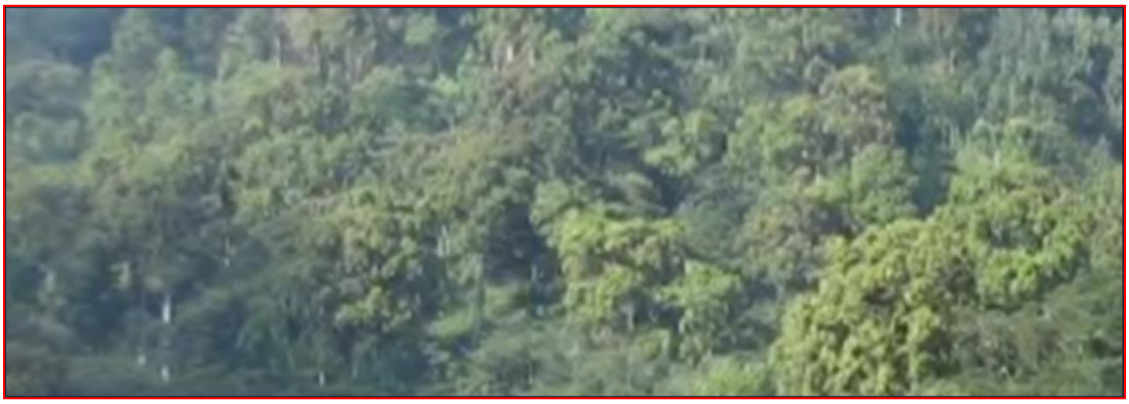
EFFECT OF NATURAL FOREST CONVERSION TO COFFEE-BASED FOREST ON CARBON STOCK AT ANFILO DISTRICT, WESTERN ETHIOPIA

MSc. THESIS



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JUNE, 2020

# EFFECT OF NATURAL FOREST CONVERSION TO COFFEE-BASED FOREST ON CARBON STOCK AT ANFILO DISTRICT, WESTERN ETHIOPIA

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A THESIS SUBMITTED TO THE

DEPARTMENT OF GENERAL FORESTRY, HAWASSA UNIVERSITY WONDO GENET COLLEGE OF FORESTRY AND NATURAL RESOURCES, SCHOOL OF GRADUATE STUDIES

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IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE

DEGREE OF MASTER OF

SCIENCE IN GENERAL FORESTRY

(SPECIALIZATION: FOREST RESOURCE ASSESSMENT AND MONITORING)

JUNE, 2020

## APPROVAL SHEET I

This is to certify that the thesis entitled "*Effect of Natural Forest Conversion to Coffee-Based Forest on Carbon Stock at Anfilo District, Western Ethiopia"* submitted in partial fulfillment of the requirements for the degree of Master's with specialization in *Forest Resource Assessment and Monitoring*, the Graduate Program of the Department/School of *General Forestry*, and has been carried out by *Yohannes Shifera Daka* Id. No *MSc/FRAM/R024/11*, under my/our supervision. Therefore, I/we recommend that the student has fulfilled the requirements and hence hereby can submit the thesis to the department.

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| ____________________ | ____________________ | ______________ |
| Name of major advisor | Signature | Date |
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| Head of department | Signature | Date |
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| Graduate program | Signature | Date |

**APPROVAL SHEET II**

We, the undersigned, members of the Board of examiners of the final open defense by *Yohannes Shifera* have read and evaluated his thesis entitled "*Effect of Natural Forest Conversion to Coffee-Based Forest on Carbon Stock at Anfilo District, Western Ethiopia*'', and examined the candidate. This is therefore to certify that the thesis has been accepted in partial fulfillment of the requirements for the degree of Master of Science in *General Forestry* with specialization in *Forest Resource Assessment and Monitoring.*

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| Name of External Examiner | Signature | Date |

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## DECLARATION

I, Yohannes Shifera, hereby declare to the school of graduate studies, Hawassa University that this is my original work and all sources of materials used are duly acknowledged. This work had not been submitted to any other educational institutions for achieving any academic awards.

Yohannes Shifera ______________________ ______________________

Signature Date

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# DEDICATION

"To my mother Martha Ayana, for her prayer, love and support throughout my life"

## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| C | Carbon |
| EFCCA | Environment, Forest and Climate Change Authority |
| FAO | Food and Agricultural Organization |
| FCSAM | Forest Carbon Stock Assessment and Monitoring |
| FDRE | Federal Democratic Republic of Ethiopia |
| FWC | Forest with Coffee |
| $g\ cm^{-3}$ | Gram per centimeter cub |
| GHG | Green House Gas |
| GPS | Global Positioning System |
| Gt | Giga tons |
| ha | Hectare |
| IPCC | Intergovernmental Panel on Climate Change |
| kg | Kilo gram |
| NFPAs | National Forest Priority Areas |
| PFMCs | Participatory Forest Management Cooperatives |
| PNF | Protected Natural Forest |
| QGIS | Quantum Geographic Information System |
| REDD | Reducing Emissions from Deforestation and Forest Degradation |
| SOC | Soil Organic Carbon |
| SOM | Soil Organic Matter |
| SSSA | Soil Science Society of America |
| $t\ Cha^{-1}$ | Ton of carbon per hectare |
| UNFCCC | United Nations Framework Convention on Climate Change |

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## ABSTRACT

*Human-made landscape modification including coffee management and intensification in natural forest has been playing incomparable roles in affecting forest carbon (C) stock potential in western and southwestern Ethiopia which is not studied well. By considering this issue, the current study was conducted with the aim to evaluate the C stock changes in different C pools as a result of conversion of natural forest to coffee-based forest at Anfilo district, western Ethiopia, 642 km west of Addis Ababa. For the present study, two adjacent land uses, protected natural forest (PNF) (1,576 ha) and forest with coffee (FWC) (2,364 ha) were considered. In light of this, primary data were collected from forest and soil. A total of 60 square plots having 35mx35m size each with nested plots of (25mx25m, 7mx7m and 1mx1m) were laid systematically and allocated proportionally for the two sites (24 for PNF and 36 for FWC). Vegetation parameters like DBH, Height and specific wood density were considered for aboveground biomass (AGB) estimation. Within each nested sample plots inventory of woody and non-woody species with the DBH of $\geq$ 5 cm , litter and herb, dead woods and soil samples (0–20, 20–40 cm layers) were collected. Similarly, a total of 120 soil samples (60 for C content and 60 for bulk density) were collected and taken to laboratory for the determination of C content and bulk density. The allometric equation of Chave et al. (2014) and Walkley-Black method were used to estimate aboveground biomass and soil C stock respectively. Belowground biomass was estimated using root: shoot biomass ratios (0.27:1) from AGB. Default value of 0.47 (47%) was used to convert biomass to carbon stock. Independent t –test was used to test for differences in C stocks of the individual C pools at significant level of 0.05. The findings of the present study revealed that the mean carbon stocks in aboveground, belowground, litter and herbs, deadwoods and soil carbon was 371.4 $\pm$ 54.6, 100.3 $\pm$ 14.7, 6.35 $\pm$ 0.846, 9.2 $\pm$ 2.02 and 136.2 $\pm$ 8.42 t C $ha^{-1}$ in PNF and 192.92 $\pm$ 49.4, 53.09 $\pm$ 13.1, 2.8 $\pm$ 0.506, 10.8 $\pm$ 2.15 and 90.76 $\pm$ 4.97 t C $ha^{-1}$ in FWC respectively, with the average aggregate carbon stocks of 623.45 $\pm$ 39.5 and 350.44 $\pm$ 63.5 in PNF and FWC respectively. This indicated that significantly higher C stock was recorded for PNF in all carbon pools assessed ($p<0.05$) except that of dead woods carbon pool which showed insignificant variation ($p>0.05$). The result implies that conversion of natural forest to coffee-based forest leads to a reduction of both biomass and SOC by 46.7% and 33.4% respectively and this is equivalent to the emission of about 1001 t $CO_2$ $ha^{-1}$ to the atmosphere. It was concluded that conservation programs aiming to ensure the long-term permanence of forest carbon stocks, such as REDD+, will remain limited in their success in the area unless the district effectively avoid this forest degradation. Thus, all stakeholders at the local, regional and national level should work together to implement effective conservation measures to maintain and enhance the carbon stock potential of this forest.*


***Keywords: Carbon loss, Coffee forest, Selective cutting, Untouched natural forest***

# 1. INTRODUCTION

## 1.1.Background

Carbon (C) stocks in tropical forests are susceptible to land use changes (Le Quéré *et al*., 2015). However, large uncertainties in tropical forest carbon fluxes arise from difficulties in estimating forest carbon stocks and carbon stock changes, especially from forest degradation (Ometto *et al*., 2014; Bustamante *et al*., 2016). This uncertainty on degradation-driven carbon emissions in tropical forests is a research priority. Forest conversion to other land-uses in the tropics is among the major factors leading to losses in carbon stocks and increasing concentration of GHGs in the atmosphere. The proximate and underlying causes of forest conversion include pressures from increased demand for forest resources; selective exploitation or destruction of tree species (IPCC, 2002). Thus, there is a need for developing sustainable systems to maintain and improve forest carbon content while mitigating greenhouse gas emissions. An accurate estimate of ecosystem carbon storages in forests is crucial for predicting the national carbon-climate feedback and guiding the implementation of mitigation policies (Beer *et al.,* 2010; Yang *et al.,* 2014). C storage in forest ecosystems involves AGB, BGB, deadwood, litter and SOC (IPCC, 2006).

Ethiopia is the cradle of worldwide Arabica coffee. In the country four coffee management systems such as wild coffee, semi-forest coffee, garden coffee and plantation coffee have been described (Taye Kufa, 2012). Coffee (*Coffea arabica L*.) occurs naturally in the undergrowth of moist Afromontane forests between 1,000 and 2,000m.a.s.l (Schmitt and Grote, 2006). Expansion of coffee cultivation leads to deforestation and forest degradation. With regard to this, in the coffee growing areas in the southwest Ethiopia, deforestation is estimated at 10,000 ha/year (Getachew Tadesse *et al.,* 2002). In many areas of western Ethiopia and particularly in the study area, farmers grow annual crops in fields and collect coffee from semi-forested coffee systems, which are forests that are managed for coffee production by selective removal of trees and shrubs. Most of these stands have a spectral signature similar to undisturbed forests in low-resolution satellite imagery and are likely to be mapped as forests. However, this situation is eventually leading to forest degradation which may result in carbon emission to the atmosphere.

The study area Anfilo district is one of the top 18 coffee producers' districts from Oromia regional state (Warner *et al*., 2015) and characterized by a broad gradient of coffee forest management. Of the 10 districts of Kellem Wollega zone, Anfilo is also predominantly known by a potential natural forest area, which is one of the remnants moist evergreen Afromontane forests in western Ethiopia and the forest has been playing a crucial role in mitigating climate change. Despite this importance, the resource has been highly degraded in the past 2-5 decades to meet the needs of increased population growth. According to District's Environment, Forest and Climate Change Authority (EFCCA) (2019) stated that expansion of coffee plantation in natural forests is the main factor currently threatening forest resource of the district. Cutting trees for timber extraction, fuel wood collection and house construction are also common. However, up until this study no information is available in the district about carbon stock change resulted from such conversion of natural forest to coffee forest.

Studying the effect of natural forest changes to coffee forest could redefine the role of the managed forest in carbon sequestration, leading to a conclusion concerning which one has more potential in mitigating climate change. To support or not support the mechanism of coffee-based forest system for climate change mitigation, it is critical to understand the amount of carbon stored by forest with coffee (FWC) relative to adjacent protected natural forest (PNF). Hence, the present study was conducted to evaluate carbon stock changes as a result of natural forest conversion to coffee-based forest in the Anfilo district.

## 1.2.Statement of the Problem

Anfilo district is potential natural forest area which its coverage is estimated to be about 39,718.85 ha (MEFCC, 2017). From the characteristic tree species and altitudinal range of the area, the study sites forest is one of the remnants moist evergreen Afromontane forests in western Ethiopia. The forest is highly dominated with large trunk and tallest woody tree species. Therefore, the forest can store a high magnitude of carbon and it has been playing a vital role in mitigating climate change. However, the forest has been mostly subjected to degradation due to the human-made landscape modification particularly coffee expansion and its management in natural forest to meet the needs of increased population growth mostly within the past 2-5 decades (Anfilo District EFCCA, 2019).

According to the Anfilo District EFCCA (2019) pointed out that, in the district, farmers grow annual crops in fields and collect coffee from semi-forested coffee systems, which are forests that are managed for coffee production by selective removal of trees and shrubs. Most of these stands have a spectral signature similar to untouched natural forests in low-resolution satellite imagery and are likely to be mapped as forests. And as most definitions of "forest" depend on a threshold land cover fraction by woody perennials, the derived systems such as coffee plantations with or without shade trees may fall under the definition (Robert, 2007). Even if, the magnitude varies depending on management intensity (Getachew Tadesse *et al.*, 2014; Vanderhaegen *et al.*, 2015), these patterns coupled with the high demand for forest resources are putting intolerable pressure on the resource which may leading to significant loss of forest carbon and its emissions to the atmosphere. This in turn can also hinder the successful implementation of REDD+. But it is not known to what extent it has been contributing to the subtle change in forest carbon stock content.

Assessment of carbon stock in such changing landscape will enable to understand the effect of such disturbances on carbon stocks, and how stocks in degraded forests compare to those found in untouched primary forests. Such data will contribute to device sustainable management options that contribute to harness emission. To my knowledge no such study has been conducted in the district. Hence, the current study was initiated to evaluate C stock changes as a result of conversion of natural forest to coffee-based forest to develop better knowledge based sustainable forest management plan of the area in the Anfilo district, western Ethiopia.

## 1.3.Objectives of the Study

### 1.3.1. General objective

The general aim of this study was to determine and evaluate carbon stock changes in different carbon pools as a result of conversion of natural forest to coffee-based forest at Anfilo district, western Ethiopia.

### 1.3.2. Specific objectives

The specific objectives of this study are;

- ☑ To determine carbon stock in each carbon pools of protected natural forest and forest with coffee;
- ☑ To assess carbon stock changes as a result of conversion of natural forest to coffee-based forest.

## 1.4.Research Questions

- ☑ How much carbon is stored in each carbon pools of protected natural forest and forest with coffee?
- ☑ How much percentage of carbon is lost as a result of conversion of natural forest to coffee-based forest?

### 1.5. Significance of the Study

The study will have its own rationalities both for study sites in one way and for carbon stock estimation literatures. This study is considered to be an important step towards the bridge of the information gap at the study area. By quantifying, analyzing and evaluating the carbon stock across untouched natural forest (forest without coffee) and forest with coffee, it helps to provide firsthand information for the conservation, management and sustainable utilization of the forest resources to reduce deforestation and forest degradation. Moreover, it can provide valuable data to policy and decision makers to design appropriate policies and strategies for monitoring forest resource degradation and promote sustainable management of the resource. Additionally, it can help as a reference if climate finance project will be implemented in the study forest and for other forthcoming studies dealing with carbon credits. A large number of government or non-government development agencies, researchers and local communities can benefit from the outputs of this research.

# 2. LITERATURE REVIEW

## 2.1. Moist Evergreen Afromontane Forest in Ethiopia

Moist evergreen Afromontane forests are forests which have evapotranspiration exceeds precipitation between one and five months (Alvarez *et al*., 2012), according to climate averages over several years. This forest type, including the cloud forests, are among the few remaining moist high forests of the country and corresponds to semi-deciduous lowland forests, which have a precipitation of approximately 1550–3500 mm $yr^{-1}$. It occurs in the southwest and southeast highlands in the country at altitudes between 1500 and 2600m (Feyera Senbeta and Danich, 2006). From the same source the mean annual temperatures range from 15-20 $^{0}$C and annual rainfall from 700 to 2500 mm.

Kitessa Hundera (2013) described that these forests are the major remaining forests in the country and are the foundation of the *Coffea arabica*. This author outlined that the presence of coffee in the forest system causes the modification of floristic composition and structural complexity of the forest through slashing and canopy opening in order to increase its productivity.  This results low or no natural regeneration takes place in the forest. Furthermore, these forests are exposed to extreme fragmentation as a result of agricultural expansion and human settlement driven by a rapid increase of the human population.

The characteristic tree species include *Pouteria adolfi-friederici, Podocarpus falcatus, Croton macrostachyus, Schefflera abyssinica, Ilex mitis, Olea welwitschi, Prunus africana, Cordia africana, Sapium ellipticum, Ekebergia capensis, Macaranga capensis, Elaeodendron buchananii* and others (MEFCC, 2018). According to Feyera Senbeta (2006), Podocarpus falcatus is predominant in the southeast and gradually becomes rare towards the southwest, while *Pouteria adolfi-friederici* becomes more prominent there.

## 2.2. The Role of Forest and Forest-Based Systems in Mitigating $CO_2$ Emissions

Forestry activities contribute to climate change mitigation either by preventing emissions or by sequestering carbon, based on their age, healthiness and susceptibility to wildfires and other disturbances, as well as on their management system. Management of native forests offers opportunities to store more carbon in the land sector through two main activities. Emissions to the atmosphere can be avoided by ceasing logging. Removals of $CO_2$ from the atmosphere can be increased by allowing forests to continue growing. Conversely, forestry activities that contribute to carbon sequestration include the expansion of land-use systems that employ trees, such as the establishment of plantations on degraded lands, natural re-growth of secondary forests and the application of agroforestry practices on agricultural lands (Smith *et al.*, 2004).

Generally, the stock in a forest is broadly divided in to two: biotic (vegetation carbon) and pedologic (soil carbon) components (Bhat *et al.*, 2013). Forests capture $CO_2$ from the atmosphere and convert it, through photosynthesis, into living biomass: tree trunks, roots, branches and leaves and also store carbon in forest soils, absorbed through leaf litter, woody debris and roots. The carbon sequestered or stored on the forest trees are mostly referred as the biomass of the forest. It is estimated that about 86% of the terrestrial above ground carbon and 73% of the earth's soil carbon are stored in the forests (Vashum and Jayakumar, 2012). Of which, 46% of the world's terrestrial carbon pool and about 11.55% of the world soil carbon pool stored in tropical forests.

The climate protection role of forests is apparent. However, it is complex to determine how much of the forest carbon sink and reservoir can be managed to mitigate atmospheric $CO_2$ and in what way to buildup. According to Canadell and Raupach (2008) identified that four major strategies are available to mitigate carbon emissions through forestry activities: (i) increase forest land area through reforestation and afforestation, (ii) increase the carbon density of existing forests at both stand and landscape scales, (iii) expand the use of forest products that sustainably replace fossil-fuel, and (iv) reduce emissions from deforestation and degradation. Trees in the forest act as major $CO_2$ sink that captures carbon from the atmosphere and stores it in the form of fixed biomass during the growth process (Bhat *et al.,* 2013). In this natural process, it removes the $CO_2$ from the atmosphere and stores the C in the plant tissues, forest litter and soils. Thus, forest ecosystem plays a very crucial role in the global C cycle by sequestering a substantial amount of $CO_2$ from the atmosphere.

### 2.3.Other Roles of Forests

It is argued that C sequestration should be seen merely 'as one co-benefit of reforestation strategies designed to protect and intensify the hydrologic cycle and associated cooling (Brack, 2019). Forest ecosystems provide many goods and services other than C storage such as timber, fuel wood, paper, food and fodder as well as environmental and social services including the protection of soil and water resources, the conservation of biological diversity and the provision of livelihoods for an estimated 1.6 billion people (World Bank, 2004). This recognition of the importance of these services have increased social and economic demands on both public and private forests, presenting a challenge for 21$^{st}$ century foresters to manage forests simultaneously for wood, biodiversity, C sequestration, energy, water quality, flood control, habitat, and recreation (Burger, 2009).

### 2.4.Forest Carbon Stock Pools

There are five carbon pools of terrestrial ecosystem involving biomass, namely the above-ground biomass, below-ground biomass, the dead mass of litter, woody debris and soil organic matter. Tree biomass is defined as the total mass (volume) of the above and below-ground dry weight of the tree per unit area (IPCC, 2006).

### 2.4.1. Aboveground biomass (AGB) carbon stock

According to IPCC (2006), aboveground biomass carbon pool consists of all living vegetation above the soil, inclusive of all woody stems, stumps, branches, leaves of living trees, bark, seeds, foliage, creepers, epiphytes and as well as herbaceous undergrowth. For agricultural lands, this includes crop and weed biomass.

There are various techniques to estimate C stocks in forests at different scales. However, all techniques ultimately rely on ground measurement of tree biomass (Gibbs *et al*., 2007). The most accurate method of estimating AGB is destructive sampling, but tree removal is prohibitively time-consuming, costly, unsustainable, labor intensive and not feasible on smallholder agricultural lands (Ketterings *et al*., 2001, IPCC, 2014). Allometric models, based on the principle that species specific relationships between dendrometric characteristics can be used to generate relatively accurate estimates of plant biomass allow us to predict biomass based on other tree characteristics such as height or diameter, are the accepted method for nondestructive biomass estimation (Chave *et al*., 2005; Picard *et al*., 2012). In the same way, climatic condition and forest structure consideration have a role in the accurate estimation of forest biomass (Yuen *et al*., 2016).

This estimation of aboveground biomass is based on plot inventories that involve in the following three steps (Chave *et al*., 2005):

1. The selection and application of an Allometric biomass function for the estimation of individual tree biomass,
2. The summation of individual tree AGB to estimate plot AGB, and
3. The calculation of an across-plot average to hectare based.

### 2.4.2. Belowground biomass (BGB) carbon stock

Below-ground biomass is defined as the entire biomass of all live roots, although fine roots less than 2 mm in diameter are often excluded because these cannot easily be distinguished empirically from SOM (IPCC, 2006). BGB is an important C pool for many vegetation types and land-use systems and accounts for about 20% (Santantonio *et al*., 1997) to 27% (Mokany *et al*., 2006) of the total biomass. Since it could account for 20– 27% of the total biomass, it is important to estimate this pool for most C mitigation as well as other land-based projects. The greatest proportion of root biomass occurs in the top 30 cm of the soil surface (Ponce-Hernandez, 2004). Re-vegetation of degraded land leads to continual accumulation of BGB whereas any disturbance to topsoil leads to its loss. Estimation of stock changes in BGB is also necessary for GHG inventory at national level for different land-use categories such as forest lands, cropland and grassland.

Estimation of BGB is much more difficult and time consuming than estimating AGB (Geider *et al*., 2001). Unlike AGB, it is not practical to measure the BGB directly because it is extremely laborious to extract, dry, and weigh the entire root structures of trees. For these reasons, it is also very difficult and resource-intensive to develop forest type or country-specific allometric equations for root biomass. Instead, it is acceptable for BGB to be indirectly using available equations that reliably predict root biomass based on shoot (i.e. aboveground) biomass. BGB accumulation is linked to the dynamics of AGB. For both AGB and BGB the amount of C stored is determined by multiplying the biomass of each pool to 0.50 (Pearson *et al., 2005*) and 0.47 according to IPCC (2006).

### 2.4.3. Dead wood biomass carbon stock

Dead wood biomass is all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots down to a diameter of 2mm, and stumps larger than or equal to 10cm in diameter or any other diameter used by the country (IPCC, 2006). Although logged dead wood, standing and lie down on the ground, is often a significant component of forest ecosystems, often accounting for 10-20% of the AGB in mature forests but it tends to be ignored in many forest carbon budgets (Delaney *et al*., 1998). The quantity of dead wood does not generally correlate with any index of stand structure (Harmon and Sexton, 1996). The primary method for estimating carbon stock in the dead wood pool is to sample and assess the wet-to-dry weight ratio, with the large pieces of dead wood measured volumetrically as cylinders and converted to biomass on the basis of wood density, and standing trees measured as live trees but adjusted for losses in branches (<20%) and leaves 5-6% for conifer species and 2-3% for broadleaved species (Pearson *et al*., 2005).

### 2.4.4. Litter carbon stock

According to IPCC (2006) and Zhu *et al*. (2010) this pool includes all non-living carbon with a size greater than the limit for soil organic matter (suggested 2 mm) and less than the minimum diameter chosen for dead wood (e.g., 10cm), and length < 0.5 m, lying dead, in various states of decomposition above or within the mineral or organic soil. This includes the litter layer as usually defined in soil typologies. Live fine roots above the mineral or organic soil (of less than the minimum diameter limit chosen for BGB) are included in litter where they cannot be distinguished from it empirically. The mechanism of species driven carbon sequestration in soil is affected by two major activities, aboveground litter decomposition and belowground root activity. Litter decomposition is one of the major sources of SOC and the quality of litter is very important in this regard (Bekele Lemma *et al.*, 2007). In the systems with high plant diversity, litters are present with various degrees of chemical resistance, creating the possibility of longer residence of carbon through slower decomposition of litters from some species. Lignin in litter is highly resistant to decomposition and therefore, litter with high lignin content would have slower decomposition rate (Mafongoya *et al*., 1998). In contrast, litter with low lignin, phenols, and high nitrogen content would have faster rate of decomposition.

### 2.4.5. Soil carbon stock

Soil organic carbon (SOC) is a significant carbon pool because it has the longest dwelling time of carbon among organic carbon pools (Lugo & Brown, 1993). Therefore, soil is considered as relatively stable pool of various organic and inorganic carbon fractions (Post and Kwon, 2000). This makes soils a critical component of the global carbon cycle. Soils hold an estimated, 1500–1550Gt (1Gt= $10^9$ ton), of organic soil carbon and soil inorganic carbon approximately 750 Gt both to 1 m depth. In the topsoil layer of 0–30 cm, the content of SOC is approximately twice the amount of carbon in atmospheric $CO_2$ and three times that in aboveground vegetation globally (Batjes, 2001).

Soil carbon is a significant determinant of site fruitfulness due to its contribution in maintaining soil corporal and substance property such as comprehensive immovability, cation switch over and water investment capability (Davidson *et al*., 2000). Soils play a key role in the global carbon budget and GHG effect. Compared with 1.7% in the atmosphere, 8.9% in fossil fuels, 1 % in biota and 84.9% in the oceans, soil contains 3.5% of the earth's carbon reserves (Lal, 2004).

Carbon is sequestered in the soils directly and indirectly (SSSA, 2001). Direct soil carbon sequestration occurs by inorganic chemical reactions that convert $CO_2$ into soil inorganic carbon compounds such as calcium and magnesium carbonates. Indirect plant carbon sequestration occurs as plants photosynthesize atmospheric $CO_2$ into plant biomass. Some of this plant biomass is indirectly sequestered as SOC during decomposition processes. The amount of carbon sequestered at a site reflects the long-term balance between carbon uptake and release mechanisms. Because those flux rates are large, changes such as shifts in land use and land cover practices that affect pools and fluxes of SOC have large implications for the carbon cycle and the earth's climate system (Lal and Bruce, 1999).

Forest soils are one of the major carbon sinks on earth, due to their higher organic matter content. Soils can act as sinks or as a source for carbon in the atmosphere depending on the changes happening to soil organic matter. Equilibrium between the rate of decomposition and rate of supply of organic matter is disturbed when forests are cleared and land use and land cover is changed (Lal, 2004). SOM can also increase or decrease depending on numerous factors, including climate, vegetation type, and nutrient availability, disturbance, and land use and management practice. About 75% of the total terrestrial carbon is stored in the global soils and 40% of it resides in forest ecosystem (Baker, 2007).

### 2.5.The importance of studying carbon stocks in a forest

Estimating the amount of forest biomass is very essential for monitoring and estimating the amount of carbon that is lost or emitted when deforestation takes place, and it also provides information about the forest's potential to sequester and store carbon in the forest ecosystem. Brown (2002) and Houghton (2005) also described that understanding of forest biomass pattern is important for improving the estimation of carbon pools and predicting the carbon budgets in response to climate change. On the other hand, estimating the carbon stocks in forest is important in assessing the mitigation effect of forests on global change and to predict the potential impact of mechanisms to reduce carbon emission. On the other hand, according to Vashum and Jayakumar (2012) the reason why carbon cycle drew much attention at global level is described that (1) it is the chief among other GHGs (2) its potentials to affect the global climate pattern and (3) relatively its long residence time in the atmosphere. Likewise, there are two key policy related reasons for measuring carbon in forests: (1) commitments under UNFCCC, and (2) for potential implementation of the Kyoto Protocol (Brown, 2002).

Therefore, assessment of the amount of carbon sequestered by a forest gives us an estimate of the amount of carbon emitted into the atmosphere when this particular forest area is deforested or degraded. Furthermore, it can help us to quantify the carbon stocks which will enable us to understand the current status of carbon stocks and also derive the near future changes in the carbon stocks.

In addition, UNFCCC requires that all Parties to the Convention commit themselves to develop, periodically update, publish, and make information available to the Conference of Parties (COP) their national inventories of emissions by sources and removals by sinks of all GHGs using comparable methods. Forestry is one of the sectors for which a national inventory of sources and sinks of GHGs must be developed. If carbon stocks can be measured accurately and precisely at some intervals using the same approaches, it provides the important information to determine the changes in carbon stocks as required by the UNFCCC and forestry projects for mitigating carbon emissions. In addition, estimates of carbon stock could be essential for natural resource management and planning mitigation strategies for climate change (Khanal *et al*., 2010).

### 2.6. Carbon stock in tropical forests

Tropical forests represent a significant yet vulnerable concentration of valuable ecosystem services (Costanza *et al*., 1997). According to UN-REDD (2010) these ecosystems have been estimated to contain nearly half of global carbon stocks, and are also recognized as biodiversity hotspots supporting unknown numbers of species. However, human activities are increasing the stocks of GHGs emitted to the atmosphere. Tropical deforestation is estimated to have released roughly 15-25% of annual global GHG emissions (Houghton, 2005). As a result the current level of GHGs in the atmosphere is raised from 280 to 430 ppm, causing the world to warm by more than 0.5$^{o}$C and will lead further warming in the future (IPCC, 2013). High altitude regions of tropical forests also provide ideal growing conditions for commercial production of coffee (IPCC, 2007).

When humans use forests for agricultural production, degradation is all but inevitable: conversion of tropical forest land is responsible for a high amount of annual anthropogenic GHG emissions. Different measures are considered to solve the problem and among these, forest fix large amount of carbon in the process of photosynthesis and store it in the form of biomass. As more photosynthesis occurs, more $CO_2$ is converted into biomass, reducing carbon in the atmosphere and sequestering it in plant tissue above and below ground (IPCC, 2003; Gorte, 2009) resulting in growth of different parts. Biomass production in different forms plays a vital role in C sequestration in trees (Chavan and Rasal, 2012).

IPCC (2013) reported the global forests cover over 4 billion hectares, which corresponds to an average of 0.6 ha per capita and contribute around 50% global GHG mitigation. The tropical forests spread over 13.76 million km$^2$ area worldwide accounted about 60% of the global forest cover and store an estimated 193-229 pentagrams of carbon in aboveground biomass and recycling 915 Gt of carbon each year, through photosynthesis and net primary production (FAO, 2005; Baccini *et al*., 2008) or roughly 20 times the annual emission from combustion and land use change (Clark and Kellner, 2012). Tropical rain forests contribute substantially to the global carbon cycle accounting for 40% terrestrial net primary production, 60% of forest biomass and 27% of carbon stored in forest soils.

## 2.7.Carbon stock in Ethiopian forests

In Ethiopia the original forest cover is not well documented, and estimates are not consistent. However, historically by the end of the 18$^{th}$ century, 40% of Ethiopia‘s land was covered by forests (Samuale Tesfaye *et al*., 2014) and declined to 11.2% in 2010 (FAO, 2010). At present this figure increased to 15.7% (MEFCC, 2018). In Ethiopia deforestation, overharvesting and permanent conversion to other forms of land use are factors leading to shrinkage of forest resources (Tesfaye Bekele, 2000). As a result, forest cover has been declining at an alarming rate and only remnant forests are confined to some areas especially in the south-western and western parts, which are less populated.

Unlike in the developed countries, Ethiopia does not have enough carbon (C) inventories and databank to monitor and enhance C sequestration potential of different forests. According to Yitebitu Moges *et al.* (2010), the forest resources of Ethiopia store an estimated 2.76 billion tons of C, playing a significant role in the global C balance. Various scholars have studied the forest of Ethiopia. However, only small efforts have been made so far to quantify the forest C stock, biomass and soil C sequestration potential at small scale level with comparing the native natural forest potential of Ethiopia with other land uses particularly forest with coffee. Because of this and to fill some of the gaps of area limitation and scarcity of data on forest C stock specifically coffee forest in comparison to untouched natural forest, the study was important for management of forest to show the win-win strategies for the welfare of human society beside their economic value.

### 2.8.Impacts of Coffee Management System on Carbon Accumulation

The coffee plant is characterized as a perennial woody shrub that belongs to the Rubiaceae family and needs different management activities to bring a high quality and quantity coffee yields which leads to selective cutting of tree species and the removal of under growth vegetation. Study made in Ethiopia by Kitessa Hundera *et al*. (2013) showed that forest thinning for coffee intensification and for conversion into other cropland is an on-going process, accounting for over 36% forest cover loss in the last four decades. In a country, the rate of deforestation is estimated at 1-1.5% per year (Maereg Teferi *et al*., 2013), mostly driven by smallholder coffee expansion (Davis *et al*., 2012).

On the other hand, Beenhouwer (2015) described that along with the protection of natural forest, coffee management is associated with a downward shift of orchid species. Local extinctions of epiphytic orchids and species losses in the outer tree zones in managed forests are most likely driven by losses of large, complex-structured climax trees and changes in microclimate. As farmers continue to convert natural forest to forest managed for coffee cultivation, further losses of habitat quality and collateral declines in epiphytic orchid diversity. This on the other hand, affects C accumulation through root mortality, and through changes in litter production and humus formation (Getachew Tadesse *et al*., 2014) and increasing concentration of GHGs in the atmosphere and influences the implementation of REDD+ program. But the amount is varies depending on management intensity (Getachew Tadesse *et al*., 2014; Vanderhaegen *et al*., 2015).

Even when coffee is grown under a canopy of native forest, it causes forest degradation as it involves clearing of the understory (Hylander *et al*., 2013), causing about 34% decline in woody species richness (Getachew Tadesse *et al*., 2014). Although the data is uncertain, a 2015 study suggested that emissions from forest degradation were a quarter of those from deforestation in the decade 2001–10, increasing to one third of those from deforestation in the period 2011–15, with substantial variation across countries (Federici *et al*., 2015).

### 2.9.Coffee production systems in Kellem Wollega Zone

In the zone, about 99% of the coffee is produced by small scale farmers, which include forest coffee, semi-forest coffee, semi-plantation coffee and garden coffee which accounts for 15%, 40%, 20% & 25% respectively (Aboma Bulcha, 2016).

## 3. MATERIAL AND METHODS

### 3.1.Description of the Study Area

#### 3.1.1. Geographical location

Anfilo District is located in the Kellem Wollega Zone of Oromia Regional State, Western Ethiopia. The district extends from 8°30′0″ to 8°48′0″N and 34°40′0″ to 34°59.99′0″E and covers an area of 167,053 ha. Its elevation range is from 500 to 2600 m.a.s.l. It shares borders with Gambella Region on the south and southwest, Gidami on the north and northwest, Yemalogi Welel on the northeast and Seyo districts on the east and southeast (Aboma Bulcha, 2016; Samuel Diro *et al*., 2017; Woreda Land Office, 2019).

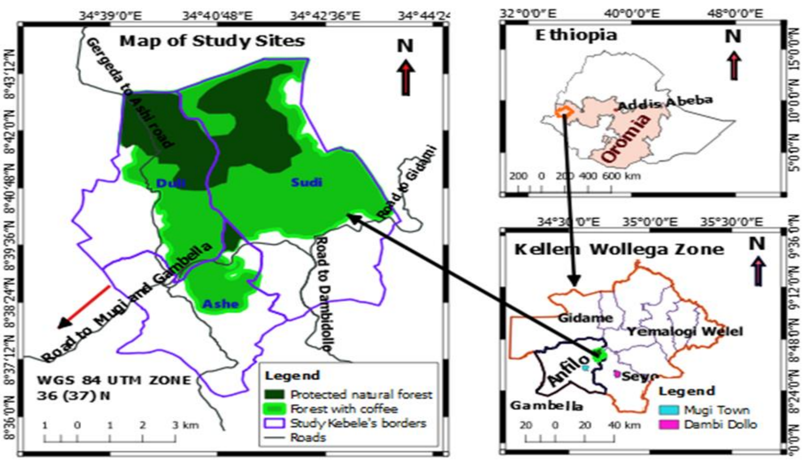



Figure1: Geographical location of the study sites

The administrative center of the district is Mugi. Anfilo has 25 kebelles, 22 rural and 3 urban kebelles. It is connected to Dambi-Dollo (Zonal capital) by 42 km rural gravel road that passes via the dense forest and crosses to Gambella region and 642km from Addis Ababa to the west. The study forest is about 26 km from Mugi town to the northeast (MEFCC, 2017; Anfilo District EFCCA, 2019) (figure 1).

#### 3.1.2. Climate

Similar to the other districts of the Ethiopia, Anfilo is located within the boundary of the tropics. Therefore, there is no significant variation in day length and angle of the sun (macro climate). In the district there is no weather station and hence the climate data were obtained from literatures. Accordingly, Anfilo district is divided in to three agro-climatic zones from which 28% is highland, 8% is mid altitude and 64% is lowland. The mean, minimum and maximum temperature of the area is 12$^{o}$C and 27$^{o}$C respectively. It has a bimodal rainy season with annual rainfall ranging from 1200-2320mm. The main rain season is from June up to September.  It is in this season that the major agricultural activities such as ploughing, sowing/planting and weeding are carried out in the nearby study area. April, May and October are short rain months (Aboma Bulcha, 2016). The district also gets a little rainfall in November and December (Source: Anfilo District EFCCA, 2019; Personal observation, 2019).

### 3.1.3. Vegetation

Anfilo district is a potential natural forest area designated as part of the Gergeda forest, one of state forests proposed in 1975 as a National Forest Priority Areas of Ethiopia (EFAP, 1994) and covers about an area of 39,718.85 ha (MEFCC, 2017). Forest of the study sites fall under moist montane forest type and forest groups are also found in southwestern part of Ethiopia elsewhere and nearly all of the forest is covered with *Coffea arabica*. Coffee is one means and source of livelihood of the Woreda community, with various annual crops like maize, wheat, sorghum, etc., and livestock production (Aboma Bulcha, 2016).

*Pouteria adolfi-friederici, Syzygium guineense, Olea welwitschi, Prunus africana, Cordia africana, Croton macrostachyus, Sapium ellipticum, Apodytes dimidiata, Ekebergia capensis, Ficus sur and Albizia schimperiana* are among species of trees that form the upper canopy in the natural forest, while *Cupressus lusitanica, Gravellia robusta, pinus pastula* and species of *Eucalyptus* are some of the planted species found in the district. In natural forests of the district there are also important species of wild animals including

Elephant, Lion, Leopard, Buffalo, Warthog, Bushbuck, Otter, Monkey, Ape, Duiker and Hyena. However, there are no reserved areas for wild life conservation in the district (MEFCC, 2017; Anfilo District EFCCA, 2019).

## 3.2.Data sources

The primary and secondary data sources were used in order to collect the relevant data to meet the objectives of this study. Primary data used to estimate carbon stock was obtained through field measurements in the study areas and the secondary data was collected from different sources like published and unpublished materials, books, journals, articles, reports, and electronic web sites.

## 3.3.Samples and Sampling Procedures

### 3.3.1. Selection of the study sites

Preliminary reconnaissance survey was carried out in August, 2019 in order to obtain the general overview of the study sites and to select it and as well as to identify the appropriate sampling sites, sampling design methods and determine representative sampling plots. During the visit, we discussed with working staff of Anfilo District Coffee and Natural Resource Office, EFCCA and some people about the purpose of the study.

For this study, two land uses, protected natural forest (forest without coffee) and forest with coffee were considered. The study sites encompass three adjacent forest kebelles selected purposively namely Ashi, Duli and Sudi and covers an area of about 3,940 ha. The reason behind this forest sites selection was that, they could be good representative of the forest which included both land uses and relatively site accessibility to carry out the study. In addition, both sites are also nearly under similar biophysical conditions except their differences in land management practices.

### 3.3.2. Delineation of the forest boundaries

On the first step study kebelles Ashi, Duli and Sudi were delineated from Oromia kebelles shapefile. Then the boundary of the study sites (study forests) found in these kebelles were digitized inseparately using high resolution satellite imagery (Google satellite). Since it was difficult to separately delineate study sites due the spatial boundaries of the study sites were not separated and properly recognized, activities like observing the study sites area (reconnaissance survey) of the general area in order to get the ways and to record GPS points for boundary delineation of these sites was done. After GPS points were recorded the two forests were separately delineated and then mapped. The above activities were made with the help of QGIS Software version 3.2.3.

### 3.3.3. Sampling design, techniques and plot allocation

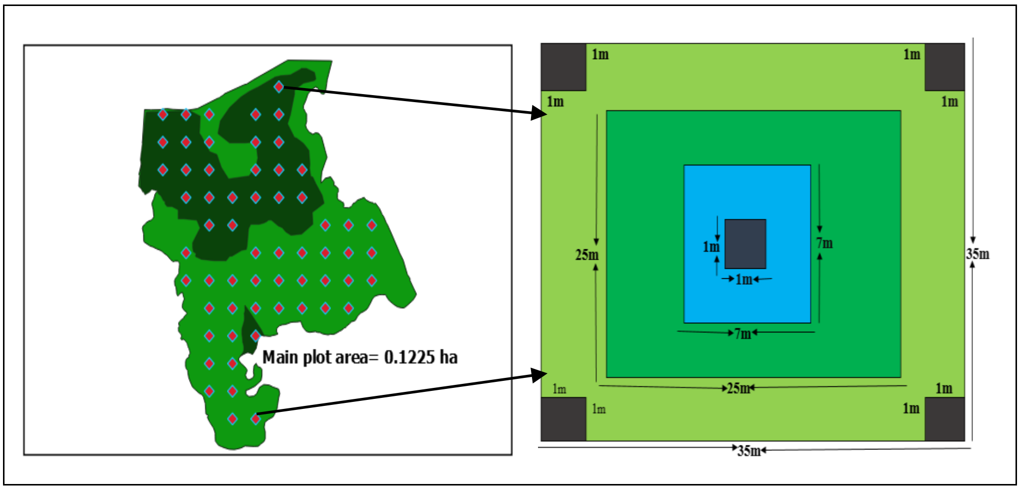
A systematic sampling scheme was used to collect vegetation and soil data of the two land uses (protected natural forest (PNF) and forest with coffee (FWC)). Accordingly, sampling sites were identified in the PNF of 1,576 ha and FWC of 2,364 ha for data collection. A parallel line transects were laid at 700m interval along altitude (16 transect lines sampling, 7 from PNF and 9 from FWC).

The number of plots was estimated from reconnaissance survey prior to the main study, whereby, five plots were established randomly and then the number of plots was computed using the Pearson *et al*. (2005) formula:

$$n= \frac{(N*S)^2}{\frac{N^2*E^2}{t^2}+N*S^2} \qquad (1)$$

Where: n= number of sampling units in the population, N = number of sampling units for the site (area of study site in hectares), s = standard deviation, E= allowable error or the desired half-width of the confidence interval (calculated by mean carbon stock ×0.1, for

10% error, or 0.2 for 20% error) and t= the sample statistic from the t-distribution for the 95% confidence level, usually set at 2 as the sample size is unknown at this stage.




Note: 35x35m for trees with DBH ≥ 50cm, 25x25m for DBH 20-50cm and dead woods, 7mx7m for DBH 5-20cm and 1mx1m for litter and herb, and soil samples. Dots represent study sample plots.

Figure 2: Geographical location and nested plot design for sampling of various C pools

Accordingly, a total of 60 square sample plots were determined and assigned systematically for the two forests proportional to their area (24 for PNF and 36 for FWC) which was navigated in the field during data collection with an area of 1225 $m^2$ (35mx35m) for trees with DBH ≥ 50cm, each was designed along transect lines with 700 m gaps between each plots. Nested plots of 25 m x 25 m sub-quadrats for trees and shrubs for DBH ranges 20 - 50 cm, 7 m x 7 m for DBH ranges 5-20 cm (Chave *et al*., 2014) and 1m x 1 m sub-quadrats for herbs/grasses, litter, and soil were set up within the main plots. Square plot was preferred because it is similar with rectangular that tends to include more of within plot homogeneity and  since the area has more or less uniform slope, and thus be more representative than the circular plots of the same area (Hairiah *et al*., 2001).

Quadrats were laid systematically at every 700m intervals along the transect line, which was laid parallel to the slope (Gemedo Dalle *et al*., 2006). Following Tessema Toru and Kibebew Kibret (2019) to eliminate any influence of the edge effects on the forest biomass, all plots were laid at least 150 m away from nearest roads. The location of the plots was marked by GPS with an accuracy of 3- 7 m.

## 3.4.Field Data Collection

### 3.4.1. Vegetation data collection and identification

Data from the two study sites were collected between November and December, 2019. After the areas of each sample plots were determined by meter tape (steel long 50m) measurement, at first, all trees found in the border of each plot were marked, and then, all trees in the main plot were numbered. Then, in each main sampling plots and subplots, circumference (C) at breast height and height were measured for every individual tree and non-tree (liana) with C $\geq$ 15.7cm (DBH $\geq$ 5cm) starting from the edge and working inwards, and marking each tree to prevent accidentally counting it twice in both study sites. DBH was calculated from $C = \pi d$, where d is diameter at breast height. Since the objective was not to monitor changes in floristic composition and the biodiversity, smaller individuals < 5cm in DBH were not considered. Circumference of each tree was measured with meter tape and height by calibrated stick (for trees $\leq$ 5 m) and others by hypsometer.

In the case of trees with multiple stems at breast height or below, the diameter of separate branches was measured to consider as individual tree, similarly, was applied to multi-stemmed shrubs (Snowdon *et al*., 2002). In addition, for buttressed tree stems, its circumference was taken at the nearest lower points. For coffee plants, stem diameter at stump height (at 40 cm) was measured. Stem diameter measurements ($d_{40}$) were taken in two perpendicular directions and the average value taken.  In the case of multistemmed coffee plants, all stem in single plant was measured and the equivalent diameter of the plant was calculated as the square root of the sum of diameters of all stems per plant (Snowdon *et al*., 2002).`

$$d \text{ or } d_{40} = \sqrt{\sum_{i=1}^{n} di^2} \quad (2)$$

Where, d (cm) = diameter equivalent at breast height, $d_{40}$ (cm) = diameter equivalent at 40 cm height, $d_i$ = diameter of the $i^{th}$ stem at breast height or 40 cm height. Besides, trees on the border of the plot were measured if ≥50% of their basal area fall within the plot otherwise were excluded (MacDicken, 1997; Banskota *et al*., 2007).

Local names of trees were first identified immediately in the forest with the aid of local people, development agents, forest guards and forestry experts and then recorded in the species checklist and later scientific names with their family names were identified from all published volumes of Flora of Ethiopia and Eritrea and Useful trees and shrubs for Ethiopia (Woldemichael Kelecha, 1987; Azene Bekele, 2007) by the researcher. Altitude and geographical locations were recorded for each sample plot by using Garmin 72GPS.

### 3.4.2. Dead wood data

Within subplots established for live trees (25m x 25m), dead wood data was collected. Dead woods were classified as standing, stump and felled woods. Standing dead woods are dead trees with stem, branches and twigs; and their circumference at breast height, height and standing status were recorded. Circumference was converted to DBH in the same procedure for live tree. From stump and felled dead trees, height (length) and mid diameter of the woods were measured (Pearson *et al*., 2005). Deadwood on the tip of the live tree was not considered because of its unavailability in the sample plots of the study sites.

### 3.4.3. Herbaceous and litter data

Destructive sampling method was used for measuring the biomass of herbs by harvesting whole parts of fresh samples within each quadrat, a size of 1 m x 1 m, using sickle. A total of five sub-quadrats (four at corners and one in the center) were used for litter collection.

In the PNF, all the herbaceous vegetation emerging within the quadrat areas were cut at the ground level, weighed, and a composite sample was sun dried for dry mass determination, while it was not measured in the FWC due to the nonexistence of herbs within the sample plots because of it was removed for coffee management. Surface litter was sampled from the sub-quadrats (1 m x1 m) and composite litter was collected. The herb and litter samples of 60 each (24 from PNF and 36 from FWC) were weighed in the field using a spring balance and recorded. The samples were mixed well and a 100g sub-sample was taken from each plot for dry to fresh biomass ratio. The samples collected were subjected to air drying and observed repeatedly until the samples reached stable weight.

### 3.4.4. Soil data

The soil samples were collected for the bulk density and soil carbon content analysis. Following Zelalem Teshager *et al*. (2018) and Asersie Mekonnen and Motuma Tolera (2019), the samples were taken from the five sub-plots used for litter and herbs at two levels of soil depths (0–20 and 20–40cm) separately.  40 cm soil depth was considered because carbon loss in the ground is intense in the top layer of soil profiles (0–20 cm) (Ponce-Hernandez, 2004) and no significant SOC change below 20 cm depth (Axel Don *et al*., 2010). It indicates stability between all land uses due to the low level of addition of biomass to lower depths (Axel Don *et al*., 2010). Therefore, sampling was considered on this section of the soil profile accumulation and twice of this depth is significantly enough to assess carbon stock variation across different land uses (mostly conversion from forest to others). The soil samples were taken from 1/2 of the total plots. The soil depth was measured using a metallic ruler. Then, from the same quadrants, soil samples for soil bulk density determination were collected for the same depth intervals as other soil samples for each plot (Roshetko *et al*., 2002). The soil samples for carbon analysis were collected manually by digging using hoe, while soil samples for bulk density were collected with soil core samplers of (6 cm diameter × 20 cm tall, 565.5 $cm^3$) by carefully driving into the soil to avoid compaction. An equal weights of each sample of the corresponding depth were pooled and mixed together from a given transect line, air dried and passed through a 2 mm sieve to separate debris and gravel. Finally, 500 g composite samples were taken as a representative sample, which were packed in plastic bags, labeled, sealed and transported to the soil laboratory. A total number of 120 soil samples (2 depths × 60 quadrats) were collected for the determination of soil carbon content and bulk density. Then, the soil samples were air-dried followed with oven dried at 105$^o$C for 24 hours at Wondo-Genet College of Forestry and Natural Resources soil laboratory. Finally, the bulk density and soil organic carbon were quantified after getting percentage of organic carbon determined in the laboratory according to the Wakley and Black method (Schnitzer, 1982).

### 3.5.Data Analysis

The carbon stocks (t C $ha^{-1}$) of woody and non-woody vegetation, deadwoods, litter and herb and soil were calculated for each of the 60 quadrats (24 for PNF and 36 for FWC). The size and variation in the carbon (C) stocks for the two sites were described by the mean and standard error. Independent t-tests were applied to compare the means of C stock of the individual C pools in the two forests to test significant differences in carbon stocks. Total protected natural forest and forest with coffee carbon stocks were also compared. Statistical mean differences were considered significant when $P < 0.05$. All activities were organized by excel 2010 and analyzed using MINITAB software version 17.

#### 3.5.1. Estimation of carbon in different carbon pools

#### i. Estimation of carbon in the above ground biomass (AGB)

The tropical rainforest has a diverse; mixed type of species, for this reason, the generic allometric equation developed by Chave *et al*. (2014) was used for this study since the general criteria described by the author are similar to the study area. The equation also covers a wide range of climatic conditions.

$$AGB = 0.0673 \times (\rho D^2 H)^{0.976} \quad (3)$$

Where: AGB is Above Ground Biomass (kg), $\rho$ is specific wood density (g $cm^{-3}$), D is diameter (cm) at breast height (1.3m) and H is tree height (m).

According to Chave *et al*. (2014) the inclusion of country specific wood density (WD) in the equation significantly improves biomass estimation. Therefore, for this study specific WD which Ethiopia reported for 421 indigenous and exotic tree species available from Ethiopia Forest Reference Level (EFRL) (2016) and WD from the Global Wood Density database (Chave *et al*., 2009) was used. In case multiple values existed for a given species, the average of all entries was used. When only the genus was determined, or when the species was not present at the database, the genus average was used.

Model developed by Putz *et al*. (1983) was used to calculate AGB (Biomass) of liana:

$$AGB = Biomass = \exp(0.12+0.91x\log(BA \text{ at } dbh)) \quad (4)$$

Where: BA is Basal Area, while BA= $\frac{\pi d^2}{4}$ (Yitebitu Moges *et al*., 2010) (5)

AGB for coffee plants was computed by Mesele Negash *et al*. (2013) model as follows:

$$AGB\ coffee = 0.147 * d_{40}^2 \quad (6)$$

Where: $d_{40}$ = Stem diameter (cm) of the coffee plant at 40 cm height

Then, for forest with coffee total above ground biomass was estimated as:

$$TAGB = AGB_{tree} + AGB_{coffee} \quad (7)$$

Where: TAGB is total aboveground biomass

### ii. Estimation of carbon in below ground biomass (BGB)

Belowground biomass was estimated from aboveground biomass on the basis of root to shoot ratio of 27% (0.27) (Mokany *et al*., 2006):

$$BGB = AGB \times CF \tag{8}$$

Where: BGB is Below Ground Biomass and CF is conversion factor of 27% (0.27)

For coffee plants, $BGB_{coffee} = 0.490AGB_{coffee}^{0.92}$ (Mesele Negash *et al.*, 2013) (9)

Then, for forest with coffee, $TBGB = BGB_{tree} + BGB_{coffee}$ (10)

Where: TBGB is total belowground biomass

The value for both AGB and BGB, the biomass stock density in kg was converted to ton by dividing it by 1000. Carbon was 47% of biomass (IPCC, 2006).

### iii. Estimation of carbon in dead wood

This type of carbon pool includes coarse and fine deadwood found in the form of logged, standing and lying deadwood (Takahashi *et al*., 2010). For standing dead wood, which has branches; its carbon stock was estimated in a similar manner using the allometric equation of AGB. However, as the standing dead wood do not have leaves, needs to subtract 5-6 percent for conifer species and 2-3 percent for broadleaved species (Pearson *et al*., 2005). In this study, most of the existing species are broadleaved, and hence 2.5 percent reduction was recommended from the total above ground biomass of each standing dead tree.

$$BSDW_1 = 0.0673 \times (\rho D^2H)^{0.976} - 2.5\% \tag{11}$$

Where: $BSDW_1$ = Biomass of Standing Dead Wood in kg and others as described above.

In addition, to determine the amount of biomass in the standing stump of dead woods, the recommended Allometric equation from REDD (2009) was used:

$$\text{BSDW}_2 = \frac{1}{3} * \pi * \left(\frac{D}{200}\right)^2 * H * S \qquad (12)$$

Where: $BSDW_2$ = Biomass of Standing Dead Wood (kg), $\pi$ is Pi (3.1416), H = Height of Standing Dead Wood (m), D = Diameter of Standing Dead Wood (cm) and S = Mean Wood Density of Dead Wood (g $cm^{-3}$).

Default value of 0.5 g $cm^{-3}$ was used for specific wood density (Hairiah *et al*., 2001).

To estimate the carbon stock of felled dead trees, first the volume of felled dead trees was calculated using the midpoint diameter and height measurements. It is then estimated as the volume of a truncated cylinder of Huber's Formula:

$$V = gm\ L \qquad (13)$$

Where: V = Volume of the Log, gm = Cross-Sectional Area at Log Mid-Point and L = Log Length

Volume was converted to dry biomass using equation available in REDD (2009):

$$\text{BDLDW} = V \times S \qquad (14)$$

Where: BDLDW = Biomass of the Down Lying Dead Wood (kg), V = Volume of the Dead Wood ($m^3$) and S = Mean Wood Density of the Dead Wood (g $cm^{-3}$).

The total biomass of the dead wood was estimated as follow:

$$\text{TBDW} = \text{BSDW}_1 + \text{BSDW}_2 + \text{BDLDW} \qquad (15)$$

Where: TBDW = Total Biomass of Dead Wood in a Given Plot

$BSDW_1$ = Biomass of Standing Dead Wood which have Branches

$BSDW_2$ = Biomass of Standing Dead Wood which haven't Branches

BDLDW = Biomass of Down Lying Dead Wood

Default value of 47% was used to convert the biomass to carbon stocks (IPCC, 2005).

### iv. Estimation of carbon stocks in the litter and herb biomass (LB)

Sun-dry weights of herb and litter subsamples were determined to compute for the total dry weights using the formula (Hairiah *et al.,* 2001):

$$\text{Total dry weight (kg m}^{-2}\text{)} = \frac{Total\ fresh\ weight\ (kg) * subsample\ dry\ weight\ (kg)}{Subsample\ fresh\ weight\ (kg) * Sample\ area\ (m^2)} \quad (16)$$

Carbon storage in herb and litter layer was calculated by Lasco *et al*. (2006) formula:

$$\text{Carbon stored (t Cha}^{-1}\text{)} = \text{Total dry weight*C content} \quad (17)$$

Carbon content is the carbon fraction of IPCC (2006) with a default value of 37% (0.37).

### v. Estimation of soil organic carbon (SOC)

SOC (kg C $ha^{-1}$) was estimated using Equation 18, which relates SOC stock in t C $ha^{-1}$ to soil volume (1 ha * soil depth in m), bulk density (BD), and the fraction of soil organic matter that is composed of carbon, assuming 58% carbon (Nelson and Sommers, 1983). It was assumed a bulk density of 1 kg $m^{-3}$ (Tonucci *et al*., 2011; Rousseau *et al*., 2013).

$$\text{SOC (kg ha}^{-1}\text{)} = \text{BD (kg m}^{-3}\text{)} * \frac{\text{Soil organic matter (\%)}}{1.72} * \text{Soil volume (m}^3\text{ ha}^{-1}\text{)} \quad (18)$$

Where: SOC = Soil Organic Carbon, BD = Bulk Density. In this equation, % must be expressed as a decimal fraction (e.g., 4.3% C is expressed as 0.043 in the equation). SOC (kg/ha) was converted to ton/ha multiplying by 1000. Then, after the weight of the gravel above 2 mm diameter was subtracted, the BD can be calculated as Pearson *et al*. (2007):

$$\text{Bulk density (g cm}^{-3}\text{)} = \frac{ODW}{CV - \frac{RF}{RD}} \quad (19)$$

Where: ODW = Oven dried weight (g), CV= Core volume ($cm^3$)

RF= Mass of coarse fragment and RD= Mass of stone fragment (2.65g $cm^{-3}$).

$$V = h*\pi r^2 \quad (20)$$

Where: V = volume of the soil in the core sampler in $cm^3$, h = height of core sampler in cm, and r = radius of core sampler in cm (Pearson *et al*., 2005). The SOC stock of 0–40 cm was calculated based on summing up the C stock in 0–20 cm and 20–40 cm soil layers.

### vi. Total carbon stock density (TCSD)

The total carbon stock density was calculated by summing the carbon stock densities of the individual carbon pools using Pearson *et al. (*2005) formula.

Carbon stock density for protected natural forest (PNF) land use was:

$$\text{Carbon density} = \text{CAGB} + \text{CBGB} + \text{CDW} + \text{C Lit \& herb} + \text{SOC} \quad (21)$$

Where: CAGB = Carbon in aboveground tree biomass (t C $ha^{-1}$), CBGB = Carbon in below-ground biomass (t C $ha^{-1}$), CDW = Carbon in dead woods (t C $ha^{-1}$), C Lit & herb = Carbon in litter and herb (t C $ha^{-1}$) and SOC = Soil organic carbon (t C $ha^{-1}$).

Carbon stock density for forest with coffee (FWC) land use was:

$$\text{Carbon density} = \text{CAGB} + \text{CBGB} + \text{CDW} + \text{C Lit} + \text{SOC} + \text{TCC} \quad (22)$$

Where, TCC represents Total Coffee Carbon

Finally, to convert C in to $CO_2$ equivalent, the tons of carbon are multiplied by the ratio of the molecular weight of $CO_2$ to the atomic weight of carbon (44/12) (Pearson *et al*., 2005).

$$\text{Carbon dioxide equivalent } (CO_2\text{-e}) = \text{carbon density} * 44/12 \quad (23)$$

Where: 44/12 is conversion factor ($CO_2$: C ratio)

# 4. RESULTS

## 4.1. Stand characteristics and existing forest conditions

The two forests considered under the present study were closely similar in biophysical conditions (adjacent to each other or no gap in between them), but they significantly differed in stand density and basal area. Stand density (stems $ha^{-1}$) and basal area $m^2$ $ha^{-1}$ was 1027 and 68.7 in protected natural forest (PNF) and 2,873 (89% coffee plants) and 32.9 in forest with coffee (FWC) respectively, while inversely the largest value of basal area was 3.6 and 6.29 $m^2$ per tree in PNF and FWC respectively. For the estimation of AGB, a total of 40 different wood plant species belonging to 26 families which have DBH $\geq$ 5 cm were identified from the two land uses (Appendix 1, 2).

Woody plant species of *Pouteria adolfi-friederici* was identified as the most abundant species in PNF. It covers 19% of the trees followed by *Schefflera abyssinica, Syzygium guineense*, *Croton macrostachyus* and *Allophylus abyssinicus,* with relative abundance of 10%, 9%, 7.5% and 7% respectively. *Coffea arabica* was the most abundant in the FWC *(90%)*, followed by *Albizia schimperiana, Millettia ferruginea*, *Croton macrostachyus and P. adolfi-friederici* with relative abundance of 2.3%, 2.2% and 1.6% and 1.1% respectively. Next to *P. adolfi-friederici*, *Vernonia amygdalina* contributes about 1% in FWC. *Dombeya torrida*, *Lepidotrichilia volkensii*, *Galiniera saxifraga*, *Maytenus undata* and Albizia species were the least abundant species with relative coverage of less than 1%, in PNF and *S. abyssinica, Ficus exasperate, Euphorbia abyssinica and Trichilia dregeana* were the least abundant species with relative coverage of less than 1%, in FWC.

A total of 727 woody plants with DBH $\geq$ 5 cm, 352 in PNF and 375 in FWC (207 woody plants other than coffee plant + 168 coffee plants) were measured in both forests for estimating AGB, as per IPCC guide line. The average DBH in all species was 48 cm in PNF and 55 cm in FWC (excluding coffee plants as their diameter was taken at 40cm).

It was observed that there was a strong difference among tree species in their size classes in the two land uses. The DBH values recorded for individual trees ranged from 5.4- 214 cm in PNF and 5.5- 283 cm in FWC with the largest average values of 105 and 113 cm recorded for *S. abyssinica* and *P. adolfi-friederici* tree species and lowest values of 6.8 and 10 cm recorded for *M. addat* and *V. amygdalina* tree species in PNF and FWC respectively. Overall, DBH classes of the two sites were shown on figure 3.

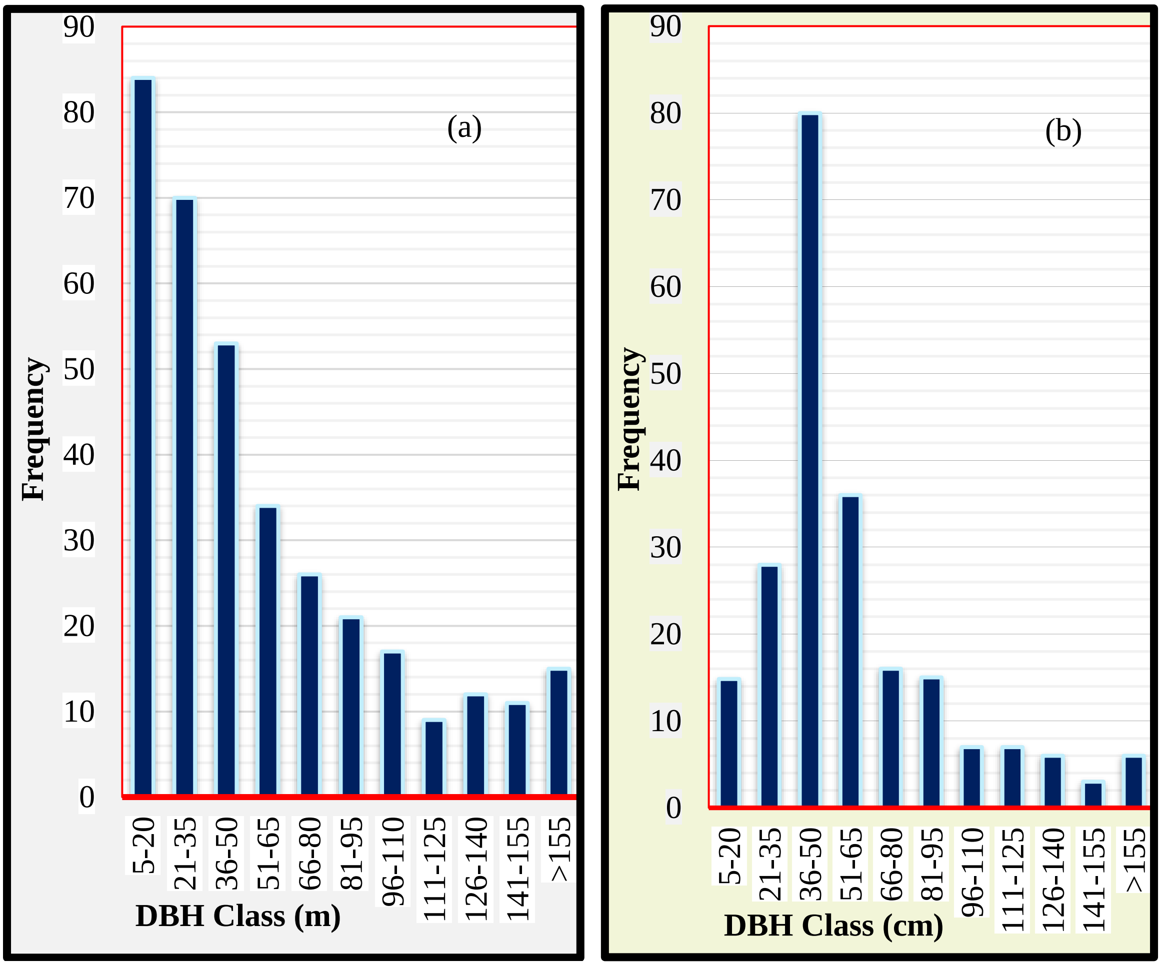



Figure 3: Diameter classes of woody plant species. Letter (a) represents protected natural forest and the graph shows inverted J-shape, which implies good forest structure (healthy forest), (b) represents forest with coffee and the graph shows bell shaped structure, which implies unhealthy forest (there was disturbance on trees with smaller and larger diameter).

The mean, minimum and maximum tree heights were 23 m, 3 m and 48 m in PNF and 24m, 6m and 50 m in FWC (excluding coffee plants) respectively. The maximum heights were exhibited by *P. adolfi-friederici* in both land uses, while the minimum heights were exhibited by *M. addat* and *V. amygdalina* in PNF and FWC respectively. The average maximum and minimum heights were also recorded for these species with the maximum values of 33 and 38 m and minimum values of 4 and 9 m in PNF and FWC respectively.

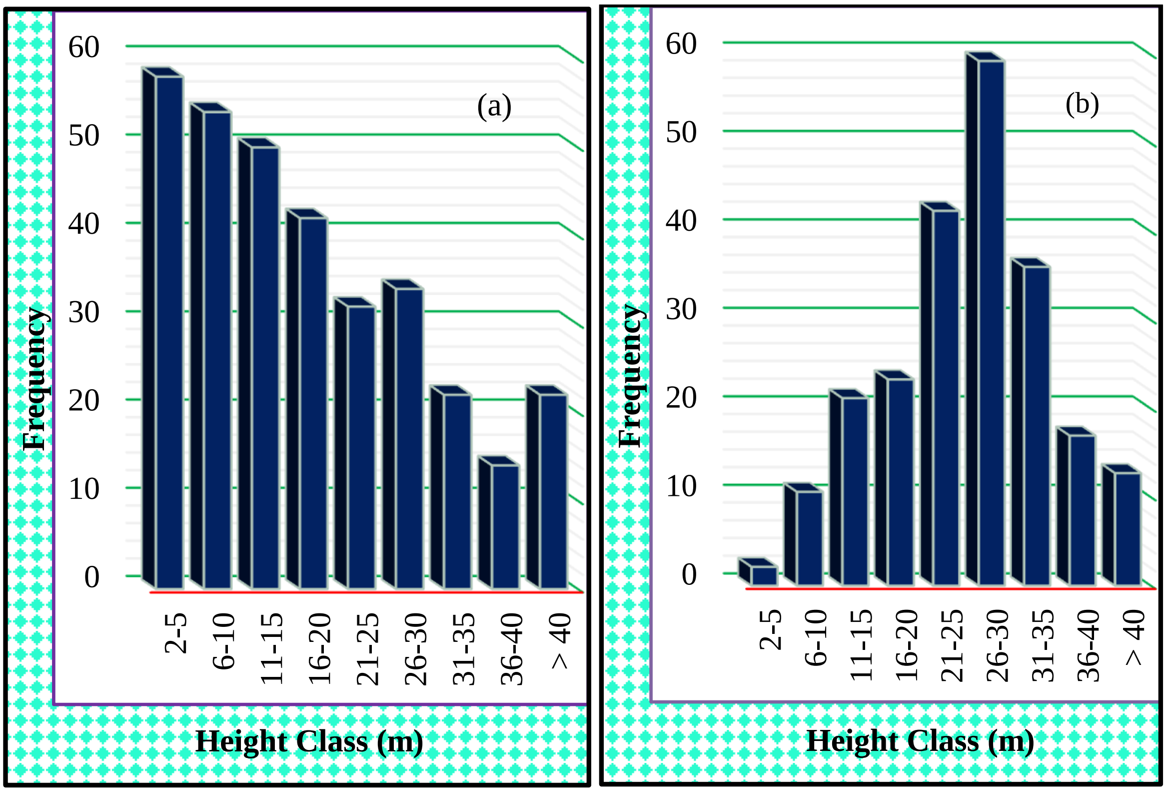



Figure 4: Height classes of woody plant species. Letter (a) represents protected natural forest and (b) represents forest with coffee and their indications are more or less similar to that of DBH class (figure 3).

## 4.2.Carbon stock estimation of various carbon pools

### 4.2.1. Aboveground live biomass carbon stock

This study indicates that, the largest carbon stock was covered by above ground live biomass with average of 59.5 % in protected natural forest (PNF) and 55% in forest with coffee (FWC) with comparison to the others pools. The mean AGB was 790.16 and 410.48 tons $ha^{-1}$ in PNF and FWC respectively. Accordingly, the AGC stock was ranged from

172.26 - 626.44 t C/plot ha$^{-1}$ and 21.43 - 592.45 t C/plot ha$^{-1}$ in FWC respectively, with the mean value of 371.4 $\pm$ 54.6 and 192.92 $\pm$ 49.4 t C ha$^{-1}$ in PNF and FWC respectively (Table 1). This is equivalent to a carbon loss of 48% and the difference was statistically significant (P= 0.025). Coffee plants were contributed 2% in the AGC of FWC. Carbon stock for liana was 0.002 t C ha$^{-1}$ and it is omitted since its contribution was insignificant.

In both land uses the highest above ground live biomass carbon stocks per tree species were recorded from *P. adolfi-friederici* (29% and 49% in PNF and FWC respectively) followed by *S. abyssinica (*24%) *and S. guineense (*15%) with their values of 108.78, 89.19 and 56.69 tons of carbon/species ha$^{-1}$ in PNF and *A. schimperiana* (15%) and *E. capensis* (11%) with values 96.35, 29.51 and 20.82 tons of carbon/species ha$^{-1}$ in FWC. Combined, the above three species contributed 68% and 75% of the AGC in PNF and FWC respectively, while the minimum was recorded from *L. volkensii* and *E. abyssinica* with 0.003 and 0.023 tons of carbon/species ha$^{-1}$ in PNF and FWC respectively.

Table 1: Above ground carbon stock (t C ha$^{-1}$) in the protected natural forest Vs forest with coffee in Anfilo District, western Ethiopia

Min = Minimum, Max = Maximum, SD = Standard deviation, SE = Standard error

| **Forest types** | **Min** | **Max** | **Mean** | **SE** | **P-Value** |
|---|---|---|---|---|---|
| Protected natural forest | 172.26 | 626.44 | 371.4 | 54.6 | |
| Forest with coffee | 21.43 | 592.45 | 192.92 | 49.4 | 0.025 |
| Difference | | | 178.48 | | |

#### 4.2.2. Below ground live biomass carbon stock

Since it is a function of the AGB, BGB was also showed similar trend in terms of the mean, plots and species recorded the maximum and minimum values. The BGC of the present study were ranged from 46.5 - 169.14 t C ha$^{-1}$ in PNF and 5.97 - 159.96 t C ha$^{-1}$ in

FWC, with the higher mean value of 100.3 ± 14.7 t C ha$^{-1}$ in PNF than the value recorded in FWC (53.09 ± 13.1 t C ha$^{-1}$) and the difference was significant (P= 0.029) (Table 2).

The highest below ground live biomass carbon stock per tree species was recorded from *P. adolfi-friederici* (29%) followed by *S. guineense (*24%) *and S. abyssinica (*15%) with their values of 29.37, 24 and 15.3 tons of carbon/species ha$^{-1}$ in PNF and *P. adolfi-friederici* (49%), *A. schimperiana* (15%) and *E. capensis* (11%) with values 26, 7.97 and 5.6 tons of carbon/species ha$^{-1}$ in FWC. As in AGB live carbon, combined, these three species contributed 68% and 75% of the AGC in PNF and FWC respectively, while the minimum was recorded from *L. volkensii* and *E. abyssinica* with values 0.00081 and 0.00621 tons of carbon/species ha$^{-1}$ in PNF and FWC respectively.

Table 2: Below ground carbon stock (t C ha$^{-1}$) in the protected natural forest Vs forest with coffee in Anfilo District, western Ethiopia

| **Forest types** | **Min** | **Max** | **Mean** | **SE** | **P-Value** |
|---|---|---|---|---|---|
| Protected natural forest | 46.5 | 169.14 | 100.3 | 14.7 | |
| Forest with coffee | 5.97 | 159.96 | 53.09 | 13.1 | 0.029 |
| Difference | | | 47.21 | | |

### 4.2.3. Carbon stock in dead wood (DWC)

For the present study, the result estimated for this pool was the sum of standing and felled dead wood. The carbon value estimated for logged dead wood was omitted in both forests as the contribution was insignificant, 0.0005 and 0.0003 t C ha$^{-1}$ in PNF and FWC respectively. The DWC recorded was ranged from 0.002 to 49.3 t C ha$^{-1}$ in PNF and 0.005 to 53.65 t C ha$^{-1}$ in FWC, with the mean value of 9.2 ± 2.02 and 10.8 ± 2.15 t C ha$^{-1}$ in PNF and FWC respectively (Table 3) and showed insignificant variation (P= 0.635). The maximum value was recorded for plot 10 and 21 in PNF and FWC respectively. These plots had the largest C stock $ha^{-1}$ because of large DBH size standing dead wood trees in PNF and felled dead wood (by human being) in FWC land use.

Table 3: Dead wood carbon (DWC) stocks (t C $ha^{-1}$) in the protected natural forest Vs forest with coffee in Anfilo District, western Ethiopia

| Forest types | Min | Max | Mean | SE | P-Value |
|---|---|---|---|---|---|
| Protected natural forest | 0.002 | 49.3 | 9.2 | 2.02 | |
| Forest with coffee | 0.005 | 53.65 | 10.8 | 2.15 | 0.635 |
| Difference | | | 1.6 | | |

### 4.2.4. Carbon stock in litter and herbs

The carbon stock in litter and herbs was ranged from 0.92 to 13.47 t C $ha^{-1}$ in PNF and 0.98 to 14.94 t C $ha^{-1}$ in FWC, with the mean value of 6.35 $\pm$ 0.846 (2.53 + 3.82 t C $ha^{-1}$, litter and herb carbon respectively) and 2.8 $\pm$ 0.506 t C $ha^{-1}$ respectively. This is equivalent to 56% of C loss. Such difference was due to the unavailability of herbaceous vegetation in FWC. This indicates that there was significant difference (P= 0.004) between litter and herbs C stock estimation of the protected natural forest and forest with coffee (Table 4).

Table 4: Litter and herb carbon stocks (t C $ha^{-1}$) in the protected natural forest Vs forest with coffee in Anfilo District, western Ethiopia

| Forest types | Min | Max | Mean | SE | P-Value |
|---|---|---|---|---|---|
| Protected natural forest | 0.92 | 13.47 | 6.35 | 0.846 | |
| Forest with coffee | 0.98 | 14.94 | 2.8 | 0.506 | 0.004 |
| Difference | | | 3.55 | | |

### 4.2.5. Total biomass carbon stock (TBCS)

The biomass carbon stock includes above and below ground live biomass, litter and herb and dead woods carbon stocks. The mean biomass carbon stock for protected natural forest and forest with coffee were 487.25 $\pm$ 39.5 and 259.61 $\pm$ 63.5 t C $ha^{-1}$ respectively and the variation was statistically significant (P= 0.012) (Table 5).

Table 5: Total biomass carbon stocks (t C $ha^{-1}$) in the protected natural forest Vs forest with coffee in Anfilo District, western Ethiopia

| **Forest types** | **Min** | **Max** | **mean** | **SE** | **P-Value** |
|---|---|---|---|---|---|
| Protected natural forest | 218.76 | 813.18 | 487.25 | 39.5 | |
| Forest with coffee | 31.23 | 762.15 | 259.61 | 63.5 | 0.012 |
| Difference | | | 227.64 | | |

### 4.2.6. Soil organic carbon (SOC)

Laboratory analysis of soil for soil organic carbon of the present study was made for the two soil layer (0-20 and 20-40 cm). The analysis showed that, the mean soil organic carbon percentage of the study forests was ranged from 2.65% to 13.1% in PNF and 0.94 to 6.55% in FWC, with the mean value of 6.82% and 3.34% in PNF and FWC respectively for the full soil depth. The average SOC percentage for the soil depth of 0-20 cm and 20-40 cm was 9.1 and 4.54% in PNF, whereas 4.3 and 2.38% in FWC respectively.

The soil bulk density ranged from 0.22 g $cm^{-3}$ to 0.75 g $cm^{-3}$ in PNF and 0.29 g $cm^{-3}$ to 0.97 g $cm^{-3}$ in FWC, while the average soil bulk density for the full depth was 0.525 g $cm^{-3}$ in PNF and 0.7 g $cm^{-3}$ in FWC, indicating the presence of high SOM in mineral soil. The average bulk density for the soil depth of 0-20 cm and 20-40 cm was 0.51 g $cm^{-3}$ and 0.54 g $cm^{-3}$ in PNF, while 0.65 g $cm^{-3}$ and 0.75 g $cm^{-3}$ in FWC respectively. The total soil carbon density was ranged from 67.75 - 177.8 t C $ha^{-1}$ in PNF and 48.2 - 148.35 t C $ha^{-1}$ in FWC, with the average value of 136.2 $\pm$ 8.42 t C $ha^{-1}$ and 90.76 $\pm$ 4.97 t C $ha^{-1}$ in PNF and FWC respectively (Table 8). 67.5% and 61 % of the total soil carbon were held within 0-20cm soil layer, with the value of 91.9 $\pm$ 8.27 and 55 $\pm$ 7.62 t C $ha^{-1}$ in PNF and FWC respectively (Table 6), while 32.5 and 38.2%, with value of 44.3 $\pm$ 6.51 and 35.6 $\pm$ 6.53 t C $ha^{-1}$ are held within 20-40 cm soil layer in PNF and FWC respectively (Table 7).

Statistical analysis showed that there was significant difference between the SOC within the full depth (0-40 cm) and soil depth 0-20 cm in PNF and FWC (P= 0.002 and 0.01 respectively), while it showed insignificant variation for 20-40 cm soil layer (P= 0.249). Overall, the result indicated that SOC in the PNF was higher than SOC in the FWC.

Table 6: SOC (0-20 cm depth) (t C $ha^{-1}$) of protected natural forest Vs forest with coffee in Anfilo District, western Ethiopia

| **Forest types** | **Min** | **Max** | **Mean** | **SE** | **P-Value** |
|---|---|---|---|---|---|
| Protected natural forest | 39.2 | 130.9 | 91.9 | 8.27 | |
| Forest with coffee | 26.4 | 97.3 | 55 | 7.62 | 0.006 |
| Difference | | | 36.9 | | |

Table 7: SOC (20-40 cm depth) (t C $ha^{-1}$) of protected natural forest Vs forest with coffee in Anfilo District, western Ethiopia

| **Forest types** | **Min** | **Max** | **mean** | **SE** | **P-Value** |
|---|---|---|---|---|---|
| Protected natural forest | 28.5 | 83 | 44.3 | 6.51 | |
| Forest with coffee | 18 | 77.68 | 35.6 | 6.53 | 0.249 |
| Difference | | | 8.7 | | |

Table 8: SOC (0-40 cm depth) (t C $ha^{-1}$) of protected natural forest Vs forest with coffee in Anfilo District, Western Ethiopia

| **Forest types** | **Min** | **Max** | **Mean** | **SE** | **P-Value** |
|---|---|---|---|---|---|
| Protected natural forest | 67.75 | 177.8 | 136.2 | 8.42 | |
| Forest with coffee | 64.3 | 197.8 | 90.76 | 4.97 | 0.001 |
| Difference | | | 45.44 | | |

#### 4.2.7. Total Carbon Stock

Total carbon stock of protected natural forest was the sum of AGC, BGC, litter and herb, DWC, and SOC and that of forest with coffee was the sum of AGC, BGC, litter, DWC, and SOC. Combining the five carbon pools assessed, the average aggregate carbon stock density (t C $ha^{-1}$ $\pm$ SE) in protected natural forest was high (623.45 $\pm$ 39.5 t C $ha^{-1}$) compared to that of forest with coffee (350.44 $\pm$ 63.5 t C $ha^{-1}$) (Table 9, Figure 5). This is equivalent to 2,285.98 $\pm$ 144.8 and 1,284.95 $\pm$ 232.8 t $CO_2$ $ha^{-1}$ in PNF and FWC respectively. The result indicated that there is a carbon stock loss of 43.8% due to conversion of natural forest to coffee forest and the difference was significant (P= 0.004).

Table 9: Total carbon stocks (t C $ha^{-1}$) in the protected natural forest Vs forest with coffee in Anfilo District, western Ethiopia

| **Forest types** | **Min** | **Max** | **Mean** | **SE** | **P-Value** |
|---|---|---|---|---|---|
| Protected natural forest | 377.27 | 948.74 | 623.45 | 39.5 | |
| Forest with coffee | 97.15 | 832.7 | 350.44 | 63.5 | 0.004 |
| Difference | | | 273.01 | | |

## Contribution of carbon pools in the study forests

Total Carbon stock in protected natural forest was 59.5% in above ground, 16% in below ground, 1% in litter and herbs, 1.5% in dead wood and 22% in the soil. Similarly, total carbon stock in forest with coffee was found 55% in above ground, 15% in below ground, 1% in litter, 3% in dead wood and 26% in soil (Table 10).

Table 10: Summary of carbon stocks under different carbon pools (with their contribution) of protected natural forest Vs forest with coffee in Anfilo District, Western Ethiopia

| | **Protected natural forest** | | **Forest with coffee** | |
|---|---|---|---|---|
| **Carbon pools** | **t C ha$^{-1}$** | **%** | **t C ha$^{-1}$** | **%** |
| Aboveground carbon | 371.4 ± 54.6 | 59.5 | 192.92 + 49.4 | 55 |
| Belowground carbon | 100.3 ± 14.7 | 16 | 53.09 ± 13.1 | 15.4 |
| Litter & herb carbon | 6.35 ± 0.846 | 1 | 2.8 ± 0.506 | 0.8 |
| Dead wood carbon | 9.2 ± 2.02 | 1.5 | 10.8 ± 2.15 | 3 |
| Soil organic carbon | 136.2 ± 8.42 | 22 | 90.76 ± 4.97 | 25.8 |
| Total carbon density | 623.45 ± 39.5 | 100 | 350.37 ± 63.5 | 100 |

AGC= Aboveground carbon, BGC= Belowground carbon, LC = Litter & herb carbon, DWOC= Dead wood organic carbon, T carbon= Total carbon

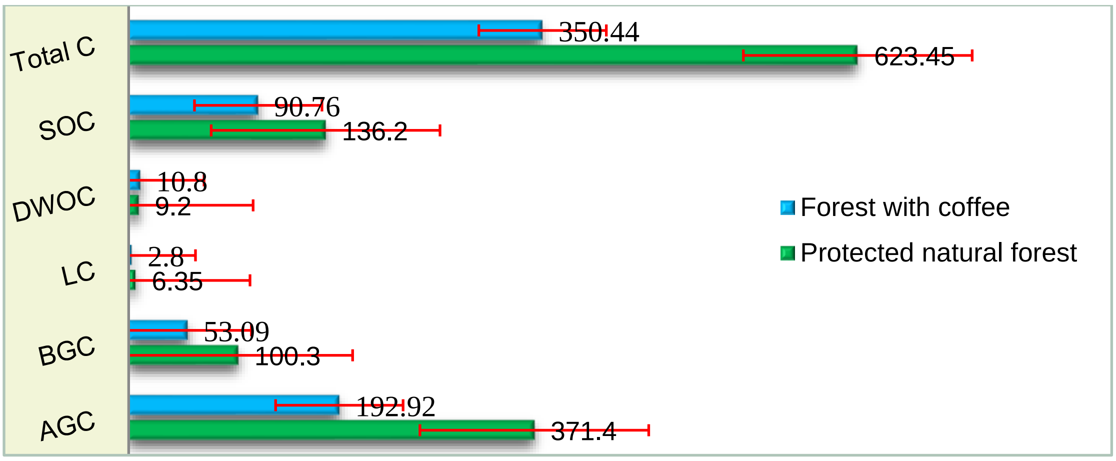



Figure 5: Summary of carbon stocks in different carbon pools across protected natural forest and forest with coffee in Anfilo district, western Ethiopia

# 5. DISCUSSIONS

## 5.1.Biomass carbon stocks

The present study was conducted for 3,940 ha (1,576 ha, for protected natural forest (PNF) and 2,364 ha, for forest with coffee (FWC)) to evaluate the variation of carbon (C) stocks in different carbon pools (biomass carbon pools (AGC, BGC, litter and herb, and dead woods carbon pools) and soil carbon pool) across the two forests. Carbon stock variability found in this study has important implications for Anfilo district natural forest carbon monitoring and emissions estimates for REDD+ and helpful for providing relevant information and understanding the changes of carbon stocks due to conversion of natural forest to coffee-based forest of a representative tropical moist Afromontane forests. This carbon stock change study was done taking in to consideration the two forests are under similar biophysical conditions and the difference was only on their management level.

In this study, more woody plant diversity, low tree density $ha^{-1}$ and higher total basal area $ha^{-1}$ were recorded at protected natural forest (forest without coffee). On the other hand, low woody plant diversity, high tree density (including about 90% coffee plants) $ha^{-1}$ and lower total basal area $ha^{-1}$ were recorded at forest with coffee land use. This may be related to more anthropogenic disturbance at forest with coffee. In the coffee management systems, farmers purposefully select certain species of trees as coffee shade trees and remove others which they believe have adverse impacts on the growth and productivity of the coffee shrub. Coffee yield was highly correlated with the number and size of the branches of coffee shade trees (Adugna Feyissa *et al.,* 2012).

Species which accumulated the highest carbon stock were species those exhibiting higher basal area and height in the study forests. Bigger trees have a significant role on the variability in carbon stocks (Slik *et al*., 2013). Thus, the plant species represented by individuals with larger diameter and height have a significant contribution to the carbon storage in this forest and their removal significantly alters the biomass dynamics of the forests. This is also supported by Gibbs *et al*. (2007) who reported bigger trees with higher diameter store the largest density of carbon within biomass.

The results of the current finding indicated that, all carbon pools assessed except dead woods contributed differently to the two land uses. In both sites, the highest carbon density was stored by AGC pool, 59.5% and 55% in PNF and FWC respectively. This was in accordance with the investigation of Pan *et al*. (2011) which reported that larger amount of carbon is stored in AGB (56%) compared to the soil (32%). The AGC pool was the most sensitive to human disturbances with disturbed primary forests containing between 18% and 57% less carbon than undisturbed ones (Berenguer *et al*., 2014).

The values of above and belowground carbon stock of this study was higher in the PNF (371.4 $\pm$ 54.6 t C ha$^{-1}$, 100.3 $\pm$ 14.7 t C ha$^{-1}$) than the FWC (192.92 $\pm$ 49.4 t C ha$^{-1}$, 53.09 $\pm$ 13.1 t C ha$^{-1}$). These values were found within the range recommended for various tropical moist forests (95-527.85 t C ha$^{-1}$) (Murphy and Lugo, 1986). AGC stock investigated for the present study (PNF) was also showed more or less similarity with Omoro *et al*. (2013) who reported plot-level mean AGC density for montane forests as 360 Mg C ha$^{-1}$, while lower than the value reported for Arba Minch riverine forest and larger than that of Gendo, Gerba-Dima and Tara Gedam forests (Table 11). The AGC value from forest with coffee is higher by 39.9 t C ha$^{-1}$ than the value reported by Getachew Tadesse *et al*. (2014) for small holder coffee farms (153 $\pm$ 59 t C ha$^{-1}$). This difference might be due to the variations from stand structure and composition, methods and tools used for tree measurement, allometric model used, disturbance level, species type and other ecological factors.

The higher average carbon (C) stocks in AGC and BGC in the protected natural forest (PNF) could be related to the higher diameter, tree height and basal area in the forest. Tree species with larger diameter and height like *P. adolfi-friederici, S. abyssinica, S. guineense and A. abyssinicus* were dominated the site, where as in forest with coffee, they highly removed and replaced with smaller diameter and height trees (coffee). In consistent to this, Feyera Senbeta and Danich (2006) and Kitessa Hundera *et al*. (2013) reported that semi-forest coffee management alters forest structure.

Surprisingly, the mean dead wood carbon (DWC) between the two forests were showed insignificant difference (9.2 $\pm$ 2.02 in PNF and 10.8 $\pm$ 2.15 t C $ha^{-1}$ in FWC) (P= 0.635). Logically, disturbed forest has more dead woods than intact forest. However, for this study site (forest with coffee) most of the felled dead woods were collected by local dwellers for fire wood which made the land use stores nearly the same magnitude of carbon with PNF. These values are larger than Gerba-Dima forest and lower than Gesha and Sayilem forest (Table 11). This difference might be related to the variations from disturbance and management intensities, climatic condition, vegetation characteristics and topography.

Mean litter and herb C in the PNF (6.35 $\pm$ 0.846 t C $ha^{-1}$ (2.53 litter + 3.82 herb)) was higher than in FWC, 2.8 $\pm$ 0.506 t C $ha^{-1}$. Even if, the variation was insignificant ($P>0.05$), litter C for FWC was higher than that of PNF (excluding herb). This condition suggested that at the FWC, the distribution and the number of trees other than coffee plant reduced, and hence relatively abundant litter fall could be available and this situation may be the cause for having exceeded litter C than forest without coffee. Compared to other studies, the litter C from the two land uses (PNF and FWC) were found within the interval value reported for the tropical and sub-tropical forest (1.4 - 4.8 t C $ha^{-1}$) (Chang *et al*., 2010) and different from other studies indicated in (Table 11) except Egdu and Gendo forest which is more or less similar. This difference might be the variations from different vegetation (species) types, different management practices and other ecological factors.

Overall, including herb C higher value was recorded for PNF than FWC. This difference could be resulted from the absence of herbaceous and undergrowth vegetation in the forest with coffee since they removed due to coffee management. This is in agreement with Aboma Bulcha (2016) who stated that the coffee management activity involves complete removal of the competing undergrowth, including the seedlings and saplings of the canopy trees on annual basis, in an effort to increase coffee productivity.

### 5.2.Soil carbon stocks

The soil C pool is known to undergo significant change after tropical forest conversion into other land uses (Cerri *et al*., 2003), but little is known about its response to disturbances in standing forests. The results from this study revealed that the first 20cm of the soil pool had the largest C stock and showed significant variation between the two forests (91.9 $\pm$ 8.27 in PNF and 55 $\pm$ 7.62 t C $ha^{-1}$ in FWC, P= 0.006), while the second 40cm of the soil pool contain a comparable value between the two forests (44.3 $\pm$ 6.51 in PNF and 35.6 $\pm$ 6.53 t C $ha^{-1}$ in FWC, P= 0.249). This was supported by several literatures elsewhere in the world (Don *et al*., 2010; Biyensa Gurmessa *et al*., 2016; Mathew *et al*., 2016) who reported the decreasing of SOC with increasing soil depth for all land uses (especially conversion from forest to others) because of the decrease in the effects of aboveground biomass accumulation and subsequent decomposition processes. The loss of SOC from the surface layer (0-20cm) following conversion from natural forest to coffee forest was also confirmed by Birhanu Biazin *et al*. (2018) who found that 77.79 and 53.59 Mg $ha^{-1}$ for natural forest and coffee agroforestry respectively and Negasi Solomon *et al*. (2018) finding that investigated higher SOC in dense forest than open forest.

Overall, the maximum soil C value recorded at PNF (136.2 $\pm$ 8.42 t C $ha^{-1}$) than FWC (90.76 $\pm$ 4.97 t C $ha^{-1}$) could be attributed to the presence of organic horizon that encompasses humus layers in the upper soil depths of the PNF than FWC. Moreover, PNF is not affected by human interventions interms of removing and slashing under growth vegetation and selective removal of large trees which were common in FWC due to coffee management.  Even local farmers, who collect the wood remains in the forest for fire wood, don't touch it so the dry leaves decompose and be changed into minerals.

On the other hand, other related studies were reported the increment of soil C stocks in the ecosystem as the AGB increases (Negasi Solomon *et al*., 2002; Mulugeta Lemenih and Itanna Fisseha, 2004; Mulugeta Lemenih *et al*., 2005). It was also reported that, more biomass production increased the aboveground litter and the belowground root activity and these make trees are an important factor for SOC (Bekele Lemma *et al*., 2007). Therefore, trees having more above and belowground biomass contribute more to the soil C sequestration. On the other hand, soil C is highly influenced by soil chemistry and physical soil characteristics through disturbances (Nave *et al*., 2010; Powers *et al*., 2011). Sagar *et al*. (2008) also argued that disturbances control the soil quality mainly due to the biomass removal that is limiting the amount of organic matter inputs into the soil. Evidently, the degree of soil fertility was reflected in the aboveground carbon density.

In addition, this could be related to soil bulk density as it was lower in the PNF than FWC which indicates the presence of high SOM content in PNF (Brady, 1974). In line to this, Hajabbasi *et al*. (1997) also reported higher SOM content improves soil texture and this resulted in a decreasing of BD in natural forests. And it is possible to suggest that erosion could perhaps be the case, a major factor affecting SOC stocks through altering soil microbial dynamics that is directly related to land use change and forest disturbance.

When the present study was compared to other studies, it was nearly similar with that of Luke (2018) for the average SOC in Ethiopia (94 to 133 t C ha$^{-1}$). Similarly, the C value recorded for FWC was similar with Vanderhaegen *et al*. (2015) for semi-forest coffee (89 t C ha$^{-1}$) and Mihert Semere (2019) for home garden agroforestry (94.2 $\pm$ 15 t C ha$^{-1}$). It was also showed similarity with Gendo and Arba Minch riverine forest and that of PNF is similar with Gesha and Sayilem forest, while it is varied from Egdu, Tara Gedam, Gera and Gerba-Dima forest (Table 11). This difference could be due to the variation from depth to which C is accounted, soil type, different management practices and climate.

**5.3.Ecosystem carbon stocks**

Ecosystem carbon (C) stock is the aggregated average C stocks of all C pools considered in the present study (623.45 $\pm$ 39.5 in PNF and 350.44 $\pm$ 63.5 t C ha$^{-1}$ in FWC). The percentage of contributions of the different C pools in this study was nearly similar to that of Birhanu Iticha (2017) who reported 63.45, 15.23, 0.99, 0.55 and 19.79% of C was stored in the aboveground, belowground, litter, dead tree and SOC pool and Ghimire *et al*. (2019) who reported 66, 13 and 21% for the first two and fifth C pools respectively. Compared to other studies, the result obtained from PNF was almost proportional with a little bit variation to Egdu, Arba Minch riverine forest and Gendo forest, while it showed dissimilarity with the findings for Gerba-Dima and Gesha and Sayilem forests (Table 11).

The discrepancies in total carbon stock among the different studies might be ascribed to stand structure and composition, topography, altitude and micro climate variation. Besides, variations in tree dendrological parameters measured, allometric equations applied, carbon fraction used and root-shoot ratio used to estimate BGB, the uncertainties associated with the different methods and tools applied and other complex ecological factors may also have resulted in the discrepancy of estimation of carbon stock. According to Brown (2002) and Yitebitu Moges *et al*. (2010), different types of models used for biomass estimation resulted different outputs of carbon estimated depending on input variables, vegetation type and geographical location from which the model was originally developed.

Table 11: Comparison of the present study (t $Cha^{-1}$) with other studies in Ethiopia

| Study area | AGC | BGC | LC | DWC | SOC | Total C | Author |
|---|---|---|---|---|---|---|---|
| Egdu forest | 278.08 | 55.62 | 3.47 | - | 277.6 | 614.72 | Adugna Feyissa *et al*. (2013) |
| Arba minch riverine forest | 414.7 | 83.48 | 1.28 | - | 83.8 | 583.26 | Belay Melese *et al*. (2013) |
| Tara Gedam forest | 306.37 | 61.52 | 0.9 | - | 274.3 | 643.11 | Mohammed Gedefaw *et al*. (2014) |
| Gera forest | 108.86 | 21.77 | 7.28 | - | 172.6 | 310.52 | Nesru Hassen (2015) |
| Gendo forest | 128.6 | 26.52 | 3.12 | - | 94.96 | 564.98 | Worku Nigussie (2016) |
| Gerba-Dima forest | 243.85 | 45.97 | 0.153 | 4.64 | 162.6 | 457.22 | Abiyot Dibaba (2019) |
| Gesha and Sayilem | 174.95 | 34.3 | 1.95 | 23.2 | 128 | 362.4 | Admassu Addi *et al*. (2019) |
| Anfilo district PNF | 371.4 | 100.3 | 6.35 | 9.2 | 136.2 | 623.45 | Present study (2020) |
| Anfilo district FWC | 192.92 | 53.09 | 2.8 | 10.8 | 90.76 | 350.44 | Present study (2020) |

The present study identified that conversion of natural forest to coffee-based forest can reduce 43.5% of C which is equivalent to the emission of 1001 t $CO_2$ $ha^{-1}$ to the atmosphere. This supports the previous studies that found C stock of the logged forest was 42.3% lower than intact natural forests (Logo *et al*., 2016) (study made at Brazilian Amazon), Getachew Tadesse *et al*. (2014) and vanderhaegen *et al*. (2015) who reported compared to nearby natural forests, semi-forest coffee systems store 50–62% and 48–65% of carbon storage respectively.

Additionally, Getachew Tadesse *et al*. (2014) also reported that small holder coffee farms store AGC of 37.8% lower than natural forests (153 $\pm$ 59 and 246 $\pm$ 7 t C $ha^{-1}$ respectively). On the other hand, Meine van Noordwijk *et al*. (2002) reported that remnant forest stored total C of 69.7% higher than shaded coffee system. Similarly, Kenya Forest Research Institute evidenced this as the degraded forest stands were found to sequester less carbon (by 9–70%) compared to undisturbed ones (Chemuku Wekesa *et al*., 2016).

# 6. CONCLUSIONS AND RECOMMENDATIONS

## 6.1.Conclusion

This study shows the result of carbon stock changes in different carbon pools, above ground, below ground, litter and herb, dead woods and soil organic carbon as a result of conversion from natural forest to coffee-based forest. Protected natural forest and forest with coffee showed large and persistent variations in carbon density.

The results from the present study mirrored that there was high variability in all carbon pools assessed except dead wood and carbon stock within 20-40 cm soil layer (which statistically showed insignificant variations) between the two land uses with higher carbon stocks observed in protected natural forest (forest without coffee) than forest with coffee. It was also observed that as the soil depth increases the soil bulk density increased while SOC decreased and the variation was statistically insignificant between the two land uses as it was also reported before by many researchers. The persistence of lower carbon stocks in forest with coffee may be linked to changes in forest structure and composition resulted from selective tree removals for coffee management and intensification that influences the carbon stock potential of the forest.

Overall, patterns that emerged from this work suggest that conversion of natural forest to coffee-based forest had great impact not only on forest biomass carbon stocks, but also on the soil carbon stocks. Therefore, compared to its adjacent protected natural forest, the role of forest with coffee found in Anfilo district in mitigating climate change is low since it has been contributing for the emission of about 1001 t $CO_2$ $ha^{-1}$ to the atmosphere.

## 6.2.Recommendations

Anfilo district natural forest is one of the remnant forests in western Ethiopia. Even though it has a huge potential to mitigate $CO_2$ concentration in the atmosphere besides of its direct economical use for the livelihood of the local people, it faces a number of challenges from the local people. It is obvious that any sort of forest degradation caused by anthropogenic factors affects the carbon accumulation of that forest. There were a number of observations understood during data collection in the field. For instance, linked to coffee management and intensification in natural forest, selective cutting and debarking of broad leaved large trees for opening canopy to create favorable conditions to enhance coffee production and illegal logging for fire wood collection and timber extraction have been taken place.

Therefore, in order to minimize the impact better management option must be established by considering the principles of REDD+ activities.

To reduce the risk of conversion of new intact natural forest to coffee-based forest by local farmers, it is suggested to develop a mechanism by which farmers could be compensated for yield losses or for failures in the market price of coffee.

Coffee is one means and source of livelihood of the Woreda community. Therefore, planting of new garden coffee on land previously without trees (unproductive croplands and grasslands) should be preferable as mitigation against carbon emissions, whilst it also improve the farmer’s livelihood.

The present study considered only two types of forests (forest with coffee and forest without coffee) from the whole Anfilo district forest types. It is known that there are a bamboo forest, plantation forest and agroforestry system which were excluded in the present study due to logistic problems. Therefore, to have more compressive information, future research works should consider these vegetation types.

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## APPENDICES

**Appendix 1**, Table 1. List of woody plant species recorded from protected natural forest, with their family and local name in Anfilo district, western Ethiopia

| No | Scientific Name | Family | Local Name (Oromiffa) |
|---|---|---|---|
| 1 | *Albizia gummifera* | Fabaceae | Muka-arba |
| 2 | *Albizia schimperiana* | Fabaceae | Shawo |
| 3 | *Allophylus abyssinicus* | Sapindaceae | Kakaye |
| 4 | *Apodytes dimidiata* | Icacinaceae | Wondebiyo |
| 5 | *Bersama abyssinica* | Melianthaceae | Lolchisa |
| 6 | *Brucea antidysenterica* | Simaroubaceae | Qomegno |
| 7 | *Cassipourea malosana* | Rhizophoraceae | Kullo |
| 8 | *Celtis africana* | Ulmaceae | chehi |
| 9 | *Cordia africana* | Boraginaceae | Wadesa |
| 10 | *Croton macrostachyus* | Euphorbiaceae | Bekenisa |
| 11 | *Dombeya torrida* | Sterculiaceae | Danisa |
| 12 | *Dracaena afromontana* | Dracaenaceae | Wechwacho |
| 13 | *Ekebergia capensis* | Meliaceae | Sombo |
| 14 | *Ehretia cymosa* | Boraginaceae | Ulaga |
| 15 | *Ficus sur* | Moraceae | Arbu |
| 16 | *Galiniera saxifraga* | Rubiaceae | Mito |
| 17 | *Lepidotrichilia volkensii* | Miliaceae | Merqeqo |
| 18 | *Maesa lanceolata* | Myrsinaceae | Abeyi |
| 19 | *Maytenus addat* | Celastraceae | Kombolcha |
| 20 | *Maytenus undata* | Celastraceae | Ilke |
| 21 | *Olea capensis* | Oleaceae | Gegema |
| 22 | *Olinia rochetiana* | Oliniaceae | Sole |
| 23 | *Olea welwitschi* | Oleaceae | Baha |
| 24 | *Polyscias fulva* | Araliaceae | Handallo |
| 25 | *Pouteria adolfi-friederici* | Sapotaceae | Kerero |
| 26 | *Prunus africana* | Rosaceae | Homi |
| 27 | *Rhus glutinosa* | Anacardiaceae | Tatesa |
| 28 | *Sapium ellipticum* | Euphorbiaceae | Bosoka |
| 29 | *Schefflera abyssinica* | Araliaceae | Getema |
| 30 | *Syzygium guineense* | Myrtaceae | Bedessa |
| 31 | *Trichilia dregeana* | Meliaceae | Shigo |
| 32 | *Vepris dainellii* | Rutaceae | Hadessa |

**Appendix 2**, Table 2. List of woody plant species recorded from study plots of forest with coffee, with their family and local name in Anfilo district, western Ethiopia

| **No** | **Scientific Name** | **Family** | **Local Name (Oromiffa)** |
|---|---|---|---|
| 1 | *Albizia grandibracteata* | Fabaceae | Yango |
| 2 | *Albizia schimperiana* | Fabaceae | Shawo |
| 3 | *Bersama abyssinica* | Melianthaceae | Lolchisa |
| 4 | *Coffea arabica* | Rutaceae | Buna |
| 5 | *Cordia africana* | Boraginaceae | Wadesa |
| 6 | *Croton macrostachyus* | Euphorbiaceae | Bekenisa |
| 7 | *Dombeya torrida* | Sterculiaceae | Danisa |
| 8 | *Ehretia cymosa* | Boraginaceae | Ulaga |
| 9 | *Ekebergia capensis* | Meliaceae | Sombo |
| 10 | *Euphorbia abyssinica* | Euphorbiaceae | Adami |
| 11 | *Ficus exasperata* | Moraceae | Balansofi |
| 12 | *Ficus sur* | Moraceae | Arbu |
| 13 | *Galiniera saxifraga* | Rubiaceae | Mito |
| 14 | *Macaranga capensis* | Euphorbiaceae | Logoma/Dogoma |
| 15 | *Maytenus addat* | Celastraceae | Kombolcha |
| 16 | *Millettia ferruginea* | Fabaceae | Sotelo |
| 17 | *Mimusops kummel* | Sapotaceae | Qolati |
| 18 | *Olea welwitschi* | Oleaceae | Baha |
| 19 | *Polyscias fulva* | Araliaceae | Handallo |
| 20 | *Pouteria adolfi-friederici* | Sapotaceae | Kerero |
| 21 | *Rhus glutinosa* | Anacardiaceae | Tatesa |
| 22 | *Sapium ellipticum* | Euphorbiaceae | Bosoka |
| 23 | *Schefflera abyssinica* | Araliaceae | Getema |
| 24 | *Trichilia dregeana* | Meliaceae | Shigo |
| 25 | *Vepris dainellii* | Rutaceae | Hadessa |
| 26 | *Vernonia amygdalina* | Asteraceae | Ebicha |

**Appendix 3**, Table 3. Total C stock density of protected natural forest of Anfilo District

| Plot No | Above ground (t/ha) | | | Below ground (t/ha) | | | Litter & herb (t/ha) | | | Dead wood (t/ha) | | | Soil Carbon (t/ha) | | Total C density (t/ha) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Biomass | Carbon | CO2-e | Biomass | Carbon | CO2-e | Biomass | Carbon | CO2-e | Biomass | Carbon | CO2-e | Carbon | CO2-e | Carbon | CO2-e |
| 1 | 609.46 | 286.44 | 1050.29 | 164.55 | 77.34 | 283.58 | 16.46 | 6.09 | 22.33 | 0.3 | 0.143 | 0.523 | 99.65 | 365.38 | 469.66 | 1722.1 |
| 2 | 1130.63 | 531.4 | 1948.46 | 305.27 | 143.48 | 526.08 | 15.92 | 5.89 | 21.59 | 0.004 | 0.002 | 0.007 | 143.3 | 525.43 | 824.07 | 3021.58 |
| 3 | 957.14 | 449.86 | 1649.48 | 258.43 | 121.46 | 445.36 | 10.51 | 3.89 | 14.25 | 8.4 | 3.95 | 14.483 | 172.96 | 634.19 | 752.12 | 2757.76 |
| 4 | 536.8 | 252.3 | 925.10 | 144.94 | 68.12 | 249.77 | 2.49 | 0.92 | 3.37 | 8.89 | 4.2 | 15.328 | 154.65 | 567.07 | 480.18 | 1760.64 |
| 5 | 1332.85 | 626.44 | 2296.95 | 359.87 | 169.14 | 620.18 | 14.19 | 5.25 | 19.26 | 0.03 | 0.014 | 0.050 | 147.89 | 542.278 | 948.74 | 3478.71 |
| 6 | 863.93 | 406.05 | 1488.84 | 233.26 | 109.63 | 401.99 | 24.22 | 8.96 | 32.85 | 0.12 | 0.059 | 0.215 | 163.55 | 599.695 | 688.25 | 2523.59 |
| 7 | 709 | 333.24 | 1221.86 | 191.43 | 89.97 | 329.9 | 17.08 | 6.32 | 23.18 | 0.01 | 0.007 | 0.026 | 67.75 | 248.4 | 497.28 | 1823.37 |
| 8 | 481.94 | 226.51 | 830.55 | 130.12 | 61.16 | 224.25 | 24.86 | 9.2 | 33.73 | 0.01 | 0.003 | 0.013 | 146.78 | 538.19 | 443.66 | 1626.74 |
| 9 | 521.77 | 245.23 | 899.18 | 140.85 | 66.2 | 242.73 | 4.11 | 1.52 | 5.57 | 19.61 | 9.2 | 33.8 | 129 | 473 | 451.17 | 1654.28 |
| 10 | 390.96 | 183.75 | 673.75 | 105.53 | 49.6 | 181.87 | 9.73 | 3.6 | 13.2 | 104.89 | 49.3 | 180.77 | 107.4 | 393.8 | 393.65 | 1443.38 |
| 11 | 663.83 | 312 | 1144 | 179.23 | 84.24 | 308.88 | 29.08 | 10.76 | 39.45 | 16.72 | 7.86 | 28.82 | 177.8 | 651.93 | 592.66 | 2173.09 |
| 12 | 854.47 | 401.6 | 1472.53 | 230.64 | 108.4 | 397.47 | 25.54 | 9.45 | 34.65 | 50.26 | 23.62 | 86.61 | 154.6 | 566.87 | 697.67 | 2558.12 |
| 13 | 872.34 | 410 | 1503.33 | 235.53 | 110.7 | 405.9 | 12.97 | 4.8 | 17.6 | 33.4 | 15.7 | 57.57 | 146.25 | 536.25 | 687.45 | 2520.65 |
| 14 | 836 | 392.93 | 1440.74 | 225.53 | 106 | 388.67 | 18.24 | 6.75 | 24.75 | 13.89 | 6.53 | 23.94 | 125.9 | 461.63 | 638.11 | 2339.74 |
| 15 | 890.85 | 418.7 | 1535.23 | 240.43 | 113 | 414.33 | 15.22 | 5.63 | 20.64 | 24.47 | 11.5 | 42.17 | 138.4 | 507.467 | 687.23 | 2519.84 |
| 16 | 909.36 | 427.4 | 1567.13 | 245.53 | 115.4 | 423.13 | 19.65 | 7.27 | 26.66 | 17.55 | 8.25 | 30.25 | 141.34 | 518.25 | 699.66 | 2565.42 |
| 17 | 1063.83 | 500 | 1833.33 | 287.23 | 135 | 495 | 14.86 | 5.5 | 20.17 | 22.13 | 10.4 | 38.13 | 130 | 476.67 | 780.9 | 2863.3 |
| 18 | 914.13 | 429.64 | 1575.35 | 246.81 | 116 | 425.33 | 7.16 | 2.65 | 9.72 | 19.6 | 9.2 | 33.78 | 133.73 | 490.343 | 691.23 | 2534.52 |
| 19 | 810.21 | 380.8 | 1396.27 | 218.72 | 102.8 | 376.93 | 8 | 2.96 | 10.85 | 17.98 | 8.45 | 30.98 | 102.6 | 376.2 | 597.61 | 2191.24 |
| 20 | 623.4 | 293 | 1074.33 | 168.3 | 79.1 | 290.03 | 22.89 | 8.47 | 31.06 | 17.02 | 8 | 29.33 | 145 | 531.667 | 533.57 | 1956.42 |
| 21 | 960.64 | 451.5 | 1655.5 | 259.36 | 121.9 | 446.97 | 15.76 | 5.83 | 21.38 | 15.64 | 7.35 | 26.95 | 119 | 436.333 | 705.58 | 2587.13 |
| 22 | 821.28 | 386 | 1415.33 | 221.74 | 104.22 | 382.14 | 18.92 | 7 | 25.67 | 31.06 | 14.6 | 53.53 | 162.7 | 596.567 | 674.52 | 2473.24 |
| 23 | 366.51 | 172.26 | 631.62 | 98.94 | 46.5 | 170.5 | 36.41 | 13.47 | 49.39 | 26.6 | 12.5 | 45.83 | 132.54 | 485.98 | 377.27 | 1383.32 |
| 24 | 842.55 | 396 | 1452 | 227.49 | 106.92 | 392.04 | 27.84 | 10.3 | 37.77 | 19.15 | 9 | 33 | 126.83 | 465.043 | 649.05 | 2379.85 |
| **Total** | **18963.93** | **8913** | **32681.17** | **5119.75** | **2406.28** | **8823.04** | **412.1** | **152.48** | **559.09** | **467.76** | **219.85** | **806** | **3269.63** | **11988.63** | **14961.28** | **54858.03** |
| **Mean** | **790.16** | **371.38** | **1361.72** | **213.32** | **100.3** | **367.63** | **17.17** | **6.3533** | **23.3** | **19.49** | **9.2** | **33.59** | **136.2** | **499.53** | **623.39** | **2285.75** |

**Appendix 4**, Table 4. Total carbon stock density of forest with coffee of Anfilo District

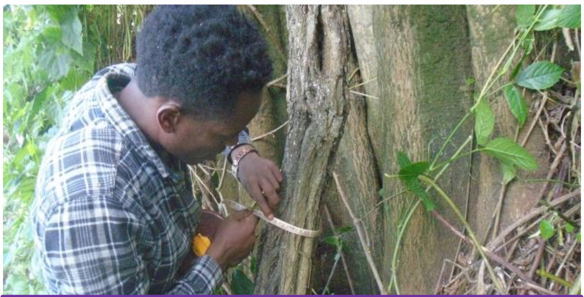
| Plot No | Above ground (t/ha) | | | Below ground (t/ha) | | | Above ground (t/ha) | | Below ground (t/ha) | | Litter & herb (t/ha) | | | Dead wood (t/ha) | | | Soil Carbon (t/ha) | | Total C (t/ha) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Trees other than coffee plant | | | | | | Coffee plant | | | | | | | | | | | | | |
| | Biomass | Carbon | CO2-e | Biomass | Carbon | CO2-e | Biomass | Carbon | Biomass | Carbon | Biomas | Carbon | CO2-e | Biomass | Carbon | CO2-e | Carbon | CO2-e | Carbon | CO2-e |
| 1 | 773.03 | 363.32 | 1332.2 | 208.7 | 98.1 | 359.69 | 4.46 | 2.1 | 3.25 | 1.53 | 9.02 | 3.34 | 12.24 | 11.15 | 5.24 | 19.21 | 148.4 | 544.04 | 622 | 2280.66 |
| 2 | 62.11 | 29.19 | 107 | 16.8 | 7.88 | 28.9 | 4.76 | 2.24 | 3.37 | 1.58 | 40.38 | 14.94 | 54.78 | 4.25 | 2 | 7.32 | 61.71 | 226.26 | 119.53 | 438.29 |
| 3 | 180.35 | 84.76 | 310.8 | 48.7 | 22.89 | 83.91 | 12.58 | 5.91 | 9.24 | 4.34 | 4.49 | 1.66 | 6.09 | 2.14 | 1.01 | 3.7 | 48.25 | 176.92 | 168.83 | 619.03 |
| 4 | 1085.79 | 510.32 | 1871.2 | 293.2 | 137.79 | 505.22 | 6.37 | 2.99 | 4.50 | 2.11 | 7.63 | 2.82 | 10.35 | 114.15 | 53.65 | 196.72 | 97.71 | 358.29 | 807.4 | 2960.47 |
| 5 | 895.32 | 420.8 | 1542.9 | 241.7 | 113.62 | 416.59 | 5.87 | 2.76 | 3.98 | 1.87 | 5.31 | 1.97 | 7.21 | 0.15 | 0.07 | 0.26 | 94.02 | 344.75 | 635 | 2328.72 |
| 6 | 463.67 | 217.93 | 799.1 | 125.2 | 58.84 | 215.75 | 7.31 | 3.43 | 3.65 | 1.72 | 9 | 3.33 | 12.21 | 5.27 | 2.48 | 9.09 | 63.14 | 231.53 | 350.87 | 1286.52 |
| 7 | 94.73 | 44.52 | 163.2 | 25.6 | 12.02 | 44.08 | 7.57 | 3.56 | 3.79 | 1.78 | 2.65 | 0.98 | 3.59 | 0.01 | 0.01 | 0.02 | 139.07 | 509.93 | 201.94 | 740.44 |
| 8 | 919.1 | 431.98 | 1583.9 | 248.2 | 116.63 | 427.66 | 5.18 | 2.44 | 2.59 | 1.22 | 21.24 | 7.86 | 28.82 | 44.26 | 20.8 | 76.28 | 197.8 | 725.27 | 778.73 | 2855.33 |
| 9 | 80.23 | 37.71 | 138.3 | 21.7 | 10.18 | 37.33 | 4.86 | 2.29 | 2.43 | 1.14 | 6.1 | 2.26 | 8.28 | 80.58 | 37.87 | 138.86 | 86.07 | 315.58 | 177.51 | 650.89 |
| 10 | 43.04 | 20.23 | 74.2 | 11.6 | 5.46 | 20.03 | 5.48 | 2.57 | 2.74 | 1.29 | 6.97 | 2.58 | 9.46 | 0.01 | 0.01 | 0.02 | 65.01 | 238.37 | 97.15 | 356.22 |
| 11 | 102.9 | 48.36 | 177.3 | 27.8 | 13.06 | 47.88 | 9.54 | 4.48 | 4.77 | 2.24 | 6.26 | 2.32 | 8.49 | 8.28 | 3.89 | 14.28 | 80.04 | 293.48 | 154.4 | 566.12 |
| 12 | 371.89 | 174.79 | 640.9 | 100.4 | 47.19 | 173.04 | 14.78 | 6.94 | 7.39 | 3.47 | 4.97 | 1.84 | 6.74 | 5.88 | 2.76 | 10.14 | 102.53 | 375.94 | 339.53 | 1244.95 |
| 13 | 1260.53 | 592.45 | 2172.3 | 340.3 | 159.96 | 586.53 | 5.02 | 2.36 | 2.51 | 1.18 | 4.68 | 1.73 | 6.34 | 15.38 | 7.23 | 26.51 | 67.79 | 248.56 | 832.7 | 3053.24 |
| 14 | 86.34 | 40.58 | 148.8 | 23.3 | 10.96 | 40.17 | 12.13 | 5.70 | 6.06 | 2.85 | 6.08 | 2.25 | 8.25 | 20.85 | 9.8 | 35.93 | 73.83 | 270.71 | 145.97 | 535.21 |
| 15 | 234.57 | 110.25 | 404.3 | 63.3 | 29.77 | 109.15 | 9.55 | 4.49 | 4.78 | 2.25 | 4.97 | 1.84 | 6.75 | 73.45 | 34.52 | 126.57 | 96.76 | 354.79 | 279.87 | 1026.20 |
| 16 | 107.66 | 50.6 | 185.5 | 29.1 | 13.66 | 50.09 | 4.89 | 2.3 | 2.45 | 1.15 | 7.22 | 2.67 | 9.79 | 26.51 | 12.46 | 45.69 | 81.02 | 297.07 | 163.86 | 600.83 |
| 17 | 643.4 | 302.4 | 1108.8 | 173.7 | 81.65 | 299.38 | 7.49 | 3.52 | 3.74 | 1.76 | 3.11 | 1.15 | 4.22 | 13.40 | 6.3 | 23.1 | 131.26 | 481.29 | 528 | 1936.14 |
| 18 | 154.85 | 72.78 | 266.9 | 41.8 | 19.65 | 72.05 | 14.32 | 6.73 | 7.16 | 3.37 | 7.58 | 2.81 | 10.29 | 23.17 | 10.89 | 39.93 | 90.76 | 332.79 | 206.98 | 758.93 |
| 19 | 853.83 | 401.3 | 1471.4 | 230.5 | 108.35 | 397.29 | 4.81 | 2.26 | 2.40 | 1.13 | 4.46 | 1.65 | 6.05 | 12.02 | 5.65 | 20.72 | 70.38 | 258.06 | 590.72 | 2165.98 |
| 20 | 1003.87 | 471.82 | 1730.0 | 271.0 | 127.39 | 467.10 | 8.51 | 4 | 4.26 | 2 | 3.62 | 1.34 | 4.91 | 7.96 | 3.74 | 13.71 | 126.77 | 464.82 | 737.06 | 2702.56 |
| 21 | 453.62 | 213.2 | 781.7 | 122.5 | 57.56 | 211.07 | 7.83 | 3.68 | 3.91 | 1.84 | 5.41 | 2.00 | 7.33 | 4.21 | 1.98 | 7.26 | 87.23 | 319.84 | 367.49 | 1347.48 |
| 22 | 360.85 | 169.6 | 621.9 | 97.4 | 45.79 | 167.9 | 13.72 | 6.45 | 6.86 | 3.23 | 3.46 | 1.28 | 4.69 | 10.49 | 4.93 | 18.08 | 66.85 | 245.12 | 298.13 | 1093.13 |
| 23 | 171.4 | 80.56 | 295.4 | 46.3 | 21.75 | 79.75 | 14.57 | 6.85 | 7.29 | 3.43 | 2.84 | 1.05 | 3.85 | 17.60 | 8.27 | 30.32 | 76.8 | 281.60 | 198.7 | 728.59 |
| 24 | 135.7 | 63.78 | 233.9 | 36.6 | 17.22 | 63.14 | 8.66 | 4.07 | 4.24 | 1.99 | 11.49 | 4.25 | 15.58 | 7.62 | 3.58 | 13.13 | 90.5 | 331.83 | 185.39 | 679.78 |
| 25 | 317.77 | 149.35 | 547.6 | 85.8 | 40.32 | 147.86 | 10.64 | 5 | 5.21 | 2.45 | 4.73 | 1.75 | 6.42 | 14.47 | 6.8 | 24.93 | 109.25 | 400.58 | 314.92 | 1154.72 |
| 26 | 256.85 | 120.72 | 442.6 | 69.3 | 32.59 | 119.51 | 7.09 | 3.33 | 3.47 | 1.63 | 2.78 | 1.03 | 3.78 | 41.34 | 19.43 | 71.24 | 82.6 | 302.87 | 261.34 | 958.23 |
| 27 | 641 | 301.27 | 1104.7 | 173.1 | 81.34 | 298.26 | 12.47 | 5.86 | 6.11 | 2.87 | 6.22 | 2.30 | 8.43 | 28.81 | 13.54 | 49.65 | 79.69 | 292.20 | 486.87 | 1785.21 |
| 28 | 335.74 | 157.8 | 578.6 | 90.7 | 42.61 | 156.22 | 13.19 | 6.2 | 6.46 | 3.04 | 5.41 | 2.00 | 7.33 | 13.19 | 6.2 | 22.73 | 103 | 377.67 | 320.84 | 1176.43 |
| 29 | 256.28 | 120.45 | 441.7 | 69.2 | 32.52 | 119.25 | 5.15 | 2.42 | 2.52 | 1.19 | 2.70 | 1.00 | 3.67 | 19.98 | 9.39 | 34.43 | 64.3 | 235.77 | 231.27 | 847.98 |
| 30 | 45.6 | 21.43 | 78.6 | 12.3 | 5.79 | 21.22 | 4.26 | 2 | 2.09 | 0.98 | 22.95 | 8.49 | 31.13 | 58.30 | 27.4 | 100.47 | 81.64 | 299.35 | 147.73 | 541.66 |
| 31 | 425.53 | 200 | 733.3 | 114.9 | 54 | 198 | 9.15 | 4.3 | 4.39 | 2.06 | 6.38 | 2.36 | 8.65 | 39.47 | 18.55 | 68.02 | 71.2 | 261.07 | 352.47 | 1292.40 |
| 32 | 632.98 | 297.5 | 1090.8 | 170.9 | 80.33 | 294.53 | 9.89 | 4.65 | 4.75 | 2.23 | 6.62 | 2.45 | 8.98 | 18.98 | 8.92 | 32.71 | 117.3 | 430.10 | 513.38 | 1882.38 |
| 33 | 174.47 | 82 | 300.7 | 47.1 | 22.14 | 81.18 | 5.96 | 2.8 | 2.86 | 1.34 | 8.51 | 3.15 | 11.55 | 27.66 | 13 | 47.67 | 91 | 333.67 | 215.43 | 789.92 |
| 34 | 146.81 | 69 | 253 | 39.6 | 18.63 | 68.31 | 9.04 | 4.25 | 4.34 | 2.04 | 7.41 | 2.74 | 10.05 | 23.40 | 11 | 40.33 | 73.3 | 268.77 | 180.96 | 663.52 |
| 35 | 214.89 | 101 | 370.3 | 58.0 | 27.27 | 99.99 | 10.1 | 4.74 | 4.84 | 2.28 | 7.46 | 2.76 | 10.12 | 19.15 | 9 | 33 | 68.27 | 250.32 | 215.32 | 789.49 |
| 36 | 480.85 | 226 | 828.7 | 129.8 | 61.02 | 223.74 | 12.6 | 5.92 | 6.05 | 2.84 | 5.41 | 2.00 | 7.33 | 16.55 | 7.78 | 28.53 | 82 | 300.67 | 387.56 | 1421.06 |
| **Total** | **14467.55** | **6799.75** | **24932.4** | **3906.2** | **1835.9** | **6731.75** | **309.78** | **145.6** | **69.3** | **75.42** | **275.49** | **101.93** | **373.75** | **830.10** | **253.1** | **1430.54** | **3267.2** | **11979.86** | **12616** | **46258.71** |
| **Mean** | **401.88** | **188.88** | **692.6** | **108.5** | **51** | **186.99** | **8.6** | **4.04** | **4.46** | **2.09** | **7.65** | **2.83** | **10.38** | **23.06** | **10.8** | **39.74** | **90.76** | **332.77** | **350.44** | **1284.96** |

**Appendix 5,** Figure 1. Photos taken during field data collection

DBH measurement for woody plant

DBH measurement for buttressed tree

Diameter measurement for coffee plant



DBH measurement for liana

Litter data collection

Soil data collection

New degradation for planting coffee

Intact natural forest

**Photo by: Abraham Mohammed and Yohannes Shifera (2019) (Anfilo district natural forest, Ethiopia).**