Carbon Stocks along Altitudinal Gradient in Gera Moist Evergreen Afromontane forest, Southwest Ethiopia

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GRADUATE PROGRAMS

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ABSTRACT

Carbon Stocks along an Altitudinal Gradient in Gera Moist Evergreen Afromontane forest, Southwest Ethiopia

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Forest plays an important role in the global carbon cycle as carbon sinks of the terrestrial ecosystem. Carbon stock estimation enables us to understand the current status of carbon stocks and to derive its near future changes. The presence of CO_2 *as main greenhouse gases in the atmosphere, its potentials to influence the global climate, its long residence time in the atmosphere and potential implementation of the Kyoto Protocol are the reasons why carbon cycle drew much attention at global level. This study was carried out to estimate the variation of carbon stock along altitudinal gradient in the Gera* Moist Evergreen Afromontane forest, *Southwest Ethiopia. The data were collected by using stratified systematic sampling method with a nested plot approach. The sampling sites were selected by dropping a regular interval of 100 m elevation gradient. From each sampling site three quadrats of 100 m apart each other were established. A total of 30 rectangular quadrats having a size of 20mx100m were used to collect data. Within these quadrats five* $1m^2$ *subplots four at the corners and one at the centre were used to collect soil, litter and non-tree vegetation samples. The biomasses of trees in the Forest were calculated by using a model developed by Chave et al. (2014). The mean total carbon density of the forest was 440.71 (t* ha^{-1}*). This is equivalent to 1617.41 t* ha^{-1} *of* CO_2 *gas. The mean carbon stocks at the higher altitude (2334 -2539 m a.s.l.) were estimated as greater in all carbon pools. The carbon density of Gera Moist Evergreen Afromontane forest can be considered as medium when compared with other studies done elsewhere in the tropics.*

Key Words: Moist Evergreen Afromontane forest, Biomass, Model, Carbon stock, Forest strata, altitudinal gradient, Anthropogenic disturbance

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ACRONYMS

AG – Above Ground

AGB – Above Ground Biomass

AGC – Above Ground Carbon

BEF – Biomass Expansion Factor

BG – Below Ground

BGB – Below Ground Biomass

BGC – Below Ground Carbon

CBD – The Convention on Biological Diversity

CDM – Clean Development Mechanism

COP – Conference of Parties

DBH – Diameter at Breast Height

GHGs – Green House Gases

H – Height of a tree

ICRAF – International Center for Research in Agroforestry

IPCC – Inter governmental Panel on Climate Change

Lc – litter Carbon

MAI – Mean Annual Increment

NTFP – Non-timber Forest Product

NTV – Non-tree Vegetation

NTVC – Non-tree Vegetation Carbon

Pg – Petagram = 1 quadrillion grams (10^{15} g) = 1 billion metric tons (Gt)

REDD^{+} **–** Reduction Emission from Deforestations and Degradation

SOC – Soil Organic Carbon

TEV – Total economic Value

(t ha^{-1})– Tone per hectare

UN – The United Nations

UNCCD – The United Nations Convention to Combat Desertification

UNFCCC – United Nations Framework Convention on Climate Chang

UNFF – The United Nations Forum on Forests

CHAPTER 1

1. INTRODUCTION

1.1. Background and Justification

Forest ecosystems serve in many important ecological services and provide wood and other numerous non-timber forest products (NTFPs) that contribute to human wellbeing at local, national, and global levels. The diverse ecosystem services provided by forests include: i) the conservation of soil and water resources, ii) positive influences on local climate, iii) the mitigation of global climate change, iv) the conservation of biological diversity, v) the protection of natural and cultural heritage, vi) subsistence resources for many rural and indigenous communities, vii) the generation of employment, and viii) recreational opportunities. Many international organizations and convention such as: i) the United Nations Framework Convention on Climate Change (UNFCCC), ii) the United Nations Forum on Forests (UNFF), iii) the United Nations Convention to Combat Desertification (UNCCD), and iv) the Convention on Biological Diversity (CBD), agreed on the centrality of forests for human wellbeing in recent environmental agreements and processes.

The economic value of forest ecosystem aims at accounting for the total economic value (TEV) which comprehensively looks for all forest services. These include direct values (such as: timber, fire wood, NTFPs, grazing and fodder, and recreation), indirect values (watershed protection, erosion control, macro-climate regulation, and carbon sequestration), and option values (considering future economic options in all affected sectors, such as: industrial, agricultural, pharmaceutical, and recreational) and existence values landscape, aesthetic, heritage, cultural, religious and ritual). But, practically the economic value of forest mostly estimated only its products which enter formal markets, although currently markets are growing for carbon and biodiversity.

The 1992 UN Forest Principles identified the multifunctional and multiservice purpose of the world's forests: Forest resources and forest lands shall be managed and used sustainably to fulfill social, economic, ecological, cultural and spiritual needs of present and future generations. However, regardless of its uses the progresses of human civilization have been made possible by the conversion of some forest areas to other uses, particularly for agricultural expansion. These resulted in extensive biodiversity loss at genetic, species, and habitat level on the world's forests. Forest loss has also had a negative impact on the provision of ecosystem services and goods mentioned earlier.

Forests have the potential to form an important component in efforts to mitigate the global climate change serving as the medium of sinks and sources of carbon. Tropical forests are considered to be a large and globally significant storage of C (FAO, 2004) and have the potential to balance the amount of CO_2 in the atmosphere. This is due to their more C content per unit area than any other terrestrial ecosystem. They store an estimated amount of 193 - 229 peta grams (Pg) (Clark and Kellner, 2012) of carbon in aboveground biomass (AGB) or roughly 20 times the annual emissions from combustion and land-use change.

Atmospheric carbon uptake by the vegetation is believed to play a major role in the global climate change of the century to come (Chave *et al*., 2001). Trees in a forest can sequester large amount of carbon over their growth cycle of many decades because of their long life span. When trees grow they start to sequester carbon in their tissue, this implies that as the biomass of the tree increases the CO_2 concentration in the atmosphere is mitigated. Active absorption of CO_2 from the atmosphere through the process of photosynthesis and its subsequent storage in different plant parts in the form of biomass in growing trees are the essence of carbon storage. As more photosynthesis occurs, more CO_2 is converted into biomass, reducing carbon in the atmosphere and sequestering it in the plant tissues above and below ground resulting in growth of their different parts.

The rate at which GHGs are being released into the atmosphere has increased mainly not only due to the burning of fossil fuels for both domestic and industrial purposes, but also as a result of land clearance and deforestation. Decomposition of cleared vegetation releases carbon to the atmosphere, mainly in the form of CO_2.

Woody and other live biomass are important indicators of the potential of forests to provide various products and services, including carbon sequestration. From 99% of the world's forest area, 432 billion tons of dry matter is aboveground (AG) woody biomass of live trees and dead trees with DBH > 10 cm size (Shvidenko *et al.*, 2005). Forest carbon stock can be grouped into two main components biotic (vegetation) and pedologic (soil) carbon stock (Bhat *et al.,* 2013).

Nowadays among goods and services that forest ecosystems provide for human being, carbon sink thereby regulating and balancing of the global carbon cycle is attracting the attention of countries and scientists around the world. This is due to the increased level of GHGs in the atmosphere mainly because of anthropogenic factors.

Carbon stocks in a forest vary depending upon various factors and processes operating in the systems. Bhat *et al.* (2013) indicated that from these factors, the most significant ones are land use, land use changes, soil erosion and deforestation. In addition, the carbon stock in the forest vegetation varies according to geographical location, plant species and age of the stand. Therefore, experts must be curious while studying those factors in order to maximize the potential of the forest in up taking CO_2 from the atmosphere. So that sustainable forest management is crucial to minimize CO_2 concentration in the atmosphere, which is the worry of the world today. According to Adugna Feyissa *et al.* (2013), forest carbon is affected by different environmental factors such as: altitude, aspect and slope by affecting the distribution of tree species.

REDD+ activities have been developed as part of international climate change mitigation efforts. They are outlined in context to implementing the principles of the UNFCCC. In these regard developing countries are encouraged to undertake activities in the forestry sector to reduce GHG emissions by: i) reducing emissions from deforestation, ii)reducing emissions from forest degradation, iii) conservation of forest carbon stocks, iv) sustainable management of forests and v) enhancement of forest carbon stocks (UN-REDD Programme, 2012).

Ethiopia has a mean value 1.17 billion tons of carbon stock of which 434.19 million tons of carbon is constituted by the high forests of the country (Yitebitu Moges *et al.,* 2010). It was also noted that the figures indicated at national for carbon stock of the country by different authors is not consistent. For instance, 153 million tons Houghton (1999), 867 million tons Gibbs and Brown, (2007a) and 2.5 billion tons, and 2.5 billion tons by Sisay Nune *et al.* (2009). In Ethiopia as one of the country in the tropics, little is known about inter site and temporal variability of forest biomass when compared to the large amount of information available in other continents (Chave *et al.,* 2001; Abel *et al*., 2014). Periodic forest inventories and monitoring in the country are lacking even though they are most useful in order to evaluate the magnitude of carbon fluxes between AGB and the atmosphere (Abel Girma *et al*., 2014). Adugna Feyissa *et al.* (2013) outline that Ethiopia has limited information about carbon stocks of forest. Similarly, Belay Melese *et al.*, (2013) described that although carbon is varying from forest to forest and soil to soil, Ethiopia has only limited number of studies regarding carbon stock.

Afromontane Moist forests are the main remnant forests, which currently exist in the country (Feyera Senbeta, 2006). This forest types are the source of organic forest coffee (*Coffea arabica*) and confined to southwest and southeastern parts of the country. But, deforestation in combination with changes in forest management has caused great changes in this pristine forest type particularly, the forest in the southwest Ethiopia, leading to significant effects on the biodiversity of the area and a substantial decrease in total biomass and C stock (Kitessa Hundra, 2013). Therefore, all the problems stated above invite research works regarding carbon stock estimation in the forest resources of the country. Accordingly, this research work on carbon stock estimation was done to provide firsthand information about carbon stock sequestered in different carbon pools in relation to altitudinal gradient in the Gera Moist Evergreen Afromontane forest, Southwest part of Ethiopia.

1.2. Statement of the problem and Significance of the study

1.2.1. Statement of the problem

Ethiopia losses it's biologically diverse forest resource from time to time due to various human induced pressures such as: expansion of agricultural land, overgrazing, fire and settlements. The increasing pressures of the above mentioned factors has accelerated the decline of forest resources and led to further environmental degradation such as soil erosion, loss of biodiversity and deterioration of the ecosystem services. The ever increasing demands for forest products and forestland driven by human population increment are putting intolerable pressure on the remaining forest fragments of the country.

1.2.2. Significance of the study

Currently the demand of reliable information regarding forest carbon stock at both country and global levels is growing (Genene Asseffa *et al.,* 2013). Reliable estimates of biomass, liter and soil carbon are needed to understand the effect of forests on atmospheric carbon dioxide. This calls researchers to direct their interests to quantify forest carbon stocks following standardized carbon stock accounting method. Therefore, measuring and estimating carbon stocks and changes in carbon stocks in various pools are very important for carbon trading (Yitebitu Moges *et al.,* 2010).

The reductions of emission from deforestation and degradation by managing the existing forests sustainably bring financial and technical incentives from industrialized nations to developing countries through REDD^{+}. To tap this opportunity, accurate and consistent data that meet international standards while creating favorable policy environment are the most important requirements to derive benefits from climate funds (Yitebtu Moges *et al.*, 2010). Therefore, carbon cycle in forests, periodic monitoring of changes in forest and carbon stocks and verifying the results and establishing empirical relationships are likely to be the issues of research and development undertakings.

Studying the carbon stock of a given vegetation in order to know its status in carbon density or content thereby get credit from reduced emission (certified reduction emission can be sold in international carbon market), its variation through time due to land use land cover change, compare its carbon density with atmospheric carbon dioxide equivalent and to estimate the impact of deforestation on carbon balance is important.

1.3. Hypotheses and Objectives

1.3.1. Hypothesis

$\mathbf{H_o}$ = Carbon stock in different carbon pools is equal at different forest strata in Gera Moist Evergreen Afromontane forest, southwest Ethiopia.

$\mathbf{H_A}$ = Carbon stock in different carbon pools is not equal at different forest strata in Gera Moist Evergreen Afromontane forest, southwest Ethiopia.

1.3.2. Objectives

1.3.2.1. General Objective

The general objective of this study was to estimate the carbon stock along altitudinal gradient in different carbon pools of Gera Moist Evergreen Afromontane forest, Southwest Ethiopia.

1.3.2.2. Specific objectives

- To record the name of woody plant species found in the Forest;
- To estimate above ground biomass of the Forest;
- To estimate below ground carbon stock of the Forest;
- To estimate litter and non-tree vegetation carbon stock of the Forest;
- To estimate soil carbon stock of the Forest; and
- To study the carbon stocks in relation to altitude, aspect and anthropogenic factors in the study area.

CHAPTER 2

2. LITERATURE REVIEW

2.1. Carbon Cycle

Naturally, the amount of carbon as any other system in the environment retains its balance. However, in the last 200 years, fossil burning in combination with deforestation have increased CO_2 concentration in atmosphere from 0.028 to 0.035% (FAO, 2004) and the concentration is continuing to increase. Terrestrial and aquatic ecosystems play an important role in the carbon cycle. Major ecosystems that are commonly considered in both global and national carbon assessments and in inventories include forests, croplands, grasslands/shrub lands, and wetlands. Among these, forest is believed to play a major role in balancing this CO_2 concentration in the atmosphere in the global climate changes of the century to come as far as these are managed sustainably (Shvidenko *et al.*, 2005).

Forests are a large carbon sinks, but they are ecosystems that gain and lose carbon continually. Trees in a forest have important contribution to the global carbon cycle, because of their large biomass per unit area of land (Adugna Feyissa *et al.,* 2013). The primary CO_2 fluxes between the atmosphere and ecosystems are uptake by plant through photosynthesis and released by respiration, decomposition, and combustion of organic matter. Therefore, a forest shows a net gain or loss of carbon based on the balance of these processes. The CO_2 absorbed by plants is transformed into carbohydrates that are then stored in plant tissues during their growth in their life cycle. Photosynthesis is the driving process behind carbon storage as a biomass, and the stored biomass eventually ends up in soils and dead organic matter pools.

A forest may be highly variable in its carbon storage capacity if it is measured over a long period of time, in part because of natural disturbances and harvest events. However, when considering many different forests in a large region, such variability in carbon storage will not be as apparent because the region is composed of forests that are in different stages of recovery and regrowth. Biomass is the total amount of live organic matter and inert organic matter (FAO 2004; Genene Asseffa *et al.,* 2013) AG and BG expressed in tones of dry matter per unit area. It includes the total mass of living organisms in a given area or volume; recently dead plant material is often included as dead biomass. The total biomass for a region or a country is obtained by up scaling or aggregation of the density of the biomass at the minimum area measured. The quantity of biomass, usually measured in units of mass ha^{-1} varies among continents, regions and landscapes because of climate, disturbance history, geochemistry and idiosyncratic site factors (Clark and Kellner, 2012).

The different components of AGB constitute different amounts of carbon. For example, according to Hairiah *et al.* (2001), trunk diameter contain the highest and forest type contain the least carbon stock from the following consecutive order; trunk diameter, wood specific gravity, total height, and forest type (dry, moist or wet). Therefore, in the case of forest inventory tree diameter particularly DBH is the most important parameter and measured variable, which is measured directly to estimate the biomass of vegetation.

Plant biomass, both AG and BG, is a main pool of carbon. The amount of carbon stored in plant biomass is influenced by land use. For example, forest clearing for cropland greatly reduces the amount of carbon stored in the vegetative biomass. In a natural system, most of the biomass production contained in living plant material is eventually transferred to dead organic matter pools, such as dead wood and litter. Dead organic matter on the ground and plant biomass below the ground decompose and transform into soil organic matter (SOM), which is another primary pool and can have varying residence times in the soil. Decomposition of SOM releases CO_2 back into the atmosphere.

Carbon is one of the essential macro organic elements stored in terrestrial ecosystems, as living or dead plant biomass (AG and BG) and in the soil. On the other hand, carbon stock in a forest refers to the amount of carbon taken from the atmosphere and stored in plant tissue in the form of carbohydrates through the process of photosynthesis. It can be quantified by estimating the biomass of given a vegetation. According to Hairiah *et al.* (2001), the C stock in an individual tree depends on its size. The carbon stored in the AGB of trees is typically the largest pool and the most directly impacted by deforestation and degradation.

By assessing carbon fluxes among all the major pools, it is possible to summarize all resulting quantities as the net ecosystem carbon balance for each ecosystem. This value accounts for net ecosystem production, which is calculated by subtracting ecosystem respiration from gross primary productivity. Net biome productivity is based on net ecosystem productivity, but further accounts for ecosystem disturbances. The net ecosystem carbon balance integrates all carbon flux terms, including lateral runoff and river transport of carbon.

2.2. The Role of Forest in Mitigating Atmospheric CO2

Forest plays an important role in the global carbon cycle as carbon sinks of the terrestrial ecosystem. Generally, carbon stock in a forest is broadly divided in to two: biotic (vegetation carbon) and pedologic (soil carbon) components (Bhat *et al.,* 2013). 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.

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 carbon dioxide from the atmosphere and stores the carbon in the plant tissues, forest litter and soils. Thus, forest ecosystem plays a very important role in the global carbon cycle by sequestering a substantial amount of carbon dioxide from the atmosphere.

When trees in a forest grow or attain large biomass, the amount of CO_2 taken by the trees is increased thereby the concentration of CO_2 in the atmosphere can be reduced. The roles of forest take major parts in activities to minimize and adapt the impact of climate change. So that knowing their roles in efforts to minimize the concentration of CO_2 in the atmosphere.

It is good to identify and control the factors (land use change, soil erosion and deforestation) for the proper management of the forests sustainably. Therefore, the amount of carbon in a forest and the rate of sequestering carbon from the atmosphere could be increased if deforestation will be altered and sustainable forest management is practiced.

2.3. The Importance of Studying Carbon stocks in a Forest

Estimating the amount of forest biomass is very crucial for monitoring and estimating the amount of carbon that is lost or emitted during deforestation, and it also provides information about the forest's potential to sequester and store carbon in the forest ecosystem. Estimations of forest carbon stocks are based upon the estimation of forest biomass, because forest carbon stocks are generally assumed to be half of its biomass (Vashum and Jayakumar, 2012). According to these authors, any sort of forest management practices affect the flux of carbon between the terrestrial forest ecosystem and the atmosphere. Hence, estimating the forest carbon stocks is mainly important to assess the magnitude of carbon exchange between the forest ecosystem and the atmosphere.

On the other hand, as described by Vashum and Jayakumar (2012) the reason why carbon cycle drew much attention at global level is that (1) it is the chief among other GHGs (2) its potentials to influence 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. Estimation of AGB is an important step in identifying the amount of carbon in terrestrial vegetation pools and is central to global carbon cycle because much of the flux takes place in above the ground of forest structure.

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 sector 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 necessary information to determine the changes in carbon stocks as required by the UNFCCC and forestry projects for mitigating carbon emissions.

2.4. Carbon pools

Carbon pools are components of the ecosystem that can either accumulate or release carbon. Different authors classified them in to different pools; this may be related to the type of forest and the objectives of the project. According to Vashum and Jayakumar (2012), there are six carbon pools applicable to afforestation/reforestation LULUCF project activities: AGB, BGB, litter, non-tree vegetation (NTV), dead wood and soil organic matter (SOC). But, not all six pools will be significantly impacted in a given project. The most important pools measured in any projects are AGB and BGB, because trees are simple to measure and contain the major portion of the carbon pool.

There are five carbon reservoirs in a forest ecosystem: soil, plant debris (dead wood, dead roots, and leaf litter), AGB, BGB, and herbaceous plants (Ekoungoulou *et al*., 2014). Forest inventory data can provide high quality information for a particular region. Biomes likely represent the most important variation of forest carbon stocks because they account for major bioclimatic gradients such as temperature, precipitation and geologic substrate. However, forest carbon stocks vary further within each biome according to slope, elevation, drainage class, and soil type and land use history.

However, classically IPCC (2006) carbon pools have been grouped into five main categories: living AGB, living BGB, DOM in wood, litter and soil. In a tropical forest ecosystem, the living biomass of trees, the understory vegetation and the deadwood, woody debris and soil organic matters constitute the main carbon pool.

2.4.1. Above Ground Biomass (AGB)

The total standing AGB of woody vegetation is often one of the largest carbon pools. It comprises all woody stems, branches, and leaves of living trees, creepers, climbers, and epiphytes as well as herbaceous under growth. It is mainly the largest carbon pool and it is directly affected by deforestation and forest degradation. The most direct way of quantifying the carbon stored in AGB is to harvest all trees in a known area, dry them and weigh the biomass. While this method is accurate for a particular location, it is prohibitively time consuming, expensive, destructive and impractical for country level analyses. All plant materials normally contain 50% carbon from their dry weight (Clark and Kellner, 2012; Basuki *et al.*, 2009; Gibbs *et al.*, 2007; Pearson *et al.,* 2005 and Hairiah *et al.*, 2001).

The other way of estimating carbon in AGB is grouping all species together and using generalized allometric relationships, stratified by broad forest types or ecological zones, is highly effective for the tropics because DBH alone explains more than 95% of the variation in aboveground tropical forest carbon stocks, even in highly diverse regions (Gibbs *et al*., 2007). It is often assumed in inventories that small trees ≤ 10 cm diameter contribute little to the total biomass carbon of a forest and thus they often tend not to be measured (Brown, 2002). However, their contribution depends on the successional stage of the stand.

2.4.2. Below Ground Biomass (BGB)

The measurement of AGB is relatively established and simple. But, measuring BGB is time consuming methods. Thus, it may be more efficient and effective to apply a regression model to estimate BGB. It is derived from the measurement of the AGB. The majority of the BGB of the forest is contained in the heavy roots, generally defined as those greater than 2 mm in diameter. However, it is recognized that most of the annual plant growth is dependent on fine or thin roots.

Roots play an important role in the carbon cycle as they transfer considerable amounts of C to the ground, where it may be stored for a relatively long period of time. Root biomass is often estimated from root: shoot ratios (R/S). According to Brown (2002), the R/S did not vary significantly with latitudinal zone (tropical, temperate, and boreal), soil texture (fine, medium and coarse), or tree type (angiosperm and gymnosperm).

The plant uses part of the C in the roots to increase the total tree biomass through photosynthesis, even though C is lost through the respiration, exudation and decomposition of the roots. Ponce-Hernandez (2004) described that some roots can extend to great depths, but the greatest proportion of the total root mass is within the first 30 cm of the soil surface. This author described that carbon loss in the ground is intense in the top layer of soil profiles (0–20 cm). Therefore, sampling should concentrate on this section of the soil profile accumulation. Gibbs *et al.* (2007) and Ponce-Hernandez (2004) stated that root biomass is typically estimated to be 20% of the aboveground forest carbon stocks.

2.4.3. Dead Standing and downed dead wood

The biomass of the dead tree can be calculated by using its DBH and subtracting 10-20% of the AGB, which is due to the absence of leaves and branches as well (Kauffman and Donato, 2012). According to Condit (2008), in tropical forests, there is less fallen wood because trunks decay much faster, so the importance of sampling is reduced, but it is still 10-15% of the living AGB. Brown *et al.* (1997) reported that dead tree constitute 5-40% of AGB. On the other hand, dead wood or litter carbon stocks (down trees, standing dead, broken branches, leaves) are generally assumed to be equivalent to around 10-20% of the AG forest carbon estimate in mature forests (Zhu *et al.*, 2010). The dead wood carbon pool is grouped in to two; dead standing and dead downed wood.

I. Standing dead wood

Standing dead trees can be measured in the same plots that are delineated for live trees. The parameters recorded for live trees are also recorded for dead standing trees. In addition to that of the parameters recorded for live trees, relative state of the wood for dead tree is needed. According to Brown *et al.* (2004), relative states for standing dead tree are described as follows:

1. Tree with branches and twigs and resembles a live tree (except for leaves)

2. Tree with no twigs but with persistent small and large branches

3. Tree with large branches only

4. Bole only, no branches

Table 1 Proportions of biomass in tree vegetation components

Wood type	**Tree parts**	**DBH (cm)**									
		10	20	30	40	50	60	70	80	90	100
		%									
Hard wood	stem	54	68	74	77	79	80	81	82	82	83
	Branches	43	29	24	21	19	18	17	16	16	15
	Foliage	3	2	2	2	2	2	2	2	2	2
Soft wood	stem	68	74	77	78	78	79	79	79	80	80
	Branches	23	19	17	16	16	16	15	15	15	15
	Foliage	8	6	6	6	6	6	6	5	5	5

Note: Values given are percentage of total above ground biomass (source: Brown *et al.,* 2004).

For state 1, biomass is estimated from DBH using the same function as that of live trees, but subtracting out the biomass of leaves, which is about 2 -3% of AGB for hardwoods and 5 -6% for softwoods. Where only a bole is remaining (class 4), volume is estimated using DBH and height measurements and an estimate of the top diameter. Volume is then estimated as the volume of a truncated cone, and converted to dry biomass using an appropriate dead wood density class (sound or intermediate). For classes 2 and 3 estimates of the proportion of the tree that is missing need to be made. The principle of conservatism should be applied. Table 1 above shows an estimated value of the proportion of biomass in the stem, branches, and foliage for living hardwoods and softwoods in the United States, which could be used to deduct the portion of AGB that is missing.

II. Downed / lying Dead Wood

Lying dead wood can be measured by complete inventory in one of the nested plot or by the line-intersect method. According to Brown *et al.* (2004), if the line is long enough (at least 100 m), the line-intersect is a time-efficient method. Two lines of 50 m in length are established that intersect at right angles through the plot center. Along the length of the lines, the diameter at the intersection point of any course (> 10 cm diameter) dead wood that intersects the line is measured. For smaller-stature forests, coarse wood could be > 5 cm diameter the method will be the same. There are several criteria that should be observed when deciding if a piece of dead wood should be measured. A piece should only be measured if: (a) more than 50% of the log is aboveground, and (b) the sampling line crosses through at least 50% of the diameter of the piece.

If the log is hollow at the intersection point, this should be noted in the data recording system and the total diameter measured; the hollow portion in the volume estimates is deleted. Each measured piece is assigned to one of three density states: sound, intermediate, or rotten. A simple and practical method for determining the density class a piece of dead wood is to strike each piece with a saw. If the saw does not sink into the piece (bounces off), it is classified as sound. If it sinks partly into the piece, and there has been some wood loss, it is classified as intermediate. And, if it sticks into the piece, there is more extensive wood loss, and the piece is crumbly, it is classified as rotten.

For each density class separately, the volume is calculated as follows:

$$\text{Volume (m}^3\text{/ha)} = \pi^2 \left(\frac{d_1{}^2 + d_2{}^2 \ldots\ldots \mathrm{d_n}{}^2}{8\mathrm{L}}\right)$$ (Brown *et al.,* 2004)

Where d1, d2 … dn = diameters of intersecting pieces of dead wood and L = length of line

Representative dead wood samples of the three density classes, representing the range of species present, should be collected for density (dry weight per green volume) determination. Using a chainsaw or a handsaw, a complete disc from the selected piece of dead wood is cut. The average diameter and thickness of the disc is measured to estimate volume. Volume can also be estimated by the water displacement method. The fresh weight of the disc does not have to be recorded. The disc should be placed in a sample bag; oven dried at 80°C to a constant weight. Density is calculated by the following formula:

$$\text{Density} = \frac{\text{mass (g)}}{\text{volume } (cm^3)}$$

Where: mass = the mass of the oven dried sample, volume = volume of the wood.

2.4.4. Litter and Duff

The forest litter layer is defined as all dead organic surface material that includes dead leaves, twigs, dead grasses and small branches and unidentifiable decomposed fragments of organic material on top of the mineral soil. Dead wood with a diameter of < 10 cm and length < 0.5 m is included in the litter layer (Brown *et al.*, 2004; Zhu *et al.*, 2010). Litter is defined as dead surface plant material that is still recognizable and is not decomposed to the point that identification is impossible to define. Similarly Brown *et al.* (2004) defines the duff layer as decomposing organic material, decomposed to the point at which there are no identifiable organic materials such as pine straw, leaves, twigs, or fruits. It is the organic material layer between the uppermost soil mineral horizon and the litter layer. Both of these layers could be combined as one pool and sampled together using small subplots.

It also includes live fine roots less than 2 mm in diameter as these cannot be distinguished empirically from the litter and dead wood (Zhu *et al.*, 2010). Litter layer can be collected from 1 m^2 four at the corners and one at the center of each main plot and weigh and take 100g from the collected sample to laboratory analysis for moisture content determination. According to Pearson *et al. (*2005), the dry biomass of litter can be calculated by using the following formula:

$$\mathbf{B_L} = \frac{\mathbf{W\ subsample\ (dry)}}{\mathbf{W\ subsample\ (fresh)}}\, X\ \mathbf{W\ Field\ X\ BEF}$$

Where, B_L is the litter dry mass (t/ ha).

W subsample (dry) is the oven dry weight of subsample

W subsample (fresh) is the fresh weight of subsample

W Field is the fresh weight of sample collected from the sampling area.

2.4.5. Non-Tree Vegetation (NTV)

Non-tree vegetation includes all plant species with less than specific maximum DBH (diameter at breast height =1.3 above the ground) in the forest floor. The maximum DBH mainly given for NTV is < 2 cm in diameter (MacDicken, 1997; Swai *et al.*, 2014). It is measured simply by harvesting techniques. According to Brown (2004), aboveground NTV may need to be measured if it is a significant component, such as where trees are only present at low densities. But, NTV is generally not a significant biomass component in mature forest. A small subplot (dependent on the size of the vegetation) is established and all the vegetation is harvested and weighed. An alternative approach, if the shrubs are large and common, is to develop local shrub biomass regression equations based on variables such as crown area and height or diameter at base of plant or some other relevant variable (e.g., number of stems in multi-stemmed shrubs) (Brown *et al*., 2004). The equations would then be based on regressions of biomass of the shrub versus some logical combination of the independent variables.

2.4.6. Soil

Soil plays an important role in the global carbon cycle. Globally, the soil carbon stock is nearly three times the amount in the AGB and about twice as large as the carbon stock of the atmosphere (Mäkipää *et al.,* 2012). Soil organic matter is the main source of soil organic carbon while vegetation is the main source of SOM. Therefore, any factor that influences SOM has impact on soil organic carbon (SOC). SOM is influenced by a number of factors, mainly climate, vegetation types, soil types and human activities. According to Mäkipää *et al.* (2012), in broad geographic areas, the role of climate and natural vegetation on the levels of SOM is very important.

Generally, in similar moisture conditions and comparable soils and vegetation, the SOM is higher in cooler climates than in warmer ones. Moreover, high rainfall promotes vegetation growth and hence production and accumulation of SOM. Since plants (particularly natural vegetation) are the major source of soil organic matter, vegetation types and their density influence the SOC stock.

To obtain an accurate inventory of organic carbon stocks in mineral or organic soil, three types of variables must be measured: (1) depth, (2) bulk density (calculated from the oven-dried weight of soil from a known volume of sampled material), and (3) the concentrations of organic carbon within the sample. The 2006 IPCC guidelines recommend using a default 0-30 cm layer is sufficient. Within this layer, the influence of management practices is more pronounced than in the deeper soil layers. The total value of carbon in the soil is calculated as follows (Brown *et al.,* 2004):

C (t/ha) = [soil bulk density (g/cm3) X soil depth (cm) X C] X 100

In this equation, the C must be expressed as a decimal fraction (e.g., 2.2% C is expressed as 0.022 in the equation).

2.5. IPCC Tires

There are three general approaches for estimating emissions or removals of greenhouse gasses set by IPCC (GOFC-GOLD, 2009). These are called Tiers which range from 1-3 increasing level of data requirement and analytical complexity. According to this author, despite they differ in approaches three of them addresses the IPCC good practice concepts of transparency, completeness, consistency, comparability, and accuracy.

Tier 3 is the most rigorous approach associated with highest level of effort. It uses actual inventory data with repeated measures on the permanently established plots in order to know direct measures of changes in forest biomass and/or uses well parameterized models in combination with plot data. This approach can thus expensive in developing country, particularly where only a single objective (estimating GHG emission) supports implementation costs. It often focuses on measurements of trees only, and uses forest or region specific default data and modeling other pools. It requires long term commitment of resource and personnel, generally involving the establishment of a permanent organization to house the program. To estimate emissions from degradation, this approach uses the stock difference approach where change in forest biomass stock is directly estimated from repeated measures or models.

Tier 2 employs static forest biomass information, but it also improves on that approach by using country specific data (i.e. collected within the national boundary), and by resolving forest biomass at finer scales through the delineation of more detailed strata. It develop disturbance matrices that model retention, transfer (e.g. from burning) among pools. For degradation, in the absence of repeated measures from a representative inventory, Tier 2 uses the gain loss method using locally derived data on mean annual increment. Done well, a Tier 2 approach can yield significant improvements over Tier 1 in reducing uncertainty, and though not as precise as repeated measures using permanent plots that can focus directly on stock change and increment, Tier 2 does not require the sustained institutional backing.

Tier 1 does not require new data collection to generate estimate of forest biomass. Rather, forest biomass and forest biomass mean annual increment (MAI) can be taken from IPCC emission factor data base (EFDB), cross ponding to broad continental forest types (African tropical rain forest). Thus it provide limited resolution of how forest biomass varies sub-nationally and has an error of ± 50% or more for growing stocks in developing countries (GOFC-GOLD, 2009). It also uses simplified assumptions of instantaneous emission from woody vegetation, litter and dead wood.

To estimate emission from degradation (i. e forest remaining as forest) it applies gain-loss method using a default mean annual increment (MAI) combined with losses reported from wood removals and disturbances, with transfers of biomass to dead organic matter estimated using default equation.

2.6. Moist Evergreen Afromontane forest in Ethiopia

Generally, 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 corresponds to semi-deciduous lowland forests, which have a precipitation of approximately 1550–3500 mm yr^{-1}. The Moist Evergreen Afromontane forests occur in the SW and SE highlands in the country at altitudes between 1500 and 2600 m (Feyera Senbeta, 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 this 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 canopy species include *Podocarpus falcatus, Pouteria adolfi-friederici, Croton macrostachyus*, *Ilex mitis*, *Olea welwitschii*, and *Schefflera abyssinica.* 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.

Landolphia buchananii and *Jasminium abyssinicum* are common lianas and *Hippocratea goetzei, Oxyanthus speciosus*, *Oncinotis tenuiloba*, *Tiliacora troupinii*, and *Hippocratea africana are* common shrubs found in this forest type*.* Epiphytes are very common and include *Peperomia tetraphylla*, *Asplenium sandersonii*, *Loxogramme lanceolata*, *Aerangis luteoalba*, *Arthropteris monocarpa*, and *Asplenium aethiopicum*.

2.7. Carbon stock studies in Ethiopia

National carbon estimating is very important to know carbon stock for the purpose of carbon trading and to evaluate the magnitude of carbon fluxes between forest ecosystems and the atmosphere. But, it is an expensive task especially for countries like Ethiopia. Ethiopia has only limited number of studies regarding carbon stock (Adugna Feyissa *et al.,* 2013; Belay Melese *et al.*, 2013).

The study done by (Adugna Feyissa *et al.,* 2013) at Egdu forest resulted that the AGC, BGC and carbon in the soil revealed a direct relationship with altitude, but carbon stock in the litter showed an irregular pattern with altitude. The carbon stock of the forest was considered as large. The mean carbon stock of the forest in ABG, BG, litter and soil with a total depth of 30 cm pools was 614.72±35.79 t ha^{-1} (ranging from 182.6 to 1416 t ha^{-1}).

A similar research work done by Belay Melese *et al.* (2013) at Arba Minch riverine forest also revealed that the mean carbon stock density was considered to be large (i.e. 583.27 t ha^{-1}). The mean carbon is high in the lower and low in the middle altitude. On the other hand, the amount of carbon stock in all carbon pools except litter pool was higher on the southern aspect as compared to other aspects. Other study done by Mesfin Sahle (2011) at Menagesha Suba State Forest based on Remote Sensing, GIS and Ground Survey the total estimated forest carbon sequestration potential of the forest in year between 1984 and 2005 were 35 tons per ha. During 1984 – 2005, plantation in Menagesha Suba State Forest has resulted in increase in forest carbon stocks of about 113,766 tons.

Chapter 3

3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1. Geographical location

The study site is located in Jimma Zone, Gera District of Oromia Region. It is located 445 km far from Addis Ababa. The Forest is part of the Belete-Gera National Forest Priority Area. It is geographically located in between 7^{0}13’–7^{0} 56′ N and 35^{0} 57’–37^{0} 37′ E (Figure 1 below). The Forest is administered by Oromia Forest and Wildlife Enterprise. The elevation of the study area ranges from 1400–3000 m a.s.l. (secondary information from Gera District Agricultural Office), but the elevation of the Forest at which sample data taken were ranges from 1819-2539 m a.s.l.

The area is known by its coffee and honey production and is one of representative coffee agro-ecosystems in the country. Coffee occurs in a wild state (sparse shrubs in the forest that are harvested without any management) and in semi forest coffee system (stands with high coffee cover managed with enrichment planting, removal of competing shrubs, and felling of some larger trees to get a higher yield) (Hylander *et al.* 2013). The coffee in forest margins is mostly of wild origin, but improved cultivars are also planted occasionally. In southwestern Ethiopia, the semi forest coffee system is the most dominant system coffee of production, and it contributes much to the local and national economy.

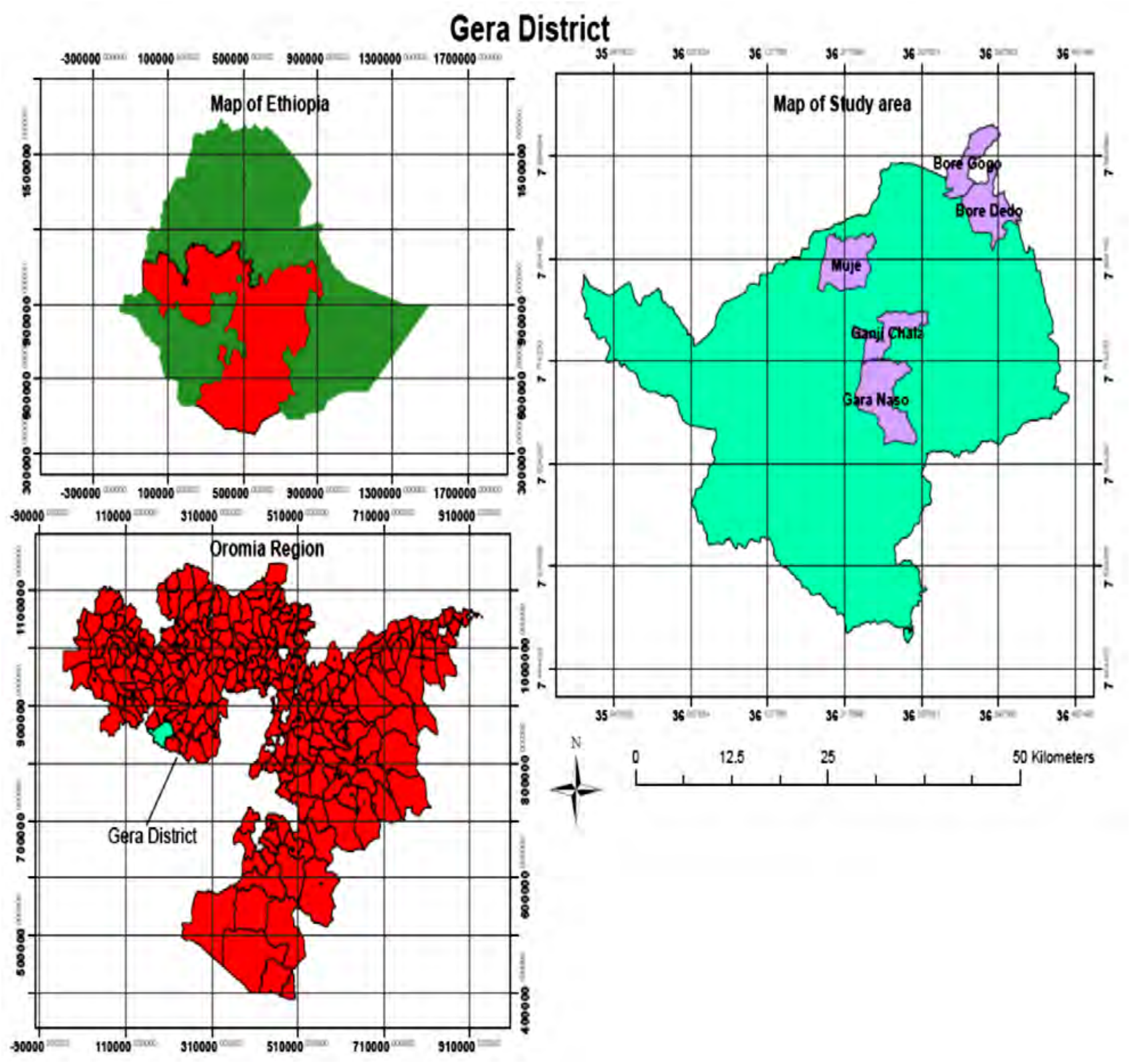


Figure 1 Map of Ethiopia showing Oromia Region and the study Area (Gera forest)

3.1.2. Climate

A twenty years climate data (rainfall and temperature) were taken from Ethiopian Metrological Agency (EMA) for Agaro station, the nearest weather station to the study site. The annual rainfall in the study area ranges from 746 – 2152 mm. Most rain falls between May and September, although occasional rainfall occurs throughout the year and the dry months in the study area are December to February (Figure 2).

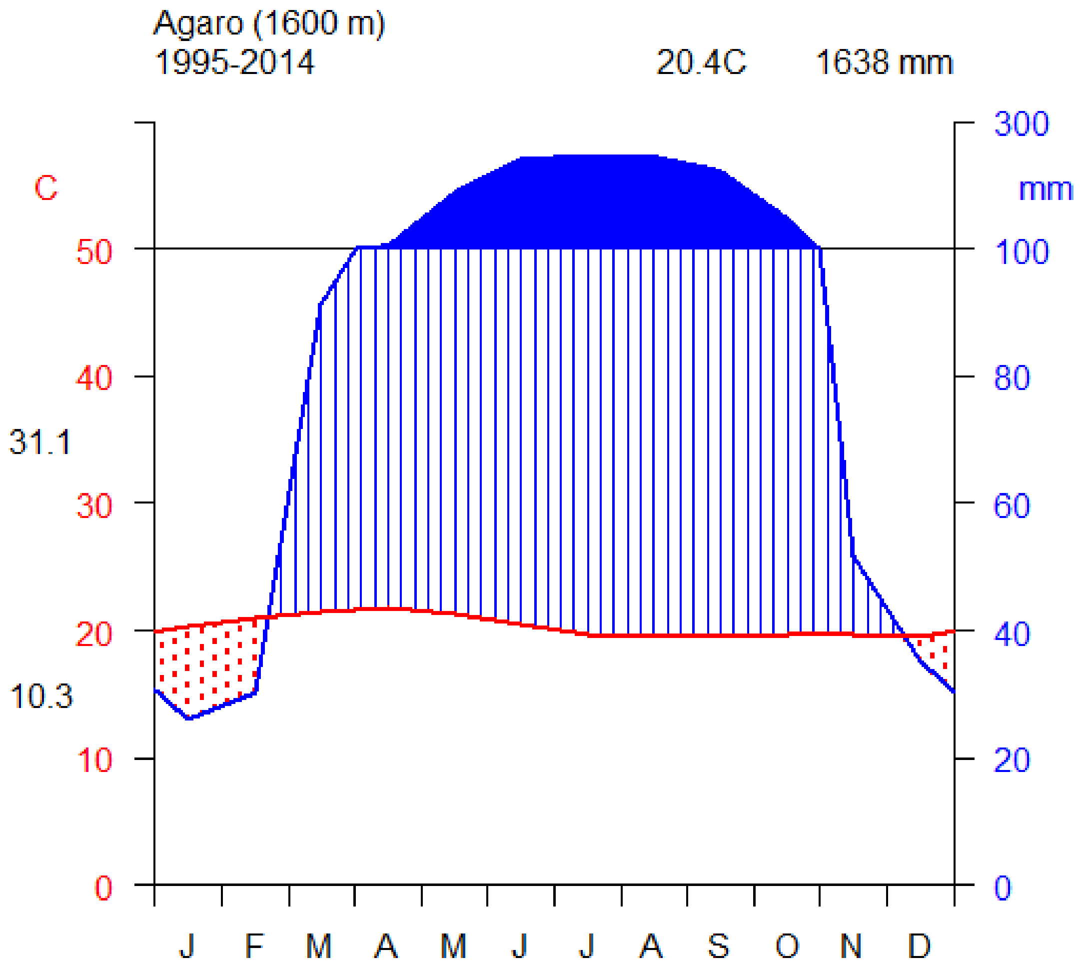


Figure 2 Climadiagram showing mean monthly rainfall and temperature of Agaro (the nearest metrological station for study area) from 1995-2014

3.1.3. Topography

The study area has an undulating terrain with high altitudinal variation between 1400–3000 m a.s.l. and it is characterized by mosaics of annual crop fields and large and small forest patches. Agro-ecological zone of the study area is categorized into Dega, Weina Dega and Kolla (secondary information from Gera District Agricultural Office). The main crops produced in Dega agro-ecological zone includes: *Zea mays, Eragrostis tef, Triticum aestivum Pisum sativum, Vicia faba* and *Hordeum vulgare. Persea americana* is a common fruit tree in the study area. *Sorghum bicolor, Guizotia abyssinica, Oryza sativa, Arachis* *hypogea, Carthamus tinctorius* are common oil crops produced at kola agro ecological zone.

3.1.4. Vegetation

There are different types of vegetation in the study area. These include agroforestry, plantation forest, natural coffee dominated forest, *Bersama abyssinica* dominated forest, bamboo forest and *Hagenia abyssinica* dominated forest. The common tree species grown in areas where agroforestry system is practiced include: *Acacia abyssinica, Erythrina brucei* and *Albizia gummifera*. *Grevillea robusta* and *Cupressus lustanica* are widely planted tree species in the plantation forest. Whereas the dominant tree species at natural coffee dominated forest are *Syzygium guineense*, *Olea capensis*, *Croton macrostachyus* and *Ficus sur*. *Bersama abyssinica, Pouteria adolfi-friederici, Ekebergia capensis* and *Prunus africana are the dominant tree species at Bersama abyssinica* dominated forest. *Arundinaria alpina* and *Hagenia abyssinica* are the characteristic tree species at higher altitude (altitude > 2600 m a.s.l.).

3.2. Sampling Technique

Reconnaissance survey was conducted on November 10-15, 2014. All secondary data pertinent to this study (agro-ecological zone type, the type forest distribution, the type of crops produced from each agro-ecological zone and the elevational variation of the district) were collected from Gera District Agricultural Office and the local people who know the forest well through interviews.

The natural forest in the study area naturally exists in to forest with coffee and forest without coffee system. Therefore, samples were taken from these to forest strata. In the present study the forest with coffee system was considered as lower (1819-1228 m a.s.l.) altitude and the forest without coffee system was considered as higher (2334-2539 m a.s.l.) altitude. Stratified systematic sampling method with nested plot approach was used to collect data. Nested plots are composed of several plots (typically two to four, depending upon forest structure), each of which should be viewed as separate (Pearson *et al*, 2005). These contain smaller sub-units of various shapes and sizes within one main plot. This approach is designed to collect discrete data for stands that had a range of stem diameter class or uneven aged forest type.

Ten sampling sites were taken by dropping a regular interval of 100 m elevation gradient starting from 2439 to 1819 m at sea level (a.s.l). The remaining three sampling sites were taken just by considering aspects due to unable to go beyond 2539 (m a.s.l.) because of inaccessibility of the area. Therefore, the altitudinal variation between these sites is not uniform. From each sampling sites three rectangular quadrats were established, the interval between two consecutive quadrats were 100 m apart from each other. Quadrats of rectangular shape, which is important to capture heterogeneity of the forest, were used from each sampling sites having the size of 20m x 100m (2000 m^2) (Figure 3), which was adopted from Hairiah *et al.* (2001). Accuracy can be improved if trees with a DBH > 30 cm are sampled in a 20m x 100 m sampling area.

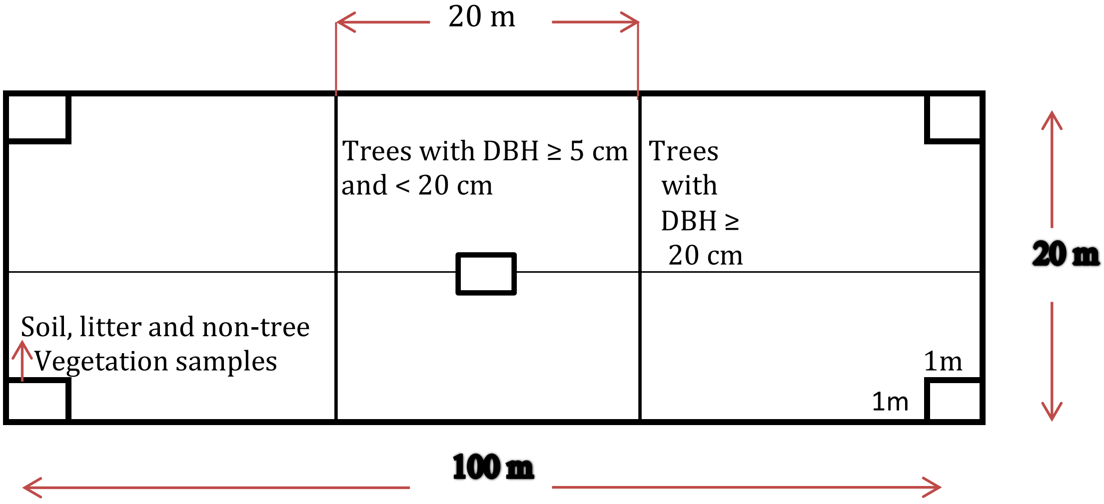


Figure 3 Sampling design used in the study area. Where trees with DBH ≥20 cm on the 20mx100m, trees with DBH ≥ 5 cm and < 20 cm within 20mx20m and soil, litter and non-tree Vegetation samples within 1m x1m plots.

3.3. Data Collection

Data were collected from November 16 – 30, 2014 from five Peasant Associations (Kebeles): Gara Naso, Ganji Chala, Muje, Bera Gogo and Bore Dedo. The Forest stratum with coffee (altitude ranges from 1819-2200 m a.s.l.) is located in the first two Peasant Associations. On the other hand, the Forest stratum without coffee (altitude ranges from 2334-2539 m a.s.l.) is located in the remaining three Peasant Associations.

Data for estimation of AGB in this study were collected by using both destructive and nondestructive sampling: for the litter, non-tree vegetation (NTV) and the trees respectively. DBH and height of all the trees and shrubs with DBH between 5 cm and 20 cm were measured in the smaller quadrats (20m x 20m) and trees with DBH ≥ 20 cm were measured on the larger quadrats (20m x 100 m).

Tree diameter at breast height (DBH) was measured by using caliper for those trees which have a circular trunk and by diameter tape for those trees which have buttressed trunks. If the tree is forked at or below the DBH, diameter was measured just below the forked point as suggested by Pearson *et al.* (2005). Individual tree height was estimated subjectively, because tree height measurement by hypsometer was difficult in such closed forest.

3.3.1. Wood density

Wood specific densities of the collected woody plant species were collected as secondary information from ICRAF wood density database (www.worldagroforestry.org) and Global wood density database (Zanne *et al.*, 2009). In this study, total numbers of forty woody plant species were recorded. Of which the basic wood density of twenty five (62.5%) woody plant species were collected as species specific basic wood density from Global Tree Wood Density data base website. The basic wood densities of eight woody plant species (20%) were taken as the mean value of basic wood densities of other species grouped in the same genus from the same data base. The basic wood densities of four woody plant species (10%) were taken from the mean value of species which are grouped to the same genus from ICRAF website. The basic wood densities of three woody plant species (7.5%) were taken as arithmetic mean value for tropical tree species (0.55 g cm^{-3}). If wood density values for corresponding forest types are not available an average wood density value can be used. According to Sharma *et al.* (2013), an average basic wood density for tropical trees is 0.55 g cm^{-3}. On the other hand, according to Ponce-Hernandez (2004), it is 0.61 kg m^{-3}. Therefore, in the current study the former value is considered as basic wood density for those species which have no specific basic wood density. This is due to it comes as the recent information than the later value. From both database websites, many of the woody species have more than one specific wood density values. In this case the mean value of a given species can be used (Chave *et al.,* 2014; Kamelarczyk, 2009), and for those woody plant species which have no exact specific wood density, genus mean value or mean value of forest type or continent can be used (Figure 4).

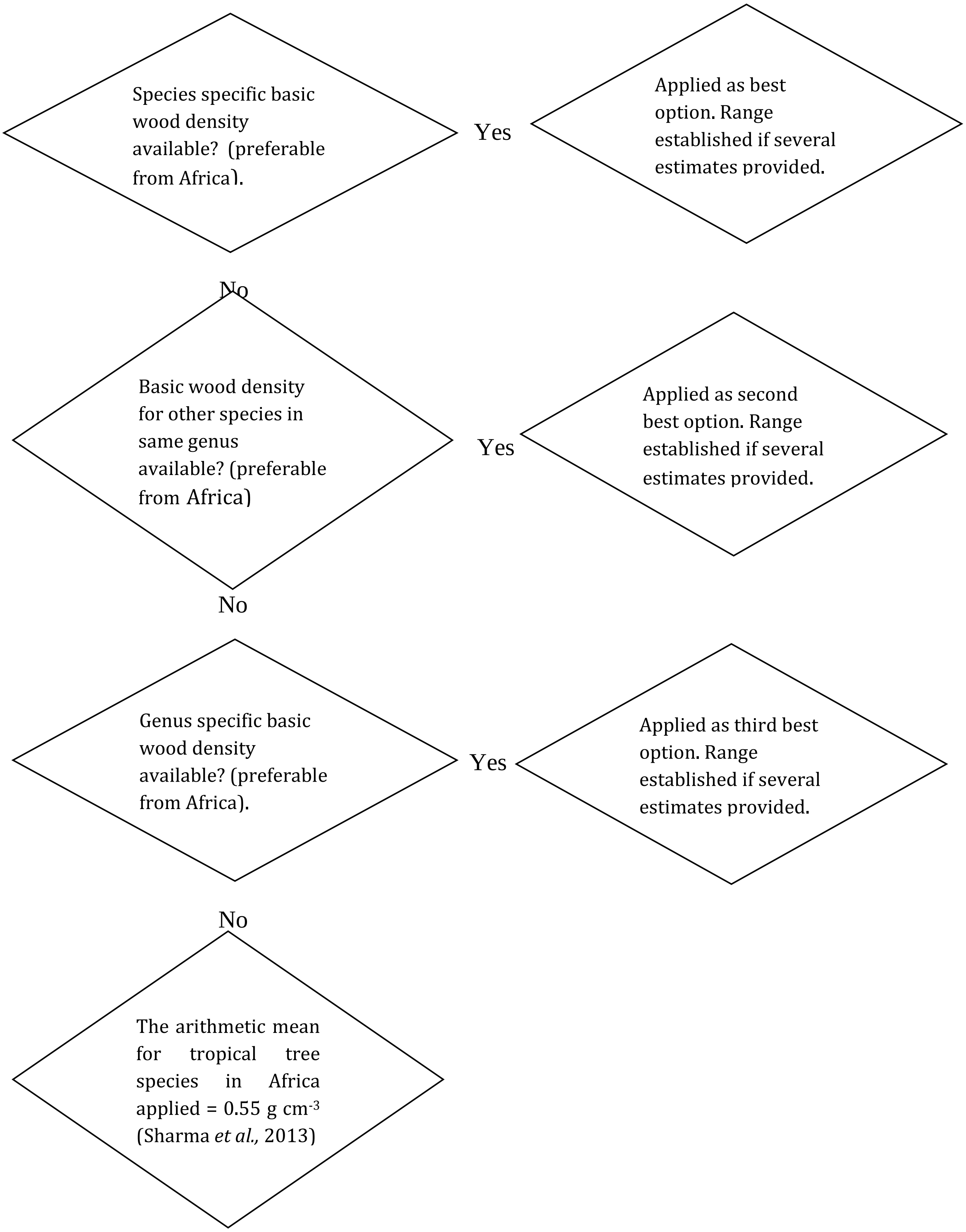


Figure 4 Decision paths for assigning basic wood density values to species (Source: Kamelarczyk, 2009)

Carbon stock in NTV carbon pool was estimated by clipping all woody plant species with diameter < 4.9 cm and other non woody plant species at ground level cut into pieces and put into a plastic bag. The fresh weight of the mixed composites of the five subplots (four at the corners and one at the center) within the main plot was recorded. Then 100 g of well mixed subsample from composite was taken and brought to Addis Ababa University Ecology Lab, Addis Ababa for dry biomass calculation. Then the subsamples were oven dried and dry mass recorded. The same procedure was followed for litter sample for fresh and dry weight biomass determination.

Procedures

Step 1 The frame (1mX1m) was placed at the corner of the quadrat where non tree vegetation samples were taken,

Step 2 All vegetation within the frame at ground level was clipped. All vegetation falling outside the boundaries of the subplot or frame (even they grown inside the subplot) were excluded, and

Step 3 The fresh weigh of sample weighed and took a well-mixed subsample for determination of dry to wet mass ratio. The subsample weighed in the field, and then oven dried at 70°C. Finally, dry mass of non-tree vegetation sample was calculated. The same procedures used for liter dry mass calculation.

Similarly, soil samples were taken from the smaller subplots to a depth of 30 cm. Two types of soil samples were taken; one for bulk density by using a 5 cm diameter and 5 cm height core sampler, and the other for chemical analysis by using soil auger.

The soil samples from the four corners and the center of the plots were composited and brought to Bedele Regional Soil Laboratory Center, which is located at Bedele, Ilu Ababora Zone, Southwest Ethiopia. The soil samples taken for bulk density calculation were oven dried at 105^0C for 48 hours as recommended by Pearson *et al.* (2005) at Addis Ababa University Ecology Lab, Addis Ababa. On the other hand, the samples collected for chemical analysis were dried by air, crushed the clods by hand to less than 2 cm to accelerate the drying process, grinded by mechanical grinder and sieved by a 2 mm sieve mesh.

According to Zhu *et al*. (2010), the one among many factors that affect the amount of carbon stocks in a given forest is anthropogenic disturbance level. Therefore, if possible it is worth to classify a given forest into disturbance regime in order to quantify accurate carbon stock. In the current study level of anthropogenic disturbance were recorded where the sampling plots are established and ranked subjectively. The disturbance was ranked 'Very high' when there was a recognition of charcoal production, cutting of trees, debarking of tees, grazing in and around the plot and short distance of it from agricultural land and village. The disturbance was ranked as 'High' when cutting, debarking, short distance of it from village and grazing was recorded in the plot.

The disturbance was ranked as 'Medium' when slashing and canopy opening for the purpose of increasing coffee production was recorded in and around the plot; and finally the disturbance was ranked as 'Less' when the sampling plot was far from agricultural land and village and absence of above listed disturbance factors.

Plant specimens pressed, air dried and brought to Addis Ababa University for identification. The plant specimens were dried in the drying room and woody plant species identification was done by using Flora of Ethiopia and Eritrea and authenticated plant specimens in the ETH.

3.4. Data analysis

The data collected from the field were analyzed by using R version 3.0.2 and Minitab version 16. Moreover, appropriate allometric equation models are important tools that used to convert field data (species, basic wood density, DBH and height) into the oven-dried weight of biomass and carbon estimates (Brown *et al*., 2004).

At regional or global scales, models based upon only DBH may have a greater associated uncertainty than more complex models especially regions for which local equations are not available (Alvarez *et al.,* 2012). According to these authors, architectural differences in branches, roots or crowns along with tree damage could also explain the failure of the idealized predictions using exponent models. To solve this inconvenience, Chave *et al.* (2005) included wood density and H within their models and proposed a global forest classification system that contains three climatic categories (dry, moist, and wet) to account for climatic constraints determining the AGB variation (Alvarez *et al*., 2012).

Wood density is an important parameter of tree to improve the accuracy of biomass estimation (Basuki *et al.,* 2009) and increases the acceptance of the method by IPCC. Currently from many published allometric equations, pan tropical models developed by Chave *et al.* (2005) are widely considered to be the best approximation for sites for which local equations are not available (Alvarez *et al.*, 2012). It can show that the predictive power of their global model differs among sites; for some regions, the relative error could also be low. But, these models may lead to biased AGB stock estimates in some under sampled vegetation types (Chave *et al.,* 2014) and data were absent from Africa.

The allometric equations developed by Chave *et al.* (2014) overcome the limitations of the models developed by Chave *et al*. (2005) by producing numerous new tree harvest dataset notably from Africa and samples were increased from previously under sampled sites. The most important predictive variables for forest biomass estimations were DBH, H, basic wood density (ρ), and forest type. Basic wood specific density plays a great role predicting accurate biomass in all regressions (Chave *et al.,* 2005).

3.4.1. Carbon Stock Estimation

Diameter measurements and/or estimates of height of tree can be converted into units of biomass using allometric equations (Clark and Kellner, 2012). The overall carbon stocks (carbon density) of a given forest obtained from adding all the carbon stocks in different carbon pools together can be extrapolated in to a hectare or landscape base multiplying by biomass expansion factor (BEF). The dry biomass obtained by using allometric equations can be converted in to carbon except for soil, which usually measures carbon directly. Carbon is 50% of the dry biomass of an individual tree (Swai *et al*., 2014; Zhu *et al.,* 2010; Basuki *et al*., 2009; Gibbs *et al*., 2007; Pearson *et al*., 2005; FAO, 2004 and Brown, 1997).

3.4.1.1. Aboveground Biomass

The current study used the equation developed by Chave *et al*. (2014) (eq. 1) to estimate the AGB of the Forest which relates DBH, tree height and wood specific density as dependent variables.

$$\mathbf{AGB_{est} = 0.0673(\rho HD^2)^{0.976} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq. 1}}$$

Where AGB_{est} = above ground biomass (kg), D =DBH (cm), H = height (m), and ρ = basic wood density (g cm^{-3}).

3.4.1.2. Litter Layer

Litter sample were collected from 1 m^2 sized subplots four at the edges and one at the center of each main quadrats. Then the subsamples weighed and took 100g from a well-mixed composite of the collected sample. They were brought to Addis Ababa Ecology Lab, Addis Ababa for dry to fresh biomass determination. The dry litter biomass was calculated using the following formula (Pearson *et al*., 2005):

$$B_L = \frac{\textbf{W subsample (dry)}}{\textbf{W subsample (fresh)}} \text{ X } \textbf{W Field} \text{ X } \textbf{BEF} \text{ --eq. 2}$$

Where, B_L is the litter dry mass (t ha^{-1})

W subsample (dry) - the oven dry weight of subsample

W subsample (fresh) - the fresh weight of subsample

W Field - the fresh weight of sample collected from the sampling area and

BEF - biomass expansion factor

Note: carbon stock of the litter was taken as 50% of its dry biomass.

3.4.1.3. Non-tree Vegetation (NTV)

All herbaceous and other woody vegetation with DBH < 4.9 cm in diameter except coffee were cut into pieces and recorded the fresh weight collected from 1 m^2 following the same procedure with that of the litter. Some authors (Macdicken, 1997; Swai *et al*., 2014) recommend that herbaceous and other woody vegetation with DBH ≤ 2 cm in diameter are considered for this carbon pool and DBH ≥ 10 cm for AG carbon pool. But, in this study DBH ≥ 5 cm were considered for AG carbon pool and DBH < 4.9 cm were considered for herbaceous and other woody vegetation (NTV) carbon pool just to make it more inclusive.

3.4.1.4. Belowground Biomass

Since direct measurement of BGB is expensive and time consuming task, it is derived from AGB (shoot root ratio). The BGB is 20% of AGB (Gibbs *et al.*, 2007; and Ponce-Hernandez, 2004):

$$\mathbf{BGB = 0.2\ X\ AGB} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ \mathbf{eq.\ 3}$$

Where BGB – belowground biomass, AGB – aboveground biomass

Extrapolating carbon stocks from a per plot basis into a per hectare basis requires the use of expansion factors. This standardization is required so that results can be easily interpreted and also compared to other studies. According to Pearson *et al.* (2005), the expansion factor is calculated as the area of a hectare in square meters divided by the area of the sample in square meters, that is:

$$\textbf{Biomass Expansion Factor} = \frac{\mathbf{10000\ m^2}}{\textbf{Area of plot,frame or soil core } \mathbf{m^2}} \ \ldots\ldots\ldots\ldots\ldots \mathbf{eq.\ 4}$$

3.4.1.5. Soil Organic Carbon

For convenience and cost-efficiency, soil sample is advised to sample to a constant depth, maintaining a constant sample volume rather than mass (Brown *et al.*, 2004). It can be collected systematically within 1 m^2 quadrats nested in the main plots for determination of carbon stock (Swai *et al.*, 2014). Soil bulk density is necessary to calculate soil organic carbon. In this study it was calculated as follows (Pearson *et al.*, 2005; Brown *et al.*, 2004):

$$\textbf{Soil bulk density } (\mathbf{g\ cm^{-3}}) = \frac{\textbf{Oven−dry sample mass (g)}}{\textbf{Sample Volume } (cm^3)} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{eq.\ 5}$$

The carbon stock of SOC was estimated by following Pearson *et al.* (2005) equation:

$$\mathbf{SOC = BD\ X\ d\ X\ \%\ C\ X100} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{eq.\ 6}$$

Where, SOC = soil organic carbon (t ha^{-1}), BD = soil bulk density (g cm^{-3}), D = the total depth at which the sample was taken (30 cm), and %C = carbon concentration (%) determined in the laboratory.

The Volume of the soil was calculated using the formula (Pearson *et al.*, 2005):

$$\mathbf{V = h\,\pi r^2} \quad \text{………………………………………………………………………………} \quad \textbf{eq. 7}$$

Where h= height of core sampler in cm, r= radius of core sampler in cm and V= Volume of the soil in cm^3.

Finally the percent of carbon in the soil samples were calculated as follows:

$$\mathbf{\%C = N} \text{ X } \frac{V1-V2}{S} \text{ X } \mathbf{0.39mcf}$$

Where: N=normality of ferrous sulphate solution (from blank titration)

V1= ml ferrous sulfate solution used for blank

V2= ml ferrous sulfate solution used for sample

S= weight of air-dry sample of soil in gram

mcf = Moisture correction factor (1.3)

Note: in this method about 77% of C is oxidized by potassium dichromate, so a correction factor of 100/77 = 1.3 is used the calculation. The value of 77% is only approximation since the ineffectiveness of composition varies with the type of organic matter present.

3.4.1.6. Total Carbon Stock

The total carbon stocks (carbon density) were calculated by summing up all the carbon stocks of each carbon pools of the forest (Pearson *et al.,* 2005). The total carbon stock was then converted to tons of CO_2 equivalent by multiplying it by 44/12, or 3.67 (Pearson *et al.*, 2007). Carbon stock density of the study area could be calculated as:

$$\textbf{C density = AGC + BGC + LC + NTVC + SOC} \quad \text{…………………………………………} \textbf{eq. 8}$$

Where: C density = the summed carbon stocks in all carbon pools (t ha^{-1}), AGC = aboveground tree carbon (t ha^{-1}), BGC = belowground carbon (t ha^{-1}), LC = litter carbon (t ha^{-1}) NTVC = non-tree vegetation carbon (t ha^{-1}) and SOC = Soil organic carbon (t ha^{-1}).

CHAPTER 4

4. RESULTS

4.1. Woody plant species list and frequency distribution in the study area

Myrtaceae, Oleaceae, Euphorbiaceae and Moraceae were the dominant plant family recorded at the lower forest stratum in their increasing order. Whereas Melianthaceae, Euphorbiaceae, Rosaceae and Myrtaceae were the dominant plant family recorded at the higher forest stratum in their increasing order. The distribution of plant species in the Forest showed variation with elevation. The diversity of plant species in the Forest is greater in the lower forest strata or forest with coffee (1819-2200 m a.s.l.) than higher forest strata or forest without coffee (2334-2539 m a.s.l.). The frequencies of collected woody plant species were illustrated in the following graphs (Table 2 and 3). Figure 2 showed the frequencies of woody tree species at lower forest strata and Table 3 depicts the frequencies of woody tree species at higher forest strata.

The characteristic woody plant species recorded at lower forest stratum include *Albizia gummifera, Coffea arabica, Ehretia cymosa, Olea capensis, Olea welwitschii* and *Sapium ellipticum.* DBH is the most frequently measured and important tree parameter in forestry. So that it is worth to establish DBH class distribution graph. Accordingly, Figure 5 (a) and (b) show the diameter class distribution of woody plant species collected from higher and lower forest strata respectively.

Table 2 Frequency of woody plant species at lower forest strata (1819-2200 m a.s.l.)

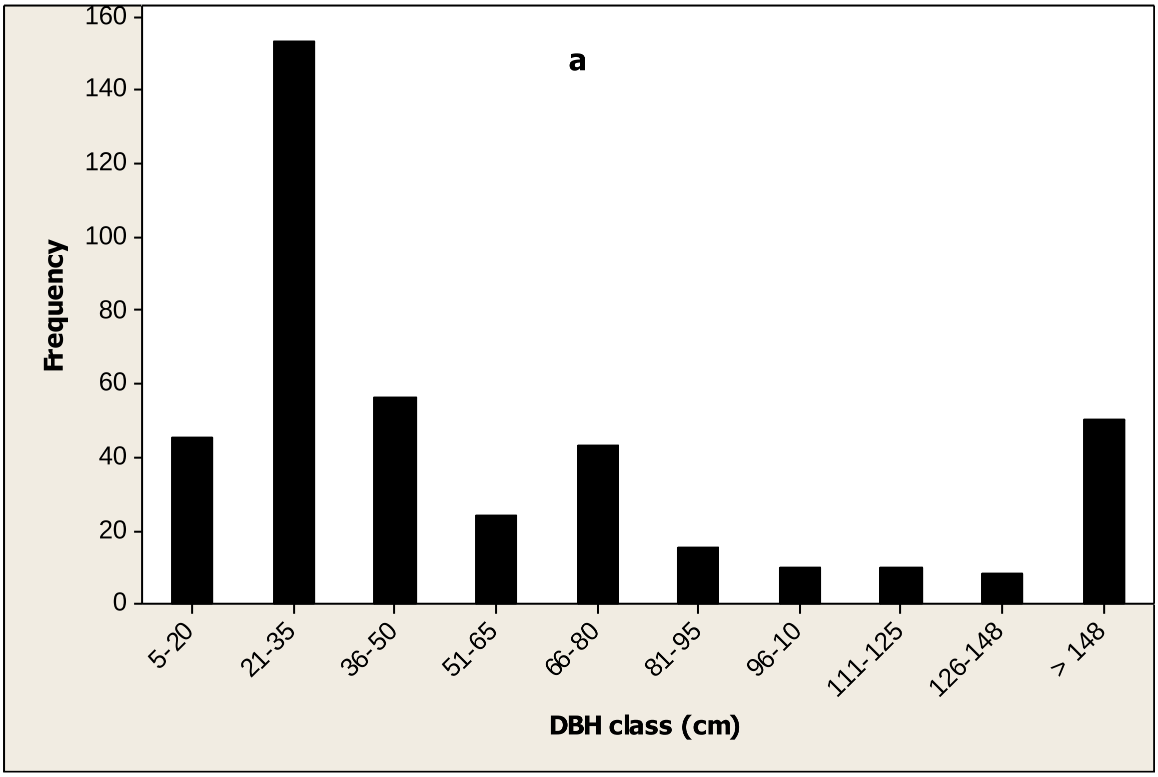
No	Scientific name	Frequency
1	*Albizia gummifera* C.A. Sm.	12
2	*Allophylus abyssinicus* (Hochst.) Radikofer	8
3	*Apodytes dimidiata* E. Mey. Ex Am.	19
4	*Bersama abyssinica* Fresen	10
5	*Byttneria catalpifolia* Jacq.	5
6	*Canthium oligocarpum* Hiern	5
7	*Cluasena anisata* Benth.	1
8	*Coffea arabica* L.	1
9	*Cordia africana* L.	17
10	*Croton macrostachyus* Del.	**31**
11	*Diospyros abyssinica* F. White	6
12	*Dombeya torrida* P. Bamps	2
13	*Dracaena afromontana* Mildbr.	4
14	*Ehretia cymosa* Thonn.	7
15	*Fagaropsis angloensis* Dale.	2
16	*Ficus sur* Forssk.	**31**
17	*Galiniera saxifraga* Bridson	8
18	*Gardenia ternifolia* Schumach. & Thonn.	6
19	*Macaranga capensis* Sim.	4
20	*Maesa lanceolata* Forssk.	3
21	*Millettia ferruginea* Bak.	22
22	*Maytenus gracilipes* Exell	8
23	*Olea capensis* L.	**37**
24	*Olea welwitschii* Gilg& Schellenb.	24
25	*Podocarpus falcatus* (Thunb.) R.B. ex. Mirb	2
26	*Polyscias fulva* Harms	12
27	*Prunus africana* Kalkm.	23
28	*Sapium ellipticum* Pax	10
29	*Schefflera abyssinica* Harms	4
30	*Syzygium guineense* DC.	**48**
31	*Teclea nobilis* Del.	25
32	*Trema orientalis* Bl.	14
33	*Vepris dainellii* Kokwaro	11
34	*Vernonia amygdalina* Del.	1
35	*Vernonia auriculifera* Hiern.	19
	Total	**443**

The frequency of woody plant species roughly shows which species can sequester more amount of carbon in the forest. In other words, the dominant tree species illustrated from Table 2 and 3 share the major part of biomass and carbon stock accumulations in the Forest.

Ekebergia capensis, Hagenia abyssinica and *Pouteria adolfi-friederici* are the characteristic woody plant species at higher forest stratum. The DBH of collected woody tree species in the field were distributed by diameter class. Tree species at higher forest strata have larger diameter class distribution than those of the plant species at lower forest strata. The presence of more tree species at the higher diameter class distribution implies that they have more amounts of biomass and carbon accumulation.

Table 3 Frequency of tree species at higher forest strata (2334-2539 m a.s.l.) in the study area

No	Scientific name	Frequency
1	*Allophylus abyssinicus* (Hochst.) Radikofer	9
2	*Apodytes dimidiata* E. Mey. Ex Am.	4
3	*Bersama abyssinica* Fresen	**145**
4	*Canthium oligocarpum*	13
5	*Canthium oligocarpum* Hiern	**103**
6	*Ekebergia capensis* Sparrm	5
7	*Ficus sur* Forssk.	7
8	*Hagenia abyssinica* I.F. Gmel.	7
9	*Macaranga capensis* Sim.	1
10	*Millettia ferruginea* Bak.	3
11	*Polyscias fulva* Harms	1
12	*Pouteria adolfi-friederici* Baehni	10
13	*Prunus africana* Kalkm.	47
14	*Schefflera abyssinica* Harms	3
15	*Solanecio gigas* C. Jeffrey	5
16	*Syzygium guineense* DC.	36
17	*Teclea nobilis* Del.	3
18	*Vernonia amygdalina* Del.	9
19	*Vernonia auriculifera* Hiern.	3
	Total	**414**



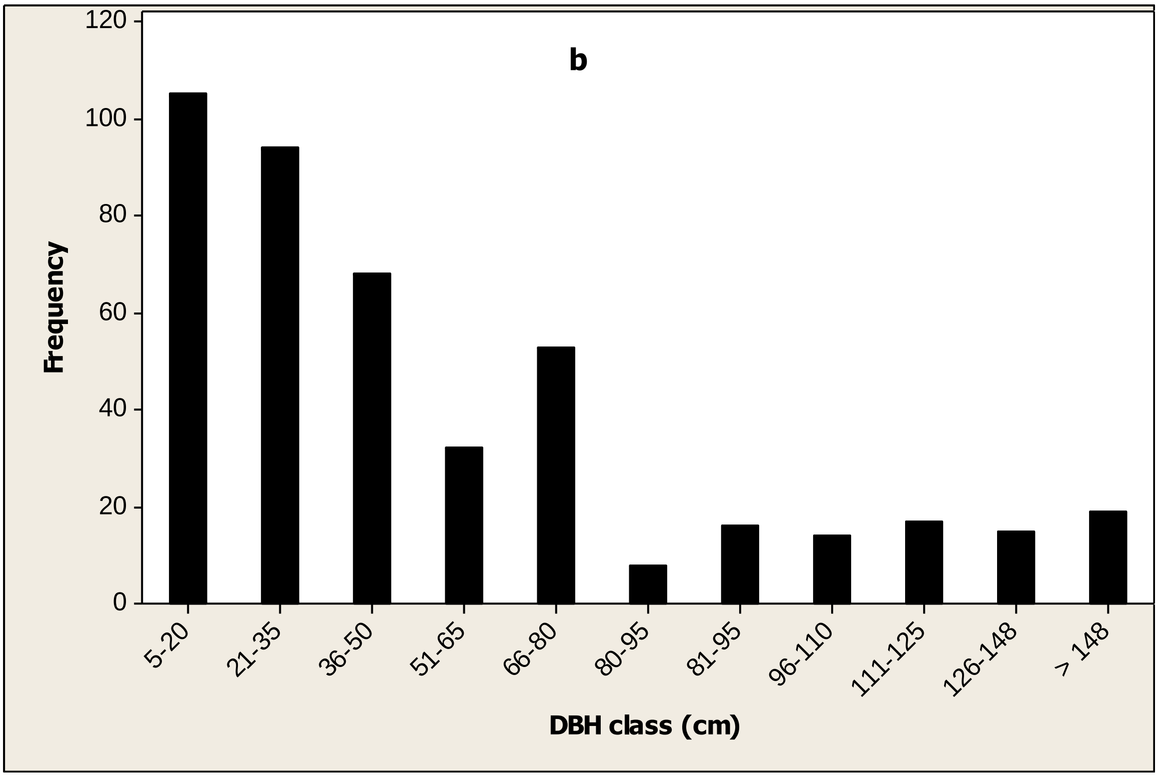


Figure 5 Diameter classes of woody plant species and their frequencies (a) at higher altitude (b) at lower altitude in the study area

4.2. Aboveground carbon

The mean AGB and AGC of the present study was 210.70 t ha^{-1} and 108.86 (t ha^{-1}) respectively. The amount of AGC in the present study was estimated along altitude. The result shows it had an irregular pattern with increasing altitude at plot level (Figure 8). For instance, the highest carbon stock was recorded at lowest altitude (1819 m a.s.l.) and the lowest carbon stock was recorded at higher altitude (2445 m a.s.l.). But, it showed a distinct variation with altitude at strata level (i.e. higher altitude or forest without coffee sequestered more carbon stock than lower altitude or forest with coffee). Larger DBH class distribution, low species diversity and low tree density ha^{-1} were recorded in higher altitude while the reverses were recorded at lower altitude.

In addition to altitude, AGC was estimated with other factors: aspect and disturbance level. However, the variation is not statistically significant (p-value > 0.005). The highest AGC was recorded at east aspect and the lowest was at northeast aspect. On the other hand, it decreases with increasing disturbance level.

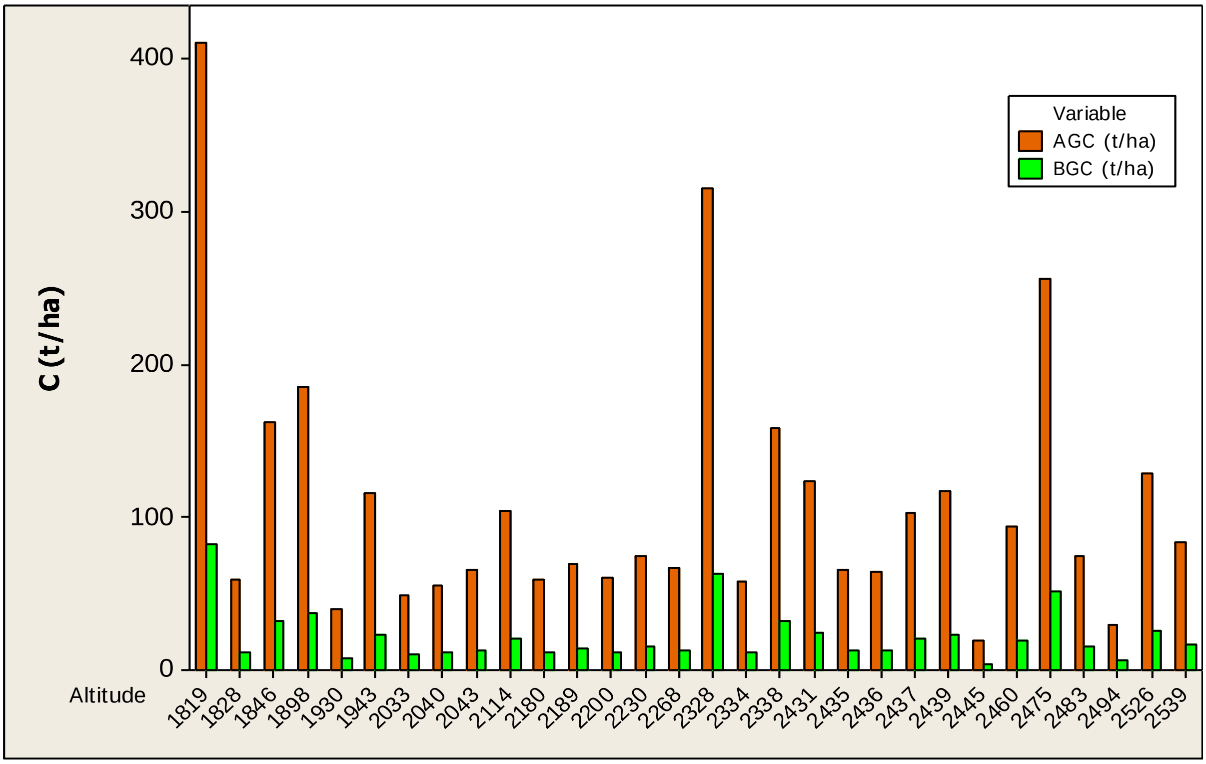


Figure 6 AGC and BGC stock along altitudinal gradient in the study area

4.3. Belowground carbon

The mean BGB and BGC of the present study was 42.14 t ha^{-1} and 21.77 (t ha^{-1}) respectively. Similar to AGC, the amount of BGC in this study was estimated against the altitude, aspect and disturbance level. Since BGC was derived from AGC it had the same increasing or decreasing pattern with AGC against all the independent factors. The variation of means in relation to these factors was not statistically significant (P-value > 0.005) Table 5 below.

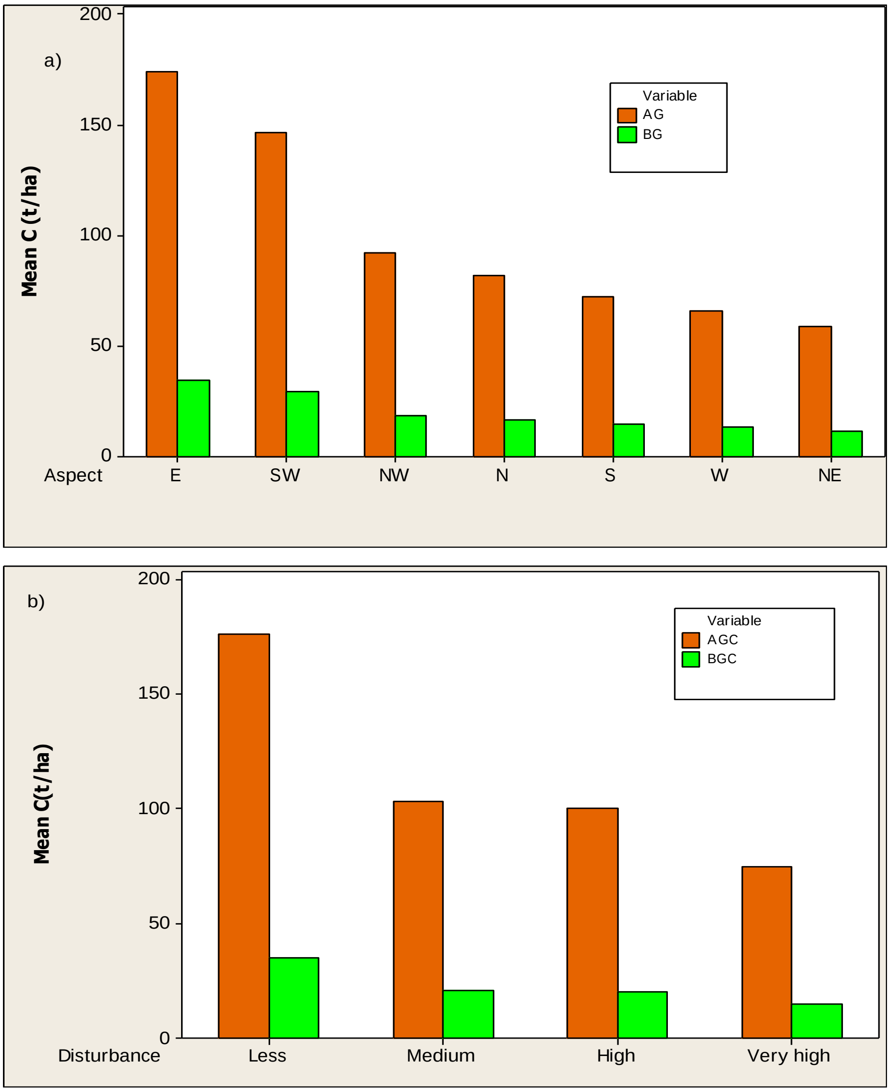
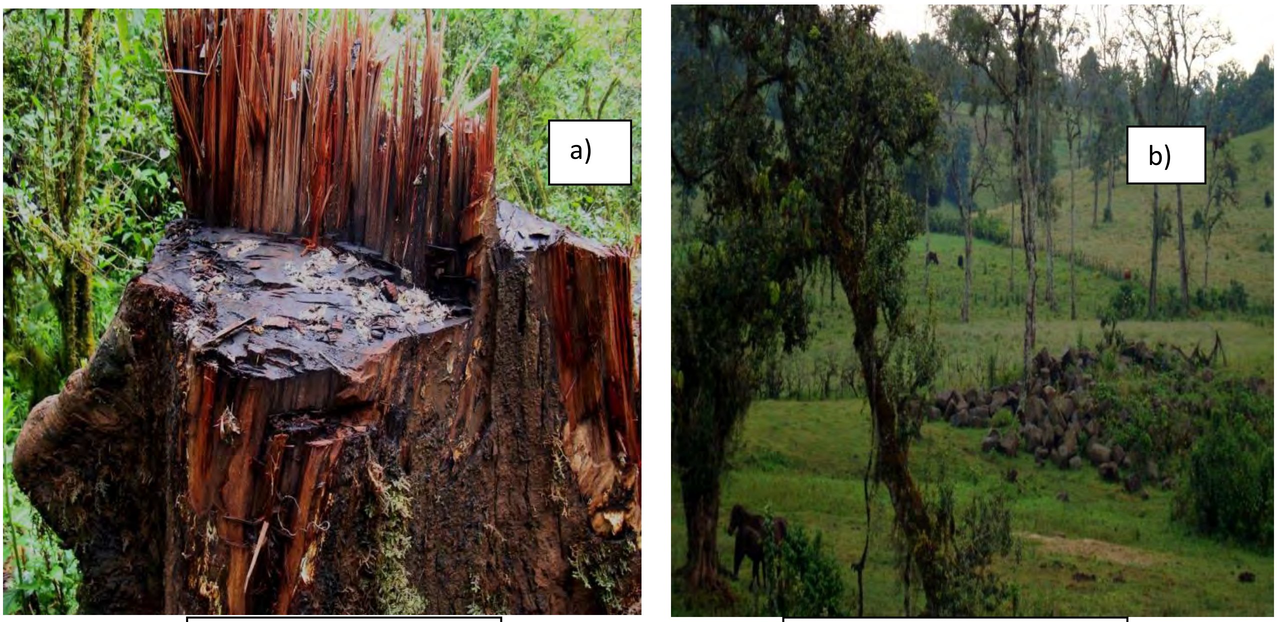
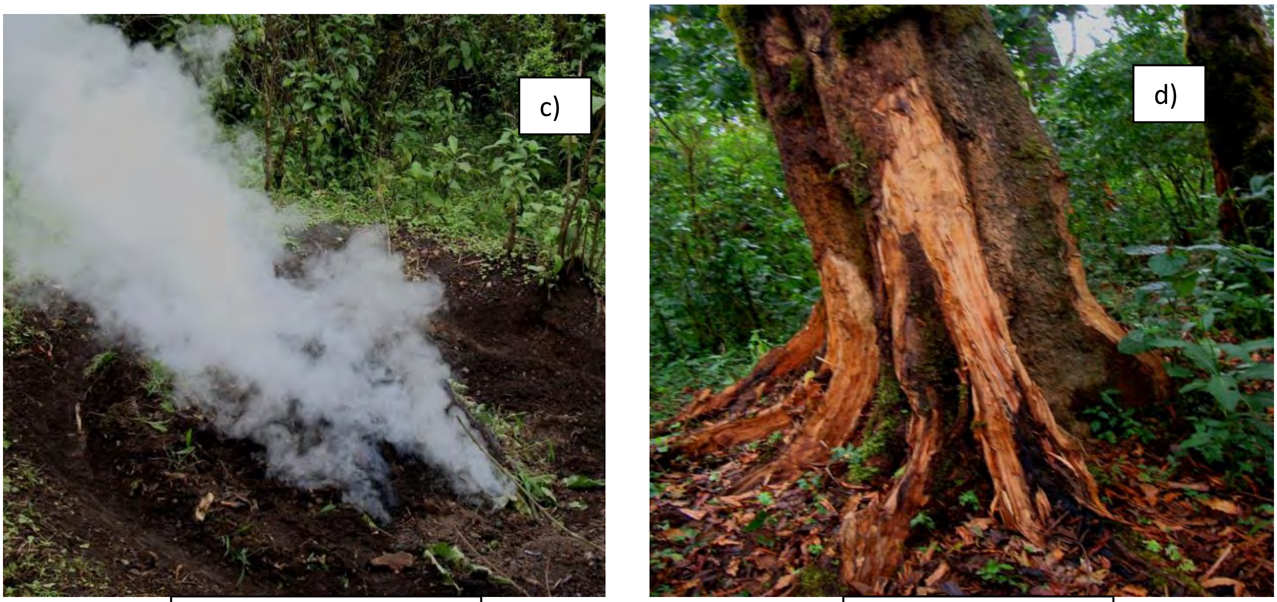


Figure 7 The relation between AGC and BGC and (a) aspect (b) disturbance level the study area



Tree cutting

Agricultural expansion



Charcoal production

Tree debarking

Figure 8 Different forms of anthropogenic disturbance in the Gera forest (Photo: Nesru, 2014)

4.4. Litter Carbon

The mean biomass and carbon stock in the litter carbon pool of the Forest was 10.16 (t ha^{-1}) and 5.08 (t ha^{-1}) respectively. The mean carbon stocks of the Forest in the litter carbon pool at higher and lower altitudes were 6.64 and 3.52 t ha^{-1} respectively. Even though the Forest stratum at higher altitude has more carbon stocks than the Forest stratum at lower altitude, it did not show a clear pattern with increasing altitude at plot level. For instance, the highest and the lowest carbon stocks were recorded at plots having an altitude of 2494 and 1846 (m a.s.l.) respectively.

The variation of means of litter carbon in different factors: altitude, aspect and disturbance level was statistically insignificant (P-value > 0.005) Table 3 below. The following Figures taken from the study area shows the effects of biomass due to anthropogenic factors.

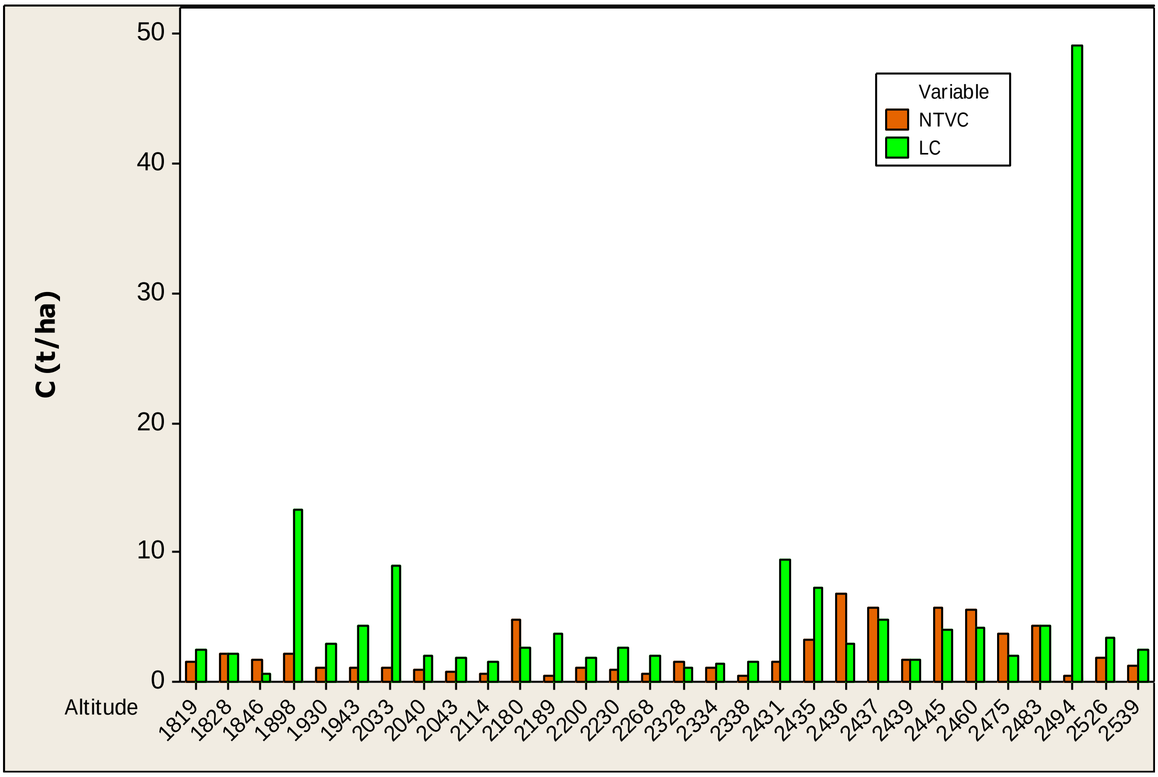


Figure 9 Litter carbon (LC) and Non-tree vegetation carbon (NTVC) along an altitudinal gradient in Gera forest

4.5. Non-tree Vegetation Carbon (NTVC)

The mean biomass and carbon of NTV carbon pool of the Forest was 4.40 (t ha^{-1}) and 2.20 (t ha^{-1}) respectively. NTVC showed a clear increasing pattern with increasing altitude at plot level.

NTVC stocks showed significant variation with altitude (p-value = 0.001) but not with aspect and disturbance level.

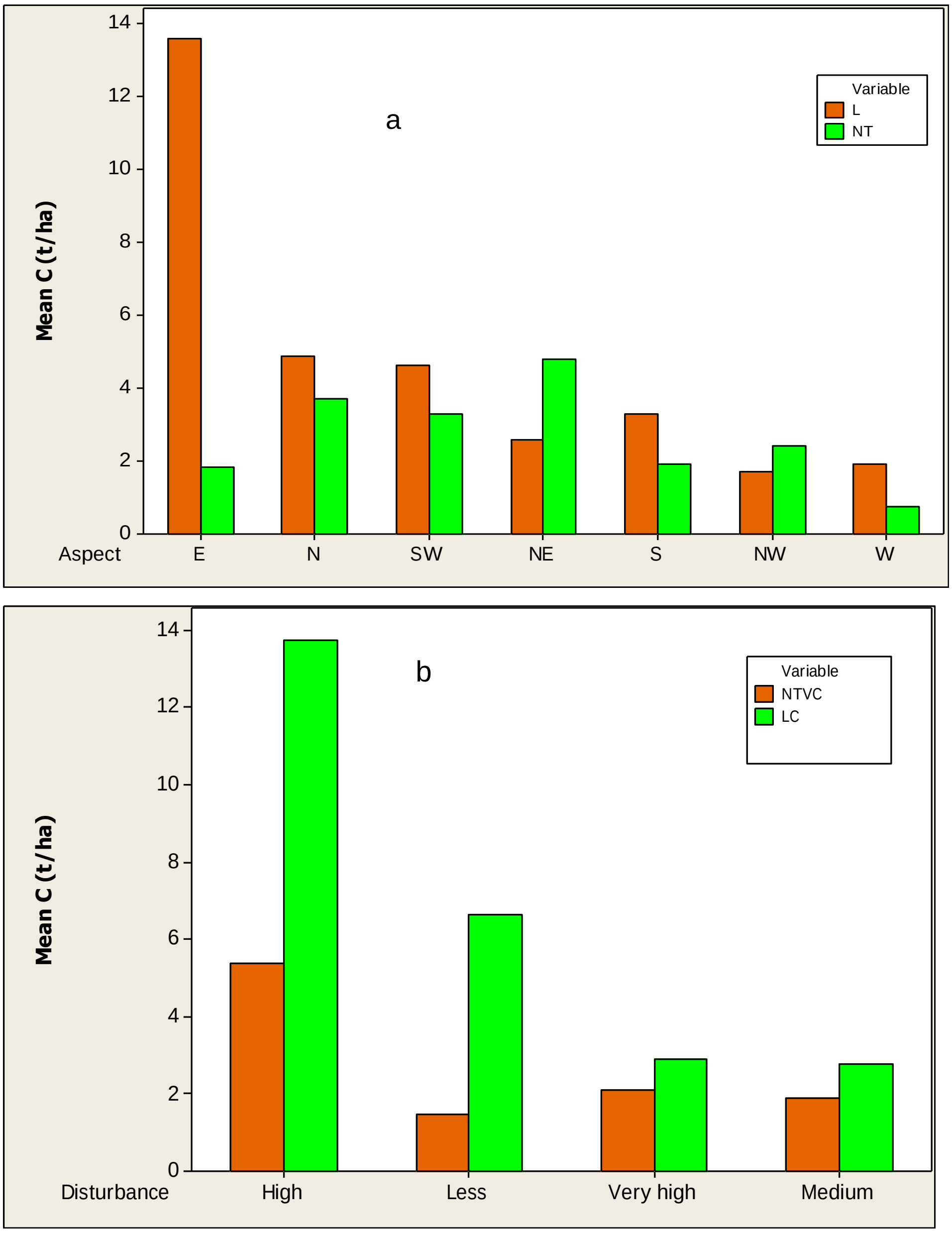


Figure 10 Litter carbon (LC) and non-tree vegetation carbon (NTVC) interaction with (a) aspect (b) disturbance level in the study area

4.6. Soil Organic Carbon (SOC)

The carbon stock estimated in the soil carbon pool was found to be the largest carbon stock in this study. The mean carbon stock in this carbon pool was 172.61 (t ha^{-1}). The mean carbon stocks of the Forest in the soil carbon pool at higher and lower altitudes were 207.03 and 138.20 t ha^{-1} respectively.

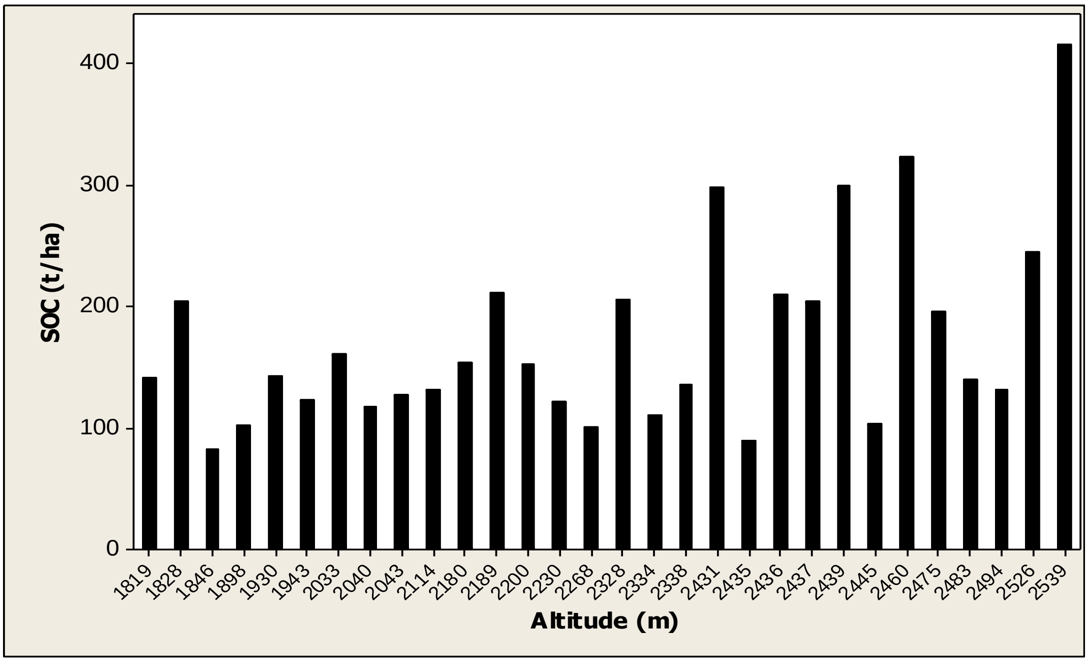


Figure 11 Soil organic carbons (SOC) along altitudinal gradient in the study area

The average bulk density of the soil in the Forest was 0.78 g cm^{-3}. In this carbon pool, the variation of means of carbon with respect to factors like: altitude, aspect and disturbance level was not significant (Table 3 below).

The following figures show carbon stock (t/ha) in soil organic matter carbon pool. Figure 11 a) designate the interface between soil organic carbon stock and different types of aspect which recorded at the sampling plots in the field. Whereas Figure b) illustrates interface between soils organic carbon stock with different levels of anthropogenic factors at plots in the study area.

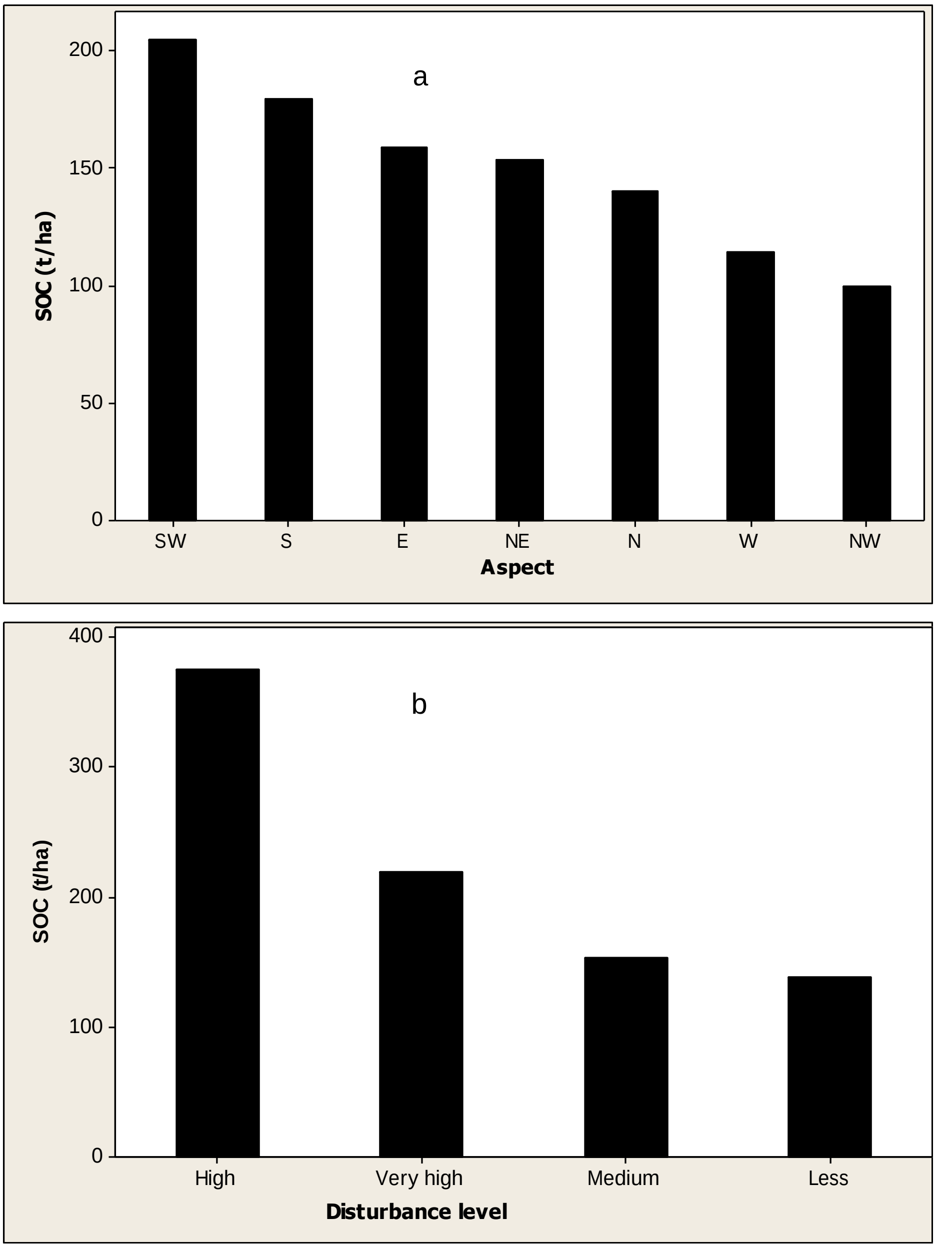


Figure 12 Soil Organic Carbon (SOC) interactions with (a) aspect (b) disturbance level in the study area

The following table shows the amount of carbon stocks in different carbon pools at both forest strata (higher altitude or forest without coffee and lower altitude or forest with coffee system.

Table 4 The estimated value of biomass and carbon in different carbon pools of Gera Moist Evergreen Afromontane forest

	Higher altitude (2328-2539 m a.s.l.)		Lower altitude (1819-2268 m a.s.l.)	
	Biomass	Carbon	Biomass	Carbon
AG	225.33 ± 160.69	112.66± 80.35	210.12± 188.61	105.6±94.3
BG	45.07± 32.14	22.53± 16.07	42.02± 37.72	21.01± 18.36
Litter	13.27± 4.31	6.64± 2.15	7.05± 6.62	3.52± 3.31
NTV	5.99± 23.94	2.99± 11.97	2.82± 2.14	1.41± 1.07
SOC	-	207.03± 94.35	-	138.62± 35.53

The variation of means in all carbon pools except in NTV carbon pool at both forest strata were not statistically significant (P-value > 0.005). The significant level of mean variation in NTV carbon pool was 0.001 (P-value < 0.005). Table 3 given below shows the significant level of mean variations of carbon stocks in different carbon pools between the two forest strata.

Table 5 The significance level of carbon stocks in different carbon pools in Gera Moist Evergreen Afromontane forest

Factors	Carbon pools				
	AGC (t/ha)	**BGC (t/ha)**	**SOC (t/ha)**	**LC (t/ha)**	**NTVC (t/ha)**
	P-value	P-value	P-value	P-value	P-value
Altitude	0.858	0.858	0.006	0.152	0.001
Aspect	0.496	0.496	0.606	0.570	0.162
Disturbance	0.710	0.710	0.325	0.631	0.406

CHAPTER 5

5. DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

5.1. DISCUSSIONS

More woody plant diversity and high tree density per hectare were recorded at lower forest stratum or lower altitude (forest with coffee) (Table 2 above). On the other hand, low woody plant diversity, less tree density per hectare and higher DBH classes were recorded at higher forest stratum or higher altitude (forest without coffee) (Table 3 above). Logically, higher altitude is characterized by minimum tree height, minimum DBH, and low species richness (Zhu *et al*., 2010). In the present study except less species richness others were recorded reversely. This may related to more anthropogenic disturbance at lower forest stratum as illustrated by Figure 8 above. The presence of coffee in the forest poses a problem on the Forest in the form of slashing under growth vegetation, debarking trees and canopy opening to maximize coffee productivity.

The total carbon stock (carbon density) of the present study was 440.71 (t ha^{-1}). Of which the carbon stock in the soil carbon pool was recorded as the largest (172.62 t ha^{-1}). The majority of carbon in the terrestrial carbon pool is stored in soils, and the majority of it stored in forest biomes (Usuga *et al.*, 2010). When carbon density of the present study compared with previous studies (Belay Meles *et al.,* 2014; Adugna Feyissa *et al.,* 2013) the carbon stock of the present study was less by 142.47 t ha^{-1} and 174.02 t ha^{-1} with Arba Minch riverine forest and Egdu forest respectively (Table 6). This may be due to difference in allometric equations used for biomass estimation, anthropogenic disturbance and other complex ecological factors. As stated by Yitebitu Moges *et al.* (2010), the different types of models used for biomass estimation have impact on the value of carbon estimated in a given forest. The tree parameters used to calculate the biomass of the forest in the current study were DBH, basic wood density and height. On the other side, the previous studies used only tree DBH to estimate the biomass of the cross ponding forests. Therefore, this may be one of the reasons that bring variation between carbon stocks of the forests in different parts of Ethiopia.

On the other hand, the current study was 4.4 times, 2 times, 1.5 times, 1.5 and 1.26 times greater than Hanang forest, Chilimo forest, Menagesha Suba State forest Selected Church forests and Mount Zequalla forest respectively (Table 6).

AGC = aboveground carbon, BGC = belowground carbon, LC = litter carbon, NTVC = non-tree vegetation carbon and SOC = soil organic carbon.

Table 6 Comparisons of present study with previous studies (Belay Melese et al., 2013)

Study Area	AGC	BGC	LC	NTVC	SOC	Total
1. GARF	217.27	43.54	5.08	2.20	172.62	440.71
2. MZ	237.39	47.56	6.49	-	57.67	348.86
3. AMGWF	414.70	83.48	1.28	-	83.80	583.18
4. EF	278.08	55.62	3.47	-	277.56	614.73
5. MSSF	133.00	26.99	5.26	-	121.28	286.53
6. SCF	122.85	25.97	4.95	-	135.94	289.71
7. CF	90.25	17.32	0.39	0.65	109.40	218.01
8. HF	48.37	-	-	0.26	45.71	94.34

Note: GARF- Gera Afromontane Rainforest, MZ- Mount Zequalla, AMGWF- Arba Minch Ground Water forest, EF- Egdu Forest, MSSF- Menagesha Suba State Forest, SCF- Selected Church Forest, CF- Chilmo Forest and HF- Hanang Forest.

5.1.1. Carbon stocks along altitudinal gradient

The result of current study revealed the carbon stocks in AG and BG carbon pools were greater in higher altitude than the lower altitude. Similar finding was reported from Abel Girma *et al.* (2014). Woody plant species with higher DBH class were recorded at higher altitude. This was one of the reasons that greater AGC and BGC at higher forest stratum were estimated. The other reason may be related to anthropogenic disturbance at lower forest stratum. The carbon stocks in AG and BG carbon pools did not show continuous increasing pattern with increasing altitude at plot level (Figure 6 above). The out layered values of AG and BG carbon showed in the Figure 6 above is due to less anthropogenic disturbance.

Similarly in all carbon pools except in litter carbon pool, Egdu forest had higher value of carbon stocks at higher altitude (Adugna Feyissa *et al.,* 2013). The carbon stocks in all pools other than AGC and BGC were reported similarly to that of present study (Belay Meles *et al.,* 2014; Swai *et al.,* 2014) (Table 7**).**

In the present study, relatively an increasing trend in mean SOC with increasing altitude was observed (Figure 11), but the trend is not sharp it is said increasing only compared with other carbon pools in the study area. Similarly in the literature (Zhu *et al.,* 2010) SOC globally increases with precipitation and clay content, even though it is mainly determined by carbon output (decomposition) and decreased with increase in temperature. As altitude increase the net primary productivity (NPP) and the carbon input (litter fall) to the soil decreases (Zhu *et al.*, 2010). The increase in SOC with increasing altitude in Gera Afromontane Rainforest despite the decrease in NPP and litter fall may be due to the carbon output (decomposition), which generally decreases with increasing altitude. But, SOC decreased with increasing altitude (Abel Girma *et al.*, 2014).

Similarly, the carbon stock estimated from the NTV carbon pool showed the same pattern with AGC and carbon in litter. This result was similar with the research report done by Swai *et al.* (2014). This may be due to low tree density per hectare which makes suitable for undergrowth vegetation and higher precipitation in the higher altitude. In contrast to the present study, carbon stock in temperate forest done by Zhu *et al.* (2010) showed a decreasing pattern with increasing altitude in all carbon pools except carbon in the NTV which did not show a clear variation.

The carbon in the litter carbon pool of this study was greater in the higher altitude (2.65 t ha^{-1}) than the lower altitude (1.41 t ha^{-1}) like that of the AGC. This result showed similar pattern with previous research reports (Adugna Feyissa *et al.,* 2013; Belay Meles *et al.*, 2014). According to Fisher and Binkly (2000; cited by Adugna Feyissa *et al.,* 2013), the biomass and its carbon stock of litter in a given forest is determined by the condition of a forest (species, stand age and density) and climate. Therefore, the carbon stock variation in litter carbon pool with respect to altitude and forest type may be the result of these factors. The out layer value of litter and NTV carbon showed in the Figure 9 above were recorded as a result of anthropogenic factors. Maximum value of litter carbon was recorded due to the presence of dead wood cut by human being. While minimum value of NTV carbon was recorded as a result of trembling due to anthropogenic factor.

Table 7 Comparison of mean carbon stocks of the present study with previous studies based on altitude (Belay Meles *et al.*, 2013, Adugna Feyissa *et al.*, 2013 and Swai *et al.*, 2014)

Study Area	Elevation	AGC	BGC	LC	NTV	SOC
1. GARF	Higher	112.66	22.53	2.65	1.20	207.03
	Lower	108.05	21.01	1.41	0.56	138.25
2. AMGWF	Higher	517.68	103.54	1.34	-	83.30
	Lower	637.75	127.54	1.17		89.24
3. EF	Higher	351.04	70.21	3.24	-	328.57
	Lower	216.97	43.39	3.05		243.38
4. HF	Higher	12.98	-	-	0.27	114.74
	Lower	71.5	-	-	0.22	137.41

Note: GARF- Gera Afromontane Rainforest, AMGWF- Arba Minch Ground Water forest, EF- Egdu Forest and HF- Hanang Forest

5.1.2. Carbon stocks versus Aspect

East aspect has the highest mean carbon density among all other recorded aspects whereas the West aspect has the least AGC stock in the Forest. This may be related to the timing of sunlight that the vegetation can absorbed. That means the vegetation that have been grown in the East direction receive sunlight earlier than vegetation in West and other directions. Rainfall is not a limiting factor in the study area as illustrated from the Climadiagram (Figure 2 above). Therefore, vegetation competes for sunlight for their growth. The vegetation grown in the east aspect can receive photosynthetic active radiation than vegetation on the other aspects. As more photosynthesis occurs, more CO_2 is converted into biomass. The research work done by Belay Meles *et al*. (2014) resulted out the south aspect stocked the highest carbon and the NE had the least carbon density. On the other hand, the research result done by Singh *et al.* (2009) revealed that the total biomass in the Southeastern aspect was slightly higher as compared to the northeastern aspect. In the NTV carbon pool, NE aspect scored the highest and the NW aspect scored the least value of carbon stock.

As indicated in Table 4 above the mean carbon stock of present study in the soil carbon pool was much larger than previous studies (Belay Meles *et al.,* 2014; Mesfin Sahile, 2011 (unpublished); Tulu Tolla, 2011; Getu Shiferaw (unpublished), 2012 and Swai *et al.,* 2014). But, it was less by 105 (t ha^{-1}) than that of Egdu forest (Adugna Feyissa *et al.,* 2013).

5.1.3. Carbon stocks in relation to disturbance level

The result shown in the (Figure 7, 10 and 12) above carbon stock varied with disturbance level. Highest AGC stock was estimated at less disturbed forest groups and least AGC stock was estimated at highly disturbed forest groups. The same was true for the BGC. When the carbon stocks have been seen at plot level, the highest AGC and BGC stock was estimated at the lowest altitude. These out layered values were estimated because of the plot was found to be the least anthropogenic disturbance was recorded. Similarly, highest litter carbon and lowest carbon stock was estimated at altitude 2494 (m a.s.l.). This is also related to high anthropogenic disturbance in the plot. There were high amount of wood debris laid down on the ground and few growth of under growth or non-tree vegetation due to high trembling in the plot.

The result shows that carbon stocks in different carbon pools vary with the level of anthropogenic disturbance. The SOC showed increasing pattern with increasing anthropogenic disturbance level (Figure 12 b). This may be related to decomposition of dead organic matter. This means that during disturbance there is high amount of litters and wood debris on the ground. At the same time since canopy is opened high sunlight reach to the forest floor that accelerates decomposition. On the other hand, the carbon stock in AG and BG carbon pools showed a reverse pattern. The carbon in the litter pool showed the same pattern with AGC and BGC.

According to Zhu *et al.* (2010), when stand age of a forest increase after disturbance, AGC and SOC density tended to increase whereas litter and dead wood C density generally followed a U-shaped pattern. This means that exactly at the time of disturbance the amount of litter and dead wood at the forest floor becomes high and they decreased when they become decomposed. They again become increased when the forest matured.

5.2. CONCLUSIONS

Different carbon stocks exist in different forest types and eco region depending on physical factors (precipitation regime, temperature, and soil type topography), biological factors (tree species composition, stand age, stand density) and anthropogenic factors (disturbance history, logging intensity). For example, secondary forests have lower carbon stock than mature forests and logged forests have lower carbon stock than unlogged forests. Associating a given area of deforestation with specific carbon stocks that is relevant to the location that is deforested or degraded will result in more accurate and precise estimates of carbon emissions. Therefore, it is worth to stratify forests based on the degree of human disturbance and other environmental variation, which affects the accumulation of biomass in a forest in order to lead to accurate and cost effective carbon emission estimates associated with a given area of deforestation or degradation.

In general, the mean carbon density in the present study in all carbon pools showed greater carbon at higher forest strata (forest without coffee) than the lower forest strata (forest with coffee). This can be due to the existence of plant species in the large diameter class. The soil carbon stock constitutes the largest stocks from all carbon pools. The overall carbon density of the Forest in this study was 440.71 (t ha^{-1}). This was equivalent to 1617.41 t ha^{-1} CO_2. Therefore, Gera Afromontane Rainforest has the potential to mitigate huge amount of CO_2 from the atmosphere. Environmental factors like: altitude, aspect, precipitation and temperature have their own effects on biomass accumulation in the given vegetation.

Moreover, anthropogenic factors have paramount effects on the biomass of the given vegetation. The decreased tree carbon stock in a forest due to anthropogenic factors can either result in increased dead wood, increased wood products or immediate emissions of CO_2. The efficiency of carbon storage in organic matter reflects the quality of environmental conditions: climate, soil structure and nutrient availability. In the current study, anthropogenic factors were become the most degrading factors in biomass of the Forest.

5.3. RECOMMENDATIONS

Gera Afromontane Rainforest is one of the remnant forests in southwest 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 biomass accumulation of that forest. There were a number of observations understood during data collection in the field. For instance, agricultural expansion into the Forest, charcoal production, cutting of trees for fire wood, beehive and construction, deforestation in the form of cutting and debarking for coffee plantation. Moreover, the Forest especially in the higher forest strata faces a problem of natural regeneration may be due to the over dominance of *Monothecium glandulosum* herb in under story of the forest forming a carpet in the ground and hampering germination under seedling emergence.

Therefore, in order to get benefit from carbon trade through $REDD^+$ better management option must be established by considering the principles of $REDD^+$ activities. The present study considered only two forest strata (forest with coffee and forest without coffee) from the whole Gera Afromontane Rainforest. It is known that there are a Bamboo forest, plantation forest, Agroforestry system and forest beyond 2540 m. a.s.l. which was excluded in the present study due to logistic problems. Therefore, to have more compressive information, future research works should consider these vegetation types. On the other hand, including basic wood density improves the accuracy of biomass estimation of a given forest. Not only improves biomass estimation it also increases the acceptance of the calculated carbon density value by IPCC. Therefore, it is recommended that including basic wood density in any biomass calculation minimizes uncertainties caused by using DBH alone for biomass calculation.

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7. APPEDICES

Appendix 1 Lists of woody plant species collected in the study area

No	Species name		Family	Frequency	Wood density
	Vernacular	Botanical			
1	Ambabesa	*Albizia gummifera* C.A. Sm.	Fabaceae	13	0.534
2	Seo	*Allophylus abyssinicus* (Hochst.) Radlkofer	Sapindaceae	17	0.568
3	Wondebiyo	*Apodytes dimidiata* E. Mey. Ex Am.	Icacinaceae	23	0.610
4	Lolchisa	*Bersama abyssinica* Fresen	Melianthaceae	155	0.671
5	Haleele	*Byttneria catalpifolia* Jacq.	Sterculiaceae	5	0.550
6	Mixoo	*Canthium oligocarpum* Hiern	Rubiaceae	18	0.715
7	Gagamaa	*Olea capensis* L.	Oleaceae	37	0.774
8	Ulmayyee	*Cluasena anisata* Benth.	Rutaceae	1	0.482
9	Buno	*Coffea arabica* L.	Rubiaceae	1	0.620
10	Wedesa	*Cordia africana* L.	Boragnaceae	17	0.493
11	Bekenisa	*Croton macrostachyus* Del.	Euphorbiaceae	134	0.479
12	Lokoo	*Diospyros abyssinica* F. White	Ebenaceae	6	0.758
13	Danisa	*Dombeya torrida* P. Bamps	Sterculiaceae	2	0.482
14	Emo	*Dracaena afromontana* Mildbr.	Dracaenaceae	4	0.413
15	Ulagaa	*Ehretia cymosa* Thonn.	Boraginaceae	7	0.466
16	Sombo	*Ekebergia capensis* Sparrm	Meliaceae	5	0.469
17	Siglu	*Fagaropsis angloensis* Dale.	Rutaceae	2	0.504
18	Arbuu	*Ficus sur* Forssk.	Moraceae	38	0.428
19	simararu	*Galiniera saxifraga* Bridson	Rubiaceae	8	0.550
20	Sude	*Gardenia ternifolia* Schumach. Thonn.	Rubiaceae	6	0.732
21	Heexoo	*Hagenia abyssinica* I.F. Gmel.	Rosaceae	7	0.566
22	Wongo	*Macaranga capensis* Sim.	Euphorbiaceae	5	0.449
23	Abeyi	*Maesa lanceolata* Forssk.	Myrsinaceae	3	0.676
24	Askira	*Millettia ferruginea* Bak.	Fabaceae	25	0.667
25	Kombolcha	*Maytenus gracilipes* Exell	Celastraceae	8	0.62
26	Bayaa	*Olea welwitschii* Gilg & Schellenb.	Oleaceae	24	0.650

Continued ...

27	Embrango	*Oxyanthus speciosus* DC.	Rubiaceae	4	0.525
28	Birbirsa	*Podocarpus falcatus* (Thunb.) R.B. ex. Mirb	Podocarpaceae	2	0.500
29	kariyoo	*Polyscias fulva* Harms	Araliaceae	13	0.237
30	Qerero	*Pouteria adolfi-friederici* Baehni	Sapotaceae	10	0.430
31	Omi	*Prunus africana* Kalkm.	Rosaceae	69	0.685
32	Bosoqa	*Sapium ellipticum* Pax	Euphorbiaceae	10	0.551
33	Botoo	*Schefflera abyssinica* Harms	Araliaceae	7	0.276
34	Xomboroqo	*Solanecio gigas* C. Jeffrey	Asteraceae	5	0.550
35	Beddessa	*Syzygium guineense* DC.	Myrtaceae	84	0.610
36	Mixirii	*Teclea nobilis* Del.	Rutaceae	28	0.745
37	qa'ee	*Trema orientalis* Bl.	Ulmaceae	14	0.416
38	hadheessaa	*Vepris dainellii* Kokwaro	Rutaceae	11	0.659
39	Ebicha	*Vernonia amygdalina* Del.	Asteraceae	10	0.413
40	Rejii	*Vernonia auriculifera* Hiern.	Asteraceae	21	0.413

Appendix 2 Analyzed and environmental data of all the sample plots

Forest strata	Plot	Mean DBH (cm)	AGC (t/h)	BGC (t/h)	L C (t/h)	NTV C (t/h)	Aspect	Level of disturbance	Elevation (m)
Higher altitude	1	24.86	94.41	18.88	4.14	5.55	SW	Medium	2460
	2	30.85	64.78	12.96	2.98	6.77	N	High	2436
	3	45.31	65.16	13.03	7.33	3.22	N	Medium	2435
	4	28.9	123.13	24.63	9.49	1.57	SW	High	2431
	5	62.46	102.95	20.59	4.71	5.68	SW	High	2436
	6	24.69	74.26	14.85	4.27	4.40	SW	Very High	2483
	7	28.16	83.51	16.70	2.49	1.26	E	Very High	2539
	8	45.54	256.46	51.29	2.05	3.65	E	High	2475
	9	30.15	29.33	5.87	49.09	0.47	E	High	2494
	10	35.37	117.55	23.51	1.65	1.73	S	High	2439
	11	29.8	128.13	25.63	3.32	1.86	S	High	2526
	12	24.19	19.07	3.81	4.05	5.74	S	High	2445
	13	39.89	315.72	63.14	1.08	1.57	E	Medium	2328
	14	45.06	157.93	31.59	1.54	0.43	Gentle	High	2338
	15	56	57.55	11.51	1.35	1.02	Gentle	Medium	2334

Continued ...

Lower altitude	16	35.66	69.27	13.85	3.71	0.53	Gentle	High	2189
	17	33.71	58.95	11.79	2.59	4.81	NE	High	2180
	18	26.84	104.19	20.84	1.51	0.65	S	High	2114
	19	19.88	59.94	11.99	1.84	1.03	S	Less	2200
	20	25.58	75.00	15.00	2.69	0.98	SW	High	2230
	21	39.21	66.49	13.30	1.96	0.68	W	Very High	2268
	22	21.1	48.55	9.71	9.02	1.10	South	Less	2033
	23	42.44	65.18	13.04	1.90	0.79	W	Medium	2043
	24	24.3	54.81	10.96	1.95	0.86	NW	Medium	2040
	25	18.67	410.15	82.03	2.47	1.48	SW	Less	1819
	26	32	59.40	11.88	2.12	2.18	S	Medium	1828
	27	28.37	162.70	32.54	0.62	1.63	NW	Medium	1846
	28	55.58	39.70	7.94	2.89	1.15	S	Medium	1930
	29	33.43	116.03	23.21	4.35	1.07	N	Medium	1943
	30	39.13	185.55	37.11	13.25	2.20	E	Less	1898

Appendix 3 Soil sample statistics

Plot No	Fresh weight (g)	Dry weight (g)	Volume sample (g/cm^3)	Bulk density (g/cm^3)	Soil depth (cm)
1	120.7	94.98	98.125	0.97	30
2	115.2	97.04	98.125	0.99	30
3	109.9	87.35	98.125	0.89	30
4	120.1	92.28	98.125	0.94	30
5	115.1	83.23	98.125	0.85	30
6	121.7	80.46	98.125	0.82	30
7	115.8	83.24	98.125	0.85	30
8	118.4	87.88	98.125	0.90	30
9	133.9	89.83	98.125	0.92	30
10	119.5	94.75	98.125	0.97	30
11	129.5	89.50	98.125	0.91	30
12	114.6	86.38	98.125	0.88	30
13	125.1	89.48	98.125	0.91	30
14	111.9	81.00	98.125	0.83	30
15	111.7	84.43	98.125	0.86	30
16	94.33	58.67	98.125	0.60	30
17	96.55	58.92	98.125	0.60	30
18	97.92	53.38	98.125	0.54	30
19	87.86	56.75	98.125	0.58	30
20	83.46	56.80	98.125	0.58	30
21	101.2	60.46	98.125	0.62	30
22	117.1	78.02	98.125	0.80	30
23	99.28	60.13	98.125	0.61	30
24	109.3	60.04	98.125	0.61	30
25	105.3	64.10	98.125	0.65	30
26	106.2	68.54	98.125	0.70	30
27	93.37	57.82	98.125	0.59	30
28	115.2	96.98	98.125	0.99	30
29	106.5	76.58	98.125	0.78	30
30	97.78	73.46	98.125	0.75	30

Appendix 4 Regression equations designed to Tropical Moist Evergreen Afromontane forest for biomass estimation

Ecological zone	Reference	Equation	Remark
Tropical Rainforest	Brown et al. (1989)	$Y = \exp[-2.4090+0.9522 \ln(S^2DH)]$	
Tropical Rainforest	Brown et al. (1989)	$Y = \exp[-3.1141+0.9719 \ln(D^2H)]$	Valid for DBH > 5 cm
Tropical Rainforest	Brown et al. (1989)	$Y = \exp[-2.4090+(0.9522*\ln(D^2*H*A)]$	Valid for DBH > 5 cm
Tropical Rainforest	Brown (1997)	$Y = 42.69 - 12.800 (D) + 1.242 D^2$	
Tropical Rainforest	Brown (1997)	$Y = \exp[-2.134 + 2.530 \text{ x } \ln D]$	Valid for DBH < 80 cm and $r^2 = 0.97$
Tropical Rainforest	Chave et al. (2014)	$Y = 0.0673(SHD^2)^{0.796}$	Valid for DBH ≤ 212
Tropical Rainforest	Chave et al. (2005)	$Y = \exp[-2.977+\ln(HD^2S)]$	
Tropical Rainforest	Chave et al. (2005)	$Y = X*\exp[-1.349+(1.980*\ln D+0.207\ln D^2-(0.0281 \ln D^3]$	
Tropical Rainforest	Chave et al. (2005)	$Y = \exp[-2.557+0.940 \ln(SD^2W)]$	
Tropical Rainforest	Chave et al. (2005)	$Y = S*\exp[-1.239+(1.98*\ln S+0.207 \ln S^2-0.0281\ln S^3]$	

Note: Y = Biomass (kg), $\pi = 3.14$; r = radius (cm); D = diameter at breast height (cm); H = height (m); S = wood density (g cm^{-3}), A = area of plot (m^2) and exp [...] = raised to the power of [...]". Rainforests are forests with annual rainfall between (1 500 < rainfall < 4 000 mm).

Source: Genene Assefa (2013); Ponce-Hernandez, R. (2004) and MacDicken (1997).

Declaration

I, the undersigned declare that this Thesis is my original work and it has not been presented in other universities, colleges or institutes for a degree or other purpose. All sources of the materials used have been duly acknowledged.

Name: Nesru Hassen Ahmed Signature: _____________ Date: ___________

This work has been done under my/our supervision.

Name: _______________________ Signature: ________________ Date: _________

Name: _______________________ Signature: ________________ Date: _________

Name: _______________________ Signature: ________________ Date: _________