samples. Standard errors of means (SEs) are indicated in parenthesis. The mean values of the restoring sites, and the nearby non-restoring sites were competed for Pair-wise-T test.

Variables	Treatments		
	Restoring site	**Nearby degraded site (control)**	**P-value**
Moisture (%)	15.52 (0.13)	9.6 (0.3)	*
OC (%)	3.16 (0.004)	0.9 (0.009)	*
TN (%)	0.26 (0.0001)	0.16 (0.0005)	*
P(mg/Kg)	12.5 (0.51)	3.83 (0.061)	*
EC (mS/cm)	0.18 (0.002)	0.05 (0.00002)	*
Mg^{2+} (cmol(+)/Kg)	14.56 (0.71)	15.9 (1.2)	ns
Na^{+} (cmol(+)/Kg)	0.45 (0.005)	0.5 (0.0006)	ns
K^{+} (cmol(+)/Kg)	1.72 (0.001)	0.04 (0.001)	*
Ca^{2+} (cmol(+)/Kg)	31.1 (1.18)	21.06 (2.38)	*
Mn (cmol(+)/Kg)	95.82 (3.72)	58.88 (4.41)	*
Fe (cmol(+)/Kg)	123.12 (11.09)	65.57 (12.21)	*
Cu (cmol(+)/Kg)	4.56 (0.03)	1.58 (0.003)	*
Zn (cmol(+)/Kg)	2.67 (0.07)	0.9 (0.0011)	*

(ns) not significantly different and (*) significantly different at $P<0.05$.

Table 3: The mean berry and bean performances of five-year-old *C. arabica* (5CA) plants growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and on non-restoring site at each monthly data collection. For each treatment, columns show the mean and ± S.E (n= 8 replicates per treatment). For each treatment, columns show the mean and ± SEs (n= 8 replicates per treatment). Standard errors of means (SEs) are indicated in parenthesis. The mean values of the four shade/light treatment sites were computed for each fruiting variables and compared for Pair-wise-T test.

Variables	Treatments				P- value
	C. macrostachyus	***E. divinorum***	***A. abyssinica***	**Full sun**	
Mean weight of berry (g)	0.94 (0.06)	1.15 (0.09)	1.43 (0.02)	0.12 (0.09)	***
Mean weight of bean (g)	0.13 (0.02)	0.19 (0.02)	0.27 (0.02)	0.01 (0.01)	*
Mean number of beans obtained per plant	106.5 (54.02)	95.25 (31.43)	169.13 (50.31)	1 (0.65)	*
Mean number of beans aborted per plant	20.25 (11.41)	22.5 (7.92)	49.25 (16.32)	0.38 (0.26)	*
Beans (g)/1000 beans	137.19 (15.15)	192.4 (22.43)	276.11 (22.82)	10 (7.33)	***
Bean length (cm)	0.66 (0.02)	0.82 (0.02)	1.16 (0.05)	0.44 (0.02)	***

(*) indicates significant difference at $P<0.05$; (**) indicates significant difference at $P<0.01$; (***) indicates significant difference at $P<0.001$.

Figures and caption

Figure 1: Partial view of the coffee plants growing at site I and soil surface, photographed during the study period at the CNTPBDE, October 2012/13: A, *C. arabica* growing under the shade of *C. Macrostachyus*; B, *C. arabica* growing under the shade of *E. divinorum*; C, *C. arabica* growing under the shade of *A. abyssinica*; D, *C. arabica* growing under open sun/less-restored area.

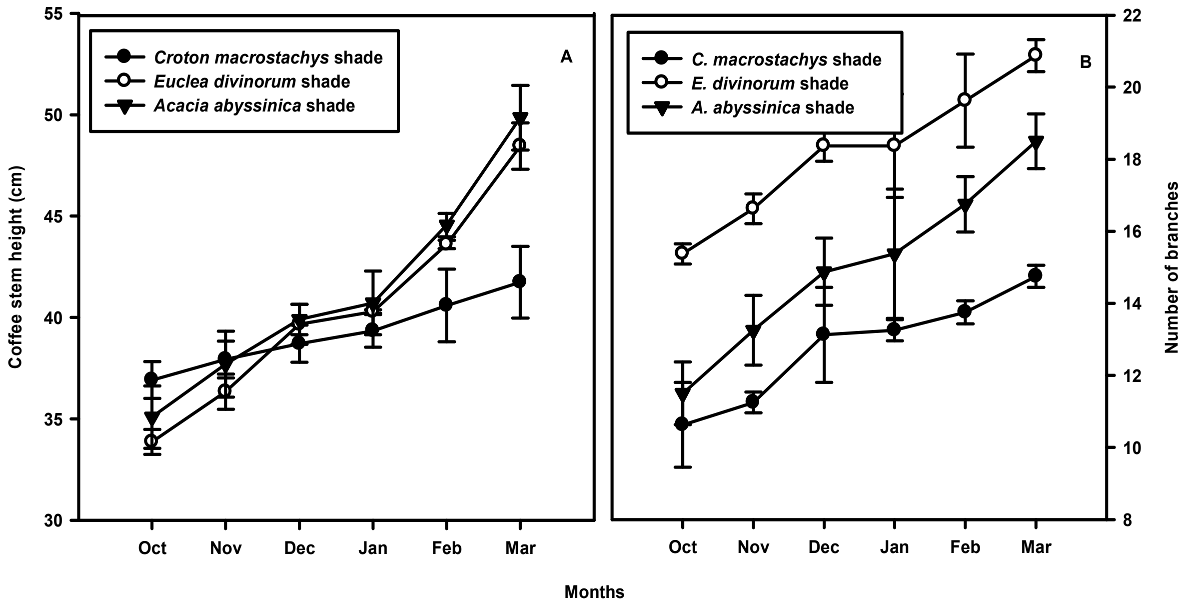

Figure 2: The mean: A, stem height (cm); B, number of branches of randomly selected three-year-old *C. arabica*, growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*. Symbols indicate mean ± SE (n = 8 replicates per treatment).

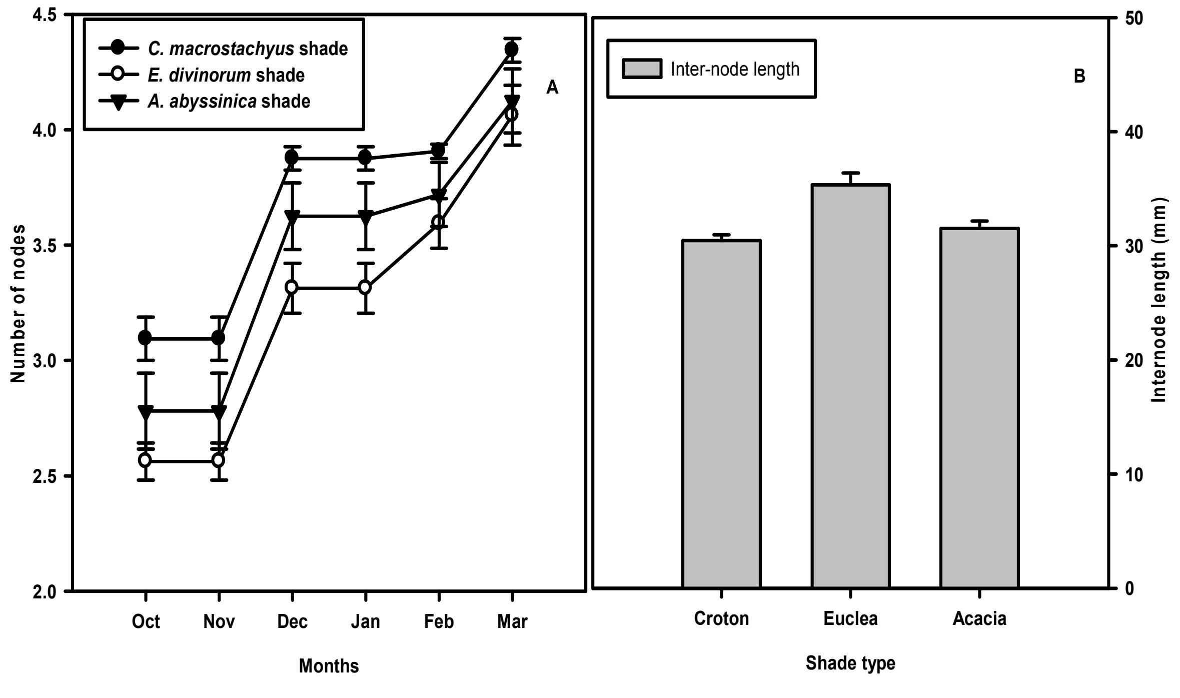

Figure 3: The mean: A, number of nodes development; B, internode length (mm) of the systematically selected four branches of three-year-old *C. arabica*, under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*. Symbols indicate ± SE (n = 8 replicates per treatment).

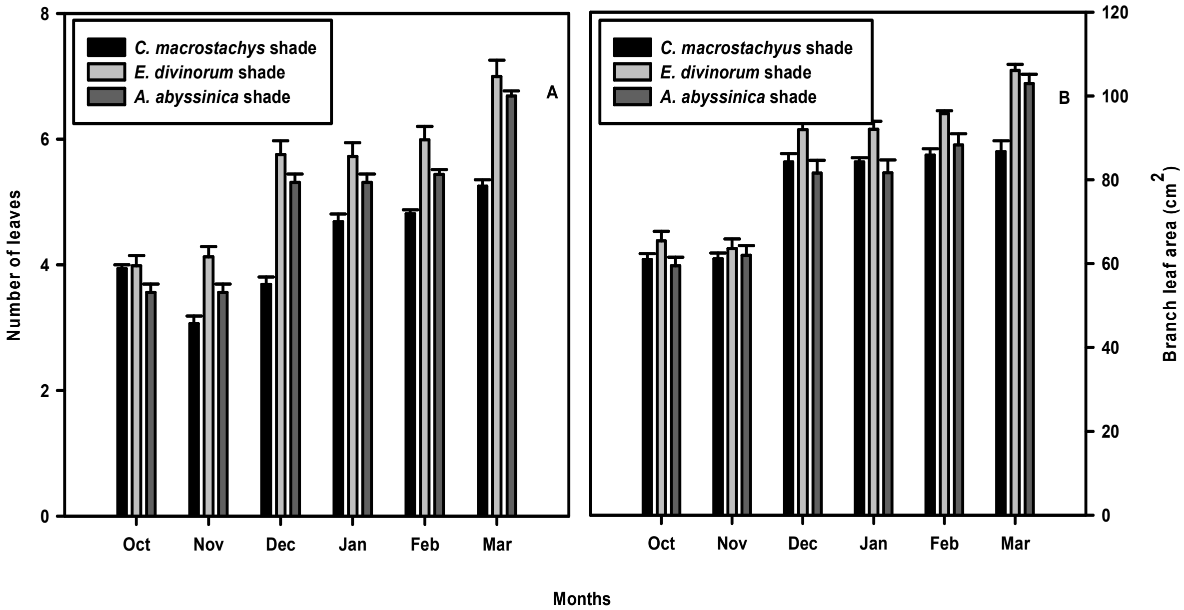

Figure 4: The mean: A, number of leaves; B, branch leaf area (cm^2) of three-year-old *C. arabica*, under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*. Bars represent ± S.E (n = 8 replicates per treatment).

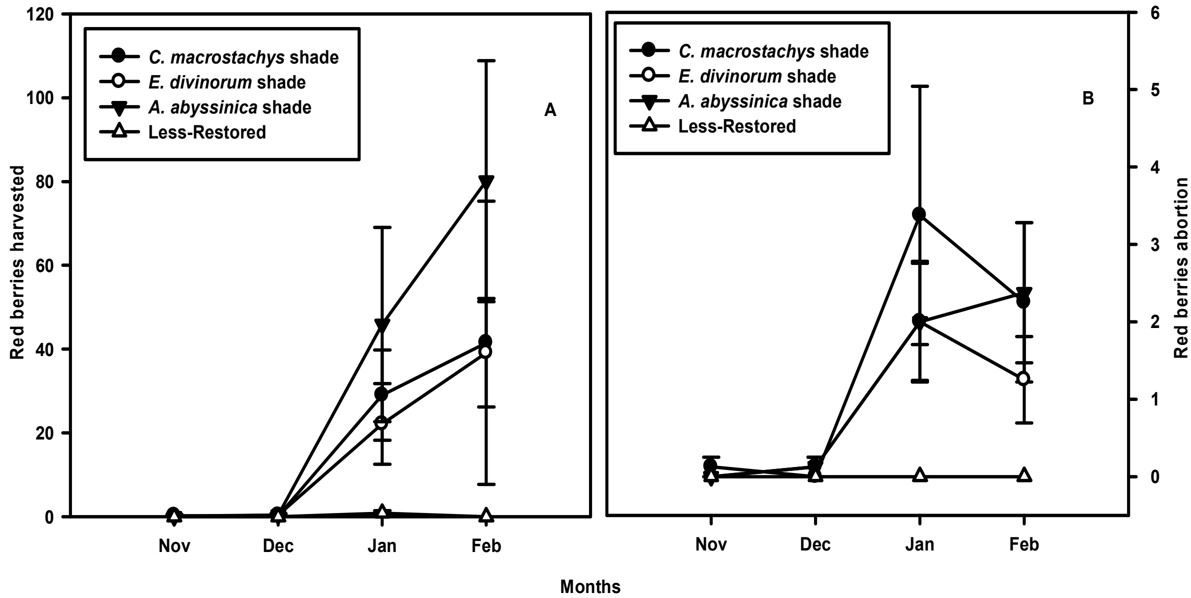

Figure 5: The mean number of: A, red berries harvested: B, red berries aborted on five-year-old *C. arabica*, growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and on open sun. Symbols indicate ± SE (n=8 replicates per treatment).

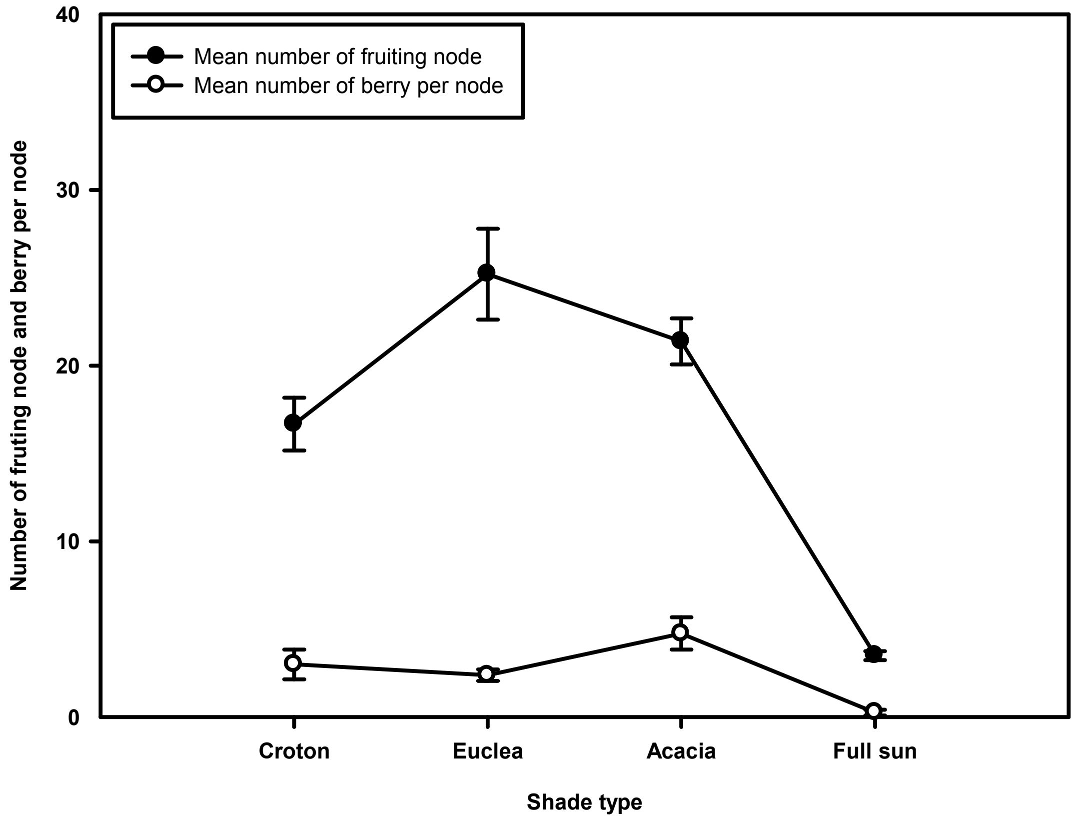

Figure 6: The mean number of fruiting nodes and berries per node on five-year-old *C. arabica*, growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and on open sun. Symbols indicate ± SE (n=8 replicates per treatment).

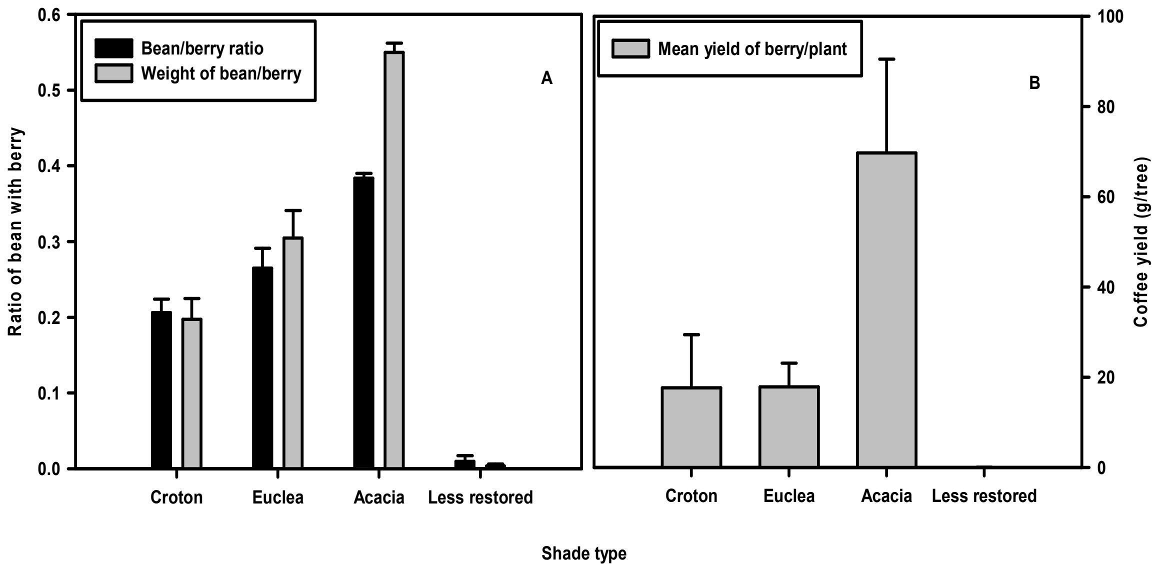

Figure 7: The mean: A, bean/berry ratio and weight of beans/berry: B, coffee yields (g/plant) obtained on five-year-old *C. arabica*, growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and on open sun. Bars indicate ± SE (n=8 replicates per treatment).