Measuring the Extent of Restoration using *Coffea arabica* L. as a Bioassay Plant

Habtamu Chekol Fantahun

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1. Prof Masresha Fetene (Examiner)	Masresha Fetene	27/06/13
2. Prof Fisseha Itanna (Examiner)		28/06/2013
3. Prof Legesse Negash (Advisor)		28/06/13
4. Prof Ensermu Kelbessa (Chairman)	Ensermu Kelbessa	28/06/2013

Measuring the extent of restoration using *Coffea arabica* L. as a bioassay plant

Habtamu Chekol Fantahun

MSc

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Abstract

This study was undertaken as part of the ongoing biological restoration efforts at the "Center for Indigenous Trees Propagation and Biodiversity Development in Ethiopia" (50-55 Km west of Addis Ababa, 09°01'188" N; 038°21'566" E). The main objective of the study was to measure extent of restoration over a degraded landscape using *Coffea arabica* L. as a bioassay plant. In order to measure this, the phrase "Restoration Bioassay" was coined for coffee plants which were established beneath *Acacia abyssinica*, *Croton macrostachyus* and *Euclea divinorum*. The trees were regenerated after 5-6 years` of intensive restoration activities. All the vegetative and reproductive responses were quantified on randomly selected 3 to 5 year-old coffee plants. Also, soil samples from the sites being restored, and those from the non–restoring adjacent areas were collected and analyzed for macro- and micro-nutrients, as well as for texture, moisture, density and electrical conductivity. Through this study, it was found that mean number of nodes, leaves, as well as internode lengths were significantly ($P<0.05$) greater for coffee plants established and maintained for 3-4 years beneath the *A. abyssinica* shades, compared to those beneath the *C. macrostachyus* and *E. divinorum* shades. Although no significant difference was found in height growth, mean leaf area of coffee plants that benefited by the shade of *A. abyssinica* was different, compared to those grown beneath the shades of *C. macrostachyus* or *E. divinorum*. Further, key physiological and/or economic indices such as number of green berries, fresh weight of berries, size of beans, mature red berry harvest per plant, berry to bean ratio, weight of bean per berry, as well as weight per 1000

beans were all significantly ($P<0.05$) higher in coffee plants grown under *A. abyssinica* than those grown under either *C. macrostachyus* or *E. divinorum*. Significant ($P<0.001$) differences in the number of flower buds and flowers were observed between the control and treatment groups in coffee plants where GA_3 levels of 100, 250 and 350 mg l^{-1} were sprayed on the leaves. Soil analyses results yielded significant ($P<0.05$) differences in soil phosphorous, total nitrogen, organic carbon, potassium and electrical conductivity between the sites being restored through use of native trees and shrubs and those that have not been restored. Compared to the non-restoring adjacent sites, the levels of available phosphorous, total nitrogen and organic carbon were found to be 54, 39 and 56 % higher, respectively, in the sites that were in the process of restoration. This study showed that restoring native trees, shrubs, herbs and grasses over a degraded landscape restores keystone natural resources with far-reaching positive consequences on economic growth, food security, biodiversity, and livelihood restoration. We, therefore, recommend that landscape restoration using native trees and shrubs must be scaled-up using mechanisms detailed in this thesis. Further, since Ethiopia`s nature and natural resources have been dilapidated for generations, and since the nation`s poverty has been the direct consequences of these actions, biological restoration must be considered Ethiopia`s priority agendum both by lawmakers and the Government that enforces the laws.

Key words/phrases: Coffee reproductive traits; Degraded landscapes; Ethiopia; Indigenous trees; Restoration Bioassay

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List of Acronyms

BLA	Branch leaf area	cm^2
CITPBDE	Center for Indigenous Trees Propagation and Biodiversity Development in Ethiopia	
GA_3	Gibberellic acid	
IL	Inter-node length	mm
LN	Leaf number	
NB	Number of branches	
NN	Number of nodes	
ns	Not significant	
PAR	Photosynthetically active radiation	$\mu mol\ m^{-2}\ s^{-1}$
r	Correlation coefficients	
s	Significant	
SE	Standard error	
SH	Stem height	cm
T_{air}	Air temperature	° C

CHAPTER ONE

1. INTRODUCTION

1.1. Scope of the problem

Deforestation has been a major problem in Ethiopia for quite a long time with serious environmental consequences. These consequences include decline or loss of biodiversity and keystone natural resources, degradation of land, possible negative effects on the local, regional and global climatic conditions as well as negative impacts on the welfare of human beings (Eshetu Yirdaw, 2002; Legesse Negash, 2010).

There have been various responses to these losses of keystone natural resources (soil and water) and biodiversity (flora and fauna). Restoration is a process that attempts to regain ecological integrity and enhance human well-being in deforested or degraded landscapes (Berger, 1993; Lamb, 1998). In the restoration process, natural succession is a key factor and the ecological principles have been used to restore degraded sites in different ecosystems (MacMahon, 1997). Natural succession on degraded sites is accompanied by an increase in ecosystem structure (species composition and complexity) and function. Therefore, the aim of restoration work is to accelerate and direct natural succession (Hobbs and Norton, 1996).

In Ethiopia, the first restoration center was established on July 2004 by Prof. Legesse Negash. The "*Center for Indigenous Trees Propagation and Biodiversity Development in Ethiopia* (**CITPBDE**)" located at Tulu-Korma (52 km west of Addis Ababa, along the highway to Ambo town in Oromia Regional Government) studies on the mechanisms for the restoration of biodiversity and keystone natural resources (including soils and water) are ongoing. Theses studies are also addressing the integrated physiological responses of various planted indigenous trees under field conditions.

Besides the efforts on restoration to recreate a stable ecosystem at the CITPBDE and its surrounding degraded landscape, is still in progress (Legesse Negash, 2010).

The mechanism of restoration requires various plant species (Bradshaw and Chadwick, 1980) and the plants should attain properties like tolerance to poor soils and water shortage (*A. abyssinica* sp.); easily dispersing seeds (e.g. *Vernonia amygdalina*); species forming mutualistic relationships with animals (e.g. *Ekebergia capensis*); fast-growing species (e.g. *Acacia abyssinica, Erythrina brucei, Millettia ferruginea*); nitrogen-fixing species (e.g. *Acacia seyal*) and species attractive to frugivores (e.g. *Dovyalis caffra*) (Berger, 1993; Elliott *et al.*, 2000; Lamb and Gilmour, 2003). Besides, plants capable of restoring water (e.g. *Ficus vasta*), restoring soil fertility (e.g. *Hagenia abyssinica*) and recycling nutrients (e.g. *Croton macrostachyus*) are essential. On the other hand, rare or threatened native species (e.g. *Juniperous procera* and *Podocarpus falcatus*) and indigenous species (e.g. *Ficus sur*, *Acacia abyssinica* and *Millettia ferruginea*) must be a part of restoration to increase their populations and enhance biodiversity (Berger, 1993; Legesse Negash, 2010).

Restoration commonly takes many years to achieve and form stable-climax community. However, some of the obvious ways to accelerate such successions are to deliberately reintroduce certain key species and seeds to hasten the process of natural recovery (Elliott *et al.*, 2000); to foster the structural complexity that attracts seed- or fruit-dispersing fauna and also to plant indigenous tree species propagated in nursery (Lamb and Gilmour, 2003). Hence the more species present the greater the structural complexity at a site is likely to be and the more likely it is to be attractive to a wider range of wildlife species (Lamb, 1998).

The extent, stability and success of restoration in a site which is being restored could be measured using different criteria such as: structural elements (plant cover, the

heights, diameters, areas and growth rate of plants); composition of the community (numbers, identity and abundance of various plant and animal species); temporal variations in biological stock (i.e., plants, animals, and microorganisms) of a given landscape (Lamb, 1998; Lamb and Gilmour, 2003); periodic analyses of restored nutrient elements in the soil, including organic carbon, N, P, K, Mg, Ca, S, Fe, Mn, Zn, etc.; and temporal increases in intensity and volume of stream and/or river discharges; and program efficiency and flexibility (http://www.ethiopian-biodiversity-restoration.org/Restoration).

The goal of this study was to measure the extent of restoration of a degraded landscape using *C. arabica* as a bioassay plant. The present study uses a new approach called Restoration Bioassay, with the aim to determine the efficiency of coffee plants on the site which is being restored through the vegetative growth, flowering and fruiting characteristics. Coffee plants are selected because of their sensitivity to direct electromagnetic radiation. They are also highly sensitive to moisture and nutrient deficits in the soil, temperature differentials of the air, the soil environment, as well as to soil micro-fauna and flora (http://www.ethiopian-biodiversity-restoration.org/Restoration). The other reason for using coffee plants was the contribution of *C. arabica* to the economic development of Ethiopia.

1.2. Objectives of the study

The general aim of the present study was to measure the extent of restoration through the vegetative growth and reproductive performance of *C. arabica* established on a site that is being restored. The other main objective was also to study the underlying eco-physiological processes such as air temperature (T_{air}), photosynthetic active radiation (PAR) and soil physical and chemical properties that associate with the *C. arabica* understory by the native woody and other plant species.

The specific aims of the present work were to:

- Measure the height, number of branches, number of nodes, inter-node length, number of leaves, leaf area and branch leaf area of three-year-old *C. arabica* established on a site that is being restored.
- Quantify the numbers of green berries, red berries, aborted green and red berries, fruiting nodes, berry per node, and beans per berry of five-year-old *C. arabica.*
- Identify the fresh and dry weight of each berries and beans obtained from five-year-old *C. arabica.*
- Determine the yield (g/tree) harvested from five-year-old *C. arabica.*
- Quantify the number of flowers, flower buds and secondary branches of four-year-old *C. arabica* (subjected to 300 mg l^{-1} GA_3, 250 mg l^{-1} GA_3, 100 mg l^{-1} GA_3 and Control) established on a site that is being restored.
- Identify and quantify the levels of soil nutrients from the restoring sites, both the physical and chemical properties, where *C. arabica* grows.
- Measure the temperature and PAR level of the study site that is being restored.
- Identify the floristic composition of the site that is being restored.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. The causes of land degradation and its consequences

Land is the basic natural resource that provides habitat and sustenance for living organisms, as well as a major focus of economic activities. Land includes not only the soil, but also water, vegetation, landscape, and microclimatic components of an ecosystem (Lamb and Gilmour, 2003). Land degradation is the process of progressive deterioration of biological (flora and fauna) and physical (soil, water, micro-climate, etc.) resources of the land, leading to declining productivity and unsustainable yields as a result of degradation of soil quality and also its loss for effective use (Singh, 1995). According to FAO (1995), land degradation refers to a temporary or permanent decline in the productive capacity of the land.

There are many driving forces compelling people in Ethiopia to over-exploit natural resources like land. The main ones are the poverty with rapid population growth, improper land use, absence of a land use policy, and ineffective implementation of existing laws and guidelines (Mulugeta Lemenih, 2004). Unplanned agricultural practices, and encroachment on forest areas for agriculture and settlements, also put pressure on scarce land resources. Unplanned or inadequate rural infrastructure development and the growing demands of increasing urbanization are also devouring productive land (Tesfay Teklay, 2005).

Land use in Africa has been characterized by a significant amount of land degradation and conversion (Malik, 1999). Deforestation, overgrazing and agricultural activities are major causes of land degradation across Africa (Oldeman *et al.*, 1990). Many poor African pastoralists and farming households respond to declining land productivity by abandoning their existing degraded pasture and cropland, and moving to

new lands for grazing and cultivation. Similar practices are certainly true in Ethiopia where agriculture accounts for most land use and thus is probably the single most powerful influence on environmental quality. At the same time, agriculture remains the principal source of livelihood for the rural poor in the country (Malik, 1999).

The lag in agricultural productivity advancement behind population growth has caused intense land use conflicts, particularly between the agricultural and the forestry sectors in Ethiopia. To compensate for the low agricultural productivity, deforestation for arable land expansion has been the principal land use change employed in Ethiopia for centuries (Mulugeta Lemenih, 2004).

Rate of deforestation in Ethiopia, which amounts to 163,000 - 200,000 ha yr^{-1}, is one of the highest in tropical Africa (Reusing, 1998). As a result, the natural forest cover in Ethiopia has declined considerably from approximately 40% to just less than 3% (Kuru, 1990), a process that has further exacerbated land degradation in the country. Deforestation has been a major problem for quite a long time with serious consequences to Ethiopia. These consequences include degradation of land and water bodies, decline or loss of biodiversity, possible negative effects on the local, regional and global climatic conditions as well as negative impacts on the welfare of human beings (Eshetu Yirdaw, 2002; Legesse Negash, 2010).

As a result of deforestation, Ethiopia's forests and woodlands have been declining both in size and species richness. Due to the continuing encroachment, it is highly probable that the present fragmented forests in the highlands are much more impoverished in terms of floristic diversity than the forests which once occupied the same site (Eshetu Yirdaw, 2002). The number of species and intra-specific genetic diversity in fragmented forests will diminish over time after isolation owing to a variety of factors, such as inbreeding and genetic drift (Turner and Corlett, 1996). In fact, deforestation has eroded

the biological diversity to such an extent that some plants are faced with local extinction. Some of the remnant tree species in the northern and central highlands are endangered, since they are found as isolated individuals, and their ability to form viable population is very much in doubt. It has been estimated that 2.5% of the higher plant species were lost due to deforestation in the montane regions of tropical Africa between 1981 and 1990 (FAO, 1993).

Land degradation in Ethiopia is also exacerbated by soil nutrient depletion arising from continuous cropping together with removal of crop residues, low external inputs and absence of adequate soil nutrient saving and recycling technologies (Bojo and Cassels, 1995; Sahlemedhin, 1999). A continental study commissioned by the FAO in 38 sub-Saharan Africa countries, including Ethiopia, showed that Ethiopia is one of the countries with the highest rates of nutrient depletion. The aggregated national scale nutrient imbalances were -41 kg ha^{-1} yr^{-1} for Nitrogen, 6 kg ha^{-1} yr^{-1} for Phosphorous and 26 kg ha^{-1} yr^{-1} for Potassium (Stoorvogel and Smaling, 1990). It has long been known that soil organic matter and other soil properties decline rapidly following tropical forest clearance, burning and subsequent cultivation (Cairns, 1988).

However, the rates and magnitudes of the loss of soil organic matter and other soil properties are highly variable depending on several factors such as soil type, climatic factors and land use intensity (Parfitt *et al.*, 1997). Even so, in Ethiopia, one of the tropical countries with considerable deforestation experience (Kuru, 1990), few scientific studies have been made on soil quality and biodiversity changes following deforestation and land use intensification (Tesfay Teklay, 2005).

These biophysical changes have both social and economic impacts, with the most immediate effects being felt by communities that depend on forests for part or their entire livelihood. Therefore, these problems call for urgent and all-out actions for the

restoration of degraded and destroyed areas using indigenous trees (Legesse Negash, 2002). Because sustainable productivity of ecosystems depends to a large extent on the buffering capacity provided by having rich and healthy indigenous forests (Legesse Negash, 1990; Reusing, 1998) it is extremely important that they are conserved, propagated, and developed to the extent possible in order to facilitate the mechanism of restoration (Legesse Negash, 2010).

2.2. Responses towards landscape degradation

There have been various responses to the losses of biodiversity and key natural resources, and variety of approaches can be used to overcome these forms of degradation (Urbanska *et al.*, 1997). Depending on the objectives of the project on the degraded landscapes, the following three responses are available.

- "**Restoration**" only for those situations where the intent is to re-establish an ecosystem as close as possible to that which originally existed at the site. The site then contains most of the original plant and animal species, retain the lost key natural resources and has a structure and productivity matching that originally present (http://www.ethiopian-biodiversity-restoration.org/Restoration);
- "**Rehabilitation**", on the other hand, is used where the original productivity or structure is regained as well as some, *but not all*, of the original biodiversity. This might be because commercial imperatives demand the use of certain agricultural or timber species to justify the rehabilitation effort or because the site has become unsuitable for some of the original species (Parrotta *et al.*, 1997); and
- "**Reclamation**" is used for situations where productivity or structure is regained but *biodiversity is not*. In fact, native species may not be used at all. In such cases there are few, if any, benefits to landscape biodiversity but there may be social or

economical advantages or functional gains such as improved watershed protection (Lamb and Gilmour, 2003).

The three approaches differ in the extent to which they enable the original biodiversity to be regained (Urbanska *et al.*, 1997). Therefore, one of the best responses to attain all the needed lost biodiversity, key natural resources and ecological stability is restoration (Elliott *et al.*, 2000). Restoration incorporates both biophysical and socioeconomic values; that is, ecosystem restoration as well as the changes in human well-being associated with it (Lamb and Gilmour, 2003). It is important to consider the social and economic impacts of forest restoration initiatives, particularly the effects on people living in or near the restored forest area (Elliott *et al.*, 2000).

2.3. Defining restoration

In a field encompassing as many disciplines as restoration ecology, an unequivocal definition of goals and directions is necessary. Restoration ecology can be defined as the scientific study of human-facilitated recovery processes (Lamb and Gilmour, 2003). In this literature, two main emphases have developed: goal-oriented and process-oriented restoration.

If goal-oriented restoration is considered, it is to create a self-supporting ecosystem that is resilient to perturbation without further assistance, recover the species composition, structure and function of the original ecosystem prior to perturbation (Bradshaw, 1990). It focuses on the science of reconstructing functioning ecological systems. A paramount value of a goal-oriented definition of restoration is its emphasis on restoring a self-maintaining and/or self-perpetuating ecosystem (i.e., restoring dynamic processes characteristic of all mature ecosystems which, over long periods of time, become characterized by ecologically acceptable structure and function despite species turnover)

(Urbanska *et al.*, 1997). Another emphasis is the integration of a restored patch into the larger ecological landscape in which it occurs (Bradshaw, 1990).

In addition, if restoration is considered as process-oriented, it deals with the integration of ecological principles and human social systems (Urbanska *et al.*, 1997). A process-oriented definition of restoration shifts the emphasis from replication of pre-disturbance condition and allows restoration to encompass all actions necessary to ensure the return of a natural ecological state (MacMahon, 1998). This concept places the goal-oriented tenets of ecosystem reconstruction and the judgment of ecological integrity into an applied perspective that concentrates on facilitating recovery without requiring historical comparisons.

For the purposes of this thesis, as in most practical applications of the term, restoration integrates components of both definitions.

2.4. Restoration of degraded ecosystems

Restoration ecology has developed from, and has been practiced primarily through on site-based approach. The restoration of a well defined area such as a mine site, wetland or a degraded ecosystem of some description is generally attempted (Backes, 2001). However, it is clear that relatively large areas of the earth are in need of some form of restoration, following degradation through overuse or inappropriate management, which has impaired the functioning of the landscape as a whole (MacMahon, 1998).

Forest restoration, in passive or active processes, can be a primary component of conservation and sustainable development programs which provide people with the opportunities not only to repairing the damaged ecology, i.e. providing the goods and help re-establish those ecological services or functions no longer being provided by the lost environment or restore some degree of biodiversity to degraded landscapes (Elliott *et al.*, 2000), but also to improve the human conditions by creating livelihood diversifications,

renewing economic opportunities, rejuvenating traditional cultural practices as well as boosting the confidence of local communities (Bradshaw and Chadwick, 1980).

In a country like Ethiopia where a rapidly growing human and animal population are inducing overexploitation of the available productive natural resources, restoration of the vast degraded landscapes that exist in the country will have a valid and important role in paving the way for sustainable development (Legesse Negash, 2010). According to Eshetu Yirdaw (2002), reversal of land degradation and restoration of the productive capacity of the degraded land is a necessity and not an option in Ethiopia, especially if most of the livelihood and economic development are to continue to emerge from the agricultural economy.

There are diverse approaches and techniques to land and vegetation restoration (Bradshaw, 1990). Past efforts to restore degraded agricultural lands in Ethiopia were predominantly characterized through import and distribution of chemical fertilizers. However, the restoration process, natural succession is a key factor and the ecological principles have been used to restore degraded sites in different ecosystems (MacMahon, 1997). Natural succession on degraded sites is accompanied by an increase in ecosystem structure (species composition, complexity and the resulting interactions) as well as function thus leading to ecosystem development. Therefore, the aim of the restoration work is to accelerate and direct natural succession. However, it is clear that these natural factors alone are rarely enough to allow rapid ecosystem development and hence they should be augmented by human input. In order to provide this input, it is necessary to understand the factors limiting succession at each point of its progress and relieve them (Bradshaw, 1990).

From the ecological and social point of view, both landscape and site-level considerations must be taken into account when deciding where to intervene restoration.

At the landscape level, a useful beginning for decision-making could be to identify remnant forests, especially those with high conservation value (critical environmental and social values) (Parrotta *et al.*, 1997). These could be used as starting points around which to carry out site-specific interventions. At the site level, restoration can be carried out on a range of locations, from severely degraded sites to those that are only slightly disturbed and need only a few years of protection before recovery is underway (Hobbs and Norton, 1996). Because of the importance of integrating both biophysical and human well-being aspects into landscape restoration, there must be a strategic focus in deciding where to take action.

2.5. Restoration approaches

A variety of methods can be used to overcome forest degradation. In many, if not most cases in the past, the most common approach has been to simply restore economic productivity (Backes, 2001). Other alternatives are now possible. Some approaches attempt "complete" ecological restoration; others have the goal of production gains together with improvements in biodiversity and ecosystem function (e.g. watershed protection, reductions in salinity) that lead to more sustainable forms of production (Hobbs and Norton, 1996).

In the case of ecological restoration, several preconditions must be met before recovery is possible, irrespective of the method used (Reay and Norton, 1999). Only then may it be feasible to attempt restoration. A key issue is deciding how much intervention is needed beyond simply protecting the site from further disturbances; that is, how many species must be deliberately brought to the site and how many can be relied upon to colonise unaided (Hobbs and Norton, 1996)? Extensive testing may be required before determining which species to use (Table 1). Native species from the immediate area are

clearly most desirable but exotic species may be appropriate in some situations (Backes, 2001).

Table 1. The characteristics of plants involving in the restoration of degraded landscapes. Taken from Lamb and Gilmour, 2003.

Species type	**Purpose**
• Native species	• to enhance biodiversity
• Species attractive to frugivores	• to encourage seed dispersal
• Species forming mutualistic relationships with animals	• to foster wildlife populations
• Rare or threatened species	• to increase their populations
• Fast-growing species	• to occupy site and exclude weeds
• Species tolerant of poor soils	• to facilitate rehabilitation
• Nitrogen-fixing species	• to improve soil fertility
• Fire tolerant trees	• to use in fire-prone landscapes

Passive restoration

In this case restoration is achieved by simply protecting the site from further disturbances and allowing natural colonisation and successional processes to restore ecosystem biodiversity and structure (Berger, 1993). This approach is best suited to situations where degradation is not extensive and residual forest patches remain or some advanced forest regrowth is already present (Lamb and Gilmour, 2003). Consequently, the best locations are likely to be places where previous disturbances occurred in the past and some recovery has already occurred (Hobbs and Norton, 1996). On the other hand, recently disturbed sites where the disturbances were slight or short-lived may also be

suitable because they are more likely to have a larger pool of residual seedlings, seed in topsoil or old but live stumps (Backes, 2001).

Enrichment planting

Not all regrowth or secondary forests have high levels of biological diversity. Many have been disturbed so many times in the past that only a small number of relatively common species remain (Allen, 1997). In these cases it may be useful to supplement biological diversity by reintroducing certain key species to hasten the process of natural recovery (Dobson *et al.*, 1997). For example, it might be necessary to quickly increase the population of several particular plant species that would find it difficult to re-establish under the passive restoration approach. These might be endangered plant species, plants with large seeds that are poorly dispersed or plants needed by a particular wildlife species (Backes, 2001).

Direct seeding

In many cases, the rate of natural succession is limited by the slow dispersal of seed across degraded landscapes (Berger, 1993). An obvious way to accelerate such successions is to deliberately reintroduce the seed (Lamb and Gilmour, 2003).

Various forms of direct sowing have been used: in some cases the seed has been broadcast or sown by hand; in others it has been sown from aircraft (Hobbs and Norton, 1996). Usually the seed must be sown on bare soil so that it can establish quickly in weed-free conditions (Berger, 1993). The advantage of direct seeding is its low cost; there is no need to raise seedlings in nurseries and they can be spread across the landscape easily, including sites that might be difficult to reach when carrying boxes of seedlings (Hobbs and Norton, 1996).

Scattered tree plantings

Another way to accelerate successions is to foster the structural complexity that attracts seed- or fruit-dispersing fauna into the degraded landscape from nearby intact forest (Allen, 1997). One method involves planting small numbers of scattered, single trees or clumps or rows of trees, which form perches for birds (Berger, 1993). Seedlings are produced from seed shed below the perch trees. Eventually the clusters of seedlings grow up to form trees and become bird perches themselves (Backes, 2001). The clumps of trees enlarge and the process continues. The trees initially planted might be one or more species with seed not dispersed by animals (e.g. species with large fruit or seed or wind-dispersed species) or those where fruiting only occurred infrequently (Brown and Ewel, 1987). The approach is probably most useful in abandoned farmlands with grasslands or shrubs and at sites without many trees (Lamb and Gilmour, 2003).

Close-spaced plantings using limited numbers of species

A variant of the approach above is to use more closely spaced plantings of a small number of species able to attract seed-dispersing birds. These early plantings act as "nurse trees". The approach has been referred to as the framework species method (Backes, 2001). Although the planting density is high (1000 trees per ha, or even more), which means the treatment cost is higher than the scattered planting approach, the total cost is reduced by the small number of species used (Lamb and Gilmour, 2003). This eliminates the need to collect seeds from a large number of species and raise them in the nursery. One option is to plant species from early successional stages, which will create the conditions for the later arrival of a more diverse community (Backes, 2001). Alternatively, species might be chosen because they are tolerant of the site conditions or because they are attractive to wildlife and are able to reproduce quickly and spread across the site (Brown and Ewel, 1987).

The advantage of this approach is that once the trees are established, they soon out-compete grass and weeds, making it easier for the species brought in by seed-dispersing animals to become established (Lamb and Gilmour, 2003). The approach is especially suited to areas close to intact forest that can act as a source of seeds (and wildlife); this allows additional species to be recruited quickly.

What all these approaches have in common is that successions are initiated or accelerated without any clear knowledge of the direction they may take (Backes, 2001). It is assumed that other plant species will colonise the sites over time from nearby forest remnants. It is also assumed that animals will be able to migrate to and reoccupy these new communities once appropriate habitats are formed (Dobson *et al.*, 1997).

2.6. Native tree as a pathway for restoration

Several studies from the world have reported that both soil fertility and diverse native flora and fauna can be restored under fast growing indigenous plants established on degraded sites (Lugo, 1992; Fisher, 1995). This phenomenon has led several ecologists to propose fast-growing plantation species as an ecological management tool for the restoration of degraded lands in the tropics (Parrotta *et al.*, 1997).

Native tree restoration established on degraded sites long devoid of a native tree cover can act as successional catalysts, facilitating the re-colonisation of native flora through their influence on understory microclimate (Colin and Lauren, 1999; Legesse Negash, 2010) and soil fertility, suppression of dominant grasses and provision of habitats for seed dispersing animals (Parrotta, 1995).

Native tree planting contribute to conservation of biological diversity, both at the site and landscape level. Extensive restoration with native species can help ameliorate long-term environmental degradation in badly eroded landscapes, restoring not only ecological functionality but also site productivity (Lamb and Gilmour, 2003). Sustainable

conservation and utilization of the remaining vegetation resources and restoration of those that have already been degraded would provide economic, social and ecological benefits (Tefera Mengistu *et al.*, 2004).

Plants are by far the most important means of primary production, and, therefore, the recovery of an adequate plant community is central to any plan for restoring degraded land (Hobbs and Norton, 1996). Some of the plants which are responsible for restoration includes Keystone species (like *Ficus vasta, F. sycomorus* subsp. *sycomorus, F. sycomorus* subsp. *gnaphalocarpa and F. sur*) and native species (including *Acacia abyssinica, Croton macrostachyus, Podocarpus falcatus, Millettia ferruginea, Prunus africana, Hagenia abyssinica*), and other indigenous plants. The common goals for vegetation establishment in restoration situations usually include:

(i) Enhanced mineral weathering (ii) input of organic matter, (iii) nutrient pumping and recycling, (iv) symbiotic N-fixation, (v) interception of particles and dusts (e.g. aerosols) in the air, and (vi) improved soil structure through root action (Lamb and Gilmour, 2003; Legesse Negash, 2010). There are also indirect beneficial effects of restoring native trees and shrubs which include improved microclimatic conditions under the stand canopy, e.g. increasing the relative humidity and modulating temperature, thus fostering effects for the recolonization of diverse flora and fauna (Legesse Negash, 2010).

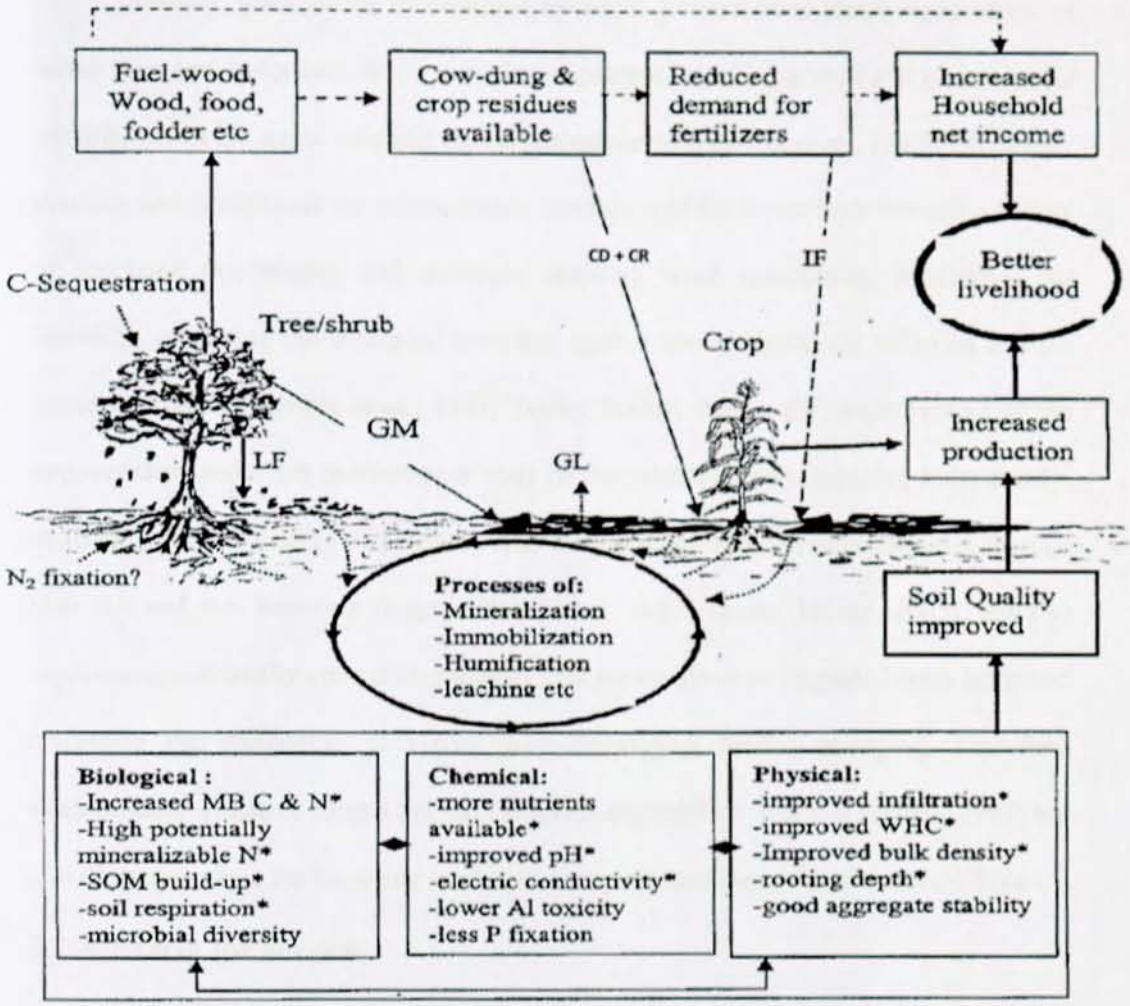

Figure 1. A theoretical model illustrating the uses of trees in improving soil quality and their contribution to better livelihood of people (Al= Aluminum; C= Carbon; CD= Cow dung; CR= Crop residues; GL= Gaseous losses; GM= Green manure; IF= Inorganic fertilizer; LF= Litter fall; MB= Microbial biomass; N= Nitrogen; P= Phosphorous; SOM= Soil organic matter; WHC= Water holding capacity). Asterisks indicate properties that can be used as minimum dataset in assessing soil quality, according to Karlen *et al.*, (1997). [For further information, see Karlen *et al.*, 1997: *Soil Science Society of America Journal* **61,** on the article "soil quality: concept, definition, and framework for evaluation"]

Similarly, some of the mechanisms by which planted trees foster regeneration of native flora and fauna include: (i) provision of perches for visiting birds and a corridor for wildlife, which are major seed and fruit dispersal agents (Parrotta *et al.*, 1997); (ii) canopy shading, which improves the microclimatic conditions of the forest floor through a variety of functions (moderating soil moisture, reducing wind desiccation, moderating air humidity, protecting the emerging seedlings against strong direct sun radiation and the consequent heat) (Keenan *et al.*, 1997; Tesfay Teklay, 2005); (iii) improvement of the impoverished and often nutrient-poor soils of degraded lands by reducing bulk density, increasing the availability of nutrients, and accumulating more organic material through litter fall and root turn-over (Lugo, 1992; Fisher, 1995; Tesfay Teklay, 2005); and (iv) suppressing potentially competitive grasses that are common to degraded open lands and increasing the probability of native shade-demanding species emerging. Therefore, establishment of native forests not only reverses degradation of a site (Fisher, 1995) but also creates a refuge for incoming seeds and emerging seedlings of native woody flora.

2.7. Criteria for success

In most situations an outcome at a particular site is said to be successful when the stated objective has been achieved without compromising the environments and rights of other land users (Lamb and Gilmour, 2003). The situation is more complicated than it seems, however. Just how closely must the restored site attributes match those of the target? Must it be a 100 per cent match, or is 80 per cent sufficient to achieve "success"? And how can success be defined in the case of restoration projects involving complex mixes of biological, physical, social and economic outcomes?

A number of possible criteria are available. These are not expressed as absolute numbers but rather as values relative to what might be expected if the site were developing appropriately (Allen, 1997). In each case an appropriate trigger for taking

remedial action (e.g. replanting) will need to be decided (Berger, 1993). Three types of indicators might be used to monitor ecological trends: indicators of landscape stability; program efficiency; and flexibility.

Landscape stability

The first type of indicators relate to landscape stability. Apart from the most obvious indicator of all, whether or not the site is still subject to disturbances, criteria include structural elements such as the extent of plant cover or tree density, the heights of plants and the extent to which the community is developing an under-storey as well as an over-storey (Brown and Ewel, 1987). Some measure of the health or vigour (i.e. growth rate) of these plants might be appropriate (Dobson *et al.*, 1997).

The second component of stability involves the composition of the community, such as number, identity and abundance of various plant and animal species, including weeds and pest species (Lamb and Gilmour, 2003). Determining the presence or absence of particular life forms (e.g. herbs, grasses, shrubs etc.) might also be useful (Reay and Norton, 1999). A particularly crucial indicator may be whether these various species are reproducing *in situ* or whether they are dependent on seed sources from outside.

The third component of stability involves indications that the new plant community has developed appropriate functional responses and has stabilized the soils or improved the quality of water in streams draining the catchment (Reay and Norton, 1999). In the case of restoration projects involving a production element, some indication of production results (yield) might be appropriate (Berger, 1993).

Program efficiency

The second ecological category of indicators measures the efficiency of the program. The efficiency determines whether the new community is self-sustaining or is it still dependent on supplements and inputs such as fertilizers or weed control (Hobbs and

Norton, 1996). Besides, the indicators also assess public involvement and participation in program, income provided to community, decreasing need for weed and pest control because these are scarce or have been excluded and decreasing need for irrigation (Reay and Norton, 1999).

Flexibility

Success might also be measured by the third category, flexibility, which indicates the capacity of the new system to be used for alternative, unforeseen purposes such as recreation, gathering herbs or mushrooms or protecting particular wildlife species (Lamb and Gilmour, 2003). In addition, the success using flexibility involves increasing kinds of alternative land use possible, increasing public ecological awareness (especially in children) and increasing economic flexibility (Backes, 2001).

Socio-economic indicators

Stability indicators reveal the extent to which human populations using the new forest and the lands surrounding it do so in a sustainable way. If the human populations are themselves more or less stable and the patterns of land use and food production are constant then the restoring landscape has a chance of being able to develop without further disturbances (Allen, 1997). A crucial element for the success of any restoration program is whether the local community is involved in its development or desires its success (Backes, 2001). The extent to which the community continues to be actively involved in a project is thus an important indicator of its likelihood of success.

However, these indicators will not be appropriate in all situations and more specialized factors might be needed in certain conditions (Lamb and Gilmour, 2003). Therefore, judging restoration success must move beyond single component comparisons to a matrix of measurements that document the structural and functional recovery of disturbed systems (Lamb and Gilmour, 2003). This synthetic approach incorporates

measures, called vital ecosystem attributes, of current and potential future plant structure and function, faunal relationships, soil condition, water and nutrient availability, and micro-symbiotic effectiveness to create a more inclusive picture of the recovering landscape (Allen, 1997).

2.8. Measuring extent of landscape restoration at CITPBDE

Can the extent of restoration be measured at CITPBDE? Yes, it can be measured at different levels. One obvious way is to observe temporal variations in biological stock (i.e., plants, animals, and microorganisms) of a given landscape. But it can also be measured through periodic analyses of restored nutrient elements in the soil, including organic carbon, N, P, K, Mg, Ca, S, Fe, Mn, Zn, etc., as well as changes in biodiversity (number of species and the concomitant interactions) of the landscape in question. Temporal increases in intensity and volume of stream and/or river discharges can also be used for measuring the degree of restoration (http://www.ethiopian-biodiversity-restoration.org/Restoration).

But extent of restoration can also be measured through use of appropriate plant species that would serve as bioassay organisms. To this effect, a phrase called "*Restoration Bioassay*" has been coined and has used *C. arabica* as a bioassay species.

Coffee plants are selected because of their sensitivity to direct electromagnetic radiation (i.e., are photoinhibited, and therefore require shade from suitable indigenous trees such as *Millettia ferruginea*, *Croton macrostachyus* and *Acacia abyssinica*) (DaMatta, 2004). 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 (http://www.ethiopian-biodiversity-restoration.org/Restoration).

2.9. Bioassay

Bioassay (commonly used shorthand for biological assay), or biological standardization is a type of scientific experiment conducted to measure the effects of biotic and abiotic components, on enzymes, cells, tissues, living organism, microhabitats and environments (http://www.en.wikipedia.org/Wiki/Bioassay).

For environmental testing, bioassays provide an integrated picture of overall toxicity of an effluent or a sample of water, sediment, or soil from a contaminated site. The idea behind these bioassays is that the test organism will react in a predictable way to various types of environmental contaminants.

However, a new concept and phrase, called **"Restoration Bioassay"** has been developed at CITPBDE by Prof. Legesse Negash, where restoration is measured through use of appropriate plant species that would serve as bioassay organisms. To this effect, *C. arabica* has been used as a bioassay species (http://www.ethiopian-biodiversity-restoration.org/Restoration). In this case, either qualitative (e.g. overall robustness) or quantitative (e.g. weight of produced coffee berries and/or beans) data of the bioassay plant may be used so as to determine and evaluate extent of restoration.

2.10. *Coffea arabica* L.

2.10.1. History, origins and spread of *C. arabica* over the world

According to legend, the rise of coffee began in the year 600 with the discovery of Arabica coffee (Smith, 1985; Tadesse Woldemariam *et al.*, 2002). The story goes that a goat herder by the name of Kaldi was herding his goats in the mountain forests of what is now called Ethiopia. Kaldi was having a nap and his goats wandered off. When Kaldi awoke hours later his goats had disappeared. Kaldi panicked and went looking for his animals. When he finally found them, the strangest thing caught his eyes. His goats were very active, dancing on their hind-legs. Further investigation showed that they had been eating from a strange tree with red cherries. Kaldi worried even more now and was afraid his goats might get sick after eating the funny cherries (Steiger *et al.*, 2002).

It took Kaldi quite some time, but finally he managed to gather his animals and take them home. Kaldi didn't tell anything to his parents, but the next day when he took his goats out, they immediately went back to the same bush and started eating again! Kaldi, seeing that the cherries didn't seem to harm his goats, took some cherries as well. He noticed the effect immediately and felt energetic and very awake (Haarer, 1962)!

Kaldi took the cherries home and showed them to his parents, which gave them to some of the monks in a nearby monastery (Steiger *et al.*, 2002). The monks were very happy with the strange berries, because chewing these kept them awake during long praying sessions. The monks started drying the cherries so that they could be transported to distant monasteries. There the monks added water to the dried cherries, ate the fruit and drank the liquid (Smith, 1985).

After Kaldi discovered the berries, words about the refreshing berries spread through the Middle-East. Coffee berries moved from Ethiopia to the Arabian Peninsula and were cultivated in what is now called Yemen. In Yemen the people used the skin of

the berry to make a sort of tea. It was not until it reached Turkey where people started to roast the coffee beans that coffee as we know it now was discovered (Steiger *et al.*, 2002).

During that time the Arabs tried to guard the secret of coffee. Nobody was allowed to travel with live coffee berries or beans. Only in roasted form was coffee allowed to be transported. Although coffee was already available in roasted form in England and other European countries around 1640, live seeds and plants had yet to be seen by non-Arabs (Chaparro *et al.*, 2004).

It was not until early 1700 that the Dutch managed to smuggle a coffee plant from Yemen and the world truly became familiar with coffee. The Dutch introduced it first in Java, Indonesia and from there it spread quickly (Steiger *et al.*, 2002). Coffee houses quickly spread across Europe, becoming centers for intellectual exchange. In the 1700's, coffee found its way to the Americas by means of a French infantry captain who nurtured one small plant on its long journey across the Atlantic (Haarer, 1962). This single plant, transplanted to the Caribbean Island of Martinique, became the predecessor of over 19 million trees on the island within 50 years. It was from this humble beginning that the coffee plant found its way to the rest of the tropical regions of South and Central America (Smith, 1985).

Today, coffee is a global industry employing more than 20 million people. It ranks second to petroleum in terms of worldwide trade. With over 400 billion cups consumed every year, coffee is the world's most popular beverage. Presently, coffee is grown in over 80 countries (http://www.en.wikipedia.org/Wiki/Coffee).

2.10.2. Taxonomy of *C. arabica*

According to studies based on morphological data coffee trees, tropical woody plants of the Rubiaceae are classified into two genera (Berthaud and Charrier, 1988). These are the genus *Coffea* L. and *Psilanthus* Hook f. The genus *Psilanthus* includes

subgenera *Paracoffea* and *Psilanthus* (Hook f.), but the genus *Coffea* L. includes two sub-genera, *Baracoffea* and *Coffea*. The genus *Coffea* L. differs greatly in phenotypic features such as size, adaptation, habits etc. and thus its taxonomic history was very debatable (Smith, 1985; Lashremes *et al.*, 1997). Although the taxonomy is debatable and confusing, different authors classify the genus *Coffea* in terms of genera and sections. For the first time, Linnaeus classified coffee tree as a separate genus *Coffea* with the only one known species of *C. arabica*. More recently, Smith (1985) classified the *Coffea* into four sections containing *Eucoffea, Argofea, Masarocoffea* and *Paracoffea*. The first three sections of the genus *Coffea* are exclusively native to Africa, Madagascar and some adjacent islands. On the other hand, most representatives of *Paracoffea* are indigenous to India, Malaysia, Ceylon and Southeast Asia. The *Eucoffea* is divided into five subsections, *Erythrocoffea, Nanocoffea Pachycoffea, Melanocoffea and Mozambicoffea* (Lashremes *et al.*, 1997). The species of the subsections of *Eucoffea*, the rainforest taxa of tropical forest, are typified by *C. arabica* which is confined to Ethiopia and the rain forest belt of the Congo River drainage of central Africa and rain forest areas of West Africa.

More recently, however, combination of morphological and molecular data set revealed that Rubiaceae is enlarged to encompass eleven genera. These include *Argocoffeopsis*, *Belanophora*, *Calycosiphonia*, *Coffea* L., *Diplospora*, *Discospermum*, *Nostolachma*, *Psilanthus*, *Tricalysia*, *Sericanthe*, and *Xantonnea* (Davis *et al.*, 2007). Among these genera, the species of the genus *Coffea* is economically the most important. Out of the 103 species of the genus *Coffea* currently enumerated by Davis *et al.*, (2006), only three species namely, *Coffea arabica* L., *Coffea liberica* Hiern. Hiern, W.P. and *Coffea canephora* Pierre ex A. Froehner belong to the subsection Erythrocoffea (Wrigley, 1988) and are economically important (Pearl *et al.*, 2004). Out of these three species, *C.*

arabica is by far the most important commercial species and is one of the world's most important commodities (Vega *et al.*, 2003).

Unlike all coffee species that exhibit the characteristics of C_3 plants and are diploid with 22 chromosomes, Arabica coffee is the only known autogamous (95%) alloteraploid (2n=4X=44) species in the genus (Smith, 1985; Lashermes *et al.*, 1995).

2.11. Geographical distribution of *C. arabica*

2.11.1. Native range

The natural habitats of all *Coffea* species are the understorey of African tropical forests, probably to the highlands of Ethiopia. Many natural populations of *C. arabica* are restricted to the highland forests of south-western Ethiopia, where the climate is considered subtropical, rainfall is high, and soil pH is slightly acidic (Berthaud and Charrier, 1988) at altitudes of 1600-2800 m. The species occur in the montane rainforest areas in Ethiopia and it is the only known center of origin and genetic diversity for the highland arabica coffee (Smith, 1985; Taye Kufa, 2012). It occurs as a mid-story species in semi-open forest, rather than in dense tropical rainforest.

The center of origin of *C. arabica* is geographically separated from all other centre of origin of other species of coffee. Distribution of wild *C. arabica* is on the opposite sides of the Great Rift Valley, which is south west of the Rift Valley and east and south east of the Rift Valley (Anthony *et al.*, 2001). In Ethiopia, the major coffee producing areas include: the administrative zones of west Wellega, Illubabore, Jimma, Lekempti, Sheka-Kefa, Bench-Maji, Yayu, Anfillo, Sidamo, Gedeo, west Harerge, Limu, Tepi and Bebeka (Tadesse Woldemariam and Feyera Senbeta, 2008). Small *C. arabica* populations from outside of Ethiopia were also reported, but are confined on the Boma Plateaus of the Sudan and Mount Marsabit in Northern Kenya (Smith, 1985; Friis, 1992).

Figure 2. Major coffee producing areas of Ethiopia.

[Source: (http://www.en.wikipedia.org/Wiki/Ethiopia/Coffee).]

2.11.2. Current distribution

Coffee is currently grown as a major crop in tropical and subtropical regions of Africa (Ethiopia, Kenya, Tanzania, Uganda) and Asia (such as India, Thailand, Indonesia, and Vietnam); South and Central America, Papua New Guinea, the Caribbean (e.g., Jamaica, Cuba, and Puerto Rico), and the Hawaiian Islands.

Coffee can be found growing in two major growing regions that are distinguishable by their periodicity of seasonal growth. Countries like Kenya, Tanzania, and central Colombia have two cycles of shoot elongation and flowering occur annually, regulated by two distinct wet/dry cycles. Shoots grow slowly during the cool/dry cycle, suggesting an additional influence of temperature (Maestri and Barros, 1977). In addition, coffee producing countries like Ethiopia, India, Central America, Brazil and Hawaii possess a single cycle of vegetative and reproductive growth (Vasudeva and Ramaiah, 1979). Shoot elongation coincides with increasing day length, the onset of a wet period after drought, and warmer temperatures, but the responses to these environmental factors interact and vary by region (Clowes and Allison, 1982).

2.12. Climatic requirements

2.12.1. Rainfall and temperature

Rainfall requirements depend on the retention properties of the soil, atmospheric humidity and cloud cover, as well as cultivation practices. The optimum annual rainfall range is 1200-1800 mm for *C. arabica* (Alegre, 1959; Willson, 1999). Abundant rainfall throughout the year is often responsible for scattered harvest and low yields. Lack of a dry period can also limit coffee cultivation in lowland tropical regions (Maestri and Barros, 1977). Precipitation in excess of 2500 to 3000 mm begins to be detrimental (Wrigley, 1995).

The optimum mean annual temperature range for *C. arabica* is 18-21 °C (Alegre, 1959). Above 23 °C, development and ripening of fruits are accelerated, often leading to loss of quality (DaMatta and Ramalho, 2006). Relatively high temperature (above 25 °C) during blossoming, especially if associated with a prolonged dry season, may cause abortion of flowers (Camargo, 1985) and growth impairment (Willson, 1985). It should be noted, however, that selected cultivars under intensive management conditions have allowed *C. arabica* plantations to be spread to marginal regions with average temperatures as high as 24-25 °C, with satisfactory yields (DaMatta and Ramalho, 2006). On the other hand, in regions with a mean annual temperature below 17 °C, growth is largely depressed. Occurrence of frosts, even if sporadic, may strongly limit the economic success of the crop (DaMatta and Ramalho, 2006) and leaves (Willson, 1985).

2.12.2. Humidity and wind

Air humidity has a significant impact on the vegetative growth of the coffee tree. Humidity plays a role in governing the loss of water or moisture by evapo-transpiration. When it is high, loss of water is reduced and vice versa. Especially it is important during the dry season as high humidity decreases the stress on the coffee trees thereby extending

the rainless period through which the plants will survive without damage (Demel Teketay, 1999). Arabica coffee successfully grows under less humid atmosphere, comparable to that of the Ethiopian highlands (Haarer, 1958; Coste, 1992).

Wind may have different effects on the growth and yield of Arabica coffee. In coffee plantations subjected to large wind shears and advection, crop yield is usually depressed. Wind stress may lead to a reduction of leaf area and internode length of the orthotropic and plagiotropic branches (DaMatta and Ramalho, 2006), in addition to severely damaging leaves and buds and exacerbating shedding of developing flowers and fruits (DaMatta *et al.*, 2004). Hot winds increase crop evapotranspiration and therefore the rainfall (or irrigation) requirements of the trees increase. Where strong wind is frequent, windbreaks or shelter trees are to be recommended as both may improve crop performance.

2.12.3. Light

Coffee has evolved as a shade adapted species, because it is native to the forested Ethiopian highlands (Cannell, 1985). The photosynthetic rate is more efficient in shade leaves (Willson, 1999). In their native habitats, arabica coffee produces few flowers, as floral initiation is light dependent. This limits the amount of fruits that a tree can produce. In high light intensities, arabica coffee trees produce greater number of flowers and thus cherries. As coffee cannot shed excess fruit, the tree becomes committed to filling these coffee beans, requiring inputs such as minerals and nutrients greater than can be sourced (Willson, 1985).

2.13. Soil requirements

Although Arabica coffee tolerates soil pH from 4 to 8, pH of 5.2 to 6.2 is preferred. Good drainage is essential, and soil textures lighter than clays are best (Willson, 1985). In fact it grows well in the clay-silcaceous soils of granite as it does on soils of volcanic origin with diverse characteristics or even on alluvial soils (Taye Kufa, 2006). Water holding capacity and depth are the other two properties to be considered. Since it provides sufficient available water, higher water holding capacity helps to maintain evapo-transpiration during dry season, while deep soils allow root proliferation by offering a larger volume of soil which contains more water and nutrients around the coffee trees (Demel Teketay, 1999). Deep soils are especially necessary in areas where there is a long dry season coupled with lower rainfall. Arabica coffee can grow well on deep soil. Soils with high organic matter and also available phosphorus (which is essential for shoot growth and leaf initiation) are highly suitable (Taye Kufa, 2006).

2.14. Morphology of *C. arabica*

2.14.1. Coffee stem, shoot growth and maturity

Arabica coffee is a perennial, C_3 understory woody species, ranging in size from small shrubs to 16 meter tall trees (Wrigley, 1995). The species is well known by its two types of branches (Demel Teketay, 1999; Taye Kufa, 2006); orthogeotropic which grow vertically and is commonly called suckers, and plagiogeotropic branches which have different orientation angles in relation to the main stem and are commonly called primaries (Taye Kufa, 2006). Primary branches give rise to secondary branches, which in turn split to tertiary branches and that also branch to form quaternary branches (Warmer, 1964). The bark of the species is light grey, thin, and becomes fissured and rough when old; and the wood is light-colored, hard, heavy, and tough (Charrier and Berthaud, 1985).

The dimorphism of branches is highly fixed; the apical meristem of the main stem gives rise to the head-of-the-series bud which appears in the axil of the leaf primordium at the stem apex; the buds-of-the-series appear only after the formation of the generative zone of the internode. The head-of-the series buds on the orthotropic branch grow out as a precocious, sylleptic, plagiotropic, first order branch (Clowes and Allison, 1982) and seem to be determined from the time of their inception in the apical meristem (DaMatta *et al.*, 2007). In the first and higher order branches the vegetative apex forms the head-of-the-series and buds-of-the-series in the leaf axils (Warmer, 1964). The former rarely gives rise to flowers, whereas the buds-of-the-series may give rise, by prolepsis, to higher order shoots, develop into inflorescences or remain undifferentiated (DaMatta *et al.*, 2007). An interaction seems to exist between the two primary meristems of the same orthotropic node that control the sylleptic ramification and between the meristems of the same node and the neighbouring ones. Regrouping secondary branches on certain first order branches and floral axes on others may take place (DaMatta *et al.*, 2007).

The arabica coffee plant enters into a reproductive stage in its third year of life, but plants do not reach full maturity until their fifth or sixth year (Cambrony, 1992). Wild coffee plants found in the montane forests of Ethiopia can reach 100 years or more, but generally arabica plants remain economically productive for around ten years (Demel Teketay, 1999).

Coffee grows throughout the year, but growth and development varies continuously due to temperatures, rainfall and day length (Wrigley, 1988). In equatorial regions there may be one or two rainy seasons each year, respectively producing one or two blossoming and fruiting stages each year. Therefore, in some countries there are two separate coffee harvests each year (Cannell, 1985).

2.14.2. Leaf morphology

The leaves of Arabica coffee are simple with short petioles and interpetiolar stipules; and arranged oppositely on stems and decussate, with successive pairs of leaves arising at 90°angles from each other around the stem. The mature leaves are evergreen, glabrous, shiny and yellowish to dark green, and newly growing leaves are brownish and shiny; ovate to elliptical blades of 7–20 cm long; 3–7 cm wide (Wrigley, 1995); prominently veined with interveinal areas raised; waxy and smooth with entire margin and acuminate tips at both ends (Gilman, 1999). Although some species lose their leaves at the start of the dry season, others maintain leaves for three or more years (Wrigley, 1988). Moreover, on the lower surface of the leaves there are small cavities called domatia bulging out on the upper surface of the leaves (Fikru Meko, 2005). According to Warmer (1964), the location, shape, size and constitution as well as the absence or presence of hairs around the opening of the leaf domatia and the presence or absence of stomata on the outermost cell layer of domatia have been used to distinguish *Coffea* species and varieties

Figure 3. Pictures representing different leaf colours: (1) a mature leaf with deep green; (2) apical leaf pairs with brownish; and (3) young leaf with light green color of *C. arabica*. [Photographed from five-year-old (**Right**) and three-year-old (**Left**) *C. arabica* at CITPBDE, Tulu-korma.]

2.14.3. Flowers and flowering

Flowers of *C. arabica* are white, fragrant, pleasant fragrant, profuse, aggregates (inflorescence), massed in thick clusters at leaf axils along the branches, corolla has 5 narrow lobes, longer than the tube, which is about 1 cm long (Barros *et al.*, 1978; Gilman, 1999). Although, self-fertilizing, *C. arabica* fertilization benefits from insect pollinators such as bees (Klien *et al.*, 2002). The floral parts are pentamorous (5 parts); united sepals; 5 linear petals fused into a slender corolla tube at their base; 5 stamens inserted in the corolla tube; long anthers on slender upright filaments; pistils with inferior, bicarpellate ovary containing 2 ovules and a short style with 2 short pointed stigma (Klien *et al.*, 2002).

Coffee flowering embraces a complex sequence of biochemical, physiological and morphological events which are affected by several factors such as temperature, light, soil and air water availability, carbon-to-nitrogen ratio, crop load and genotype (Barros *et al.*, 1999). Unequal fruit ripening is practically inevitable under natural conditions because coffee blossoming in non-equatorial regions as in south-central Brazil occurs at different times (e.g., from August to November in major Brazilian coffee production areas), in two to four or more gregarious and synchronized blossom periods (Klien *et al.*, 2002). In addition to the temporal and physiological hierarchy of flower bud initiation and differentiation within each branch, and also among different nodes of the same plagiotropic branch (which are strongly affected by environment-genotype interactions), the occurrence of sporadic and sometimes low-intensity rains during the latter phases of flower bud development is believed to be one of the factors responsible for several blossom periods in arabica coffee (Rena *et al.*, 1994).

Under natural conditions, dormancy of flower buds is often broken by the first rains in the season following a dry period (Barros *et al.*, 1978). The time between

breaking of the dormancy and anthesis may vary between four to ten days depending on temperature and atmospheric humidity (Taye Kufa, 2006). The flower of *C. arabica* remains for two to four days, and the flower buds start to wither and its all parts drop except the ovaries (DaMatta *et al.*, 1999).

Figure 4. The flowering parts of *C. arabica*: (A) newly growing Flower buds; (B) flower buds about to blossom; and (C) blossom coffee flower. [The pictures were taken from CITPBDE. Tulu-korma.]

2.14.4. Fruits and fruit formation

The fruit of coffee trees, known as coffee berries or beans, range in size and colour depending upon the species and stage of maturity. Fruit is dark red, yellow, or pink when ripe, drying to dark brown, ovoid, fleshy berry about 1.2–1.6 cm long, 1–1.2 cm in diameter, usually containing two seeds (Wrigley, 1995).

While *C. arabica* is self-compatible, most, if not all other coffee species are self-sterile (DeMatta and Ramalho, 2006). Phillips (1970) observed little effect on the initial fruit set in *C. arabica* bushes caged with honey bee colonies, though the yield of mature berries increased by 50 %. These results are suggestive of a pollen grain population effect; as a large number of pollen grains germinate on the stigma and usually several pollen tubes grow within the style (Raju *et al.*, 1975). It is thus conceivable that fertilization and

initial fruit set are not affected by the degree of pollination, but further retention of the fruits has some relation with the number of germinated pollen grains.

Several factors affect fruit set in coffee including both leaf (Phillips, 1970) and flower (Raju *et al.*, 1975) number on the branch, carbohydrate supply (Cannell, 1971) and flower atrophy (Huxley and Ismail, 1969). Apart from any effect of floral atrophy, fruits will not develop if a viable embryo sac is not formed, pollination does not occur or, after pollination, if the normal process of fertilisation is affected in any way (Huxley and Ismail, 1969; Klein *et al.*, 2002). Fruit set is also affected by environmental factors such as heavy rains both during flower expansion and at anthesis (Awatramani and Satyanarayana, 1973), mineral nutrition, and sudden temperature drops (Barrose *et al.*, 1999). In addition to varying with species and cultivars (Srinivasan, 1972), fruit set also depends on the flower position on the plant (Barrose *et al.*, 1999): the higher the branch position the greater the percentage of fruit set.

The developmental stages for coffee fruit after fertilization have been recognized differently and it is summarized as follows (Clowes, 1977; Cannell, 1985; Barros *et al.*, 1999):

(1) The pinhead stage, which spreads over the first 6 to 10 weeks after blossoming, when growth is negligible. Fruits at this stage cannot be regarded as dormant, since they have a high respiration rate. Growth of the pericarp and seeds is mostly by cell division instead of by cell expansion.

(2) The second phase, the rapid swelling stage, lasts about 10 weeks, somewhere from the sixth to the 17th week of development; fruits increase rapidly in size and fresh mass. The expansion of the integument sets the maximum size of the bean. Cell expansion predominates by the end of this stage.

(3) The stage of suspended and slow growth lasts approximately two weeks, when the final size of the fruit is attained, but its dry matter is still low.

(4) In the endosperm filling stage, from approximately the 17th to 28th weeks, dry matter increases regularly, with little change in fresh mass. Dry matter is deposited mainly in the beans (seeds), which reach their final dry mass when the fruit is still green. Maturity of the beans becomes complete when not only their maximum dry matter content is reached, but maximum germination capacity as well.

(5) During the last stage of development, the ripe stage, changes occur mostly in the pericarp, which increases in size and fresh and dry mass, and becomes red or yellow. Ripening may spread over a period of about l0 weeks, from the 24th to the 34th week from blossoming. It must be added that while the whole fruit may still accumulate dry mass the seed may lose dry mass once matured, if it remains attached for a longer time to the mother plant (Clowes, 1977). Loss of seed dry mass may be due to interruption of the translocation of photo assimilates from the fruit to the seed, seed deterioration and substrate consumption by respiration. In fact, respiration of the pulp increases during ripening, as does the sugar content (Eira *et al.*, 2006).

The growth pattern of *C. arabica* fruits has been described either as following a double sigmoid-shaped curve (Geromel *et al.*, 2006), or an approximately linear curve (Cunha, 2007). In any case, the growth pattern may vary with a number of factors including environmental conditions, characteristics used to measure fruit growth (e.g. length, diameter, volume, fresh and dry mass etc.), fruit component parts (whole fruit, seed or embryos), sampling frequency, statistical models and coffee species, variety or even clones (Ronchi *et al.*, 2006).

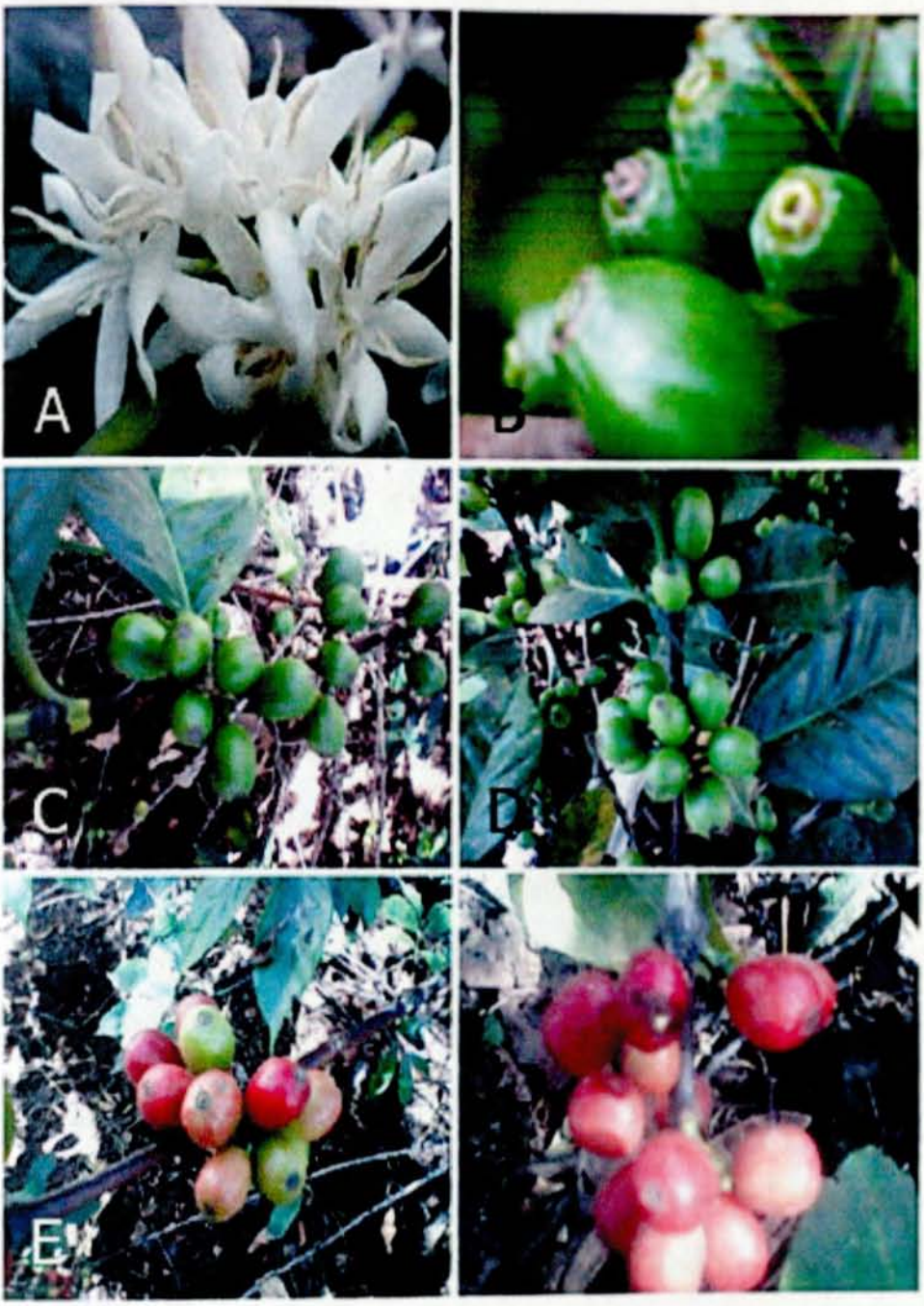

Figure 5. Stages on the development of coffee berries: (A) coffee flowering; (B) pinhead stage (size of pinheads is around 2-4mm); (C) rapid swelling stage; (D) suspended and slow growth stage; (E) endosperm filling stage; and (F) ripening stage. [Photographed in different time of the study at CITPBDE, Tulu-korma.]

The coffee beans or seeds are contained within the fruits of the coffee tree, which at maturity turn red and are thus referred to as coffee cherries/ berries. There are typically two seeds per coffee berry packed with the flat end facing each other, but that is not always the case. A special case which is common is called pea berry which is a single seed (Barros *et al.*, 1999). But, there can be more than two in a coffee berry also (Barros *et al.*, 1999).

The outer skin (exocarp) of the coffee berry is generally tough and can withstand handling. The inner pulp (mesocarp) of the coffee berry is generally mushy (Eira *et al.*, 2006). In a few types of coffee plants, the pulp is more valuable than the bean itself. This is because the coffee berry pulp has high sugar content and can be fermented making coffee liquor or a tea made from the pulp. The coffee berry parchment (endocarp) shell is fairly tough. This is taken off in the last coffee bean processing stage. However, the coffee silver skin is so thin and attached so well it tends to stay with the coffee bean right up to roasting. When roasted, the silver skin can, and usually does, crack off the coffee bean. The silver skin cracks off because it does not expand like the inner coffee bean does when roasted (Barros *et al.*, 1999).

2.14.5. Roots

The main part of the root system of an arabica coffee tree is generally concentrated in the first 0.30 m layer from the soil surface and distributed in a circle of about 1.50 m in diameter around the trunk (Huxley and Turk, 1976). The root system of arabica coffee species is highly plastic and its distribution and length are also age-dependent, in addition to varying with planting density, genotypes, soil characteristics, cultural practices, and weed competition (Ronchi *et al.*, 2006). Root growth of arabica coffee varies markedly in the soil profile as well as along the seasons (DaMata *et al.*, 2007). In Kenya, following a

long dry period, a relatively greater growth of roots was observed between 0.45 m and 0.75 m from soil surface and nearby the main trunk. After a rainfall, however, the greatest growth was found in the soil surface at 0.70 m from the trunk. The growth of the roots is thus seasonal and often precedes the start of shoot growth (Huxley and Turk, 1976).

The movement of assimilates towards the trunk-root system increased when the shoot growth was depressed, which might lead to an increase in the root growth (Cannell and Huxley, 1969). During the Kenyan hot dry season (January-February), dry matter of all the vegetative parts of the arabica coffee trees increased negligibly with the exception of the rootlets less than 3.0 mm in diameter (Cannell, 1971). At the beginning of the Long-Rains period in Kenya (February-March), when shoot growth was high, some growth of the rootlets still occurred, but roots thicker than 3.0 mm practically ceased growing.

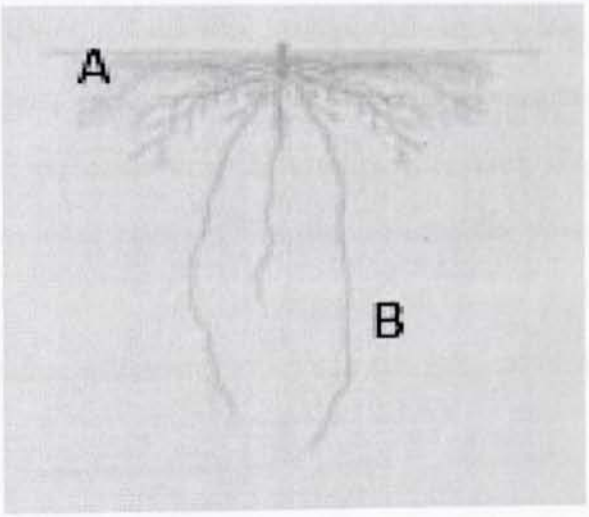

Figure 6. Mature root morphology of *C. arabica*: (A) surface root (10-25 cm); and (B) deep root (70-90 cm). [Source: (http://www.en.wikipedia.org/Wiki/Coffee).]

2.15. Photosynthesis, stomatal activity and photo-inhibition in *C. arabica*

2.15.1. Photosynthesis and stomatal activity

Arabica coffee tree has low rates of net CO_2 assimilation (**A**), typically in the range of 4-11 mmol m^{-2} s^{-1} with current natural atmospheric CO_2 concentration and saturating light, which is in the lower range recorded for trees (Ceulemans and Saugier, 1993). Values for **A** have been averaged at 7.2 µmol m^{-2} s^{-1}, and maximum stomatal conductance at 108 µmol m^{-2} s^{-1}, for arabica coffee. The photosynthetic capacity for *C. arabica*, determined under saturating light and CO_2 (~5 kPa), reaches values as high as 30-40 µmol m^{-2} s^{-1} (Silva *et al.*, 2004). The low values of *in situ* **A** has been associated with diffusive (stomatal and mesophyll), rather than biochemical, limitations to photosynthesis (DaMatta *et al.*, 2001).

For single leaves, the saturating irradiance is relatively low, ranging from about 300 to 600-700 µmol photons m^{-2} s^{-1}, with shade leaves showing the lowest values (Fahl *et al.*, 1994). However, because many leaves are partly to deeply shaded within the coffee canopy, with leaves in the interior of the crown of adult coffee trees receiving as little as 1.5% of full solar radiation, it may be suggested that canopy photosynthesis would be saturated at irradiances considerably higher than 600-700 µmol photon m^{-2} s^{-1} (DaMatta, 2004).

Coffee plant exposition to high irradiance can seriously impact on its performance by limiting photosynthesis, resulting in reduced net carbon gain and plant growth (Almeida and Maestri, 1997). When the light intensity is too high, there will be inadequate reaction center in the leaves of the crop to accommodate the light energy and convert it into biochemical energy. As a result, the coffee tree excessively photorespires and eventually most of the stored carbohydrates become depleted. Consequently, the tree

may suffer from a serious die-back. Besides, excessive evapo-transpiration and severe drought stress, death of actively growing shoot parts, seasonal crinkling of leaves, frost damage and subsequent yield reduction are common problems observed in unshaded coffee orchards (Wrigley, 1995).

In as much as stomatal aperture is not limiting, **A** (net assimilation) of field-grown coffee trees appears to be higher in sun than in shade leaves (DaMatta, 2004). Stomata typically close early in the morning in coffee trees, with stomatal conductance reaching values as low as 10-20 mmol m^{-2} s^{-1} during the afternoon (Ronquim *et al.*, 2006). This has been attributed to strong stomatal sensitivity to increasing vapour pressure deficit as the day progresses (DaMatta and Ramalho, 2006; Van Kanten and Vaast, 2006) which would largely constrain the CO_2 influx into leaves, thus limiting photosynthesis particularly in the afternoon. According to Ronquim *et al.*, (2006), arabica coffee leaves would increase their A integrated over the course of the day by three times if the morning photosynthetic photon flux (800-1100 µmol m^{-2} s^{-1}) and air vapour pressure deficit (0.5-2.5 kPa), such as occurs on a cloudy day in the wet season in south-eastern Brazil, could be maintained throughout the day. Decreases in **A** in the afternoon have been associated with stomatal closure (Ronquim *et al.*, 2006) and also circumstantially with photo inhibition of photosynthesis and feedback inhibition coupled to an accumulation of soluble sugars in coffee leaves (Ronquim *et al.*, 2006). In contrast, compelling evidence has been presented that diurnal changes of A, assessed on cloudless days in field-grown arabica coffee trees, were unrelated to both photo inhibition (DaMatta *et al.*, 2008) and direct end product mediated feedback down-regulation of photosynthesis (Almeida and Maestri, 1997; Van Kanten and Vaast, 2006) but rather, they were related to stomatal closure.

2.15.2. Photo-inhibition

Among the many environmental factors, light is perhaps the most influential factor involved in the survival, growth and reproduction of tropical species. Light responses usually provoke physiological alterations, which are determinant for CO_2 assimilation and optimization of gas exchange (Goncalves *et al.*, 2007). Environments that are either shaded or under high irradiance light can inhibit the photosynthesis processes simply because there is too little or too much light (Almeida and Maestri, 1997). Although *C. arabica* is said to be shade loving plant, it thrives best in moderate shading (Vaast *et al.*, 2006). Excessive shading by upper two to three canopy strata of various tree species under forest environment is reported to reduce the growth and productivity of the coffee plant (DaMatta, 2004). In such conditions, the plant spends much of its photosynthetic activities for maintenance purposes resulting in lower whole-tree carbon assimilation. Heavy shading due to light interception by the upper strata can result in increased competition for light for photosynthesis which, in turn, leads to undesirable growth of single stemmed coffee trees with thin and reduced reproductive efficiency (Goncalves *et al.*, 2007). Moreover, coffee productivity considerably decreases as a result of death of heavily shaded productive middle and bottom primary branches which is induced by dark respiration (Almeida and Maestri, 1997). Dense shading also results in reduced coffee fruit load through their effects on coffee physiology, such as longer internodes, fewer nodes formed per branch and flower buds at existing nodes (DaMatta, *et al.*, 2007). Because the fruit load is the key component of coffee production, its reduction results in decreased productivity (DaMatta *et al.*, 2007). The study of Vaast *et al.*, (2006) showed that a rather dense shade level of 45% reduced the productivity of trees by only 18% over three consecutive production cycle in optimal ecological conditions for coffee growth. Temporary shading has also been adopted for young coffee plantations for protection against frost, as that obtained with the use of shelter shrubs such as pigeon pea (*Cajanus*

cajan) (DaMatta and Ramalho, 2006) and also in intercropping systems with fast growing trees to increase ground cover and maximize the efficiency rate of nutrient and water utilization during the juvenile phase of the coffee crop (DaMatta *et al.*, 2007)

Shade-grown coffee has become a well-recognized trend which is often defined with terms such as "sustainable coffee" and "environmentally friendly coffee". In line with this, the use of shelter for coffee plantations can be allotted in to sustainable production, ecological sustainability and level and quality of input available to improve the environment for the coffee tree (Almeida and Maestri, 1997).

2.16. Caffeine in *C. arabica*

Caffeine (1,3,7-trimethylxanthine) is an alkaloid of the methylxanthine family known as a central nervous system stimulant through its adenosine antagonist action (Eggers *et al.*, 2001). Caffeine is naturally found in the leaves, seeds and/or fruits of at least 63 plant species worldwide. The most commonly known sources of caffeine are coffee, cocoa beans, kola nuts and tea leaves (Barone and Roberts, 1996). Coffee beans contain between 0.8 and 2.8% caffeine, depending on species and origin, and it contributes to 10 to 30% of the bitter taste of coffee brews (Eggers *et al.*, 2001). The amount of caffeine in coffee beverage varies depending upon the serving size, the type of product, and brewing method (Alves *et al.*, 2007).

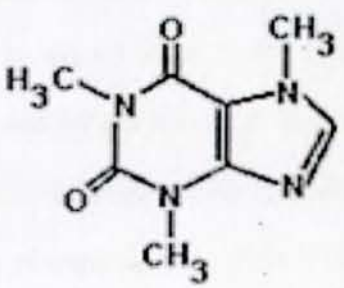

Figure 7. Molecular structure of caffeine (1,3,7-trimethylxanthine) indicating carboxylic and methyl group.

Based on the data reviewed (Dorea and Costa, 2005), that epidemiological and experimental studies have shown positive effects of regular coffee drinking on various aspects of health, such as psychoactive responses (alertness, mood change), neurological condition (infant hyperactivity, Parkinson's disease), metabolic disorders (diabetes, gallstones), and gonad and liver function. However, high doses may produce negative effects in some sensitive individuals, including anxiety, tachycardia and insomnia (Barone and Roberts, 1996). Alves *et al.*, (2007) recommended upper limits of caffeine for healthy adults below 300-500 mg daily, pregnant women must stay below 150-200 mg daily and children should stay below 50 mg daily. Amounts exceeding 700 milligrams of caffeine can be dangerous.

2.17. Coffee production systems in Ethiopia

The production systems of *C. arabica* in Ethiopia are mainly grouped into four categories. These are forest coffee, semi-forest coffee, garden coffee and plantation (Demel Teketay, 1999; Tadesse Woldemariam *et al.*, 2002).

2.17.1. Forest coffee

The ***forest coffee*** also referred to as wild coffee, and is a self-sown and grown in natural forest. In this system, coffee is produced in its natural habitat by collecting coffee berries where the forest biodiversity is maintained. In forest coffee production system, there is no human intervention for coffee management to improve coffee production and coffee also regenerates in its natural forest. Forest coffee accounts for about 10% of Ethiopian total coffee lands and 5-6% of the total coffee production of the country (Demel Teketay *et al.*, 1998). Forest coffee areas are largely located in South-Western parts of the country which is the center of origin for *C. arabica* (Tadesse Woldemariam and Feyera Senbeta, 2008). Some of these areas include the administrative zones of West Wellega, Illubabor, Sheka-Kefa, Bench-Maji, Yayu and Anfillo.

2.17.2. Semi-forest coffee

In the semi-forest coffee production system, also referred to as semi-wild coffee, the coffee berries are picked and collected from naturally grown coffee trees as in the forest coffee. However, there is human intervention in the coffee management by clearing competing under story trees and shrubs regularly in order to improve production of the wild coffee. It is the main production system in south west and South-East part of the country. Semi-forest coffee production system represents about 24% of the total land covered by coffee and accounts for about 20% of total Ethiopian coffee production. This production system is also found in the south and South-Western parts of the country; including Ilubabor, Jimma, Keffa-Sheka, Benchi-Maji and West Wellega zones (Arega Zeru, 2006). Generally, the two production systems together represent about 34% of the land covered by coffee and 25% of the annual coffee production in the country.

2.17.3. Garden coffee

Sometimes garden coffee production system is referred to as small holder coffee, which is produced in plots of varying sizes around dwellings. In this system, coffee is planted and managed in the farmer's backyard within small area (Volkmann, 2008). The coffee is planted at low densities, ranging from 1,000 to 1,800 trees per hectare, is mostly fertilized with organic waste and is intercropped with other crops. Demel Teketay (1999) reported that it accounts for about 35% of the total production system of the country. It is mainly found in Southern and Eastern parts of the country; Sidamo, Gedeo, West Harerge and West Wellega (Arega Zeru, 2006).

2.17.4. Plantation coffee

Plantation coffee includes that grown on plantations owned by private coffee farmers or the government on a large scale and some well-managed smallholder coffee farms. In this production system, recommended seedlings are used, and proper spacing,

mulching, manuring, weeding and pruning are practiced. It is well managed, representing about 15% of the total coffee productions. Only state-owned plantations use chemical fertilizers and herbicides. They are intensified plantations found in Limu, Tepi and Bebeka (Arega Zeru, 2006).

2.18. Economic, ecological and cultural importance of coffee

2.18.1. Economic importance

The contribution of coffee to export market and foreign currency earning is very high for Ethiopia. According to Arega Zeru (2006), coffee contributes about 10% and 5% of government revenues and gross domestic product, respectively. Besides, about 25% of Ethiopia's populations also depend on coffee for their livelihood (Tadesse Woldemariam, 2003). It can be said that, no other product or service in Ethiopia has earned high labor intensive tree crop and provide much employment in rural areas and a means of living for many millions of people in Ethiopia. Moreover, being an important export commodity, coffee plays a vital role or has tremendous impact on both social and spiritual life of the people in different geographical location and cultural backgrounds of the country.

2.18.2. Ecological importance

As an exotic species in the New World forests, coffee has had a gentle impact on biodiversity and contributes to wildlife food and cover, and soil stability. The wood is used mainly for fuel in the New World, but is turned into chairs and other types of furniture in Africa (Cheney, 1925). Coffee is a good honey plant and yields a light colour honey (Center for New Crops and Plants Products, 1996). Coffee berries, edible and slightly sweet, are eaten occasionally by children and field workers. The fruit pulp, which is removed during processing, is sometimes fed to livestock but more often is composted for fertilizer and mulch (Center for New Crops and Plants Products, 1996).

2.18.3. Uses as stimulants

Coffee seeds have been chewed as a stimulant in East Africa from ancient times (Center for New Crops and Plants Products, 1996). The hot drink "coffee" is brewed from the roasted and ground seeds (or "beans") and is one of the world's most popular beverages. It is used to flavour candies, liquors, and pastries. Probably the principal reason for its popularity is the addictive stimulant alkaloid, caffeine (1,3,7-trimethylxanthine) (Fig. 7), 1.1 to 1.3 percent in the beans, but varying greatly in the beverage due to different brewing practices. The alkaloid is present in the leaf at 0.30 percent, twig, 0.04 percent, stem 0.01 percent, and central root, 0.01 percent. Other chemicals such as alkaloids, xanthine, guanine, and trigonelline, which have stimulant and diuretic properties, are also present (Burkill, 1997). Caffeine protects vegetative plant parts from insect and fungal attack and inhibits the growth of plants and bacteria near germinating seeds (Cheney, 1925). Purified caffeine is widely sold as a medicinal stimulant, dietary aid, and headache remedy.

2.18.4. Cultural importance

Leaf poultices are used to treat sores in Trinidad, and root sap or root infusions are drunk to relieve scorpion stings (Burkill, 1997). Coffee is also employed in folk medicine to treat asthma, flu, headache, jaundice, nephrosis, malaria, sores, and vertigo (Center for New Crops and Plants Products, 1996).

CHAPTER THREE

3. MATERIALS AND METHODS

3.1. The study site

The study was conducted at the "**Centre for Indigenous Trees Propagation and Biodiversity Development in Ethiopia**" established on 10 July 2004 by Professor Legesse Negash. Located over a degraded landscape, the center is found 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). The major objective of the center is to restore native trees, shrubs, herbs and grasses, as well as keystone natural resources including water, soils and biodiversity.

The rainfall pattern of the area is bimodal with 'little' rainy season with 1140mm mean annual rainfall and annual minimum and maximum temperature of 8° C and 26° C, respectively. The soil type is Vertisol on the lower slope and Nitosol on the upper slope.

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 center, native trees such as *Juniperus procera*, *Podocarpus falcatus*, *Millettia feruginea*, *Olea europaea* subsp. *cuspidata*, *Acacia abyssinica*, *Acacia seyal*, *Faidherbia albidda*, *Vernonia amygdalin*, *Allophyllus abyssinicus*, *Dovyalis caffra*, *Dovyalis abyssinica*, *Albizia schimperiana*, *Prunus africana*, *Syzygium guineense* were planted and successfully established. Also, keystone tree species such as *Ficus vasta*, *Ficus sycomorus* subsp. *sycomorus*, *Ficus sycomorus* subsp. *gnaphalocarpa*, and *Ficus sur* were established. Natural regeneration of native shrubs such as *Carissa spinarum*, *Maytenus arbutifolia*, *Osyris quadriparita*, and *Rumex nervosus*, as well as diverse number of herb species including *Achyranthes aspera*, *Bidens ghedoensis*, *Crassocephalum sarcobasis*, *Hygrophila auriculata*, and *Scadoxus multiflorus* occurred

following establishment of native trees and protection of the area. Grass species such as *Andropogon schirenis*, *Pennisetum setaceum* and *Arthraxon micans* were also the part of the site that is being restored. As a result of these conditions, establishment of *C. arabica* became evident.

For measuring extent and success of restoration, the center developed a new concept known as "**Restoration Bioassay**" where coffee plants were used as a bioassay organism.

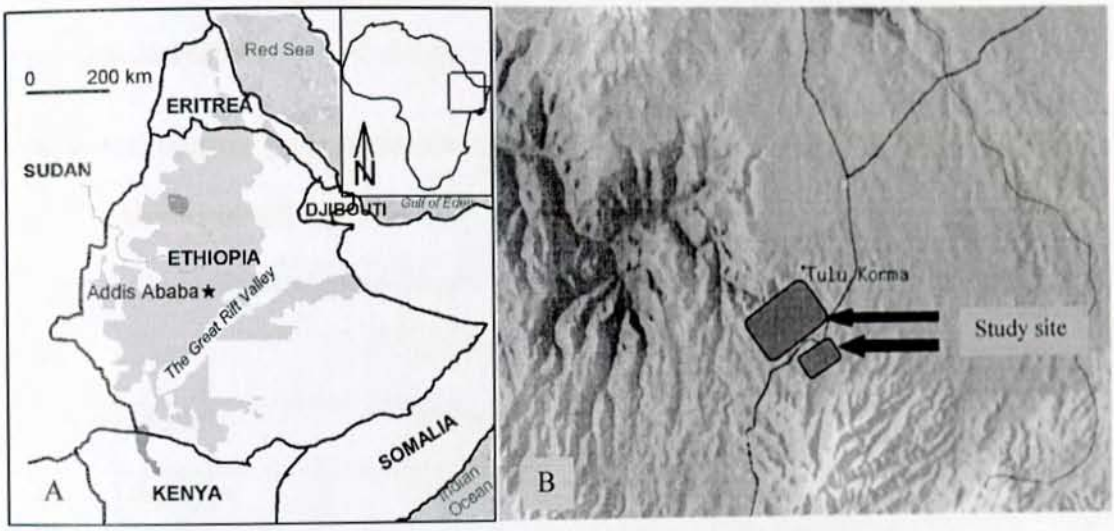

Figure 8. Pictures representing: (A) map of Ethiopia (2.63-15.56° N; 32.49-48.85° E) (Reproduced from Tesfay Teklay, 2005); and (B) location of the study site (9° 01' 00" N; 38° 22' 00" E). [Source: (http://www.fallingrain.com/Ethiopia/Tulu korma)]

3.2. Plant material and experimental design

The study was conducted during the months of October to March 2012/13 with five, four and three-year-old plants of *C. arabica*. Within the study area two spots with restored vegetation containing young *C. arabica* were identified. The coffee trees were planted randomly under the shade of *C. macrostachyus*, *A. abyssinica*, *M. ferruginea*, *P. falcatus* and *E. divinorum*, over a total area of 495 m^2 giving a tree population of approximately 176.

Based on soil type, shade arrangement and slope, the study site was divided in to two sub-sites called **site I** and **site II**.

Table 2. Difference between the restoring study sites (**site I** and **site II**) based on slope, shade and soil type.

Major site description	**Site I**	**Site II**
Slope	31 %	12 %
Shade	Did not overlap	Multiple shade
Soil type	Nitosol	Vertisol

Site I: It was situated within the restoring area of CITPBDE office and categorized into four blocks depending on the shade: *C. macrostachyus*, *A. abyssinica*, *E. divinorum* and less restored/open sun blocks. Based on age, the coffee plants were grouped into two, i.e. three-year-old (**3CA**) and five-year-old (**5CA**) *C. arabica* plants.

A total of 78 three-year-old *C. arabica* plants were selected and 24 of these were systematically selected for the vegetative growth measurement under three shade levels (*C. macrostachyus* shade, *A. abyssinica* shade, and *E. divinorum* shade). The selected

plants were then tagged as $3CA_1$, $3CA_2$, $3CA_3$ up to $3CA_{24}$ for monthly measurements starting from October 2012 to March 2013.

In total, 74 five-year-old coffee plants were selected and 32 of these were systematically selected under the four shade levels of (*C. macrostachyus* shade, *A. abyssinica* shade, *E. divinorum* shade and open-sun light conditions) for use in the berry and bean measurements: These plants were permanently marked as $5CA_1$, $5CA_2$, $5CA_3$ up to $5CA_{32}$ for use in the monthly measurements over the study period.

In addition, the 3CA plants were subjected to three treatments (*C. macrostachyus* shade, *A. abyssinica* shade, and *E. divinorum* shade) in which 24 plants (eight replicate per treatment) were randomly selected for vegetative data collection. Similarly, the 32 randomly selected 5CA plants were subjected to four treatments (*C. macrostachyus* shade, *A. abyssinica* shade, *E. divinorum* shade and open-sun light conditions) and: eight replicate per treatment were used for berry and bean data collection.

Figure 9. *C. arabica* growing: under the shade of (A) *C. macrostachyus*; (B) *E. divinorum*; (C) *A. abyssinica*; and on (D) open sun. [Partial view of the coffee plants and soil surface, photographed from **Site I**.]

Site II: It was situated within the main research and restoring site of CITPBDE. In addition, it is assigned as fourth block without any classification of the site for its similarity in multiple-shade (a combined shade of *M. ferruginea*, *P. falcatus*, *C. macrostachyus* and *A. abyssinica*).

A total of 24 four-year-old *C. arabica* plants were systematically selected for flower induction under the multiple shades of *M. ferruginea*, *P. falcatus*, *C. macrostachyus* and *A. abyssinica*. They were tagged as $4CA_1$, $4CA_2$, $4CA_3$ up to $4CA_{24}$ for monthly GA_3 treatment. In addition, the coffee plants were subjected to GA_3 treatments (300 mg l^{-1} GA_3, 250 mg l^{-1} GA_3 and 100 mg l^{-1} GA_3) and control with double distilled water starting from October to December 2012, where the first bud development observed. The 24 plants (six replicate per treatment) were randomly selected for flower induction. At each site (site I and site II), farming husbandry was carried out in accordance with standard procedures of Mwangi (1983).

3.3. Data collection

3.3.1. Vegetative growth measurement

The vegetative development of the three-year-old coffee plants was evaluated on the four plagiotropic branches per tree. The branches were situated on the middle third of the trees, oriented to the north, south, east and west directions. On these branches the number of nodes (NN), inter-node length (IL) and number of leaves (NL) were counted. Where as area of each leaf (length and width) and branch leaf areas (BLA), of the selected branch were also measured based on the formula found out following the works of Tavares-Junior *et al.*, (2002) and Catalina *et al.*, (2010).

The area of each leaf was calculated from the area of the rectangle determined by the leaf dimensions, adjusted by the equation:

$$c = Y/X$$

Where c= coefficient index value

Y= actual leaf area (cm^2) and

X= estimated leaf area (cm^2)

The coefficient index (c) for determining leaf area was calculated by dividing the actual leaf area by estimated leaf area. The actual leaf area (**Y**) were found out, first by collecting 15 leaves from the study site which can represent all the leaves developed on the plagiotropic branches of the coffee plants, and placed on a square paper where the area of one square accounts 0.25 cm^2 . Then the area that all the leaves cover on the square paper was counted and recorded. Where as the estimated leaf area (**X**) of the same leaves were obtained by measuring and multiplying the length and width of each leaf collected. The mean values for the actual and estimated leaf area of the 15 leaves were calculated and the coefficient index obtained.

However, instead of cutting the leaves from the coffee plants and measure the area, it was possible to determine the leaf area (**Y**) simply by measuring the estimated area (**X**) and multiply with the coefficient index (c=0.668) calculated.

Leaf area (Y) = 0.668 X

The study found out nearly similar equation with Tavares-Junior *et al.*, (2002) where Y= 0.667 X and Catalina *et al.*, (2010) where Y = 0.667 X. The leaf area of the branch was determined by multiplying (*) the average leaf area by the number of leaves per branch.

Branch leaf area= average leaf area*number of leaves

Growth responses such as coffee height and number of branches were also recorded. The height of each coffee tree was taken 5cm away from the ground surface. All

the measurement was conducted using a standard Phoenix measuring tape with a scale of 50 cm (Made in China).

Figure 10. Measuring the (A) height; (B) leaf area; (C) inter-node length; and (D) quantifying the number of nodes of three-year-old *C. arabica*, at each months of the study period. [Pictures were taken from CITPBDE, Tulu-korma.]

3.3.2. Berry and bean measurements of *C. arabica*

The five-year-old selected coffee plants were subjected to monthly measurement of coffee height. Counting the number of branches, number of green berries, number of red berries, number of berries aborted, number of fruiting node and number of berries per node were also done. Besides, the developmental stages of the fruits starting from the pin-head stage to the final ripening stage were identified and photographed using a digital Sony camera. The height of the coffee plants was measured above 10cm from the ground surface using a standard measuring tape with a scale of 2 metes.

Figure 11. Laboratory processed: (A) mature red berries; (B) removed pulps; (C) removed parchments; (D) beans with parchment; (E) randomly selected beans from each treatments; and (F) size of beans from each treatments. [Coffee processed using wet methods, at plant propagation laboratory of Addis Ababa University (AAU).]

Counting the number of green berries at monthly intervals, already developed on the coffee plants, started as of October 2012 up to January 2013. Where as counting and harvesting of fully mature red berries were performed at weekly intervals starting from the end of December 2012 to the final day of March 2013. Since only a few berries were ripe in December, they were added to the berries that were harvested in January.

Mature red berries were selectively picked by hand when they had turned completely red and before they started to dry. The red berries were collected in ventilated

plastic bags and placed in a cooler water and ice for transport to the laboratory of Plant Propagation at Addis Ababa University. On that day the fresh weight of berry per plant, fresh weight of pulp /plant and fresh weight of parchment with beans/plant were weighed using a ADP 2100/L balance and allowed to dry under room condition with a light of 110 $\mu mol\ m^{-2}\ s^{-1}$ and temperature of 12-23 ℃ for two weeks, at each harvest, until a constant weight of beans with parchment obtained. Then the beans were separated from the parchment and both were weighed using the same instrument used for measuring fresh weight of berries. Each measurement was taken in gram (gm).

The processing of freshly harvested coffee berries was done using the conventional wet method. The coffee berries from each plant were subjected to pulp separation using hand. The aborted beans were separated by weight as they were put in a glass beaker containing water. The aborted beans were floated to the top, while the heavier and ripe beans were submerged to the bottom of the glass beaker.

After separation, the fresh beans with parchment were weighed and transported to large water-filled fermentation plastic containers. They were left in these containers for about 48 hours. The purpose of this process was to dissolve and remove the slick layer of mucilage (called the parenchyma) that was attached to the parchment. When fermentation was complete the beans felt rough, rather than slick, to the touch. Then the parchments with beans were allowed to dry for a week and subjected to separation of the parchment from the bean using a hand. Subsequently the dry weight of the beans and parchments were taken using an ADP 2100/L balance. At that point in time, the beans were rinsed by immersing and washing in additional water plastic container. The beans were then ready for drying until a constant weight was obtained. Finally, the dried beans were weighed.

The number of healthy berries per tree, number of aborted berries per tree, number of berries per node, fresh weight of berry, fresh weight of pulp, fresh weight of parchment

with beans, dry weight of parchment with beans and dry weight of beans were counted and weighed. In addition, size (length) of beans was measured. Using the above data, bean-berry weight ratio, weight of beans per fruit, beans (g)/1000 and coffee yield were calculated.

Using the following formulas (DaMatta *et al.*, 2007), some of the data outcomes were obtained as follows.

- Weight of beans per fruit= weight per fruit*bean/fruit weight ratio
- Number of fruits per tree= number of fruiting nodes per tree*number fruits per node
- Yield per tree= number of fruits per tree*weight of beans per fruit

3.3.3. Flower initiation and flowering data

The selected four-year-old coffee plants were treated with aqueous solutions of 100, 250 and 300 mg l^{-1} GA_3 (Sigma, St. Louis; dissolved in ethanol and diluted with distilled water) plus 0.2 % Tween 20 (US Biochemical Corp., Cleveland). GA_3 treatments were performed on each branch of the selected six coffee plants per treatment, using a foliar hand spray on the branch leaves and stems. But the branches and stems of the control groups were treated with solutions containing Tween-20 and distilled water. Each treatment had six coffee replicates for GA_3 application.

The preparation of the GA_3 solutions took place at the plant propagation laboratory of Addis Ababa University. The procedures were as follows:

- 100, 250 and 300 mg GA_3 powder was weighed using a *Sartorius analytic* sensitive balance.

- Each weighed GA_3 powder was placed in three different small glass beakers and subjected with 5 drops (using *Eppendorf pippet*) of ethanol to dissolve the GA_3.
- 1000ml double distilled water was added in three different *E-flasks* and was introduced with the prepared dissolved GA_3 solution respectively on each E-flask.
- Then each solution placed on *ARE magnetic stirrer* (Velp scientifica) with a magnetic stirrer on each solution and allowed for 30 minutes to be mixed.
- After that, 6 drops of Tween 20 added to each solution and finally placed within a refrigerator at 5°C.
- During the time of application, the chemicals were transferred in to a hand sprayer and transported in to the research site placed within a plastic pot containing cooler water and ice.

The GA_3 solutions were applied on the leaves of each coffee plant with a hand sprayer beginning from 14th of October to December 2012, until bud development observed during January 2013. Number of flower buds per plant, number of open flowers per plant, the number of flowers per node and number of secondary branches per plant were counted and recorded at weekly intervals from January up to March, 2013.

3.3.4. Eco-physiological measurements

3.3.4.1. *Temperature* (T_{air})

Air temperature (T_{air}) was recorded with a minimum-maximum thermometer situated in the study area. The mean daily T_{air} of the study site was recorded starting from October 2012 to March 2013, and the mean monthly minimum, maximum and average T_{air} were calculated.

3.3.4.2. *Photosynthetic active radiation (PAR)*

Photosynthetic active radiation was measured using a PAR sensor (Li-Cor; li-189; USA) device. The data were collected starting from October 2012 to March 2013, and the mean PAR (μmol m^{-2} s^{-1}) values were recorded. The measurements were taken on the open sun, under the restoring canopy of *C. macrostachyus*, *A. abyssinica* and *E. divinorum*, and bottom of coffee canopy. The measurements were taken monthly during the day time of 9 AM, 12 PM and 3 PM.

3.3.4.3. *Soil*

Soil samples were collected from the restoring (site I and site II) and non-restoring study sites. In order to avoid excess soil moisture, sample collections took place during February, one of the dry seasons on the study site. W-methods and random sampling were used to collect the samples from the restoring and non-restoring sites, respectively, both from the soil profiles of 0-15 cm and 16-30 cm.

From each sample site, nine sub-samples were collected and balked in to one composite soil sample. Each field was sampled separately depending on appearance of the soils or in elevation/slope of the area. Surface litters were scraped away (fertilized, old bunds, marshy spots, near tress, compost piles, other non-representative locations were avoided) and sub-samples were collected in a clean plastic bucket using a stainless steal. The sub-samples were poured from the bucket in to clean plastic containers. The sub-samples were mixed thoroughly, discarded, by quartering, all but 4 Kg of soil. Quarterly was done by mixing samples well, divided it into four equal parts, then rejected two opposite quarters, mixed the remaining two portions, again divided into four parts and rejected two opposite quarters, until 500g of composite soil sample were obtained. From each site, composite samples from 0-15cm and 16-30cm were prepared separately and a total of six composite samples were prepared. Each sub-sample was labelled and marked

properly, and delivered to *JIJE Analytical Testing Service Laboratory* for both physical and chemical analysis.

In the laboratory, the soil analyses were done using the following methods: soil pH was measured in a 1:2.5 soil: water mixture; soil moisture were analysed through drying overnight at 105 °C; soil texture by hydrometer; bulk and particle density through core and volumetric flask methods, respectively; organic carbon using Walkley-Black method; total nitrogen by means of Kjeldahl method; available phosphorous using Olsen *et.al.*, method; electrical conductivity by means of conductivity-water extract process; cation exchange capacity through sodium equivalent by flame photometer process; ammonium acetate extraction and AAS titration mechanism for Ca^{2+} and Mg^{2+}; ammonium acetate extraction and flame photometery mechanism for Na^{+} and K^{+}; and soil micronutrients using DTPA extraction and flame AAS for determination.

3.4. Vegetation survey

To determine the floristic composition of the site that is being restored, parallel line transects 100m apart from each other were laid across the study area. Along the line of transects a total of 60 sample quadrats i.e. 20m x 20m for shrubs and woody species and 1m x 1m herbaceous and grass species were laid down at 50m intervals. In addition, the current floristic compositions of the restoring site were compared with the selected degraded landscape located near the study site.

In each of these quadrants, the identities of the plant species were determined and recorded. For plants, which could not be identified in the field, herbarium specimens were collected, properly dried in a plant press, and identified at the National Herbarium (Addis Ababa University), where voucher specimens were deposited. Nomenclature follows that of the published volumes of the flora of Ethiopia and Eritrea.

3.5. Statistical analysis

Statistical analyses were performed according to the following procedures. The mean vegetative growth, flowering and fruiting performance of *C. arabica* on the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica* shade, and those coffee plants growing on less restored site/open sun were analyzed using ANOVA (analysis of variance) using Sigma Plot 8.0 (Systat Software, Inc.). T-test for monthly repeated measurements and among treatments were used for determining significant differences between mean values of treatments. The association of the growth, fruiting and flowering performance of coffee trees to each other and with environmental variables were run using Pearson's correlation analysis. Unless stated otherwise, 5 % significant level has been used to indicate statistically significant differences between/among treatments. All the graphs statistical analyses were performed with the Sigma Plot 8.0.

CHAPTER FOUR

4. RESULTS

4.1. Environmental variables

4.1.1. Temperature (T_{air})

Air temperature, during the study period at the site which is being restored, showed a continuous increment in maximum air temperature starting from October to January and afterwards, maximum T_{air} declined, while the minimum T_{air} showed fluctuation during the measurements (Fig. 12). The lowest minimum and highest maximum temperature were recorded during the months of December and January, respectively. In December, minimum air temperature fluctuated within a fairly constant range along with constant increases in maximum T_{air}. The maximum T_{air} fluctuate between 19 and 26 °C, and the minimum T_{air} range between 8 and 11 °C.

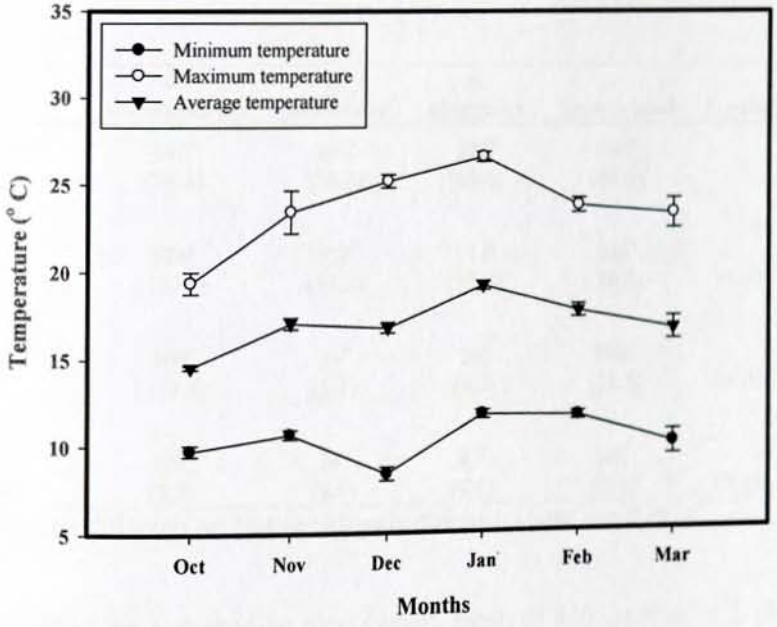

Figure 12. Minimum, maximum and average air temperature (°C) at CITPBDE study site. Data were collected starting from October to March 2012/13.

Monthly T_{air} values differed significantly ($P<0.001$) exhibiting an average maximum value with 23.5±0.98 °C and minimum value with 10.3±0.51 °C. The mean maximum value was about twice higher than the minimum temperature, and this variation was statistically significant.

4.1.2. Photosynthetically active radiation (PAR)

Extent of shading afforded by the native trees, namely *C. macrostachyus* and *A. abyssinica*, and one native tree/shrub *E. divinorum* were quantified by measuring the quantum flux densities at the top of the shade trees/shrub, just above and at the bottom of the studied coffee plants (Table 3).

Table 3. 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. Standard errors of means (SEs) are indicated in parenthesis.

	C. macrostachyus	*E. divinorum*	*A. abyssinica*	Non-shaded	F-value	P-value
Top of shade tree	840^{a} (36.6)	840^{a} (36.6)	840^{a} (36.6)	840^{a} (36.6)		$>0.05^{ns}$
Top of coffee	374^{a} (123.8)	107^{b} (13.2)	117^{c} (13.3)	840^{d} (28.6)	39.05	<0.001*
Bottom of coffee	309^{a} (117.4)	33^{b} (5.3)	30^{c} (4.5)	794^{d} (28.6)	42.03	<0.001*
PAR difference	65^{a} (8.2)	74^{b} (9.5)	87^{c} (9.1)	46^{d} (9.0)	59.88	<0.001*

*: Significantly different; ns: Not significantly different; Units: µmol $m^{-2}s^{-1}$

Compared to the non-shading plots (which received 840 µmol $m^{-2}s^{-1}$), photon flux densities beneath *C. macrostachyus*, *E. divinorum* and *A. abyssinica* and at the top of the

coffee plants were 374, 107 and 117 µmol $m^{-2}s^{-1}$, respectively. These values represent 45, 13 and 14 % respectively of shades afforded by the two shade trees and the shrub/tree.

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 $m^{-2}s^{-1}$, respectively. These values represented light absorption of 17, 69 and 74 % by coffee plants grown beneath *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, respectively.

The pattern of diurnal changes in light intensity measured as photosynthetic active radiation (PAR) over the study period showed a significant ($P<0.001$) change among AM, MM and PM.

4.1.3. Soil nutrient analysis

Analysis of physical and chemical soil properties revealed that there is site-to-site relative similarity and significant differences on various soil parameters analyzed (Appendix 3). The results showed that, significant ($P<0.05$) difference occurred on the levels of organic carbon, total nitrogen, available phosphorous and electrical conductivity in between the soil samples of the restoring and non-restoring sites.

The highest average surface (0-15 cm) and subsurface (16-30 cm) sand content was observed under the non restoring sites (22 %) and the lowest was recorded in the restoring sites (13 %), whereas the average clay fraction of the restoring sites and non-restoring sites were 56 and 45%, respectively. In addition, the average silt fractions of the restoring sites were 31 %, unlike 33 % silt fraction of the non-restoring sites. There were no textural class differences between the restoring and non-restoring sites. The textural class of the surface and the subsurface soils was also clay. Considering the two soil depths, higher mean sand fraction (22 %) was observed within the surface soils of the non-restoring sites, than the restoring sites which accounted 19 %. Opposite to sand, higher clay fraction (63 %) was found in the subsurface soil of the restoring sites (Appendix 3).

The soil pH values were not significantly ($P>0.05$) affected by the restoration differences and soil depth. The pH of restoring sites was slightly acidic with a mean value of 6.89, whereas the mean pH of the non-restoring sites was 6.9. Considering the two soil depths, the higher mean values of pH with 6.86 and 6.82 were observed within the surface soils of the restoring and non restoring sites, respectively. In general, pH values increased with increasing soil depth (Appendix 3). Furthermore, soils from the study sites showed a significant ($P<0.05$) difference in terms of moisture content, where the highest mean value was identified on the restoring sites (15.52 %), than the non-restoring sites with the mean value of 13.63 %. The results of the electrical conductivity of the restoring soils (0.18 mS/cm) were significantly higher than the non restoring sites (0.05 mS/cm). The levels of the electrical conductivity also decreased on the lower soil depth than the surface soils.

The level of soil organic carbon was highest (3.16 %) under the restoring conditions and lowest (1.42 %) on the non-restoring sites. With regard to the levels of organic carbon on the soil depth, both on the restoring and non-restoring sites, the level decreases from the surface to the subsurface soil profile. Similarly, soil organic carbon contents in the 0-15 cm and 16-30 cm soil depths were highest on the restoring sites and lowest under the non-restoring sites (Fig. 13).

The level of soils total nitrogen was highest (0.25 %) under the restoring conditions, whereas the lowest total nitrogen (0.16 %) was from the non-restoring sites. Similar with the level of organic carbon on the soil depth, both on the restoring and non-restoring sites, the level of total nitrogen decreases from the surface to the subsurface soil profile. Similarly, soil organic carbon contents in the 0-15 cm and 16-30 cm soil depths were highest on the restoring sites and lowest under the non-restoring sites.

The level of available phosphorus in the restoring sites appeared to be significantly ($P<0.05$) higher than the non-restoring sites. Accordingly, the highest (12.5 mg/kg) and the lowest (7.25 mg/kg) available phosphorus contents on the surface layer were observed under the restoring and the non-restoring sites, respectively. The data also revealed that available phosphorus was higher in the subsurface of the restoring sites (3.12 mg/kg) than in the non-restoring sites (0.41 mg/kg) (Fig. 13).

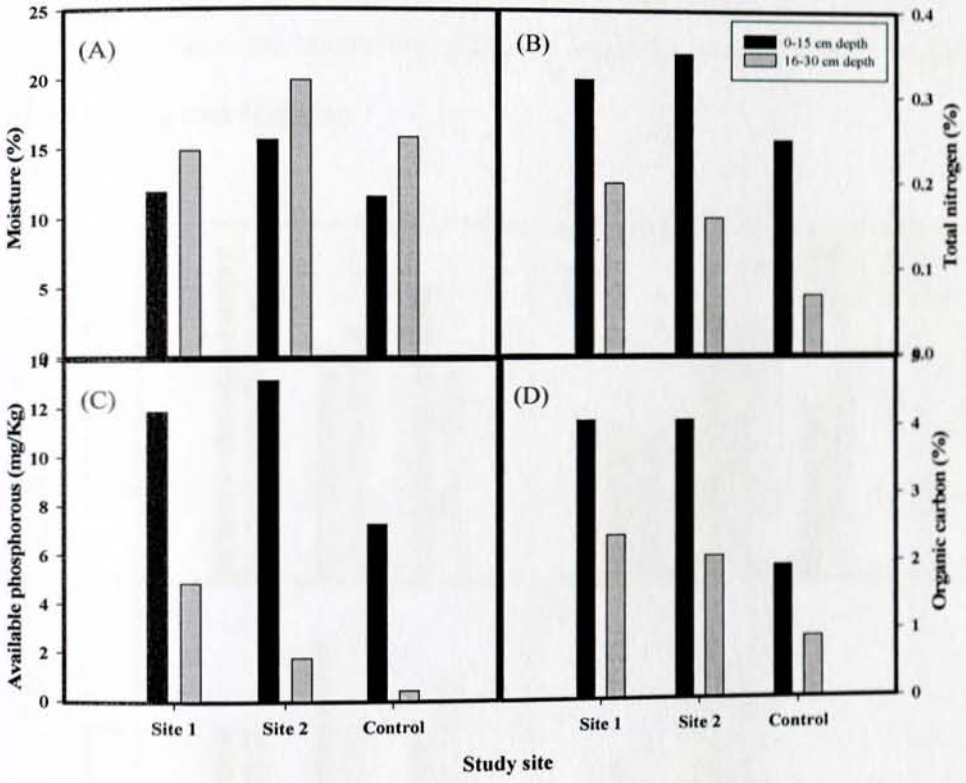

Figure 13. Soils: (A) moisture content (%), (B) total nitrogen (%), (C) available phosphorous (mg/Kg) and (D) organic carbon (%), at the restoring (site I and site II) and non-restoring sites (control).

Unlike potassium (K), the levels of exchangeable Calcium (Ca), Magnesium (Mg), Sodium (Na) were not significantly ($P>0.05$) different between the restoring and non-restoring sites. The mean values of exchangeable Calcium (Ca) under the restoring and

non-restoring sites were 31.09 and 29.06 cmol (+)/kg, respectively. Considering the mean exchangeable Magnesium (Mg) levels on the restoring and non-restoring sites were 14.61 and 15.91 cmol (+)/kg, respectively. However, the exchangeable Sodium levels on the restoring and non-restoring sites were similar with the values of 0.45 and 0.45 cmol (+)/kg, respectively. On the other hand, the result of available potassium on restoring and non-restoring sites were significantly ($P<0.05$) different, having the mean levels of 1.7 and 0.35 cmol (+)/Kg, respectively. In view of the soil depths, the levels of exchangeable bases showed higher at the surface layer than at the subsurface depth on both the restoring and non-restoring sites (Fig. 14).

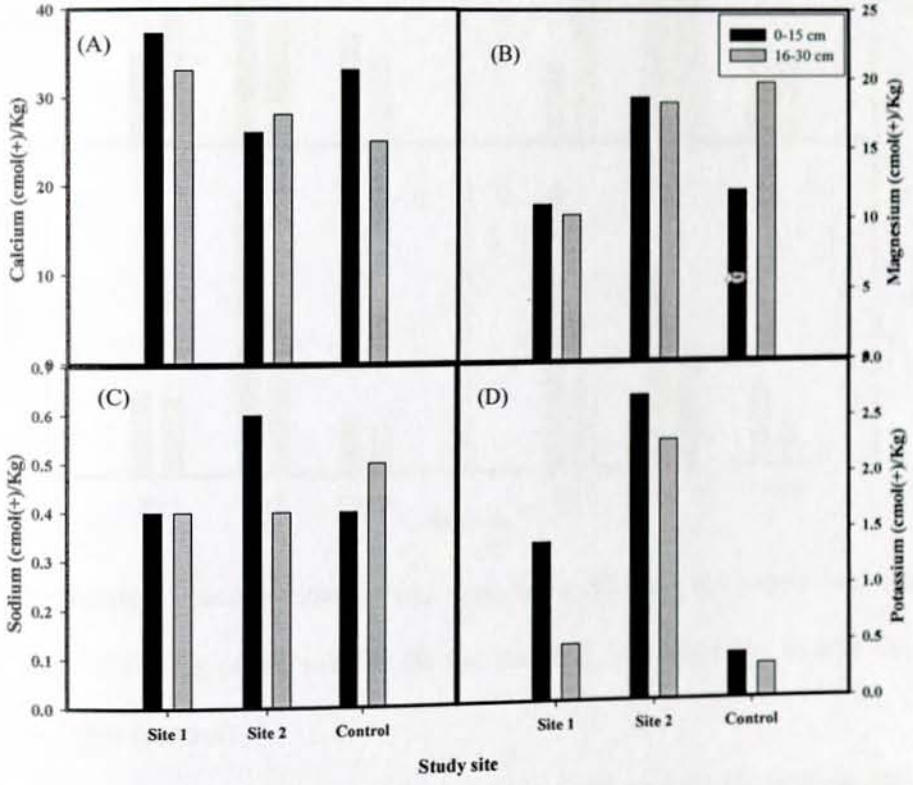

Figure 14. Exchangeable bases of: (A) calcium; (B) magnesium; (C) sodium; and (D) potassium in cmol (+)/Kg of the soils, at the restoring (site I and site II) and non-restoring sites (control).

The contents of available micronutrients (Fe, Mn, Zn and Cu) were not significantly (P>0.05) different between the restoring and non-restoring sites and along soil depths. But the levels of micronutrients on the surface soils of the restoring sites indicated that: Mn, Fe, Cu and Zn accounted 116.9, 128.3, 5.44 and 3.68 cmol (+)/Kg, respectively. Whereas the level of micronutrients on the non-restoring sites showed: Mn, Fe, Cu and Zn accounted 65.9, 73.9, 1.7 and 1.1 cmol (+)/Kg, respectively (Fig. 15).

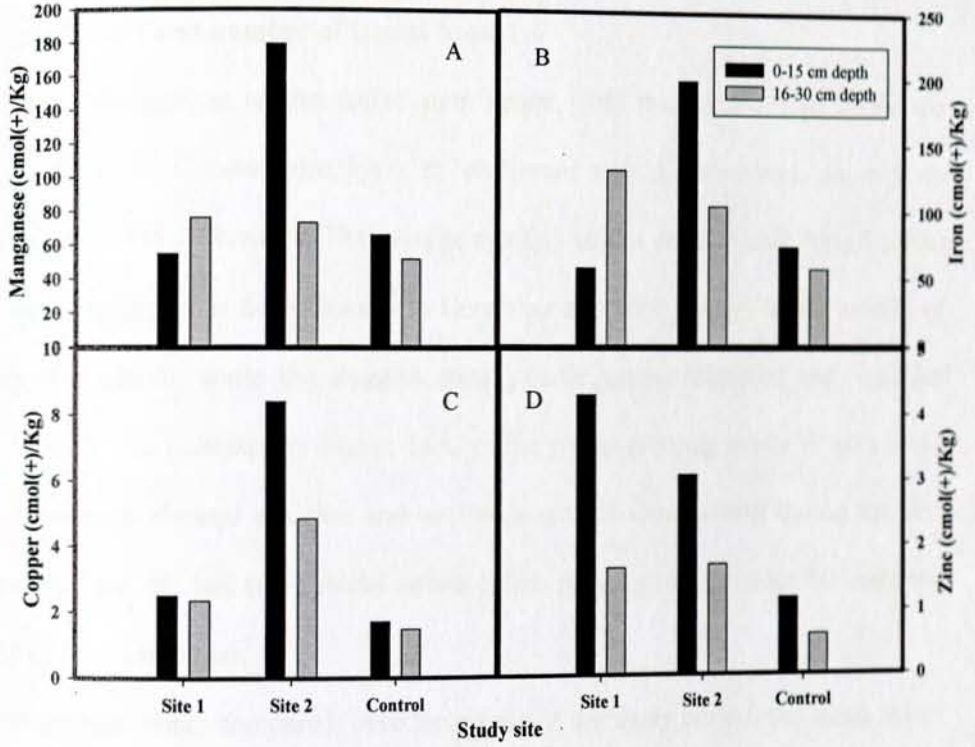

Figure 15. Micronutrient concentrations of: (A) manganese; (B) Iron; (C) copper; and (D) zinc in cmol (+)/Kg of the soils, at the site restoring (site I and site II) and non-restoring sites (control).

In short, in between the site that is being restored and nearby non-restoring sites, there existed differences on the major soil physical and chemical properties. The very difference that occurred on the sites that are being restored were due to the role and

contribution of various indigenous and keystone plant species in recycling, extracting and processing the essential soil nutrients, both macro and micronutrients, within the soil.

4.2. Vegetative Growth performances

Starting from October to March, the data on vegetative growth parameters of three-year-old *C. arabica* such as stem height, number of branches, number of nodes, inter-node length and branch leaf area were measured and recorded. The result is summarized and presented in the following sub-sections.

4.2.1. Stem height and number of lateral branches

Vegetative growth of the coffee stem height (SH) that were grown under the restoring shade of *C. macrostachyus*, *E. divinorum* and *A. abyssinica* showed no significant ($P>0.05$) differences. The average monthly height development for all coffee plants was most vigorous from October to December and after January in the months of February and March, while the sluggish stem growth pattern identified and recorded during January. As indicated in Figure 16A, coffee plants growing under *E. divinorum* and *A. abyssinica* showed a higher and similar pattern of stem growth during the first three months and the last two months unlike coffee plants growing under the restoring shade of *C. macrostachyus*.

When treatments compared, over the course of the study period, the mean SH of coffee plants showed no significant difference ($P>0.05$) on the three shade status. For instance, the over all mean SH increment for those coffee trees grown under the restoring shade of *C. macrostachyus*, at the end of measurement were 39.2±0.7 cm, and 40.36±2.1 cm and 41.3±2.1 cm for those coffee trees growing under the restoring shade of *E. divinorum* and *A. abyssinica*, respectively.

The number of branches (NB) development in those coffee populations under the restoring shade of *C. macrostachyus*, *E. divinorum* and *A. abyssinica* showed no

significant (P>0.05) change through out the study period. Referring to the growth pattern of branches, January showed no branch increment comparing to the other months which were characterized by increasing the NB on each monthly measurement (Fig. 16B).

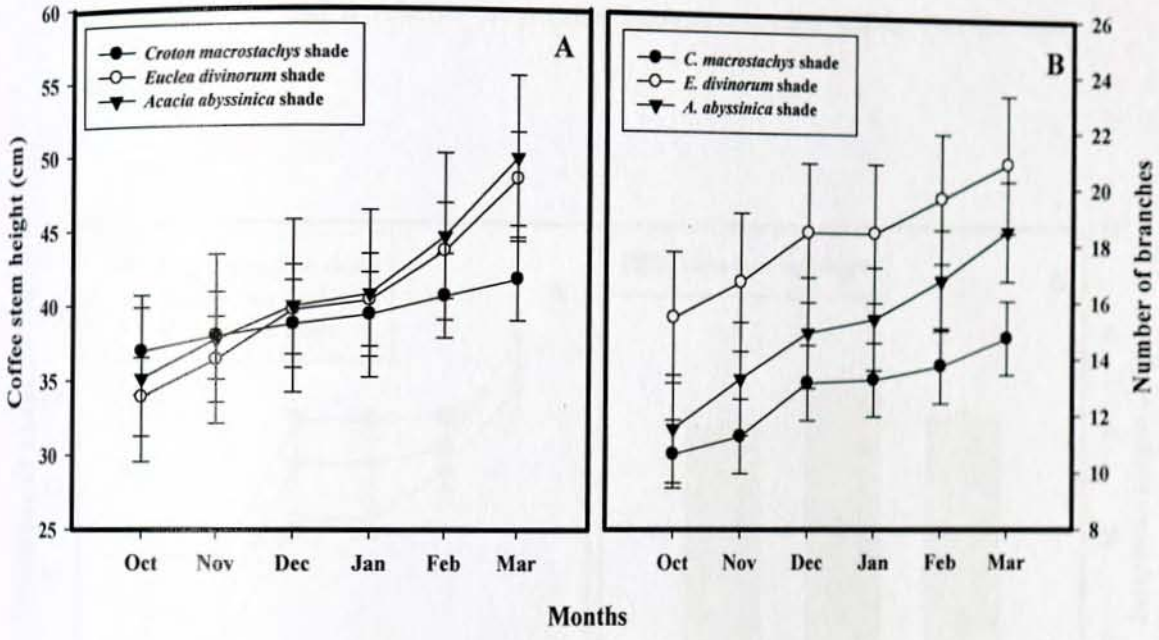

Figure 16. The mean: (A) height (cm); and (B) number of branches of three-year-old *C. arabica*, growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*. Symbols indicate mean ± SE (n = 8 replicates per treatment).

When determining the number of branches development within the three shades, there were no significant (P>0.05) difference within the coffee trees growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and hence indicated the presence of equal performance on the development of plagiotropic branches.

The mean total NB increment by the end of measurement is found to be 18.20±0.81 for coffee trees grown under the restoring shade of *E. divinorum*, while the NB under the shade of *A. abyssinica* were 15.04±1.01. Considering the NB development under the shade of *C. macrostachyus* showed a mean value of 12.79±0.63.

4.2.2. Number of nodes and internode length

The mean number of nodes (NN) per branch, from the selected four branches directed to the east, west, north and south showed no change during the months of October, November and January but an increment on the number of nodes showed up during December, and a relative progressive increase recorded during February and March (Fig. 17A).

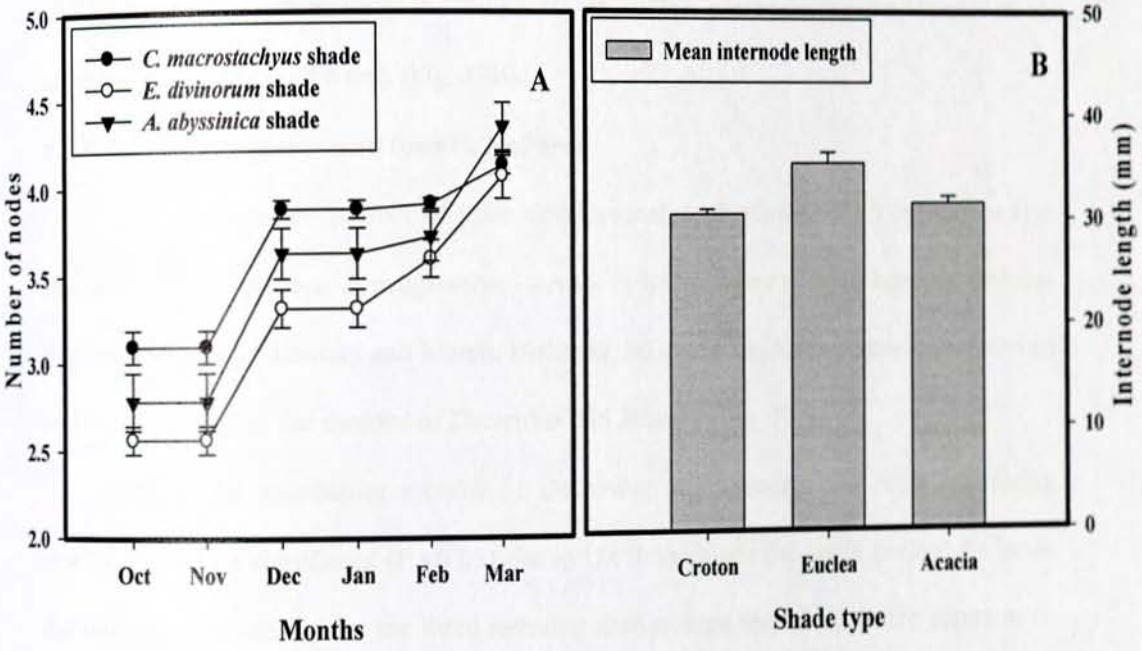

Figure 17. The mean: (A) number of nodes development; and (B) internode length on the selected four branches of *C. arabica*, under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*. Symbols indicate ± SE (n = 8 replicates per treatment).

The NN development on those coffee trees growing within the three restoring shade trees showed a significant ($P<0.01$) difference through out the study period. The mean NN on those coffee trees growing under the restoring shade of *C. macrostachyus*

was 4.13±0.05. Whereas, coffee plants grown under the shade of *E. divinorum* and *A. abyssinica* showed a mean NN with the value of 4.06±0.13 and 4.43±0.14, respectively.

The result indicated that, the mean inter-node length (IL) under the restoring shade of *E. divinorum* was significantly ($P<0.01$) more pronounced and higher than *A. abyssinica* and *C. macrostachyus* coffee plants. The mean IL in the case of *E. divinorum* based coffee plants is 35.34±1.05 mm, while the lowest mean IL recorded on those coffee plants growing on the restoring shade of *C. macrostachyus* with a mean length of 30.48±0.4 mm. Furthermore, the mean IL of coffee plants under the shade of *A. abyssinica* was 31.51±0.6 mm (Fig. 17B).

4.2.3. Number of leaves and branch leaf area

Similar with the number of node development, leaf number (LN) increment also showed the same pattern. A progressive increase in leaf number showed between October and December, and January and March. However, no change in leaf number was observed and recorded during the months of December and January (Fig. 18A).

Unlike the measuring months of December and January, the other measuring months showed a significant ($P<0.05$) rise in LN through out the study period. As far as the number of leaves under the three restoring shades were recorded, coffee plants in *C. macrostachyus* shade showed a significantly ($P<0.05$) higher than coffee plants under the restoring shade of *E. divinorum* and *A. abyssinica.*

In view of the mean number of leaves on those coffee trees growing under the restoring shade of *A. abyssinica* was 6.69±0.28. But, coffee plants grown under the shade of *E. divinorum* and *C. macrostachyus* showed a mean number of leaves, with the value of 6.13±0.26 and 6.25±0.1, respectively.

Similar with the number of leaves, the branch leaf area (BLA) during the course of the study showed to ascend on the months of December and March, as compared to the

other measuring months. The BLA on the remaining measuring months showed relatively no change (Fig. 18B).

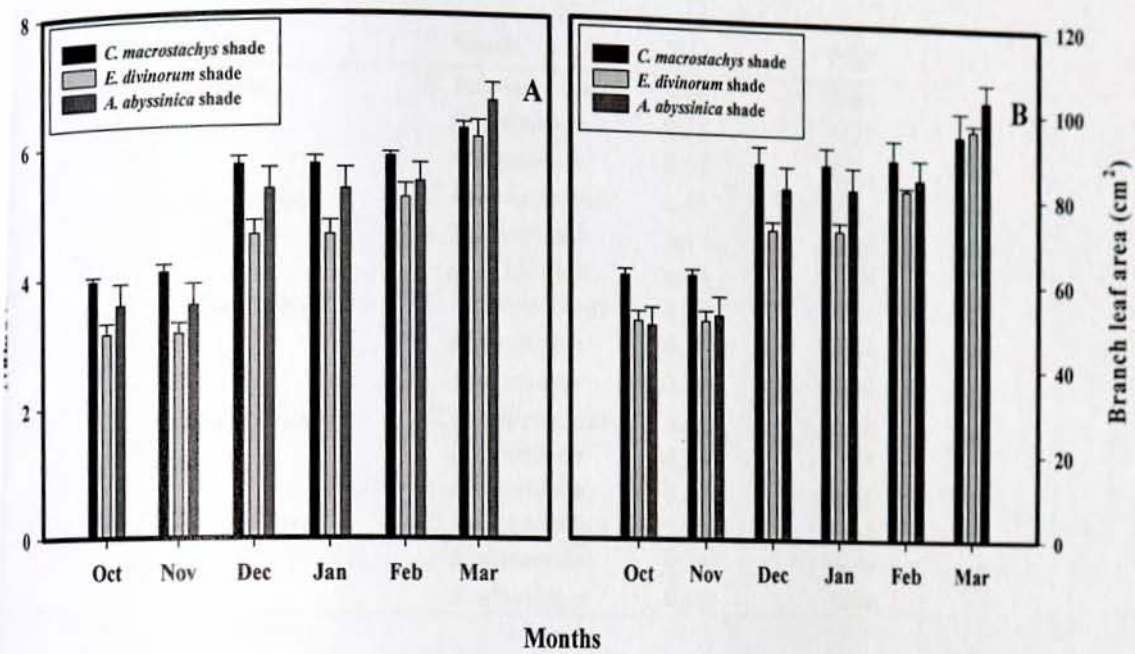

Figure 18. The mean: (A) number of leaves; and (B) branch leaf area of *C. arabica*, under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*. Bars represent ± S.E (n = 8 replicates per treatment).

When comparing the BLA of coffee trees, there existed a significant ($P<0.05$) change among the three restoring shades. The BLA on those coffee plants growing under the restoring shade of *A. abyssinica* were higher and possessed a mean BLA of 103±4.1 cm^2. Whereas, the mean BLA of coffee plants grown under the restoring shade of *E. divinorum* and *C. macrostachyus* were 96.2±1.3 and 94.75±5.5 cm^2, respectively.

4.2.4. Effects of PAR and T_{air} on growth parameters

Impacts of PAR and T_{air} on vegetative growth performances of *C. arabica* were assessed by running correlation analyses on PAR and T_{air} on the one hand and on stem length, branch, node and leaf numbers, as well as leaf area, on the other (Table 4)

Table 4. Correlation coefficients (r) between vegetative growths and environmental parameters (PAR and T_{air}) of three-year-old *C. arabica*, on the restoring sites. Significant (P<0.05) correlations are printed in bold letters.

Parameter	Shade	T_{air}	PAR
Stem height	*C. macrostachyus*	0.44	0.80
	E. divinorum	0.38	0.77
	A. abyssinica	0.33	0.73
Branch number	*C. macrostachyus*	**0.51**	**0.84**
	E. divinorum	**0.47**	**0.85**
	A. abyssinica	**0.49**	**0.83**
Node number	*C. macrostachyus*	0.52	**0.84**
	E. divinorum	0.38	**0.84**
	A. abyssinica	0.39	**0.81**
Number of leaves	*C. macrostachyus*	**0.54**	**0.86**
	E. divinorum	**0.38**	**0.84**
	A. abyssinica	**0.40**	**0.81**
Branch leaf area	*C. macrostachyus*	0.53	**0.85**
	E. divinorum	0.36	**0.83**
	A. abyssinica	0.45	**0.84**

P<0.05(significant)

The responses were highly dependent on specific environmental conditions when measurements were taken. For *C. macrostachyus*, *E. divinorum* and *A. abyssinica* shade, light intensity measured as PAR had a significant (P<0.05) positive association on the number of branch, node number, number of leaves and branch leaf area, while the traits showed no significant association with T_{air}. However, number of branches and leaves on coffee plants under the restoring shade of *C. macrostachyus*, *E. divinorum* and *A. abyssinica* were associated positively with T_{air} and in PAR. Amazingly, stem height did not show an association to either of the environmental variables (T_{air} and in PAR).

4.3. Fruiting and yield performances

The fruiting and yield performances of five-year-old *C. arabica* trees growing under the restoring shade of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and growing exposed to open sun (less restored) showed a number of differences on the berry

Table 4. Correlation coefficients (r) between vegetative growths and environmental parameters (PAR and T_{air}) of three-year-old *C. arabica*, on the restoring sites. Significant ($P<0.05$) correlations are printed in bold letters.

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4.3. Fruiting and yield performances

The fruiting and yield performances of five-year-old *C. arabica* trees growing under the restoring shade of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and growing exposed to open sun (less restored) showed a number of differences on the berry

and bean traits, including the yield. All the traits measured and quantified on the site that is being restored are as shown on the following sub-sections.

4.3.1. Green berries developed, counted and aborted

The number of green berries, during the period starting from October to December, showed a continuous increment (Fig. 19A) and decline on January which was associated with increasing the number of red berries.

The mean number of green berries per plant on the four treatment groups were significantly ($P<0.05$) different at the end of the measurement. Green coffee berries on the restoring shade of *A. abyssinica* showed a significant ($P<0.05$) highest number of berries with a mean value of 125.56±11.1 than coffee plants on the restoring shade of *C. macrostachyus* and *E. divinorum* having a mean number of green berries 69.31±8.07 and 61.6±5.8, respectively. However, coffee plants growing in open sun showed significant ($P<0.001$) lowest green berries than the rest of the shade plants with a mean value of 1.62±0.4.

As far as green berry abortion on the restoring sites was concerned, high significant ($P<0.05$) abortion were recorded during January followed by November and December. Similar number of green berry abortion, on the four treatments groups, occurred during the study period of October and differed afterwards (Fig. 19B).

Referring to the restoring shade types of the site, the highest significant ($P<0.05$) abortion of green berries showed on *A. abyssinica* shaded coffee plants with a mean value of 4.34±2 , while the second abortion recorded on coffee trees under the shade of *E. divinorum* with a mean value of 2.6±1.1. However, the lowest significant ($P<0.05$) abortion were found out on coffee plants growing under the restoring shade of *C. macrostachyus* and growing on open sun with a mean value of 1.31±0.5 and 0.53±0.3, respectively.

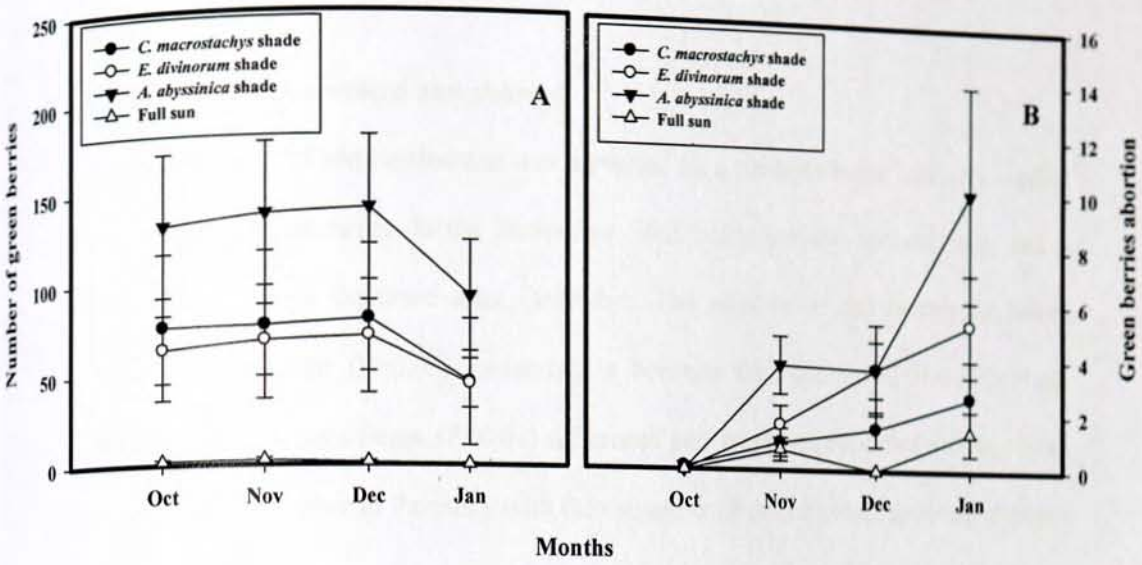

Figure 19. The mean: (A) green berries counted; and (B) green berries aborted on five-year-old *C. arabica*, growing under the restoring shades of *C. macrostachyus*, *E. divinorum*, *A. abyssinica*, and on open sun. Symbols indicate ± SE (n=8 replicates per treatment).

Furthermore, there is no significant ($P>0.05$) relationship between temperature and the number of green berries developed from October to January in all coffee plants growing under the four treatment conditions. There is positive significant ($P<0.05$) correlation (r) in between temperature and green berries abortion in those coffee plants growing under the shade of *C. macrostachyus* (r=0.963), *E. divinorum* (r=0.911) and *A. abyssinica* (r= 0.978). The result also indicated no association between T_{air} and green berry abortion in those coffee plants growing exposed to open sun (r=0.866). When the association of PAR and green berry development is concerned, there exists a positive association under the restoring shade of *C. macrostachyus* (r=1) and negative relation with those coffee plants exposed to the sun (r= -0.952). In addition, negative correlation

occurred between T_{air} and the number of green berries obtained on the four treatment groups.

4.3.2. Red berries harvested and aborted

The amount of red berries that was harvested on a monthly basis was very similar among the four treatments during November. Red berry harvest became high and a continuous increment occurred after December. The number of red berries harvested showed no significant ($P>0.05$) increment in between the months of November and December, while a significant ($P<0.01$) difference and increases recorded starting from the months of December to February with the exception of coffee plants growing exposed to the sun (Fig. 20A).

Referring to red berry harvest based on restoring shade types a significant ($P<0.01$) highest red berries were harvested in those coffee plants growing under the shade of *A. abyssinica* 126.37±37.5 than coffees in *C. macrostachyus* with 70.625±37.1 and *E. divinorum* with 61.75±17.5. Hence no significant ($P>0.05$) difference in red berry harvest obtained between *C. macrostachyus* and *E. divinorum* shade treated coffee plants. Further more, red berry harvest from coffee plants exposed to the sun showed the least result with 0.875±0.5 mean value.

The harvest of red berries on the four shade status showed no significant ($P>0.05$) relation with the temperature of the environment, although harvesting of red berries positively ($P<0.05$) related with PAR in those coffee plants growing under the shade of *C. macrostachyus* ($r=0.695$) and exposed to sun ($r=0.107$). However, a positive association occurred in between T_{air} and red berries abortion on the restoring shade of *C. macrostachyus* ($r=0.944$), *E. divinorum* ($r=0.947$) and *A. abyssinica* ($r=0.932$).

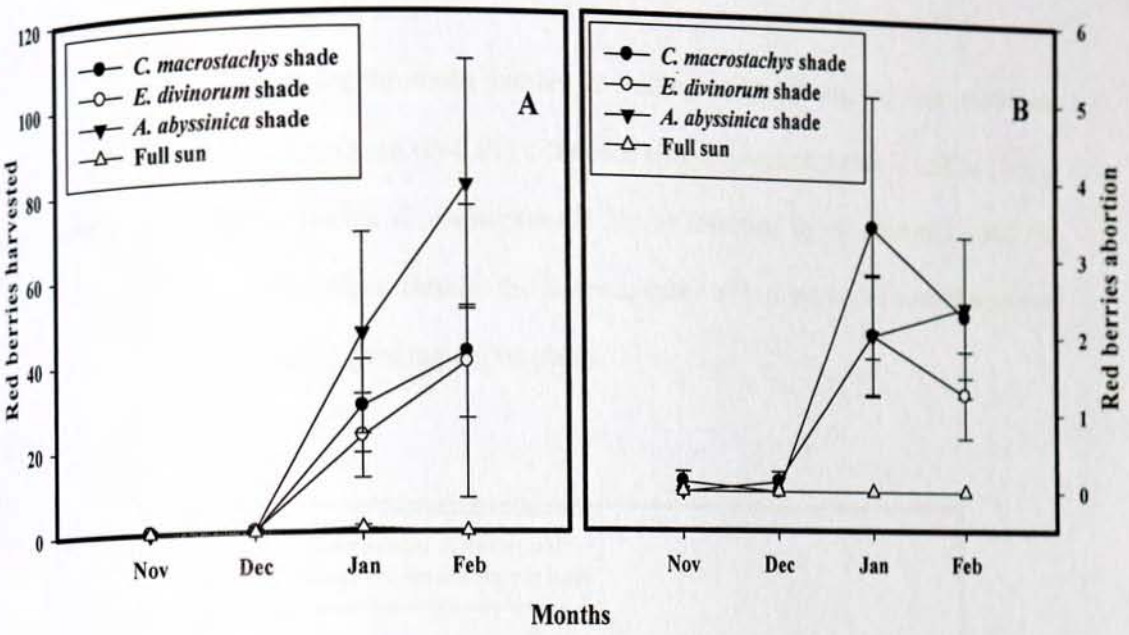

Figure 20. The mean: (A) red berries harvested; and (B) red berries aborted on five-year-old *C. arabica*, growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and on open sun. Symbols indicate ± SE (n=8 replicates per treatment).

Similar with the number of green berry abortion, the amount of aborted red berries in the study period showed significantly ($P<0.001$) higher during January. The lowest ($P<0.001$) significant abortion recorded on the months of November and December. Furthermore, concerning on abortion of coffee plants within the treated groups showed no significant ($P>0.05$) difference (Fig. 20B).

4.3.3. Number of fruiting nodes and berries per node

With regard to the number of fruiting node, variations on the four shade status was characterized by a comparably high number in those coffee plants under the restoring shade of *E. divinorum*, followed by *A. abyssinica* based and *C. macrostachyus* based coffee plants respectively. As shown (Fig. 21) maintaining the three restoring shaded

coffee plants with a significant ($P<0.01$) higher value, the lowest fruiting node found from coffees growing exposed to sun.

When comparing the mean number of fruiting nodes among the four treatment groups, there was a significant ($P<0.01$) difference with the highest value in coffee plants growing under the restoring *E. divinorum* (25.2±6.5) followed by *A. abyssinica* and *C. macrostachyus* based coffees. Besides the lowest number of fruiting nodes were found out on exposed sun (3.5±0.2) growing coffee plants.

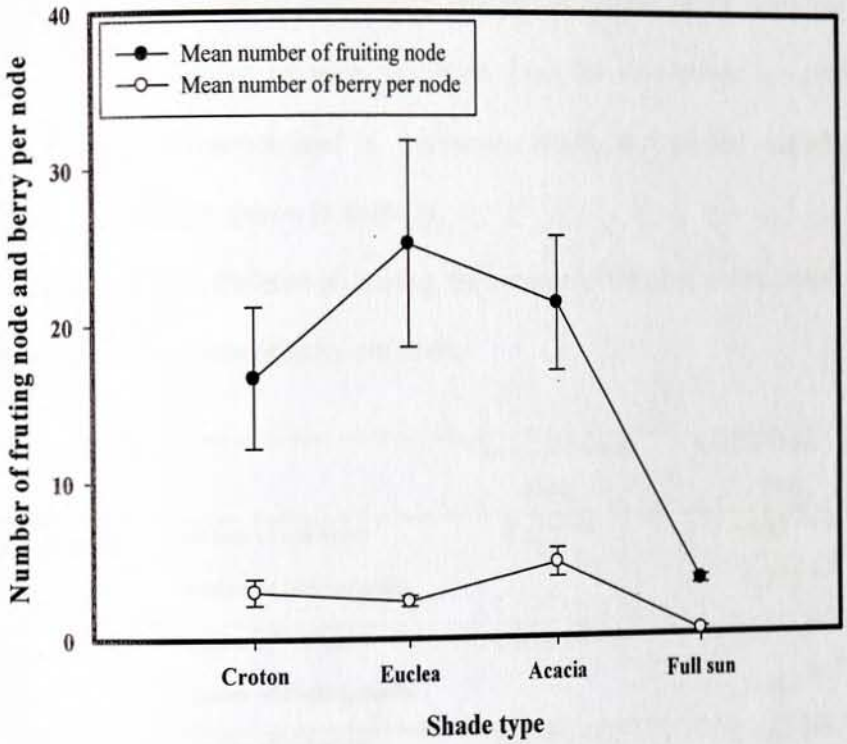

Figure 21. The mean number of fruiting nodes and berries per node on five-year-old *C. arabica*, growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and on open sun. Symbols indicate ± SE (n=8 replicates per treatment).

Like the number of fruiting nodes per plant on the restoring site, number of berries per node also showed the same result i.e. berries per node significantly different on the four treatment groups but with different significant level ($P<0.001$) (Fig. 21).

Meanwhile, the mean number of berry per node was significantly highest on the restoring *A. abyssinica* shaded coffee plants (4.75±0.92) than *C. macrostachyus* and *E. divinorum* based coffee populations. Still in those coffees growing on the sunny exposed degraded land showed a significant ($P<0.001$) least number of berry per node (0.25±0.1) than the rest (Fig. 21).

Pearson's correlation (r) coefficients among the number of red berry, number of fruiting nodes and number of berry per node from the data across the restoring *C. macrostachyus*, *E. divinorum* and *A. abyssinica* shade, and on the degraded sunny exposed coffee plants are shown in Table 5.

Table 5. Correlation coefficients (r) among the number of fruiting nodes, number of red berries and number of berry per node.

		Number of fruiting nodes	Number of berry per node
C. macrostachyus	**Number of red berry**	0.839 **	0.952 ***
	Number of fruiting nodes		0.773 *
E. divinorum	**Number of red berry**	0.939 ***	0.849 **
	Number of fruiting nodes		0.662 ^{ns}
A. abyssinica	**Number of red berry**	0.925 ***	0.986 ***
	Number of fruiting nodes		0.890 **
Full sun	**Number of red berry**	1.000 ***	0.987 ***
	Number of fruiting nodes		0.987 ***

ns = $P>0.05$, *$P<0.05$, **$P<0.01$, *** $P<0.001$

Number of red berry harvested showed significant positive correlation with the number of fruiting nodes and number of berry per node in all the treatment groups. Associations between the numbers of fruiting nodes with the number of berry per node on

the shade of *C. macrostachyus*, *A. abyssinica* and in those coffee plants growing exposed to sun showed significant positive correlations, but no significant correlation occurred on the shade of *E. divinorum* where the PAR level is high.

4.3.4. Number of beans within berry and beans obtained and aborted

The amount of beans within a single berry on the four treated groups varies significantly ($P<0.05$). As it is shown (Fig. 22A), the highest one, two and three beans per berry obtained from the restoring shade of *A. abyssinica* which were followed by coffees in *C. macrostachyus* and *E. divinorum* respectively, while coffees in the full sun showed significantly ($P<0.05$) the least value.

On the same case, the mean berry with one bean containing within it on the four treatment group were significantly ($P<0.05$) highest on *A. abyssinica* based coffee plants with a mean number of 37.62±12.5 than coffee plants on *C. macrostachyus* with 14.6±9.1, *E. divinorum* with 13.1±5.7 and full sun with 0.37±0.2 mean number, respectively. Similar result was found out that a significant difference on the mean berry with two beans on the four treatment group providing the restoring *A. abyssinica* shade with the highest number of 85.5±24.7. However, berry containing three beans on the four treatment groups of coffee plants showed no significant difference ($P>0.05$).

During the wet method processing, aborted beans were identified and statistically analyzed as follows. The number of aborted beans on the four treatment groups is significantly ($P<0.05$) different. Similar with the number of beans obtained, the highest mean abortion per plant (49.2±16.3) is also found in those coffee plants growing under the restoring shade of *A. abyssinica* while *E. divinorum* and *C. macrostachyus* followed with a mean value of 22.5±7.9 and 20.25±11.4, respectively. The least aborted beans 0.37±0.2 were also found on coffees growing in the degraded sunny exposed area (Fig. 22B).

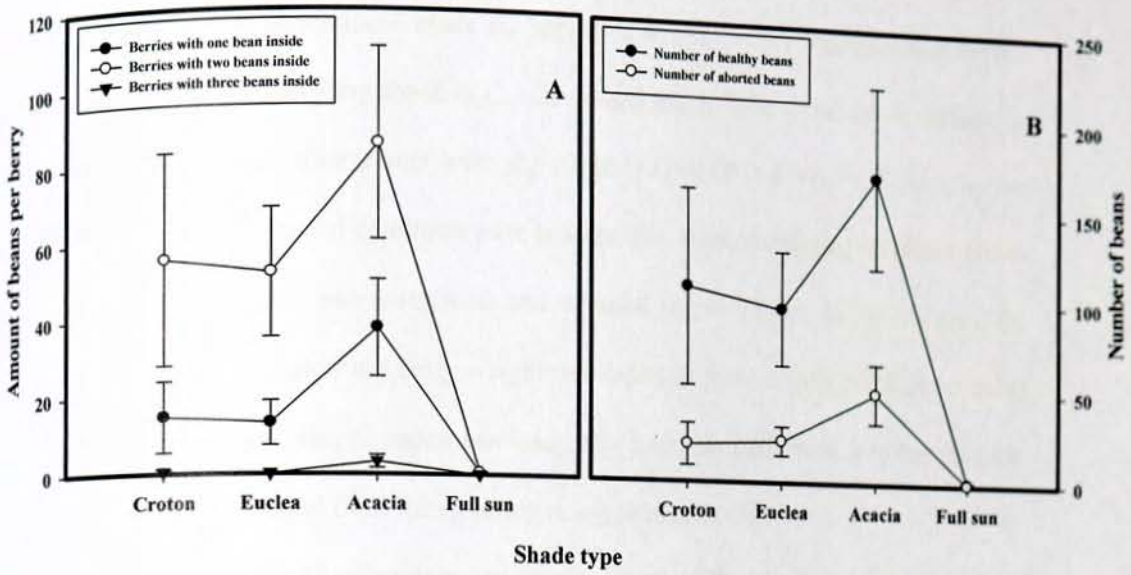

Figure 22. The mean: (A) number of beans per berry; and (B) number of beans obtained and aborted on five-year-old *C. arabica*, growing under the rstoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and on open sun. Symbols indicate ± SE (n=8 replicates per treatment).

As far as the number of beans obtained is concerned, coffee plants in the restoring *A. abyssinica* shaded provide the highest (169.1±50.3) yield. Meanwhile, the restoring *C. macrostachyus* and *E. divinorum* shaded coffee plants flourish the second and the third yield with a mean bean number of 106.4±54 and 95.2±31, respectively. However, coffee populations on the degraded sunny area showed the least bean providing group with a mean of 1±0.6 (Fig. 22B).

Correlations (r) between the number of bean obtained and aborted from the coffee plants on the restoring shade of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and from degraded-sunny exposed showed that, a positive significant associations (r_C=0.994***, r_E=0.969***, r_A=0.827* and r_F=0.933***) were observed between number of beans obtained and aborted.

4.3.5. Fresh and dry weight of berries, pulps, parchments and beans

Berry weight assessment made on harvested coffee berries indicated that berries developed under the restoring shade of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and degraded-sunny coffee plants were significantly ($P<0.001$) different. Coffee berries under *A. abyssinica* shaded condition were heavier than those developed on plants grown under *E. divinorum*, *C. macrostachyus* and exposed to sun (Table 6). In addition, the mean minimum and maximum berry weight developed in those coffee populations under the shade of *E. divinorum*, *C. macrostachyus* and direct sun light were also significantly lower than those obtained from the restoring *A. abyssinica* shade.

Table 6. The mean weight of mature red berries from coffee plants growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and on open sun.

variable	Treatments				Significance
	C. macrostachyus	*E. divinorum*	*A. abyssinica*	Full sun	
Average weight of berry(g)	0.94	1.14	1.42	0.12	s
Minimum weight of berry(g)	0.72	1.02	1.33	0.11	s
Maximum weight of berry(g)	1.19	1.33	1.48	0.13	s

($P<0.001$): (s) significantly different

As shown in (Table 6; Fig. 23A) the mean maximum berry weight is significantly higher than the minimum berry weight in the case of coffee plants grown under the restoring shade of *C. macrostachyus*, *E. divinorum* and *A. Abyssinica*. However, no significant ($P>0.05$) difference found in those berries obtained from coffee plants growing on the open sun.

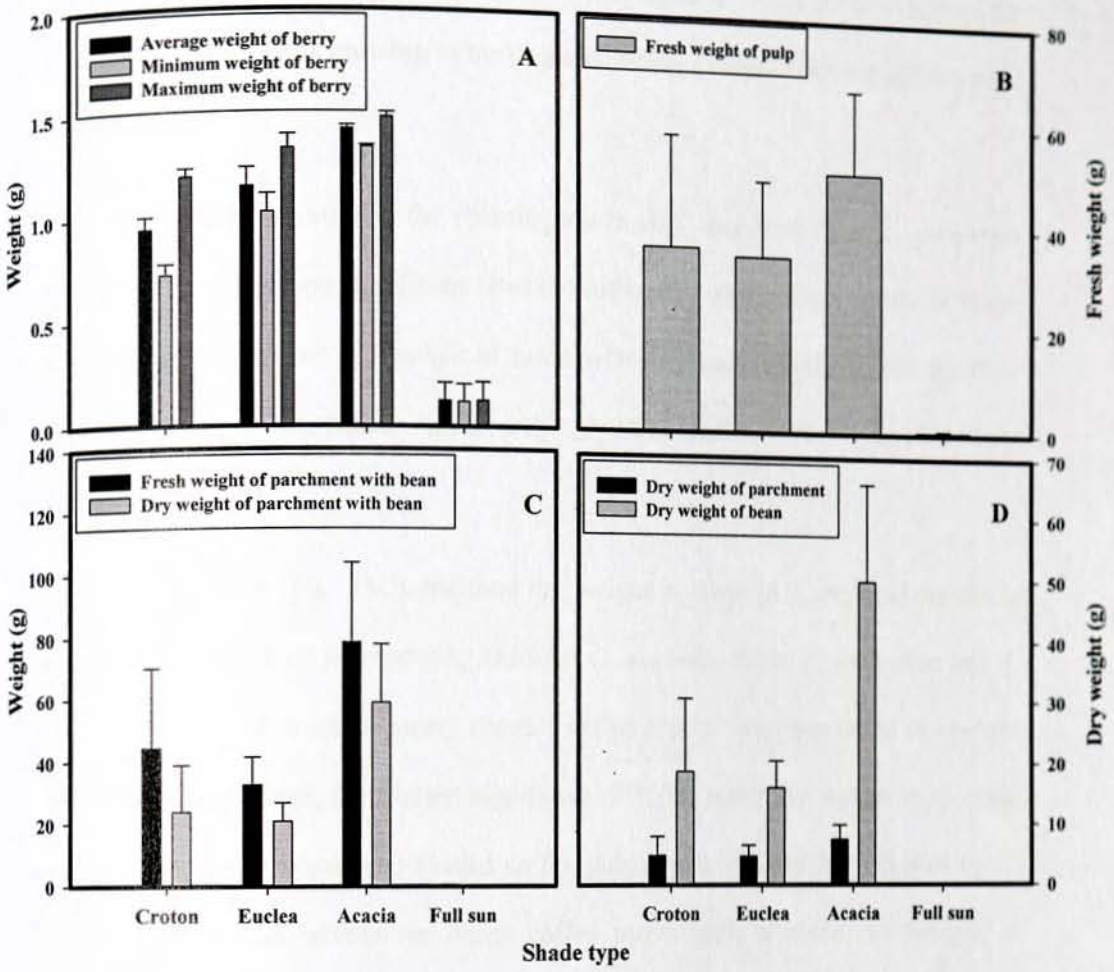

Figure 23. The mean: (A) weight of berry; (B) fresh weight of pulp; (C) fresh weight of beans with parchment and dry weight of beans with parchment; and (D) dry weight of beans and parchment on five-year-old *C. arabica*, growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and on open sun. Bars indicate ± SE (n=8 replicates per treatment).

As illustrated in (Fig. 23B) the pulp fresh weight of berries from the three restoring shades and degraded-sunny exposed showed a significant ($P<0.05$) different weight. When comparing the mean fresh weight of pulp harvested from each group, there is a significant higher mean 50.67±16.2g weight value in the restoring *A. abyssinica* shaded coffee populations than the weight of the pulp from *C. macrostachyus* with 35.52±21.9g

and *E. divinorum* with 33.9±14.9g. The lowest significant ($P<0.05$) fresh weight of the pulp is from coffee plants growing in the degraded sunny exposed with the mean weight value 0.49±0.3g.

Coffee plants growing in the restoring shade of *C. macrostachyus*, *E. divinorum* and *A. abyssinica* have no significant ($P>0.05$) difference on the fresh weight of beans with parchment. However, the weight of beans with parchment obtained from the three restoring shaded coffee plants significantly ($P<0.01$) differed from degraded-sunny exposed coffee plants.

As it is shown (Fig. 23C), the total dry weight is lower than the fresh weight of beans with parchment on the restoring shade of *C. macrostachyus*, *E. divinorum* and *A. abyssinica* coffee plants unlike sunny exposed coffee plants. Referring to the dry weight of beans with parchment, the highest significant ($P<0.05$) mean dry weight is recorded from the restoring *A. abyssinica* shaded coffee plants with 58.8±18.9g, followed by *C. macrostachyus* and *E. divinorum* based coffee plants with a mean dry weight of 23.7±15.1g and 20.8±5.9g, respectively. The lowest significant ($P<0.05$) dry weight of beans with parchment obtained from those coffee plants growing exposed to sun and with a mean dry weight of 0.09±0.05g.

The dry weight of beans obtained are higher and significantly ($P<0.001$) different than parchment dry weight on the same treatment groups. Although such dry weight difference occurred in between beans and parchment, no significant ($P>0.05$) changes occurred among the groups when the parchment dry weight is concerned. However, the dry weight of beans from coffee plants under the restoring shades and degraded-sunny exposed showed a significant ($P<0.05$) difference (Fig. 23D).

The highest mean dry weight of beans recorded in those coffee plants growing under the restoring shade of *A. abyssinica* with 49.8±15.9g, whereas *C. macrostachyus*

and *E. divinorum* shaded plants attained 18.5±11.9g and 15.9±4.4g, respectively. Similar with the fresh weight of beans with parchment, the lowest significant ($P<0.05$) bean dry weight is found in coffee plants growing on the degraded-sunny area. Weight associations between the traits of berry and beans were all positive, and a significant ($r_C=0.999$, $r_E=0.968$, $r_A=1.000$ and $r_F=0.881$) association occurred on the four treatment groups.

4.3.6. Bean size and bean weight per thousand (g/1000 beans)

The randomly selected coffee beans from the four treatment groups showed a significant ($P<0.001$) difference. The mean bean length obtained from coffee trees under the restring *A. abyssinica* shade were significantly the highest (1.16±0.05 cm) than *E. divinorum* and *C. macrostachyus* with a mean length of 0.82±0.02 cm and 0.66±0.02 cm respectively. Furthermore, the lowest significant mean bean length (0.44±0.02 cm) was recorded from those coffee plants growing exposed to the degraded-sunny area (Fig. 24A).

The mean coffee bean weight per thousand beans (g/1000 beans) among the treatment groups showed statistically significant ($P<0.001$) difference. The coffee bean weight (g/1000 beans) of five-year-old *C. arabica* L. plants decreased significantly ($P<0.001$) from 276.1g from *A. abyssinica* shade to 192.3g *E. divinorum* shade, then to 137.1g *C. macrostachyus* shade and further to the sunny exposed coffee plants with 10g (Fig. 23). The result indicated that the highest and the lowest g/1000 beans obtained from coffee plants under the restoring shade of *A. abyssinica* and on those coffee plants growing exposed to sun, respectively (Fig. 24B).

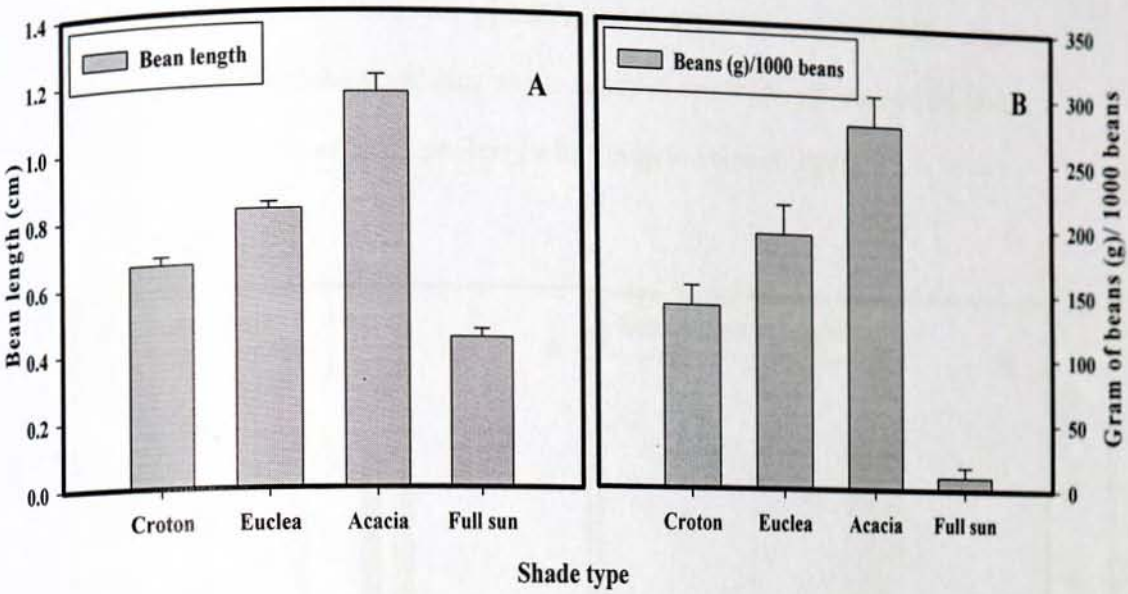

Figure 24. The mean: (A) bean size; and (B) beans (g)/1000 beans obtained on five-year-old *C. arabica*, growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and on open sun. Bars indicate ± SE (n=8 replicates per treatment).

4.3.7. Bean-berry weight ratio and coffee yield

There was also considerable significant ($P<0.001$) variation in the bean/berry ratios measured from those coffee plants beneath the restoring shade and degrade-sunny area. The shade of *A. abyssinica* had the highest bean/berry ratio with 0.38, while the result from coffee plants growing exposed to degraded-sunny area had the lowest bean/berry ratio with the value of 0.01. The bean/berry ratios identified from the restoring shade of *C. macrostachyus* and *E. divinorum* were also about 0.20 and 0.26, respectively (Fig. 25A).

There was a very noticeable significant ($P<0.001$) difference among the four treatment groups concerning weight of beans per berry. The mean weight of beans per

berry in the restoring shade of *A. abyssinica* stands was significantly (P<0.001) higher with 0.55g than that in *E. divinorum* with 0.3g and *C. macrostachyus* with 0.19g stands. Additionally, the coffee plants growing on the degraded-sunny site still showed the lowest value in terms of weight of beans per berry with the mean value of 0.003g.

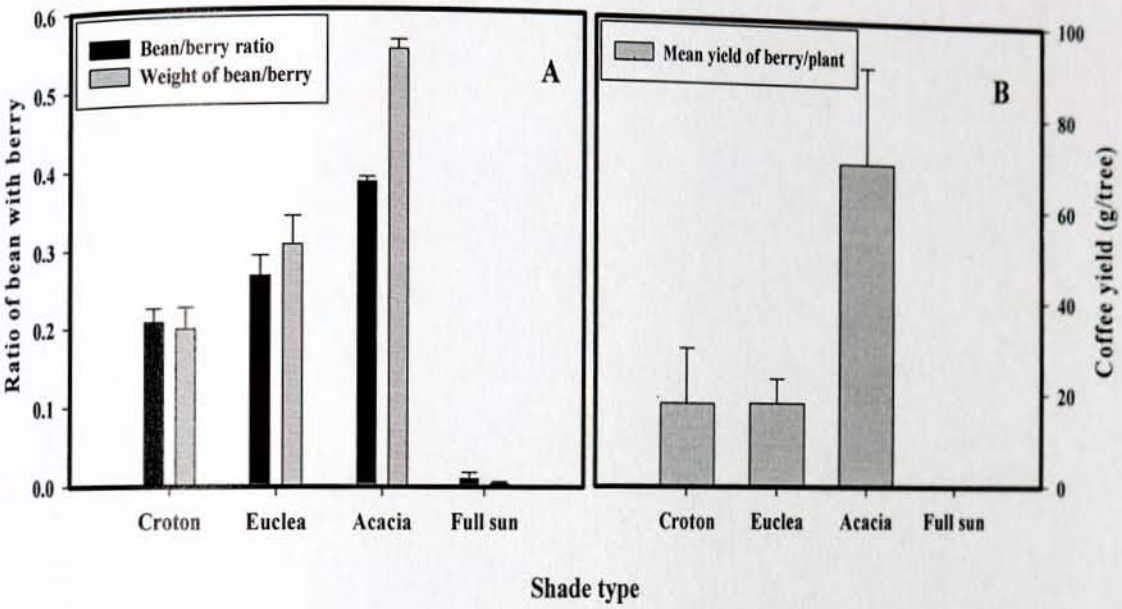

Figure 25. The mean: (A) bean/berry ratio and weight of beans/berry; and (B) coffee yields (g/plant) obtained on five-year-old *C. arabica*, growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and on open sun. Bars indicate ± SE (n=8 replicates per treatment).

Following the formula described in the methodology, *C. arabica* grown under the restoring shade of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and on sunny exposed site showed significant (P<0.01) yield response. The overall average results depict that coffee trees planted under the restoring shade of *A. abyssinica* resulted in significantly (P<0.01) highest clean coffee yield with a value of 69.7±20g/tree followed by *E. divinorum and C. macrostachyus* with a value of 17.8±5.2 g/tree and 17.6±11

berry in the restoring shade of *A. abyssinica* stands was significantly (P<0.001) higher with 0.55g than that in *E. divinorum* with 0.3g and *C. macrostachyus* with 0.19g stands. Additionally, the coffee plants growing on the degraded-sunny site still showed the lowest value in terms of weight of beans per berry with the mean value of 0.003g.

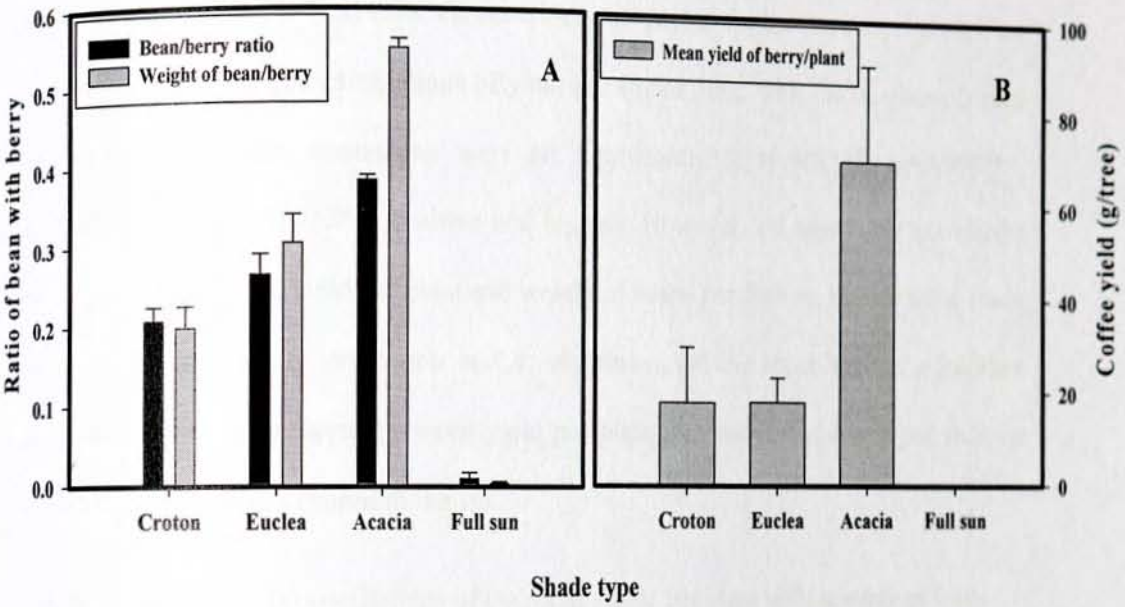

Figure 25. The mean: (A) bean/berry ratio and weight of beans/berry; and (B) coffee yields (g/plant) obtained on five-year-old *C. arabica*, growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and on open sun. Bars indicate ± SE (n=8 replicates per treatment).

Following the formula described in the methodology, *C. arabica* grown under the restoring shade of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and on sunny exposed site showed significant (P<0.01) yield response. The overall average results depict that coffee trees planted under the restoring shade of *A. abyssinica* resulted in significantly (P<0.01) highest clean coffee yield with a value of 69.7±20g/tree followed by *E. divinorum and C. macrostachyus* with a value of 17.8±5.2 g/tree and 17.6±11

g/tree, respectively. This was in contrast to the least significantly ($P<0.01$) value obtained from those coffee plants growing on the degraded-sunny exposed area with a value of 0.01±0.008 g/tree, indicating that it is not amongst the suitable coffee growing site (Fig. 25B).

Correlation coefficients between bean yield and number of fruits per tree, and yield and weight of beans per fruit from the combined data across the four treatment groups are shown in (Table 7). The associations of yield per coffee plant with the number of fruits per tree, on the four treatments, were all significantly (r_C=0.988***, r_E=0.950***, r_A=1.000*** and r_F=0.925**) positive and highest. However, no significant correlation was observed between yield per plant and weight of beans per fruit on the restoring shade of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*. On the other hand, a significant positive correlation occurred between yield per plant and weight of beans per fruit on coffee plants growing exposed to the sun.

Table 7. Correlation (r) coefficients of the mean yields per plant with number of fruits per tree and weight of beans per fruit.

		Yield per plant
C. macrostachyus	**Number of fruits per tree**	0.988***
	Weight of beans per fruit	0.581^{ns}
E. divinorum	**Number of fruits per tree**	0.950***
	Weight of beans per fruit	-0.0721^{ns}
A. abyssinica	**Number of fruits per tree**	1.000***
	Weight of beans per fruit	0.0811^{ns}
Full sun	**Number of fruits per tree**	0.925**
	Weight of beans per fruit	0.990***

ns = $p>0.05$, *$p<0.05$, **$p<0.01$, *** $p<0.001$

4.4. Effect of various gibberellic acid (GA_3) on flower development

The flowering efficiency and prospective flowering power of four-year-old *C. arabica* on the restoring second site, that is being restored and comprised of various indigenous tree species, were compared with coffee plants subjected to 100, 250 and 300 mg l^{-1} GA_3 solutions. The flowering parameters that were measured during the study period are analyzed as follows.

4.4.1. Flower bud and flower development

GA_3 significantly enhanced early anthesis of coffee flower buds that were treated with 100, 250 and 300 mg l^{-1} GA_3 including the control groups. Branches that received the highest GA_3 concentration (250 mg l^{-1} GA_3) developed the highest significant number ($P<0.001$) of flowering buds at anthesis. The lowest significant number of flower buds occurred on coffee plants treated with 300 mg l^{-1} GA_3 followed by 100 mg l^{-1} GA_3 treated coffee plants. In contrast, flower buds developed on control branches showed significantly higher next to 250 mg l^{-1} GA_3 treated coffee plants (Fig. 26).

The flower bud development on those coffee plants treated with 250 mg l^{-1} GA_3 solution showed a mean number of 212±6.3. The lowest and the second most flower development occurred on coffee plants treated with 100 mg l^{-1} GA_3 solution and control coffee plants, with the mean flower bud number of 43.3±3.2 and 97.1±1.6, respectively.

The flowering parameters which were measured showed significant ($P<0.001$) differences between treatments. Flowering among the treatment groups showed variation, the largest one observed on coffee plants treated with 250 mg l^{-1} GA_3, followed by progressively decreasing in groups of control, 100 mg l^{-1} GA_3 and 300 mg l^{-1} GA_3. Hence similar with flower bud development, the second largest flowering found on coffee plants of the control group.

When comparing the number of flower bloomed, a significant ($P<0.001$) maximum number of flower recorded on lateral branches of four-year-old coffee plants treated with 250 mg l^{-1} GA_3 and a mean flower number of 206.3±6.3, while those coffee plants treated with 100 mg l^{-1} GA_3 and 300 mg l^{-1} GA_3 attained a mean flower number of 41±3.2 and 25.5±2.7, respectively. The control treatment had a mean 96.8±1.3 flowers per coffee plant, which is the second highest flower number.

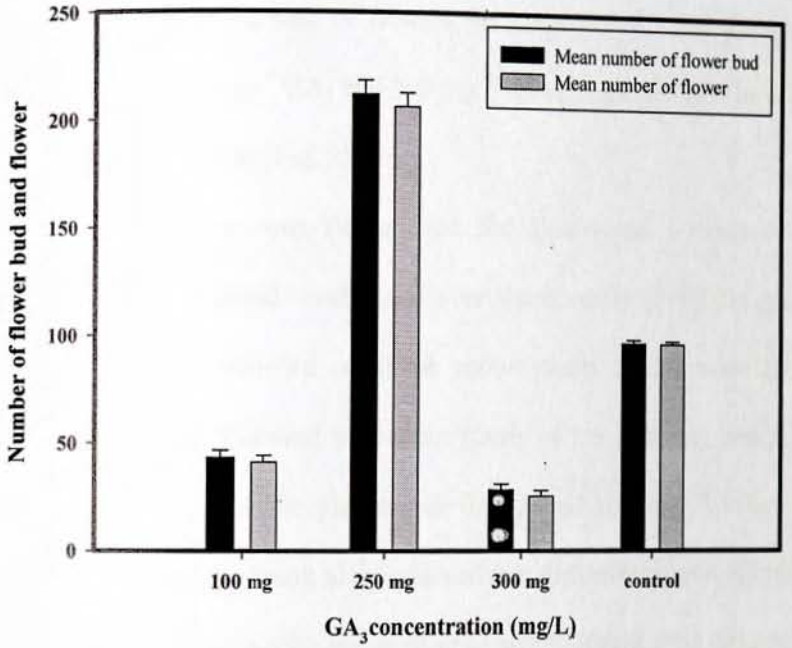

Figure 26. Effects of GA_3 (100, 250 and 300 mg l^{-1} GA_3) solutions on the mean number of flower buds and flower developments on four-year-old *C. arabica*, growing under the restoring multiple shades of native trees at site II. Control treatment was double distilled water. Bars indicate ± SE (n=6 replicates per treatment).

When considering the efficiency of developing from flower bud in to coffee flower, 97 % of the flower buds that were treated with 250 mg l^{-1} GA_3 developed (bloomed) in to flower. But the control group showed a conversion of flower bud in to flower, with a flowering percentage of 99. The rest, i.e. on 300 mg l^{-1} GA_3 treated coffee

plants 89 % of flower buds developed on to flowers and 94 % of flower buds treated with 100 mg l^{-1} GA_3 developed in to flowers.

4.4.2. Flower bud per node and number of secondary branch

In the case of flower number per node, a significant ($P<0.001$) difference occurred in between the treatment groups. The number of flowers per node was significantly ($P<0.001$) highest on 250 mg l^{-1} GA_3 treated coffee plants with a mean value of 6.1. Whereas the second higher significant ($P<0.001$) mean flowers per node recorded 3.6 in the control groups. The number of flowers per node was 2.3 and 1.5 for those coffee plants treated with 100 mg l^{-1} GA_3 and 300 mg l^{-1} GA_3, respectively. The difference of the flower per node is shown in (Fig. 27).

An association between flower bud and flower, as a result of various GA_3 chemicals and environmental conditions, were significantly ($P<0.001$) positive, and the highest correlation (r) recorded on those coffee plants treated with 250 mg l^{-1} GA_3 ($r_{250}=0.999$) which are followed by coffee plants of the restoring control site ($r_{control}=0.997$), 300 mg l^{-1} GA_3 coffee plants ($r_{300}=0.982$) and 100 mg l^{-1} GA_3 treated coffees ($r_{100}=0.978$). However, the result also indicated that the development of secondary branch and flowering on the same coffee plants showed no significant ($P>0.05$) correlations.

Vegetative growth of the secondary branches that were treated with different growth regulators showed significant ($P<0.001$) differences between control and GA_3 treatment. The average secondary branch growth for all treatments was most vigorous in those coffee plants treated with 300 mg l^{-1} GA_3 solution, with the mean number of 48.6 per plant (Fig. 27).

Meanwhile, the growth of secondary branch decreased consistently on coffee plants treated with 100 and 250 mg l^{-1} GA_3 solutions, which mean number of 27.5 and

14.8, respectively. Nonetheless the control group showed the least number of secondary branch development.

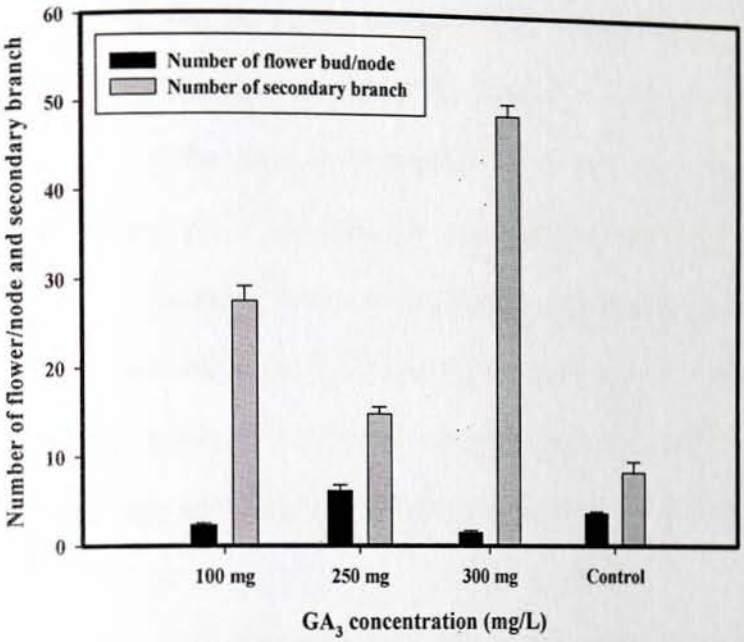

Figure 27. Effects of GA_3 (100, 250 and 300 mg l^{-1} GA_3) solutions on the number of flower buds per node and secondary branches development on four-year-old *C. arabica*, growing under the restoring multiple shades of native trees at site II. Control treatment was double distilled water. Bars indicate ± SE (n=6 replicates per treatment).

4.5. Floristic composition of the study sites

A total of 112 species was found across all experimental and reference plots during the study period, and a significant ($P<0.05$) higher number of floristic composition existed on the site which is being restored than the degraded site. A complete listing of species by treatment combination is given in Appendix 1 and 2.

Species belonging to 42 families were recorded from the selected sample plots in the site which is being restored, and showed a significant ($P<0.05$) difference on the

number of plant species among grass, herb, shrub and tree. However, no significant ($P>0.05$) difference occurred on the number of plant species present in between shrub and tree vegetation type. Fabaceae, Asteraceae, Achanthaceae and Poaceae families were represented comparatively by the highest number of plant species, while the majority of the families including Podocarpaceae family represented by only one species. Trees accounted for 32 % of the naturally-regenerated woody species, such as *Hagenia abyssinica*, *Juniperus procera*, *Podocarpus falcatus*, *Millettia feruginea*, *Olea europaea* subsp. *cuspidata*, *A. abyssinica*, *Vernonia amygdalin*, *Allophyllus abyssinicus*, *Prunus africana*, *Syzygium guineense* as well as keystone tree species such as *Ficus vasta*, *F. sycomorus* subsp. *sycomorus*, *F. sycomorus* subsp. *gnaphalocarpa* and *F. sur*. Shrubs accounted for 31 %, herbs accounted for 24 % and grass accounted for 13 % on the study site which is being restored.

However, the nearby degraded reference plots were comprised of 10 plant species from different 7 families, and showed no significant ($P>0.05$) difference on the number of plant species within the grass, shrub and tree. The vegetation type included grasses, shrubs and few drought tolerant tree species. For example, the grasses were *Pennisetum setaceum*, *Andropogone schirenis*, *Eleusine floccifolia* and *Panicum ruspolli*. Shrubs included *Carrisa spinarum*, *Rumex nervosus* and *Sida schimperina*. The tree species included *A. abyssinica*, *Eucalyptus globules* and *Eucalyptus camaldulensis*.

CHAPTER FIVE

1. DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

5.1. DISCUSSIONS

This study was undertaken with the explicit goal of investigating the impacts of restoring native trees and/or shrubs such as *C. macrostachyus*, *E. divinorum* and *A. abyssinica* on the successful regeneration of soil fertility and provision of favorable conditions (air temperature) for the re-instatement of critical life support systems. To this end, the phrase Restoration Bioassay was coined and an environmentally demanding plant (*Coffea arabica* L.) was used to test extent of restoration of previously degraded landscape.

5.1.1. Environmental conditions of the study site

5.1.1.1. Air temperature (T_{air})

Temperature is known to be an important determinant of growth and reproduction of *C. arabica* (DaMatta, 2004). A number of previous studies indicate that coffee is a climatically sensitive crop, and the optimal air temperature (T_{air}) for production of coffee ranges between 18-22 °C (Alegre, 1959; Demel Teketay, 1999).

In this study, the site which is being restored fulfilled the desired T_{air} for the growth and reproduction of *C. arabica*. Maximum and minimum T_{air} ranges between 19-26 °C and 8-11 °C, respectively, while the mean annual T_{air} ranges between 10-23 °C. Consequently, the negative effect due of low T_{air} inducing chilling or cold stress as reported elsewhere (Alegre, 1959) was not detected in this study. For a comparative study, T_{air} between the site which is being restored and the nearby non-restoring sites were compared and found out higher in the latter, where it ranges between mean values of 15-30 °C. As a result of the mean T_{air} difference between the two sites, it is possible to state that the lower T_{air} range in the site which is being restored is clearly due to the

presence of various indigenous (like *A. abyssinica*, *C. macrostachyus* and *E. divinorum*) plant species that have a potential in regulating extreme T_{air} either by reducing excess air CO_2 or providing shade to the environment or reducing direct incidence of solar radiation (Legesse Negash, 2010). The shade has an impact in stabilizing both the soil and T_{air} (Morais *et al.*, 2006). Shaded soil has the ability to stabilize the local thermal balances and also to reduce the heat flux caused by the accumulated plant based biomass (Morais *et al.*, 2006). Shading buffers the extreme T_{air} variations and provides a microclimate which attenuates extreme T_{air} and soil and preserves surface soil humidity (Campanha *et al.*, 2005; Legesse Neegash, 2010). Siebert (2002) also reported that shading reduces and stabilizes the soil temperature by reducing the radiant flux reaching the soil and modifying the temperature amplitude at the soil surface, which in turn promotes restoration (John, 1997; Legesse Neegash, 2010).

5.1.1.2. Photosynthetically active radiation (PAR)

Although, coffee plants are said to be a photo-inhibited plant with greater quantum utilization efficiency for photosynthesis, excessive shading would decrease growth and productivity of coffee trees because the plant spent much of their photosynthetic activities for maintenance purpose (Campanha *et al.*, 2005; Mayoli and Gitau, 2012). In this study, the site which is being restored was assessed through PAR value due to the interception of solar radiation by various shade trees. The incident solar radiation, PAR, was greatly reduced and significantly different for coffee trees grown under the restoring shades of *A. abyssinica*, *E. divinorum* and *C. macrostachyus*, than the nearby non-restoring sites.

Compared to the non-shading plots (which received 840 µmol $m^{-2}s^{-1}$), photon flux densities beneath *C. macrostachyus*, *E. divinorum* and *A. abyssinica* and at the top of the coffee plants were 374, 107 and 117 µmol $m^{-2}s^{-1}$, respectively. These values represent 45, 13 and 14 % respectively of shades afforded by the shade trees. The reduced PAR under

the restoring shade trees as it is explained in Table 3, provide a suitable shade for coffee plants either by utilization or reflection of the excessive light radiation coming from the sun and helps understory photo-inhibited plants like *C. arabica* to obtain suitable photon flux radiation (PAR) for the process of photosynthesis (Mayoli and Gitau, 2012).

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 $m^{-2}s^{-1}$, respectively. These values represented light absorption of 17, 69 and 74 % by coffee plants grown beneath *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, respectively. Coffee trees growing under the tree shades had a more photosynthetic rate, this condition can be explained by the fact that coffee trees growing under shade showed certain morphological modifications and physiological adaptations (Campanha *et al.*, 2005; Mayoli and Gitau, 2012), and their leaves are capable of absorbing more than 90 % of the energy contained in the wavelengths between 400 and 700 nm (Muschler, 2001). Hence, light availability under shade was reduced by 75 % compared to open sun conditions which are the vital requirement for the growth of photo-inhibited plants (John, 1997).

5.1.1.3. Soil

Only a few studies have been conducted in Ethiopia with the aim of investigating the impacts of indigenous tree species such as *A. abyssinica*, *E. divinorum* and *C. macrostachyus* used for the mechanism of restoration and there impacts on soil properties.

Indigenous tree species have extremely valuable biological attributes, which are particularly useful for soil regeneration (Legesse Negash, 2010). These attributes are manifested through trees: deep roots, which extend into ground for selectively extracting essential macro- and micro-nutrients to be used in the growth and development of the trees massive body; fast leaf senescence and abscission rates, which enable the tree to produce large quantities of leaf litter or necromass (dead fine roots, outer bark

components, secondary branches, leaflets, flowers, pods, and seeds) per unit time; tender leaves, which easily break down into pieces during the dry season, and decompose readily during the wet season (Cadish and Giller, 1997; Legesse Negash, 2010). This ensures rapid nutrient turn over, thus making indigenous trees an efficient facility for pumping nutrient elements from the ground/subsurface to the surface of soil. The trees also improve soil fertility through fixing atmospheric nitrogen as well as micro-site improvement through the provision of shade (Raymond and Roy, 1995; Legesse Negash, 2010).

Soil fertility restoration depends on numerous factors including species used, provenance, density of trees, climate, season, age and decomposition rate of litters or necromass (Nelson and Sommers, 1982; Legesse Negash, 2010).The decomposition process itself is controlled by three interacting factors: the physical and chemical environment (e.g. climate, soil mineralogy), substrate quality and the decomposer biota (Lavelle *et al.*, 1993; Myers *et al.*, 1994; Cadish and Giller, 1997).

The presence of favorable soil texture (56 % clay, 31 % silt and 13 % sand) on the site that is being restored provided a suitable condition for the vegetative and reproductive growth of *C. arabica*. Such soil composition together with the presence of high organic matter and soil biota results in producing essential plant nutrients, well aerated (oxygen supply) and conducive water holding capacity of soils (Adel and Travis, 2010). Consequently, due to the restoration of various plants in the site that is being restored, less bulk (1.46 g/cm^3) and particle density (2.52 g/cm^3) were restored than the non-restoring sites, and could serve as an indication of restoration success that we have measured the successful establishment and life-cycle completion of *C. arabica*. Compaction resulting from intensively grazing animals might have caused the relatively higher bulk density values in the surface soil of the non-restoring sites than that of the respective soil surface

of the restoring sites. The reason for the lowest soil bulk density on the restoring sites is clearly due to the presence of less disturbance of the land under restoration unlike the non-restoring sites.

Also, optimal pH range from 6-7, favorable exchangeable bases and micronutrients were also established on the restoring sites and such condition is responsible for the successful growth and development of *C. arabia*. The lowest value of pH under the restoring sites may be due to the depletion of basic cations in crop harvest and drainage to streams in runoff generated from accelerated erosion. Generally, the pH values observed in the study area are within the ranges of moderately acidic to neutral soil reactions as indicated by Foth and Ellis (1997).

The results also showed that the restoring sites had higher contents of total nitrogen, organic carbon, available phosphorous and electrical conductivity than the nearby, non-restoring sites. According to the classification of soil organic carbon as per the ranges suggested by Landon (1991), the soils of the non-restoring sites are very low to low (0.99-1.85 %) in organic carbon content than the organic carbon of the restoring sites which falls on the *medium* range. Following the rating of total N of > 1 % as very high, 0.5 to 1 % high, 0.2 to 0.5 % medium, 0.1 to 0.2 % low and < 0.1 % as very low N status as indicated by Landon (1991), the level of mean total nitrogen (0.34 %,) analysed in soil samples collected from the soils of the restoring sites falls within *medium* range which is 0.25-0.36 %, while the mean level of total nitrogen (0.24 %) obtained from the non-restoring site falls within *low* range which is 0.13-0.25 % (Landon, 1991; Raymond and Roy, 1995). Additionally, the level of available phosphorus (12.5 mg/Kg) analysed on soil samples collected from the soils of the restoring sites falls within *very high* range which is >11 mg/Kg. However, the level of available phosphorus (7.25 mg/Kg) obtained from the non-restoring sites falls within the *medium* range which is 4-8 mg/Kg.

The highest levels of organic carbon, total nitrogen and available phosphorus on the restoring sites are clearly due to the presence of native and keystone tree/shrub species capable of pumping nutrients deep under the surface of the earth to be used for the growth and development of vegetative and reproductive parts (Raymond and Roy, 1995; Legesse Negash, 2010). When these 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 (Raymond and Roy, 1995; Legesse Negash, 2010). In well-aerated soils, the end products of decomposition are carbon containing compounds, NH_3^+ and $H_2PO_4^-$, and these boosts the level of organic carbon, total nitrogen and available phosphorus in the soil (Landon, 1991; Legesse Negash, 2010). In general, deforestation, overgrazing, leaching, limited recycling of dung and crop residue in the soil, continuous cropping and soil erosion have contributed to depletion of organic carbon, total nitrogen and available phosphorus and potassium on the non-restoring sites as compared to the adjust restoring sites.

This study indicated that the level of fertility indicators (namely, presence of adequate available phosphorus, total nitrogen, organic carbon and electrical conductivity) in the restoring soils were significantly higher, compared to those sampled from the non-restoring sites. The lower levels of macro- and micronutrients on the non-restoring sites is clearly associated with the removal of vegetation cover, overgrazing, soil erosion and low content of organic matter (Landon, 1991).

5.1.2. Vegetative growth responses of the coffee plants

In this part, the vegetative growth responses and efficiencies of *C. arabica* on the site which is being restored, growing under the shade *C. macrostachyus*, *E. divinorum* and *A. abyssinica* will be discussed. In this study, stem height development of the *C. arabica* trees was slow during the dry season (December and January) where the T_{air} is also high. The growth of stems was also rapid in the rainy season (March) and period of low temperature (October and November). The same result were identified in Viçosa, southeastern Brazil, where increasing temperatures in Vicosa would temporary depress the growth of shoot, as noted by Barros *et al.*, (1997). The result showed that the three-year-old coffee plants grown under the three restoring shades showed no significant change in stem height. When associating the growth of stem height with the T_{air} and PAR, the result indicated no significant correlation.

Coming to the number of branches under the restoring shade of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, no significant difference occurred. However, the number of coffee lateral branches developed in the shade of *E. divinorum* showed relatively higher than *A. abyssinica* and *C. macrostachyus* shaded coffee trees. The result of this study disagrees with the works of Catalina *et al.*, (2010) where branch development depends on the shade level (PAR).

Quite the opposite, the number of nodes significantly differs in between the three restoring shades and the highest node and leaf number observed on the shade of *A. abyssinica* which is followed by *C. macrostachyus* and *E. divinorum* shaded coffee plants. The study found out that a negative significant correlation exists in between the number of nodes at each restoring shade and the PAR value under the shade. When the PAR level decreases the number of nodes increases (Adugna and Paul, 2010). The finding of this study agrees with the work of Cannell (1976), which describes fewer nodes formed per

branch as the shade level increases. Node production on lateral branches parallels the oscillations in growth of plagiotropic branches in *C. arabica* (Ronchi *et al.*, 2007). Moreover, similar with the works of DaMatta *et al.*, (2007) the shade variety with different PAR level on top of the coffee plants influenced in enhancing growth of more nodes with short internode length.

The highest branch leaf area were found in the restoring shade of *A. abyssinica*, and was an indication of high chlorophyll content for increasing absorption of light (Adugna and Paul, 2010). The result of this study is in agreement with Robakowski *et al.*, (2003) which concluded that branch leaf areas decreases as light intensity increases. In this study, lower branch leaf area was obtained from coffee plants grown in the shade of *C. macrostachyus* which exhibited the highest PAR level. For shaded coffee plants, the increased branch leaf area was mainly attributed to the higher nitrogen content found in their leaves (DaMatta *et al.*, 1999), which is clearly associated with presence of relatively high nitrogen content on the soil. As stated by Sylvana *et al.*, (2008) shaded plants undertake certain modifications such as developing thinner and larger leaves (Friend, 1984) with more thylakoids per granum and more grana per chloroplast (Fahl *et al.*, 1994). These modifications allow them to efficiently capture and utilize the available light energy in order to increase their dry matter production (Sylvana *et al.*, 2008). 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. 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 (Catalina *et al.*, 2010). The findings of this study indicated that, positive response on the vegetative growth of *C. arabica* under the two restoring shade trees (*C. macrostachyus*

and *A. abyssinica*) and one tree/shrub (*E. divinorum*) indicated the success of restoration at the CITPBDE.

5.1.3. Berries and beans performances of the coffee plants

The growth pattern of *C. arabica* fruits has been described either as double sigmoid-shaped curve (Geromel *et al.*, 2006), or an approximately linear curve (Cunha, 2007). The current study at the site that is being restored identified the presence of linear curved arrangements of berries on the fruiting nodes of the five-year-old *C. arabica.*

In fact, fruits that expand during the wet weather become larger, with larger locules (Animm and Boamah, 2010), which are subsequently filled with larger beans than fruits which expand during the hot and dry weather. However, the result of this study showed similar expansion of berries during the hot and dry month of December and afterwards. The rains during the season are a key ecological factor in determining the interval between flowering and seed maturation (Adugna and Paul, 2010). In many coffee species adapted to dry regions this interval is very short, only about three months for some species from eastern Africa such as *Coffea racemosa* (Charrier and Berthaud, 1985). However, the result of this study showed that the interval between flowering and seed maturation, took only 8 months and it defines how the site is becoming successful and efficient like some of the coffee growing regions/zones of Ethiopia, where the development of coffee berries took period of 8-12 months (Adugna and Paul, 2010).

The vegetative growth in the case of fruit bearing coffee plants showed on significant increment in stem height and number of branch. Rapid vegetative growth and fruit development appear to occur at different times, suggesting incompatibility or competition between the two processes (Animm and Boamah, 2010). Climatic factors may modulate the vegetative growth and fruit production, in such a way that usually they

do not coincide (Maestri and Barros, 1977; Barros *et al.*, 1999). In fact, coffee berries act as priority sinks so that dry matter allocation to them may be more than four times that allocated to branch growth over the annual production cycle (Vaast *et al.*, 2005). In addition, during the latter stages of growth, fruits may accumulate over 95 % of the current uptake of potassium, phosphorus and nitrogen, where the nutrients are available in the restoring sites. Therefore, reduced shoot growth is commonly observed (Mayoli and Gitau, 2012).

C. arabica planted under the restoring shade trees showed significant response in most of the parameters undertook, with the exception of red berry abortion and fresh weight of beans with parchment. The overall average results on the number of green and red berries counted and harvested during the study period depict that coffee trees planted under the restoring *A. abyssinica* shade resulted in the significantly highest number of coffee berries followed by the restoring shades of *C. macrostachyus*, and *E. divinorum*. In view of the number of beans within a berry, the result also described the same as the mean number of green and red berries per plant. The highest one and two bean containing berries were found on coffee plants under the restoring shades of *A. abyssinica*, followed by *C. macrostachyus* and *E. divinorum*. Therefore, the presence of favorable soil nutrients, such as organic carbon, total nitrogen and available phosphorous, plays a vital role for those coffee plants growing under the restoring shades of *A. abyssinica*. This was in contrast to the harvest obtained from coffee plants growing on the open sun and less restored site, indicating that it was not amongst the suitable coffee growing sites (Adugna and Paul, 2011). Nonetheless, the most unstable berry number and unequal growth of beans were noted from coffee plants under the restoring shade of *C. macrostachyus*, and it is clearly associated with the deciduous nature of its leaves and this made the coffee plants growing under its shade exposed 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.

In addition, the significant highest mean fruiting nodes per plant occurred on coffee plants growing under the restoring shade of *E. divinorum*, even if the coffee plants within this shade attained the lowest mean berry per node. As the work of Catalina *et al*., (2010) indicated, high shade levels under the canopy of various tree species reduces the number of harvest and berries per node, keeping the number of fruiting nodes high.

The study showed a significant difference on the amount of beans per berry, and the highest one and two beans per berry were identified on coffee plants under the restoring shade of *A. abyssinica*, than *C. macrostachyus*, *E. divinorum* and those grown on open sun. However, there is no significant difference on three beans per berry among the four treatments. The fresh weight of berry assessment made on harvested coffee berry indicated that beans developed under the restoring shades showed a significantly different and higher than and coffee trees grown on open sun, similar with the works of Adugna and Paul (2011). The fact that shade resulted in heavier and larger size coffee beans was mainly caused by its effect on temperature and the duration of the ripening period (Adugna and Paul, 2011). Muschler (2001), who found comparable results, indicated that coffee bean weight and size significantly and consistently increase even with increasing shade levels. Similarly, the shade effect on the current study showed a comparable weight and size difference, where the highest weight and size recorded on *A. abyssinica* shaded coffee plants while the lowest berry weight and size found on those coffee plants growing on open sun. The same shade influence identified on the weight of beans growing on the four treatment groups, and higher bean weight obtained from coffee plants growing on the restoring shade of *A. abyssinica*.

The works of (Vaast *et al.*, 2006) indicated shade grown coffee gave lower yields than coffee in the open sun. However, the study performed by Adugna and Paul (2011) showed the highest yield of coffee is from shaded coffee plants. The result of this study is in agreement with Adugna and Paul (2011) since the highest yields were obtained from those coffee plants growing under the restoring shades of *A. abyssinica*, *C. macrostachyus* and *E. divinorum* than from coffee plants of the less restored site.

This study showed that the restoring sites caused by native trees enhance coffee weight of berry, weight of beans, and bean size and yield than coffee plants growing on open sun. Therefore, restorations of native trees are the alternative means of obtaining high yield. Therefore restoration of degraded landscapes using various indigenous trees and/or shrubs will promote sensitive plants to grow and indicates the success of restoration.

5.1.4. The effects of GA_3 solutions

Coffee flowering embraces a complex sequence of biochemical, physiological and morphological events which are affected by several factors such as temperature, light, soil, air and water availability, carbon-to-nitrogen ratio, crop load and genotype (Rena *et al.*, 1994). Under natural conditions, dormancy of flower buds is often broken by either the first rains in the season following a dry period or by means of GA_3 (Reddy, 1979; Barros *et al.*, 1999). In this study, the flowering developments of four-year-old coffee plants were assessed using GA_3 solutions and just the environmental triggering factors (control groups). Unlike the GA_3 treated coffee plants, the control/untreated coffee plants began to blossom when the first rains occurred during the end of February and early of March. Probably, the developmental stage of flower buds, which can be circumstantially affected by endogenous and environmental factors (such as total nitrogen, available phosphorous, organic carbon etc.), seems to be the most suitable parameter to be

considered when irrigation must be resumed, perhaps more so than water deficit severity per se, for successful blossom concentration (Reddy, 1979; Rena *et al.*, 1994).

The growth and development of the first buds was observed during the months of late January. However, all the developed buds grew in to secondary branches during that month. The development of the first flowering buds observed and identified during late February, and the peak of the flower buds occurred during the month of March which was associated with the fall of rain in the site of the study.

The result suggests that GA_3 at concentrations of 100, 250 and 300 mg l^{-1} had the potential of enhancing flowering on the treated coffee plants similar with the works of Ursula and Leslie (1992) and Schuch *et al.*, (1990). The result of this study identified a significant difference on the flowering performance among the treatments. The largest significant flowering buds among the treatment groups occurred on those coffee plants treated with 250 mg l^{-1} GA_3. But the control group developed a significant higher mean number of flower buds than the 100 and 300 mg l^{-1} GA_3 treated coffee plants. The reasons why the control coffee plants developed the second largest flower buds is clearly due to the presence of favorable soil nutrient, suitable temperature and available water on the restoring site (Barros *et al.*, 1978; Schuch *et al.*, 1990; Crisosto *et al.*, 1992; Jean *et al.*, 2010).

When considering flowering percentage from the developed buds, it was the control group that resulted in developing 99 of the bud in to flower, while only 97 of the bud treated with 250 mg l^{-1} GA_3 bloomed. This is an indication of the presence of essential key natural resources on the site which is being restored. Conversely, the control groups exhibited the least flower bud abortion unlike the GA_3 treated coffee plants. Such variations in flowering rate under different GA_3 concentrations may be related to the multi-factorial control model of flowering (Schuch *et al.*, 1990), explaining the

differences among results from experiments involving application of plant growth regulators.

Similar with the work of Ursula (1990) and Jean *et al.*, (2010) coffee trees treated with 250 mg l^{-1} GA_3 had the most flower buds per node. Irrigation and available nutrients combined with GA_3 applications increased the number of flowers per plant when this regulator was sprayed at 250 mg l^{-1}. Even GA_3 application increased the number of flowers per plant, the control coffee plants also showed a compatible flowering performance which clearly indicates the restoration success, as a result of restoring the native trees, fertile soils and favorable atmospheric conditions.

Growths of secondary branches were affected by the different GA_3 treatments. To this effect, repeated sprays of 100, 250 and 300 mg l^{-1} GA_3 affected the growth and development of secondary branches, which is significantly different on the four treatment coffee groups. The highest secondary branches were found in those coffee plants treated with 300 mg l^{-1} GA_3, where this group developed the lowest flower bud. On the other hand, the control group developed the lowest secondary branches. The result indicated that, the effect of GA_3 suppressed the development of secondary branches over flowering similar with the works of Cannell (1971). As it is discussed, maximum vegetative growth coincided with the flowering period, which is reported for many coffee growing areas (Clowes and Allison, 1982). In January vegetative growth remained vigorous for one month before flowering was started. Rainfall in March was higher than the other study period and probably contributed to more secondary branch growth.

5.1.5. Floristic composition of the study site

Early successional stages were marked by widely dispersed pioneer species exploiting the community niches left empty by the disturbance (Myster and Pickett, 1994). The goal of any restoration project must be to accelerate this process by (a)

increasing the colonization rate by providing suitable seed source and/or (b) decreasing the decolonization rate or failed colonization by removing impediments to colonization (Harris *et al.*, 1996). When judging restoration success, it is necessary to weigh the merit of any restoration efforts in comparison to the successional processes that would take place. In this study, the nearby non-restoring sites were served as the successional controls and the benchmark with which the CITPBDE floristic composition was compared.

In general, there was a significant higher variation in the number of floristic composition of grasses, herbs, shrubs and woody species in the site which is being restored than the non-restoring sites (Appendix 1 and 2). Moreover, there were very few plant species which were present in the nearby degraded landscapes and hence included in the site that is being restored i.e. 13.08 % of the plant species found in the site that is being restored were also found in the nearby non-restoring sites. The result of this study also agrees with the work of John (1997), where the higher vegetation cover found on the site which is being restored.

This increased floristic cover of the site that is being restored is associated with: the involvement of fast growing plants (such as *A. abyssinica* and *Millettia ferruginea*) which can colonize the area easily (Berger, 1993; Legesse Negash, 2010); the presence of deciduous plants (*C. macrostachyus* and *Hagenia abyssinica*) which may recycle nutrients (Elliott *et al.*, 2000; Legesse Negash, 2010) and increase the soil fertility to create a conducive environment for the growth of other plants (Lamb and Gilmour, 2003; Legesse Negash, 2010); involvement of various keystone plants (*Ficus sur* and *Podocarpus falcatus*) which may restore water in the surrounding and create a suitable condition for the emergence of other plants (Legessee Negash, 2010); the presence of species tolerant to poor soils (*Carissa spinarum* and *Maytenus arbutifolia*) which may facilitate

restoration process (Legesse Negash, 2010); involvement species attractive to frugivores (*Dovyalis caffra* and *Psidium guajava*) to encourage seed dispersal (Legesse Negash, 2010).

The work of Allen (1997) indicated the presence of fast growing species and those having the potential to recycle nutrients are responsible to boost the floristic composition of a restoring site. According to Leps (1987) the total nitrogen, organic carbon, available phosphorous and potassium become more abundant in a restoring site when such nutrients are compared with the non-restoring sites.

Some of the plants which were identified on the site that is being restored included: native trees such as *Juniperus procera*, *Podocarpus falcatus*, *Millettia feruginea*, *Olea europaea* subsp. *cuspidata*, *A. abyssinia*, *Vernonia amygdalin*, *Dovyalis abyssinica*, *Dovyalis Caffra*, *Allophyllus abyssinicus*, *Prunus Africana* and *Syzygium guineense*; as well as keystone tree species such as *Ficus vasta*, *Ficus sycomorus* subsp. *sycomorus*, *Ficus sycomorus* subsp. *gnaphalocarpa* and *Ficus sur*; naturally regenerated native shrubs such as *Carissa spinarum*, *Albizia schimperiana* and *Maytenus arbutifolia*; herbs such as *Achyranthes aspera*, *Bidens ghedoensis*, *Crassocephalum sarcobasis*, *Hygrophila auriculata* and *Scadoxus multiflorus*; and grasses such as *Andropogon schirenis*, *Pennisetum setaceum* and *Arthraxon micans*.

Finally the total plants which were identified on the nearby degraded and sunny exposed landscape included: *Eucalyptus globules*, *Eucalyptus camaldulensis*, *Carrisa spinarum*, *Rumex nervosus*, *Sida schimperina*, *Pennisetum setaceum*, *Andropogone schirenis*, *Eleusine floccifolia* and *Panicum ruspolli*. Additionally, one of the drought resistant trees, *A. abyssinica*, was also the part of the nearby degraded landscape. This high difference in understory species composition suggests that, restoration of previously

degraded landscapes was the main source of restoring various floristic compositions, animal diversity and lost key natural resources.

The highest floristic composition on the restoring sites than the non-restoring sites clearly indicated the success of restoration in terms of structural elements (such as plant cover and tree density) and composition of the community (such as number, identity and abundance of various plants).

5.2. CONCLUSIONS

Restoration ecology is a relatively young field. As the success of many ecological restoration activities may not be known for many decades or even centuries, it is necessary to state very explicitly what is intended for each restoration project so that the degree of success or failure can be determined on a site-specific basis. This means that any restoration plan should be accompanied by an explicit statement of criteria for success and failure that will permit rigorous examination of the activity itself and, equally important, identify changes in strategy more likely to reach intended goals. Moreover, considering the rate of modification all natural systems are currently undergoing, it is necessary to develop wide-ranging restoration objectives with the aim to ameliorate past, present, and future damage.

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 *Coffea arabica*;
- extent of restoration success can be quantified through measuring vegetative, fruiting and flowering characteristics of *Coffea arabica*;
- the highest coffee yield performances were obtained from coffee plants established under *Acacia abyssinica*, *Croton macrostachyus* and *Euclea divinorum*, compared to those grown in an exposed and relatively less restored site;
- coffee plants grown under shady and relatively restored soil conditions produced larger and heavier beans than coffee plants grown in the exposed and less restored soil conditions;

- compared with the flowering potential of those coffee plants treated with various GA_3 solutions, the response of coffee plants grown over a previously degraded landscape and, after a restoration period of 8 years has been favorable;
- coffee plants grown in the restoring shade of *Acacia abyssinica* had higher vegetative growth performances when compared with coffee plants grown under the shade of *Croton macrostachyus* and *Euclea divinorum*; 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.

5.3. RECOMMENDATIONS

Based on the results reported in this thesis, it is recommended that:

- restoration of critical watersheds using native trees and shrubs, followed by the restoration of plants that are essential for economic development, food and livelihood security must be scaled-up using mechanisms detailed in this thesis; and
- since Ethiopia`s nature and natural resources have been dilapidated for generations, and since nation`s poverty has been direct consequences of these actions, such restoration activities must be considered by policy makers and the Government as nation`s priority issues.

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Appendices

Appendix 1. List of trees, shrubs, herbs and grasses at the restoring sites of CITPBDE.

S. No	*Botanical Name*	*Family*	*Vegetation type*
1	*Acacia abyssinica* Hochst.ex.Benth.	Fabaceae	Tree
2	*Achyranthes aspera* L.	Amaranthaceae	Herb
3	*Albizia schimperiana* Oliv.	Fabaceae	Tree
4	*Allophylus abyssinicus* (Hochst.) Radlk.	Sapindaceae	Tree
6	*Andropogon schinzi* Hach.	Poaceae	Grass
5	*Andropogon schirenis* Hochst.ex.A.Rich.	Poaceae	Grass
7	*Arthraxon micans* (Nees) Hochst.	Poaceae	Grass
8	*Aspilia africana* (Pers.) C.Adams	Asteraceae	Herb
9	*Aspilia mossambicensis* (Oliv.) Wild	Asteraceae	Herb
10	*Berkheya spekeana* Oliv.	Asteraceae	Herb
13	*Biden prestinaria* (Sch.Bip.) Cufod.	Asteraceae	Herb
11	*Bidens macroptera* (Sch.-Bip. Ex Chiov.) Mesfin	Asteraceae	Herb
12	*Bidens pachyloma* (Oliv. & Hiern) Cuf.	Asteraceae	Herb
14	*Buddleja polystachya* Fres.	Buddlejaceae	Shrub/Tree
15	*Caesalpina spinosa* (Molina) Kuntze	Fabaceae	Shrub/Tree
18	*Carduus nyassanus* REFries	Boraginaceae	Shrub
16	*Carissa Spinarum* (Forssk.) Vahl.	Apocynaceae	Shrub
17	*Carthamus lanatus* L.	Asteraceae	Shrub
19	*Casimiroa edulis* LaLiava	Rutaceae	Tree
20	*Cirsium schimperi* (Vatke) Cuf.	Boraginaceae	Shrub
21	*Citrus aurantifolia* (Christm.) Swingle	Rutaceae	Tree
22	*Citrus limon* (L.) Burm.f.	Rutaceae	Tree
23	*Citrus sinensis* (L.) Osb.	Rutaceae	Tree
24	*Coffea arabica* L.	Rubiaceae	Shrub/Tree
25	*Commelina benghalensis* L.	Commelinaceae	Shrub
26	*Cordia africana* Lam.	Boraginaceae	Tree
27	*Coriandrum sativum* L.	Apiaceae	Shrub
28	*Crassocephalum sarcobasis* (DC) S.Moor	Asteraceae	Herb
29	*Crassocephalum vitellinum* (Benth.) Moore	Asteraceae	Herb
30	*C. macrostachyus macrostachys* Hochst. ex Del.	Euphorbiaceae	Tree
31	*Cymboopogon commutatus* (steud.)Stapf	Poaceae	Grass
32	*Dactylocetenium scindicum* Boiss.	Poaceae	Grass
33	*Datura stramonium L.*	Solanaceae	Herb
34	*Dicliptera maeulata* Nees.	Acanthaceae	Shrub
35	*Dodonaea angustifolia* L.F.	Sapindaceae	Shrub
36	*Dovyalis abyssinica* (A. Rich) Warb.	Flacourtiaceae	Shrub

37	*Dovyalis caffra* (Hook.f. &Harv.) Hook.f.	Flacourtiaceae	Shrub
38	*Drocenea stuinderi* Engl.	Dracaenaceae	Tree
39	*Ekebergia capensis* Sparm.	Meliaceae	Tree
40	*Eleusine floccifolia* (Forssk.) Spreng.	Poaceae	Grass
41	*Eragrostis papposa* (Roem. And Schult.) Steud	Poaceae	Grass
42	*Eragrostis schweinfurthii* Chiov.	Poaceae	Grass
43	*Eucalyptus camaldulensis* Dehnh.	Myrtaceae	Tree
44	*Eucalyptus globulus* Labill.	Myrtaceae	Tree
45	*E. divinorum* Hiern.	Ebenaceae	Tree
48	*Faidherbia albida* (Del.) A. Chev.	Fabaceae	Tree
47	*Ficus sur* Forssk.	Moraceae	Tree
46	*Ficus sycomorus* L. subsp. *gnaphalocarpa* (Miq.) C.C. Berg	Moraceae	Tree
49	*Ficus sycomorus* L. subsp. *sycomorus*	Moraceae	Tree
50	*Ficus vasta* Forssk.	Moraceae	Tree
51	*Flacourtia indica* (Burm.f.) Merrill	Flacourtiaceae	Tree
52	*Galinsoga parviflora* Cav.	Asteraceae	Herb
53	*Grevillea robusta* R.Br.	Proteaceae	Tree
54	*Guizotia abyssiniea* (L.f.) Cassini	Asteraceae	Herb
55	*Hagenia abyssinica* (Bruce) J.F. Gmel.	Rosaceae	Tree
56	*Helichrysum glumaceum* DC.	Asteraceae	Herb
57	*Hygrophila auriculata* (Schum.) Heine	Acanthaceae	Herb
58	*Hypoestes triflora (Forssk.)* Roem. & Schult.	Acanthaceae	Herb
59	*Isoglossa laxa* Oliv.	Acanthaceae	Herb
60	*Jasminum abyssinicum* Hochst.ex.Dc.	Oleaceae	Shrub
61	*Jasminum stans* Pax.	Oleaceae	Shrub
62	*Juniperus procera* Endl.	Cupressaceae	Tree
63	*Justicia heterocarpa* T.Anders	Acanthaceae	Shrub
64	*Justicia ladanoides* Lam.	Acanthaceae	Shrub
65	*Justicia schimperiana* (Hochst.ex.nees) T.Anders.	Acanthaceae	Shrub
66	*Kalanchoe glaucescens* Britten.	Crassulaceae	Herb
67	*Laggera pterodonata* (DC.) Sch.-Bip.	Asteraceae	Herb
68	*Leucas martinicensis* (Jacq.) R.Br.	Lamiaceae	Shrub
69	*Maesa lanceolata* Forssk.	Myrsinaceae	Herb
70	*Maytenus arbutifolia* (Hochst. Ex A.Rich.) Wilczek	Celastraceae	Shrub
71	*Millettia ferruginea* (Hochst.) Bak	Papilionaceae	Tree
73	*Nicandra physalodes* (L.) Gaertn.	Solanaceae	Herb
72	*Ocimum urticifolium* Roth.	Lamiaceae	Herb
74	*Olea europaea* L. var. *africana* (Mill.) P. Green	Oleaceae	Tree
75	*Olea europaea* L.subsp. cuspidata (Wall. ex DC.)	Oleaceae	Tree
76	*Osyris quadriparita* Decn.	Santalaceae	Shrub
77	*Otostegia tomentosa* A.Rich	Lamiaceae	Shrub

78	*Panicum ruspolli* Chiov.	Poaceae	Grass
79	*Pennisetum setaceum* (Forssk) Chiov.	Poaceae	Grass
80	*Pennisetum villosum* Fresen.	Poaceae	Grass
81	*Phaulopsis lmbricata* (Forf)sk.) Sweet.	Acanthaceae	Herb
82	*Phoenix reclinata* Jacq.	Arecaceae	Tree
83	*Pittosporum abyssinicum* Del.	Pittosporaceae	Tree
84	*Plantago lanceolata* L.	Plantaginaceae	Shrub
85	*Plectranthus lanunginosus* (Benth.) Agnews	Lamiaceae	Herb
86	*Podocarpus falcatus* (Thunb.) Mirb.	Podocarpaceae	Tree
87	*Polypogon viridis* (Govan) Breistr	Poaceae	Grass
88	*Prunus africana* (Hook.f.) Kalkm.	Rosaceae	Tree
89	*Psidium guajava* L.	Myrtaceae	Tree
90	*Rhamnus prinoides* L'Herit.	Rhamnaceae	Shrub
91	*Ricinus communis* L.	Euphorbiaceae	Shrub
92	*Rosa abyssinica* R. Br.	Rosaceae	Shrub
93	*Rostraria cristata* (L.) Tzvelev	Poaceae	Grass
94	*Rumex nervosus* Jacq.	Polygonaceae	Shrub
95	*Ruta chapensis* L.	Rutaceae	Shrub
96	*Satureja abyssinica* (Jacq.)	Lamiaceae	Herb
97	*Scadoxus multiflorus* (Martyn) Raf.	Amaryllidaceae	Herb
98	*Senna baccarinii* (Chiov.)Lock.	Fabaceae	Shrub
99	*Sida schimperiana* Hochst. Ex Rich.	Malvaceae	Shrub
100	*Sideroxylon oxyacantha* Bail.	Sapotaceae	Shrub
101	*Solanum incanum* L.	solanaacee	Shrub
102	*Solanum melongena* L.	solanaacee	Shrub
103	*Spathodea nilotica* Seem.	Boraginaceae	Tree
104	*Stephania abyssinica* (Dillon & A. Rich.) Walp.	Menispermaceae	climber
105	*Syzygium guineense* (Wild.) DC. *subsp.* Guineense	Myrtaceae	Tree
106	*Urera hypselodendron* (A. Rich.) Wedd.	Urticaceae	Herb
107	*Urtica simensis* Hochst. ex Steud.	Urticaceae	Herb
108	*Verbascum sinaiticum* Benth.	Scrophularicuceae	Herb
109	*Verbena officinalis* L.	verbenaceae	Herb
110	*Vernonia amygdalina* Del. in Caill.	Asteraceae	Shrub
111	*Vernonia auriculifera* Hiern	Asteraceae	Shrub

Appendix 2. List of floristic compositions found on the nearby degraded landscapes.

S. No	*Botanical Name*	*Family*	*Vegetation type*
1	*Acacia abyssinica* Hochst.ex.Benth.	Fabaceae	Tree
2	*Andropogone schirenis* Hochst.ex.A.Rich.	Poaceae	Grass
3	*Carrisa spinarum* (Forssk.) Vahl.	Apocynaceae	Shrub
4	*Eleusine floccifolia* (Forssk.) Spreng.	Poaceae	Grass
5	*Eucalyptus camaldulensis* Dehnh.	Myrtaceae	Tree
6	*Eucalyptus globules* Labill.	Myrtaceae	Tree
7	*Panicum ruspolli* Chiov.	Poaceae	Grass
8	*Pennisetum setaceum* (Forssk) Chiov.	Poaceae	Grass
9	*Rumex nervosus* Jacq.	polygonaceae	Shrub
10	*Sida schimperina* Hochst. Ex Rich.	Malvaceae	Shrub

Appendix 3. Physical and chemical properties of the soils collected from the restoring sites (site I and site II) and nearby degraded landscapes.

				Texture			
	Depth (cm)	Moisture (%)	pH (1:2.5)	Clay (%)	Silt (%)	Sand (%)	Soil class
Site I	0-15	11.86	6.67	43	37	20	Clay
	16-30	14.78	6.81	59	27	14	Clay
Site II	0-15	15.58	7.05	56	27	17	Clay
	16-30	19.88	7.06	67	33	0	Clay
Control	0-15	11.53	6.82	41	37	22	Clay
	16-30	15.78	7.01	49	29	22	Clay

			Exchangeable bases (cmol (+)/Kg)					
	Depth (cm)	EC (mS/cm)	Ca	Mg	Na	K	P(mg/Kg)	TN (%)
Site I	0-15	0.3	37.26	11.08	0.4	1.4	11.86	0.32
	16-30	0.1	33.06	10.33	0.4	0.5	4.84	0.2
Site II	0-15	0.19	26.01	18.72	0.6	2.7	13.15	0.35
	16-30	0.13	28.05	18.34	0.4	2.3	1.77	0.16
Control	0-15	0.07	33.13	12.05	0.4	0.4	7.25	0.25
	16-30	0.03	24.99	19.78	0.5	0.3	0.41	0.07

	Depth (cm)	Micro Nutrient (cmol (+)/Kg)				BD (g/cm3)	PD(g/cm3)	OC (%)
		Mn	Fe	Cu	Zn			
Site I	0-15	54.79	58.17	2.49	4.3	1.44	2.55	4.08
	16-30	76.17	131.27	2.35	1.64	1.48	2.48	2.4
Site II	0-15	179.1	198.47	8.39	3.07	1.39	2.47	4.08
	16-30	73.22	104.58	4.84	1.69	1.56	2.59	2.09
Control	0-15	65.94	73.95	1.7	1.18	1.47	2.6	1.95
	16-30	51.81	57.8	1.46	0.61	1.51	2.57	0.9

Appendix 4. The mean vegetative growth performances of three-year-old *C. arabica* (3CA) plants growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, at each monthly data collection. For each treatment, columens show the mean and ± S.E (n= 8 replicates per treatment).

		C. macrostachyus		*E. divinorum*		*A. abyssinica*	
Coffea arabica	Months	Mean	± SE	Mean	± SE	Mean	± SE
Stem height (cm)	Oct	36.91	2.9	33.86	2.62	35.09	5.54
	Nov	37.92	2.91	36.34	2.86	37.7	5.62
	Dec	38.7	2.91	39.66	2.99	39.9	5.75
	Jan	39.33	2.8	40.29	3.09	40.71	5.57
	Feb	40.58	2.79	43.6	3.20	44.55	5.58
	Mar	41.73	2.77	48.45	3.14	49.85	5.59
Number of branchs	Oct	10.63	1.18	15.38	2.28	11.5	1.87
	Nov	11.25	1.29	16.63	2.41	13.25	1.97
	Dec	13.13	1.32	18.38	2.43	14.88	1.93
	Jan	13.25	1.29	18.38	2.43	15.38	1.79
	Feb	13.75	1.32	19.63	2.29	16.75	1.77
	Mar	14.75	1.31	20.88	2.45	18.5	1.76
Number of nodes	Oct	3.09	0.09	2.56	0.08	2.78	0.16
	Nov	3.09	0.09	2.56	0.08	2.78	0.16
	Dec	3.88	0.05	3.31	0.11	3.63	0.14
	Jan	3.88	0.05	3.31	0.11	3.63	0.14
	Feb	3.91	0.03	3.59	0.11	3.72	0.14
	Mar	4.13	0.05	4.06	0.13	4.34	0.14
Internode length (cm)	Oct	2.85	0.12	3.55	0.17	2.94	0.09
	Nov	2.98	0.12	3.89	0.17	3.27	0.09
	Dec	3.09	0.11	3.58	0.12	3.10	0.08
	Jan	3.09	0.11	3.58	0.12	3.10	0.08

	Feb	3.19	0.11	3.52	0.13	3.10	0.07
	Mar	3.09	0.13	3.09	0.10	2.81	0.07
	Oct	3.94	0.06	3.13	0.16	3.56	0.33
	Nov	4.06	0.12	3.13	0.16	3.56	0.33
Number of leaves	Dec	5.69	0.12	4.63	0.22	5.31	0.33
	Jan	5.69	0.12	4.63	0.22	5.31	0.33
	Feb	5.81	0.06	5.19	0.21	5.44	0.28
	Mar	6.25	0.10	6.13	0.26	6.69	0.28
	Oct	60.97	1.39	50.41	2.29	49.46	4.12
Branch leaf area (cm^2)	Nov	61.17	1.38	50.60	2.29	51.96	4.35
	Dec	87.26	4.01	71.96	1.97	81.61	5.03
	Jan	87.28	4.01	72.03	1.97	81.69	5.05
	Feb	88.83	4.56	81.78	0.71	84.29	4.66
	Mar	94.75	5.57	96.14	1.38	103.00	4.14

Appendix 5. The mean vegetative and fruiting performances of five-year-old *C. arabica* (5CA) plants growing under the restoring shades of *C. macrostachyus*, *E. divinorum* and *A. abyssinica*, and on open sun at each monthly data collection. For each treatment, columens show the mean and ± S.E (n= 8 replicates per treatment).

		C. macrostachyus		*E. divinorum*		*A. abyssinica*		Full sun	
Coffea arabica	Months	Mean	± SE	Mean	± SE	Mean	± SE	Mean	± SE
	Oct	103.35	4.98	122.75	4.60	99.05	4.84	60.13	1.46
	Nov	103.37	5.17	122.85	4.63	99.13	4.66	61.00	1.34
Stem height (cm)	Dec	103.38	5.36	122.50	4.76	99.75	4.55	61.13	1.55
	Jan	104.25	5.02	123.38	4.40	100.63	4.40	62.00	1.79
	Feb	104.25	5.02	123.38	4.40	100.63	4.40	62.00	1.79
	Mar	105.88	5.00	126.50	4.38	104.50	4.38	62.50	1.83
	Oct	35.25	5.14	35.25	3.34	44.00	6.37	20.38	3.57
	Nov	35.13	5.15	37.13	3.64	44.00	6.44	20.50	3.36
Number of branches	Dec	36.38	4.96	37.38	3.76	45.25	6.35	21.00	3.32
	Jan	36.38	4.96	37.63	3.70	45.50	6.26	21.00	3.32
	Feb	36.88	4.88	37.63	3.70	45.50	6.26	21.00	3.32
	Mar	38.63	4.78	38.38	3.71	47.00	6.22	21.00	3.32
	Oct	75.63	40.16	63.38	18.52	131.25	39.39	2.00	0.94
	Nov	76.50	40.52	68.13	19.54	137.75	39.51	2.63	1.22
Green berry obtained	Dec	79.88	40.89	70.50	19.38	140.75	39.84	1.38	0.80
	Jan	45.25	34.55	44.50	13.47	92.50	30.37	0.50	0.50
	Oct	0.13	0.13	0.00	0.00	0.00	0.00	0.00	0.00
Green berry aborted	Nov	1.00	0.50	1.63	0.68	3.75	1.03	0.75	0.41
	Dec	1.50	0.63	3.63	1.61	3.63	1.00	0.00	0.00
	Jan	2.63	1.35	5.25	1.85	10.00	3.90	1.38	0.80
	Nov	0.25	0.25	0.13	0.13	0.00	0.00	0.00	0.00

Red berry obtained	Dec	0.13	0.13	0.38	0.38	0.38	0.18	0.00	0.00
	Jan	29.00	10.76	22.13	9.63	45.88	23.22	0.88	0.58
	Feb	41.50	33.78	39.13	12.96	80.13	28.74	0.00	0.00
	Nov	0.13	0.13	0.00	0.00	0.00	0.00	0.00	0.00
Red berry aborted	Dec	0.00	0.00	0.13	0.13	0.13	0.13	0.00	0.00
	Jan	3.38	1.67	2.00	0.78	2.00	0.76	0.00	0.00
	Feb	2.25	1.03	1.25	0.56	2.38	0.91	0.00	0.00

Appendix 6. 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 open sun at each monthly data collection. For each treatment, columens show the mean and ± S.E (n= 8 replicates per treatment).

	C. macrostachyus		*E. divinorum*		*A. abyssinica*		Full sun	
Coffea arabica	Mean	± SE	Mean	± SE	Mean	± SE	Mean	± SE
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
Bean/berry ratio	0.21	0.02	0.27	0.03	0.38	0.01	0.01	0.01
Weight of bean per berry (g)	0.20	0.03	0.31	0.04	0.55	0.01	0.00	0.00
Mean number of beans obtained	106.50	54.02	95.25	31.43	169.13	50.31	1.00	0.65
Mean number of beans oborted	20.25	11.41	22.50	7.92	49.25	16.32	0.38	0.26
Number of fruting node	16.67	4.50	25.21	6.59	21.38	4.31	3.50	0.25
Number of berry per node	3.00	0.85	2.38	0.32	4.75	0.92	0.25	0.16
Beans (g)/1000 beans	137.19	15.15	192.40	22.43	276.11	22.82	10.00	7.33
Bean length (cm)	0.66	0.02	0.82	0.02	1.16	0.05	0.44	0.02
Coffee yield (g) per tree	17.64	11.78	17.81	5.26	69.73	20.72	0.01	0.01

Appendix 7. The mean flowering performances of four-year-old *C. arabica* (4CA) plants, growing under the restoring multiple shades. For each treatment, columens show the mean and ± S.E (n= 6 replicates per treatment).

	100 mg GA_3/L		250 mg GA_3/L		300 mg GA_3/L		Control	
Coffea arabica	Mean	± SE	Mean	± SE	Mean	± SE	Mean	± SE
Number of flower buds	43.33	3.21	212.00	6.40	28.50	2.67	97.17	1.66
Number of flowers	41.00	3.21	206.33	6.40	25.50	2.70	96.83	1.35
Number of flower buds per node	2.33	0.21	6.16	0.65	1.50	0.22	3.66	0.21
Number of secondary branchs	27.50	1.67	14.83	0.79	48.67	1.33	8.33	1.23

DECLARATION

I, the undersigned, declare that this is my original work, has not been presented for a degree in any other University and that all sources of materials used for the thesis have been fully acknowledged. I cede copyright of the thesis in favor of Addis Ababa University.

Habtamu Chekol Fantahun

Date of submission: 16/07/2013 **Signature:** _____

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