ESTIMATION OF CARBON STOCK FROM *Eucalyptus camaldulensis* Dehnh. WOODLOTS AND THEIR MANAGEMENT PRACTICES IN DAMOT SORE DISTRICT, WOLAITA ZONE, SOUTHERN ETHIOPIA.

MSc. THESIS

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OCTOBER, 2019

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MSc. THESIS SUBMITTED TO THE

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

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN FOREST RESOURCE ASSESSMENT AND MONITORING

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APPROVAL SHEET - I

This is to certify that the thesis entitled ‘’Estimation of Carbon Stock from *Eucalyptus camaldulensis* Dehnh. woodlots and their management practices in Damot Sore District, Wolaita Zone, Southern Ethiopia’’ submitted in partial fulfillment of the requirements for the degree of Master of Science with specialization in Forest Resource Assessment and Monitoring of the Graduate Program of the Department of General Forestry, Wondo Genet College of Forestry and Natural Resources, and is a record of original research carried out by Tadewos Tesfaye Chare Id. No. MSc/FRAM/R0018/09, under my supervision, and no part of the thesis has been submitted for educational institutions for achieving any academic awards.

The assistance and help received during the course of this investigation have been duly acknowledged. Therefore, I recommend that it be accepted as fulfilling the thesis requirements.

Abdella Gure (PhD)	______________________	______________________
Name of Supervisor	Signature	Date

APPROVAL SHEET - II

We, the undersigned, members of the board of examiners of the final open defense by Tadewos Tesfaye Chare have read and evaluated his thesis entitled ‘‘Estimation of Carbon Stock from *Eucalyptus camaldulensis* Dehnh. woodlots and their management practices in Damot Sore District, Wolaita Zone, Southern Ethiopia’’, and examined the candidate. This is therefore to certify that the thesis has been accepted in partial fulfillment of the requirements for the degree of Master of Science in Forest Resource Assessment and Monitoring at Hawassa University, Wondo Genet college of Forestry and Natural Resources.

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Name of the Chairperson	Signature	Date
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Final approval and acceptance of the thesis is contingent upon the submission of the final copy of the thesis to the CGS through the DGC of the candidate’s department.

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DEDICATION

I dedicate this thesis to my father Tesfaye Chare and my mother Tante Geta for their inspiration, love and support throughout my life and also my beloved wife Wubalem Bekele too.

STATEMENT OF AUTHOR

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

Tadewos Tesfaye Chare _	______________________	_____________________
Full Name	Signature	Date

Table of Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

ABBREVIATIONS AND ACRONYMS

A/R	Afforestation/Reforestation
AGB	Aboveground biomass
AGBC	Aboveground Biomass Carbon
BA	Basal Area
BCEFs	Biomass Conversion and Expansion Factors
BD	Bulk Density
BEFs	Biomass Expansion Factors
BGB	Belowground biomass
CO_2	Carbon Dioxide
CSA	Central Statistical Agency
DAs	Development Agents
DBH	Diameter at Breast Height (1.3m)
DOM	Dead Organic Matter
FAO	The Food and Agriculture Organization of the United Nations
FRA	Forest Resources Assessment
GHGs	Greenhouse Gases
HHs	Households

HWPs	Harvested Wood Products
IPCC	Intergovernmental Panel on Climate Change
KP	Kyoto Protocol
LOI	Loss on Ignition
masl	Meters above sea level
Mg	Mega Gram (1 Mg=106 grams)
Mg C ha^{-1}	Mega gram carbon per hectare
REDD+	Reducing emission from deforestation and forest degradation
SFM	Sustainable Forest Management
SNNPR	Southern Nations Nationalities and Peoples Regional State
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SPSS	Statistical Package for Social Science
t C ha^{-1}	Ton of carbon per hectare
tco_2 e	Ton of carbon dioxide equivalent
UNFCCC	United Nations Framework Convention on Climate Change

Estimation of Carbon Stock from *Eucalyptus camaldulensis* Dehnh. woodlots and their management practices in Damot Sore District, Wolaita Zone, Southern Ethiopia.

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ABSTRACT

Eucalyptus plantations on farm woodlot system represent a short term and cost efficient alternative for sequestrating CO_2 from the atmosphere while sustainably meeting the wood demand of local communities. Despite the known potential of fast growing trees species to store carbon in their biomass, there are relatively few studies indicating precise estimates of carbon stocks in plantations of such species as Eucalypts, especially those on farmers' woodlots. This study evaluated C pools in soil and tree biomass in woodlots of Eucalyptus camaldulensis Dehnh. and their management practices in Damot Sore district. Three kebeles were randomly selected from the district since all kebeles within the district were dominated by intensive plantation of privately owned Eucalyptus camaldulensis woodlots. Reconnaissance surveys were carried out on farmers' Eucalyptus woodlots in the study kebeles prior to data collection to identify different sizes of representative woodlots with Development Agents (DAs). A total of 62 plots (10x10m) were established on woodlots of randomly selected households across woodlot size classes based on their proportional representation (14 for large, 26 for medium, 22 for small) and the field data was collected by measuring trees with a DBH of ≥ 3cm and total tree height. Already developed allometric equations were used for biomass estimation. In each main plot, three 1m×1m subplots were used to collect litter samples and soil samples for SOC estimation were collected using a core sampler from five sampling points using 'X' design with two replications. A total of 248 samples (i.e. 124 for SOC and 124 for bulk density) from two depths were sampled. All statistical analysis was made using statistical software of SPSS (version 16). The results revealed that, the mean total carbon stock (biomass plus soil, 0-60cm) was significantly higher in E. camaldulensis woodlots of large and small households (respectively 97.9 ± 9.17 and 90 ± 7.06Mg C ha^{-1}) than medium sized households (83.29 ± 13 Mg C ha^{-1}). The soil organic carbon (SOC) accounted 72% for large, 84% for medium and 88% for small households. Carbon stocks (biomass and soil) were strongly correlated (Spearman r=0.753 and 0.864, p=0.001) with woodlot size classes of households. Pruning, thinning, composting, weeding and cultivation, burning stump after harvest, application of commercial fertilizer, and watering were the most common management practices that affect carbon stocks in both biomass and soil in the area. This study concluded that the carbon stock value of E. camaldulensis woodlots is large , and the carbon storage in different carbon pools of the system varies with different size classes of the woodlot. Therefore, climate change mitigation efforts on farmers Eucalyptus woodlots should also be considered the factors other than size of woodlot and management practices affecting carbon accumulation of the system.

Keywords: *Biomass carbon; soil carbon; carbon sequestration; plantations; climate change*

1. INTRODUCTION

1.1. Background and justification

Now, current global climate change (global warming) is the most serious environmental problem affecting human lives on a global scale; and primarily it is because of the increase in atmospheric concentrations of greenhouse gases (GHGs) mainly carbon dioxide (CO_2) (Nair *et al.,* 2008; Nakakaawa *et al.,* 2010).

Human activity has significantly altered the global carbon cycle as land use change and fossil fuels burning have increased levels of CO_2 in the atmosphere, causing changes in our climate at an alarming and accelerating rate (IPCC, 1996; IPCC, 2007). Deforestation and forest degradation are also significant causes of the global warming recorded over the past two decades and accounted for 12–20% of global anthropogenic greenhouse gas (GHG) emissions, more than the entire transport sector (Dudley and Stolton, 2008; Harris *et al.*, 2012 and Le Quéré *et al.,* 2012).

In 1997, The Kyoto Protocol proposed that C reduction could take place by decreasing fossil fuel emissions (i.e. emission reductions), or by accumulating C in vegetation and in the soil of terrestrial ecosystems (UNFCCC, 1997). The introduction of programs such as the United Nation's collaborative program on reducing emissions from deforestation and degradation (UN-REDD) in developing countries is believed to be an incentive to promote forest conservation (Moutinho *et al.,* 2005). Recently, the impact has been receiving increasing attention as countries begin to look at forests as a means of mitigating greenhouse gas emissions and carbon storage (Brown, 1997). Forest resources play important role in the global carbon cycle by storing a large amount of carbon in vegetation biomass and soil, and can significantly contribute to the mitigation of global climate change (Ciais *et al.,* 2013; Settele *et al.,* 2014; Sulistyawati *et al.,* 2006). The United Nations

Framework Convention on Climate Change (UNFCCC) has recognized the importance of plantation forestry as a GHGs mitigation option and to monitor, preserve and enhance terrestrial carbon stocks.

Globally, total plantation forest area is estimated to be 264 million ha, corresponding to 7% of the global forest area and expands each year by around 5 million ha on average (FAO, 2010). Developing short rotation fast-growing plantations such as *Eucalyptus spp.* that are planted on farms and degraded lands as small woodlots for timber and land restoration has contributed to global relevance in terms of carbon sequestration and reduction on greenhouse effects in addition to improvement of rural livelihoods (Torres *et al.,* 2011; Nyandzi *et al.,* 2003).

In the tropics and subtropics, *Eucalyptus* species are the most widely planted genus and second to pines in global importance as plantation trees (Alebachew *et al.,* 2015; Bekele, 2011). In Ethiopia, recent figures shows that today's, tree plantation cover including commercial plantations, small holder *eucalypt* woodlots and community forests is approximately 972,000 ha (MFCC, 2018). *Eucalyptus species* (58%) and *Cupressus* (29%) are the dominant plantation species. Other species include *Juniperus procera* (4%), *Pinus* species (2%) and the rest (7%) (FAO, 2010). *Eucalyptus spp.* are planted and adapted to grow across a wide range of agro-ecological conditions; some hardy species grow in semi-arid areas, while others are able to grow on marshy and swampy sites. It is potentially productive and economically grown in different forms from woodlots at household level to large plantation projects (Alebachew *et al.*, 2015). Among others, *Eucalyptus camaldulensis* Dehnh. are the most commonly planted and used eucalyptus species in Ethiopia due to its wide ecological range and multi-functional advantage farmers (those living in diverse soil and climatic conditions with different needs) can plant and use it (Amare, 2010).

Since the root system of *eucalyptus* grow deep and extensive the need for irrigation and fertilizer are comparatively low. In Ethiopia, the well spread traditional knowledge for the establishment and management of eucalyptus is sufficient for the management of the small woodlots of smallholders (Kebebew and Ayele, 2010; Dessie and Erkossa, 2011; and Whitesell *et al*, 1992 cited in Ketsela, 2012).

The same is true for study area, Damot Sore district, *E. camaldulensis* woodlots are often planted and managed on small-scales and planted on degraded lands to produce wood for timber and for land rehabilitation (Bajigo *et al*., 2015).

Therefore, the present study is aimed to underline the benefits of *E. camaldulensis* woodlots in mitigating carbon emissions through offsetting emissions as carbon sinks by estimating the carbon stock of *Eucalyptus* species at Damot Sore district.

1.2. Statement of the problem

Highlands of Ethiopia are under constant threat from multiple stresses and challenges, which occur as a result of a complex interplay of natural processes and human-induced processes (Reyer *et al.*, 2009). To contribute to reduction in GHG emissions, and to partly offset deforestation, the Kyoto protocol (KP) explicitly considered reforestation and afforestation activities for carbon sequestration accounting (IPCC, 2007).

Forest vegetation and soils are capable of absorbing atmospheric carbon and accumulate it for relatively long periods in standing biomass, deadwood, soil and harvested materials (Negash and Starr, 2015). The recognized importance of forests in mitigating climate change has led countries to study their forest carbon budgets and initiate the assessment of enhancing and maintaining carbon sequestration of their forests resources (IPCC, 2007).

Several studies so far conducted in Ethiopia and other part of the tropics have paid great attention to estimating the carbon stocks in the standing biomass and soil in forest ecosystems (Negash and Starr, 2015). Forest plantations, especially those with fast growing species such as *Eucalyptus* and its cultivars, represent a short term and cost efficient alternative for sequestrating the carbon which would otherwise be emitted to the atmosphere (Stern, 2007; Zhang *et al.*, 2012).

In the study area, Damot Sore woreda, *E.camaldulensis* is the most commonly observed tree species in community and household woodlots. Farmers' in the area grow it for the purpose of construction, to as cash crop, and fuel wood. However, the contribution of such a farming system to carbon sequestration and the exisisting knowledge of farmers' in managing *Eucalyptus* woodlots have inadequately documented through research. Previous studies on the woodlot agroforestry system of Gedeo was concentrated only on characterization and their management (Mikrewongel, 2012), Management of Traditional Agroforestry Practices in Gununo watershed (Madalcho and Tefera, 2016). *Eucalyptus* based woodlots have been observed to hold high promise in their carbon sequestration to mitigate climate change in the study area but little information is available on the carbon sequestration potential of these land use system in the district.

Thus, this study intended to fill the knowledge gaps of carbon studies and the management effects in carbon stored in *Eucalyptus* woodlots of the Damot Sore District.

1.3. Objective of the study

1.3.1. General objective

The overall objective of this study was to estimate carbon stock from *E.camaldulensis* woodlots and their management practices in Damot Sore district.

1.3.2. Specific objectives

- To determine the living woody biomass carbon stock of *E.camaldulensis* woodlots of the study area.
- To determine soil organic carbon stock of *E.camaldulensis* woodlots of the study area.
- To assess the effect of management practices on biomass carbon stocks of *E.camaldulensis* woodlots of the study area.

1.4. Research questions

To achieve the stated objectives, the study focused on the following research questions:

- What amount of living woody biomass carbon is stored in each of the pools?
- Do management activities carried out by the local farmers affect biomass carbon stock in the *Eucalyptus* woodlots of the study area?

1.5. Hypothesis of the research

The hypotheses to be tested for each objective in this study are:

- The biomass carbon stocks of woodlots vary among the different woodlot size classes of households.
- The soil organic carbon stocks of woodlots vary among the different woodlot size classes of households.

- The management activities undertaken by households affect the biomass carbon stocks in woodlot systems of the study area.

1.6. Significance of the study

Climate change is one of the most serious environmental problems posed by the continued accumulation of GHGs in the atmosphere. The capacity of forest ecosystems to face global climate change through reducing the atmospheric concentrations of GHGs has been recognized by the international climate negotiations (Corona *et al.,* 2014). So, the international climate change adaptation strategies provide the opportunity to account for carbon sinks in forests through the Kyoto protocol. Thus, this study will provide scientific evidences regarding carbon accumulation potential of *Eucalyptus* plantations in the standing biomass of farmers' woodlots. Moreover, the study will provide valuable information to researchers and policy makers on the contributions of *E.camaldulensis* to climate change mitigation through carbon sequestration.

The output of this study will also provide knowledge to be used by development agents (DAs) as a reference document to assist their extension approach on previous management practices of *Eucalyptus* and facilitate planning and implementation of *Eucalyptus* tree plantation interventions in agriculture and plantation forestry leading towards an improved sustainability as well as to an expansion of knowledge in the subject area that can be used by researchers and academicians in similar and related studies.

2. LITERATURE REVIEW

2.1. Definition of terms and concepts

Woodlots are defined as small plantings or clumps of trees near villages as well as large plantings which are intended for fuel wood, building material, poles, laths and droppers for local villages but not for industrial purposes such as production of saw timber, mining timber, or pulpwood. Thus, woodlots are usually associated with a community (Van der Merwe, 2000).

Carbon pool:- A system which has the capacity to accumulate or release carbon. Examples of carbon pools are forest biomass, wood products, soils and atmosphere (Lui and Han, 2009).

Biomass:- Forest biomass, can be defined as the organic material that has been generated and accumulated above and belowground in the forest ecosystem, expressed as mass per unit area (FAO, 2004; FRA, 1990).

Carbon sequestration:- The removal of carbon from the atmosphere and long term storage in sinks, such as marine or terrestrial ecosystems (Watson *et al*., 2000).

Carbon stock:- The mass of carbon contained in a carbon pool (IPCC, 2007).

Carbon:- is one of the most common elements in the universe. Carbon is in the air, in the water, in the soil, in the forest and even in humans. Carbon is in all things on earth. All life on earth needs carbon to grow and survive. But there is also carbon in non-living things such as rocks, gases, or fossil fuels (Susan and Mario, 2010).

Carbon sink:- is a carbon pool from which more carbon flows in than out: Forests can act as sink through the process of tree growth and resultant biological carbon sequestration.

Activities like afforestation reforestation (AR), sustainable forest management (SFM), Conservation and Enhancement of forests acts as carbon sinks (Brown, 2002).

Carbon source:- is a carbon pool from which more carbon flows out than flows in: Forests can often represent a net source of carbon due to the processes of decay, combustion and respiration. Activities like deforestation, forest fire and forest degradation acts as sources of carbon. Therefore, forests can switch between being a source and a sink of carbon over time depending on the type of activity they are experiencing. As both carbon sources and sinks, they have the potential to form an important component in efforts to combat global climate change. That is why forests play an important role in the global carbon balance (Brown, 2002).

2.2. Biomass, carbon pools and forest carbon stocks accounting

Forest biomass is organic matter resulting from primary production through photosynthesis minus consumption through respiration and harvest. Assessment of biomass provides information on the structure and functional attributes of a forest and is used to estimate the quantity of timber, fuel and fodder components (Brown, 1997). With approximately 50% of dry forest biomass comprised of carbon (Westlake, 1966), biomass assessments also illustrate the amount of carbon that may be lost or sequestered under different forest management regimes. Carbon is lost to the atmosphere as CO_2. Estimating the biomass density of forest components is, therefore, the first step in forest carbon accounting (Lui and Han, 2009).

Nowadays, there is a growing demand for reliable information on forest and tree carbon stock at both country and global levels. This implies that monitoring the state and changes of forests carbon pools is an important element. Therefore, measuring and estimating carbon stocks and changes in carbon stocks in various pools are very important to carbon trading and marketing (IPCC, 2006). This requires transparent and verifiable methods, quantification of uncertainties and appropriate monitoring systems for carbon stocks. Carbon stock assessment is one of the important step to start with sustainable land use planning in relation to low carbon emission. The change in carbon stock with the dynamics of land use changes may result in either carbon emission or sequestration.

According to the IPPC (2006), carbon pools in forest ecosystems comprise of carbon stored in the living trees aboveground and belowground (roots); in dead matter including standing dead trees, down woody debris and litter; in non-tree understory vegetation and in the soil organic matter (figure 1).

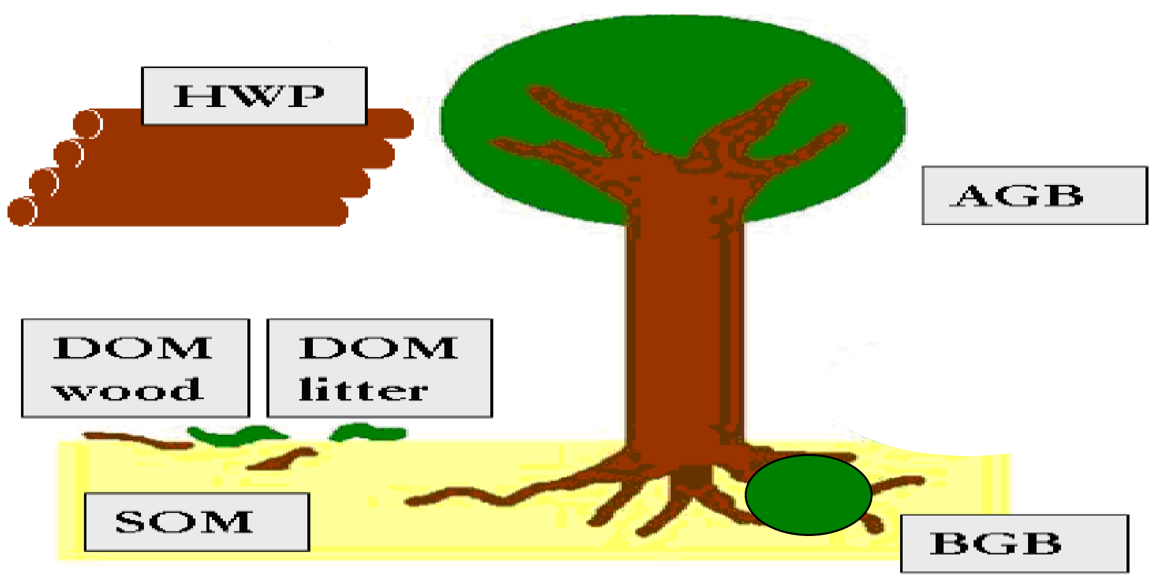

Figure 1 Diagrammatic representation of carbon pools

(Source: Lui and Han, 2009 cited in Genene *et al.*, 2013).

When trees are cut down, there are three destinations for the stored carbon- dead wood, wood products or the atmosphere. The decreased tree carbon stock can either result in increased dead wood, increased wood products or immediate emissions. Dead wood stocks may be allowed to decompose over time or may after a given period, be burned leading to further emissions. When deforestation occurs, trees can be replaced by non-tree vegetation such as grasses or crops. In such cases, the new land use will consistently have lower plant biomass and often lower soil carbon, particularly when converted into annual crops (IPCC, 2007).

Forest carbon pools can be grouped as key categories or minor categories based on ecosystems and land-use changes. Key categories represent pools that could account for more than 25% of the total emissions resulting from deforestation or degradation. In all cases, it makes sense to include trees, as trees are relatively easy to measure and represent a significant proportion of the total carbon stock. The remaining pools represent varying proportions of total carbon depending on local conditions. If the pool is a significant source of emissions as a result of deforestation and degradation, it is worth including in the assessment. The relative percentage proportion of carbon stocks in each pool is represented as below (Table 1) (Zerihun *et al.*, 2012).

Table 1. Relative percentage proportion of carbon stocks in each pool

No.	Type of Forest Carbon Pool	Relative Percentage Proportion (%)
1	Above-ground biomass (AGB)	15 - 30
2	Below-ground biomass (BGB)	4 - 8
3	Woody necro-mass	1
4	Organic litter	0.4
5	Soil	60 - 80

2.2.1. Aboveground biomass and carbon stock

Carbon sequestration can be defined as the removal of CO_2 from the atmosphere and store into green plant biomass (sink) where it can be stored indefinitely through the process of photosynthesis (Watson *et al*., 2000). These sinks can be above ground biomass (trees), living biomass below the ground in the soil (roots and micro organisms) or in the deeper sub-surface environments (Nair *et al*., 2009). Forests are major contributors to terrestrial carbon sink, mitigating climate change and associated economic benefits (Waston *et al*., 2000; FAO, 2005; Sheikh *et al*., 2009).

The AGB carbon pool consists of all living biomass above the soil, inclusive of woody stems, stumps, branches, bark, seeds and foliage of living trees, creepers, climbers and epiphytes as well as understory plants and herbaceous growth. For accounting purposes, it can be broadly divided into trees and the understorey. The most comprehensive method to establish the biomass of this carbon pool is destructive sampling, whereby vegetation is harvested, dried to a constant mass and the dry-to-wet biomass ratio established. Destructive sampling of trees, however, is both expensive and somewhat counter-productive in the context of promoting carbon sequestration. Two further approaches for estimating the biomass density of tree biomass exist and are more commonly applied. The first directly estimates biomass density through biomass regression equations. The second converts wood volume estimates to biomass density using biomass expansion factors (Brown, 1997).

Where stand tables, the tally of all trees in a particular diameter class are available, the biomass per average tree of each diameter class of the stand table can be estimated through biomass regression equations, also called allometric equations. Alternatively, the results of direct sampling of tree diameter in the area of interest can be used in these regression equations. The total biomass of the forest stand is then derived from the average tree biomass multiplied by the number of trees in the class, summed across all classes. In both tropical and temperate forests, such diameter measurements explain more than 95% of the variation in tree biomass (Brown, 2002).

There are a number of databases and publications that present default regression equations, stratified by rainfall regime and region (Brown, 1997; IPCC, 2003). These default equations, based on a large sample of trees, are commonly applied as the generation of local allometric equations is often not feasible. However, the application of default equations will tend to reduce the accuracy of the biomass estimate. For example, rainfall guides generally apply to lowland conditions. However, as elevation increases potential evapotranspiration decreases and the forest is wetter at a given rainfall: thus a regression equation applied to highland forest may give inaccurate biomass estimates.

Where information on the volume of wood stock exists, such as from commercial inventories, biomass density can be estimated by expanding the merchantable volume of stock, net annual increment or wood removals, to account for biomass of the other above-ground components. To do this, either Biomass Expansion Factors (BEFs) or Biomass Conversion and Expansion Factors (BCEFs) are applied. BEFs expand dry wood stock volume to account for other, non-merchantable, components of the tree. To establish biomass, the volume must also be converted to a weight by multiplication of the wood density as well as the BEF. In contrast, BCEFs use only a single multiplication to transform volume into biomass; this is useful where wood densities are not available. Default BEFs and BCEFs reported in the literature can be applied in forest carbon accounting. However, unless locally-specific equations exist to convert direct measurements of tree height and diameter to volume, regression equations to directly estimate biomass from tree diameter are preferable (IPCC, 2003).

With the tree component of a forest, the major fraction of biomass, and so carbon, the understorey is often omitted from accounting. This omission results in a conservative carbon stock estimate but is justified only in areas where trees are present in high density; neglecting the shrub layer in open woodlands, savannah or in young successional forest may significantly underestimate carbon density.

2.2.2. Belowground biomass and carbon stock

It refers to living and dead roots, soil fauna and the microbial community, living biomass of live roots includes fine roots (< 2 mm diameter), small roots (2 - 10 mm diameter), and large roots (> 10 mm diameter). The BGB carbon pool consists of the biomass contained within live roots. As with AGB, although less data exists, regression equations from root biomass data have been formulated which predict root biomass based on above-ground biomass carbon (Brown, 2002; Cairns *et al.*, 1997). Cairns *et al.* (1997) review 160 studies covering tropical, temperate and boreal forests and find a mean root-to-shoot (RS) ratio of 0.26, ranging between 0.18 and 0.30. Although roots are believed to depend on climate and soil characteristics (Brown & Lugo, 1982), Cairns *et al.*, (1997) found that RS ratios were constant between latitudes (tropical, temperate and boreal), soil texture (fine, medium and coarse), and tree-type (angiosperm and gymnosperm) (Cairns *et al.*, 1997). As with AGB, the application of default RS ratios represents a trade-off between costs of time, resources and accuracy. BGB can also be assessed locally by taking soil cores from which roots are extracted; the oven dry weight of these roots can be related to the cross-sectional area of the sample, and so to the BGB on a per area basis (Cairns *et al.*, 1997; MacDicken, 1997).

Roots are important part of the carbon balance, because they transfer large amounts of carbon into the soil. More than half of the carbon assimilated by the plant is eventually transported below-ground via root growth and turnover, root exudates (of organic substances) and litter deposition. Depending on rooting depth, a considerable amount of carbon is stored below the plow layer and better protected from disturbances, which leads to longer residence times in the soil. With some trees having rooting depths of greater than 60 m, root carbon inputs can be substantial, although the amount declines sharply with soil depth (Cairns *et al.,* 1997). Root biomass in ecosystems is often estimated from root-to-shoot ratios. The ratio ranges from 0.18 to 0.30, with tropical forests in the lower range and the temperate and boreal forests in the higher range (Cairns *et al.,* 1997).

Roots make a significant contribution to SOC (Strand *et al*., 2008). About 50% of the carbon fixed in photosynthesis is transported belowground and partitioned among root growth, rhizosphere respiration, and assimilation to soil organic matter (Lynch and Whipps, 1990; Nguyen, 2003). Roots help in accumulation of SOC by their decomposition and supply carbon to soil through the process known as rhizodeposition (Rees *et al*., 2005; Weintraub *et al*., 2007). Increased production and turnover rates of roots lead to increased SOC accumulation following root decomposition (Matamala *et al*., 2003).

2.2.3. Dead organic matter (Wood) carbon stock

The DOM wood carbon pool includes all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil and includes standing and fallen trees, roots and stumps with diameter over 10cm. Often ignored, or assumed in equilibrium, this carbon pool can contain 10-20% of that in the AGB pool in mature forest (Delaney *et* *al*., 1998). However, in immature forests and plantations, both standing and fallen dead wood are likely to be insignificant in the first 30-60 years of establishment.

The primary method for assessing the carbon stock in the DOM wood pool is to sample and assess the wet-to-dry weight ratio, with large pieces of DOM measured volumetrically as cylinders and converted to biomass on the basis of wood density, and standing trees measured as live trees but adjusted for losses in branches (less 20%) and leaves (less 2-3%) (MacDicken, 1997).

NB: Necromass includes dead fallen trees and stumps, other coarse woody debris, the litter layer and charcoal (or partially charred organic matter) above the soil surface.

2.2.4. Dead organic matter (Litter) carbon stock

Dead organic matter-Litter (DOM) includes all non-living biomass with a diameter less than a minimum diameter chosen by a given country (for example 10 cm), lying dead, in various states of decomposition above the mineral or organic soil. The original material (e.g. needles) should still be identifiable to be considered litter. Carbon is stored in trees (stem, branches, leaves and root), understory, forest litter and forest soils. The mechanism of species driven carbon sequestration in soil is influenced by two major activities: aboveground litter decomposition and belowground root activity (Lemma *et al*., 2007). Litter decomposition is one of the major sources of SOC and the quality of litter is very important in this regard (Lemma *et al*., 2007).

This pool comprises biomass in various states of decomposition prior to complete fragmentation and decomposition where it is transformed to SOM. Local estimation of the DOM litter pool again relies on the establishment of the wet-to-dry mass ratio. Where this is not possible default values are available by forest type and climate regime from IPCC ranging from 2.1 tons of carbon per hectare in tropical forests to 39 tons of carbon per hectare in moist boreal broadleaf forest (IPCC, 2006).

2.2.5. Soil organic carbon (SOC) stock

The term ‘‘soil carbon sequestration’’ implies the removal of atmospheric CO_2 by plants and storage of fixed carbon as soil organic carbon. SOC includes carbon in both mineral and organic soils and is a major reserve of terrestrial carbon (Lal and Bruce, 1999). The strategy is to increase SOC density in the soil, improve depth distribution of SOC and stabilize SOC within stable micro aggregates, so that carbon is protected from microbial processes or as recalcitrant carbon with long turnover time. Soil carbon sequestration also increases SOC stocks through judicious land use and recommended management practices. The potential of soil carbon sink capacity in managed ecosystems approximately equals to the cumulative historic carbon loss estimated. The attainable soil carbon sink capacity is only 50-66% to the potential capacity. The strategy of soil carbon sequestration is cost-effective and environmentally friendly (Lal, 2004).

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

The Soil Science Society of America recognizes that carbon is sequestered in the soils directly and indirectly (SSSA, 2001). Direct soil carbon sequestration occurs by inorganic chemical reactions that convert CO_2 into soil inorganic carbon compounds such as calcium and magnesium carbonates. Indirect plant carbon sequestration occurs as plants convert atmospheric CO_2 into plant biomass through photosynthesis. Some of this plant biomass is indirectly sequestered as SOC during decomposition processes. The amount of carbon sequestered at a site reflects the long-term balance between carbon uptake and release mechanisms. Because those flux rates are large, changes such as shifts in land use and land cover practices that affect pools and fluxes of SOC have large implications for the carbon cycle and the earth's climate system (Lal, 2008).

2.2.6. Harvested wood products (HWP)

HWP comprises timber and other wood materials harvested and transported out of the forest ecosystem. Harvested wood products (HWPs) increasingly recognized as an additional and potentially substantial carbon pool which exists outside of traditional forest boundaries (Lui and Han, 2009).

2.3. The role of tree plantation on climate change mitigation

Globally, forests cover about 4 billion ha of land, or 30% of the Earth's land surface. The global forest ecosystem as a whole, including dead wood, soils, and litter, contains 638 billion tons of carbon. This is approximately equals to the amount of carbon in atmosphere. As the area of natural stands has decreased in recent decades, tree plantations have become increasingly important components of the planet's forest resources. Thus, area of plantation forest has been increasing annually by an average of 5 million ha between 2000 and 2010 and now represents 6.6 % (264 million ha) of the global forest area (FAO, 2008, 2010, 2006 cited in Getahun, 2017 and IPCC, 2001). Sustainably managed forests not only provide the industry's raw material, but also provide a range of economic and environmental benefits, including the storage and cycling of vast amounts of carbon. Tackling climate change is one of most important roles of forest by storing and sequestering carbon. Thus, one of the economically viable strategies for sequestering atmospheric carbon and mitigation the climate change could be development of plantations on suitable land areas (Dabas and Bhatia, 1996). Therefore, well-designed, multi-purpose plantations can reduce pressure on natural forests, restore some ecological services provided by natural forests and mitigate climate change through direct carbon sequestration (Paquette and Messier, 2010).

The greenhouse effect is one of the most widely discussed environmental issues. In the last few years many in the plantation industry have been promoting tree plantations as a carbon sink to offset the rise in atmospheric clevis from fossil fuel burning (Kurtz, 1989). Carbon credits could be pursued as additional financial benefit from plantations. Yet much of the analysis that led to the conclusion that tree plantations provide a carbon sink does not include the complexities of the plantation life cycle (MacLaren and Wakelin, 1991). However, plantations planted onto pasture or croplands that substitute methane emissions make a positive contribution towards reducing greenhouse gas emissions (Klitscher, 1990).

A natural forest is generally in a state of carbon balance, where an equivalent amount of carbon extracted from the air is released through decomposition. Huge amounts of carbon are held as a "steady state" (up to 500 tones/ha of carbon in old growth temperate and tropical forests) (Sedjo, 1989). Regenerating native forest is rapidly accumulating the carbon lost when the forest was cleared. Tree planting carried out as forest restoration with no wood harvest intended will be storing considerable quantities of carbon (Klitscher, 1990). Plantation forest stores more carbon than unmanaged forests (Cannell, 1990). Afforestation with pine and *Eucalyptus* plantations may rebuild about 93% of the initial soil carbon in degraded marginal land (Kudrick, 2003).

2.4. Overview of tree plantation in Ethiopia

Deforestation, high population growth, low productivity and expansion of agricultural land are the major causes for environmental degradation in developing countries. To overcome the environmental challenges and save the remaining natural forest, planting of fast growing tree species is the solution in order to satisfy the ever increasing demand for forest products (Ketsela, 2012 cited in Amisalu, 2013; Schiettecatte *et al.,* 2008).

The establishment of monoculture forest plantations with exotic, fast-growing species is common in tropical countries. In Ethiopia, large-scale plantations, mainly monocultures of *Eucalyptus*, *Cupressus* and *Pinus spp.* have been established with the aim of increasing the supply of timber products, fuel wood and construction materials, protect the remaining natural forest and achieve ecological restoration of degraded sites (Poultouchidou, 2012; Lemma, 2006).

Eucalyptus was first introduced into Ethiopia between 1890 - 1895, in response to depletion of indigenous forest around Addis Ababa for fuel and construction (Sertse *et al.,* 2012). In the year 2005, it was estimated that Ethiopia had 509,000 hectares of plantations, mainly monocultures, of *Eucalyptus*, *Cupressus* and *Pinus* species and 20,000 hectares more were expected to be established by the year 2010 (FRA, 2010).

Eucalyptus planted on woodlots by small-scale farmers is another form of forest plantations that has evolving as a result of the problem of wood shortage. The expansion of small-scale plantations of *Eucalyptus* in the form of farm forestry is mainly observed in the highlands of Ethiopia due to the appropriate climatic conditions (Dessie and Erkossa, 2011). *Eucalyptus* species is most commonly planted in household yards, around agricultural fields as farm boundaries or in another piece of land (Lemenih, 2010). There are different drivers behind the trend of *Eucalyptus* tree plantings: Studies showed that (1) the shortage of wood in combination with the high household demands for firewood and construction wood and (2) the need for income generation are the top two drivers (Lemenih, 2010).

Eucalyptus is more attractive to farmers and the reasons are its' profitability, and its generation of quick return. It can be grown on degraded lands, is easily cultivated and gives high amount of biomass suitable for construction and energy purposes (Gemechu, 2010 cited in Amisalu, 2013).

2.5. Historical perspective of *Eucalyptus* woodlot establishment and management

Due to the expansion of the city and population growth, the demand for fuel and construction wood has increased steadily. At the end of the 19^{th} century, there was a fear that the recently established capital city, Addis Ababa, should be abandoned due to the deepening fuel wood shortage (Pohjonen and Pukkala, 1990). To meet the demands, the natural forest on the surrounding hills of the city were deforested and that in turn aggravated the wood shortage. As a potential solution to overcome the deepening fuel wood shortage, Menelik II, in 1895 introduced species of *Eucalyptus* for reforestation of the hills around Addis Ababa (Brietenbach, 1961). Hence, the first forest plantation in the country was established around Addis Ababa at the turn of the century. Emperor Menelik II, assisted by a French railway engineer and a physiologist Mendon-viddle introduced first growing exotic tree species of some 15 *Eucalyptus, Acacia* and *Pine* species from southern Europe (Portugal, Italy, Greece), and Australia in 1895 (Amare, 2001).

The introduction was a success and the farmers' around the city adopted the species for fuel wood and construction poles and started planting their own woodlots at the same time as larger plantations were established for commercial purposes. The peri-urban plantation increased steadily until the land reform in 1974 (Yohannes, 2001).

2.5.1. *Eucalyptus* woodlot establishment in Ethiopia

Due to lack of fuel wood, households increasingly use cow dung and agricultural residues for cooking and/or prepare fewer cooked meals. Although it is difficult to quantify the relative importance of the "mining" of forest resources, it is certain that they directly or indirectly deepen and widen the incidence of poverty (EFAP, 1994). Therefore, the establishment of woodlots for fuel wood purposes does form part of an overall development package where as integrated approach is taken to rural development. Woodlot development should ideally be promoted in such a manner that it generates economic and social spillover by complimenting agriculture, and encouraging small businesses and other rural development activities (Van der Merwe, 2000).

Most *Eucalyptus* species require a completely cultivated and weed -free site for rapid early growth. In South Africa, experiments comparing methods of establishing *Eucalyptus* in grassland have shown that complete soil cultivation is greatly superior to all other methods including chemical weed control, fertilizing, digging pits, etc. (Evans, 1992). Before a woodlot is planted the soil has to be prepared usually by digging and ploughing using oxen-plough. To accommodate seedlings small pits are dug while planting. Generally planting takes place during the rainy season and should proceed only after substantial rain has fallen. If planting cannot avoid soaking rain, the planting hole pit should be watered before the seedling is placed therein, so that the dry loose soil will not absorb moisture from the plant (Van der Merwe, 2000).

The size of woodlot depends on local requirements for wood products and the amount of land that could be made available. Research findings from North Gonder, Ethiopia, indicated that because of acute shortage of agricultural lands the average farmers set aside only about 13 - 16% of the total area of hiss/her land holdings for the production of *Eucalyptus* with a range of 0.01-2ha (Amare, 1999; Asaye, 2002). Furthermore, a study report from the central highlands of Oromia, Ethiopia, showed that a farmer set aside 12% of his agricultural land for growing *Eucalyptus* woodlots (Zerihun, 2002). According to this studies farmer's major reason for growing *Eucalyptus* were obtaining firewood, increasing income from the sale of wood products and securing wood products for local house construction.

2.5.2. *Eucalyptus* woodlot management

After establishment, seedlings are weeded at least once per year for the first two consecutive years and protected from livestock damage by complete fencing and/or guarding (Pohjonen and Pukkala, 1990). After planting, if deaths are unacceptably high, the failures are replaced through the operation called blanking or beating up. In the tropics for fat-growing trees such as *Eucalyptus*, blanking must be done within a few weeks of planting (Evans, 1992). Farmers' undertake access pruning of very thin branches after two years. In most cases, actual thinning is not practiced but some farmers selectively thin out poorly performing trees and also when trees are needed for consumption (Asaye, 2002).

2.6. Impact of planted woodlots on biomass and soil carbon stocks

Soil is a thin layer of material on the earth's surface comprising broken rock particles and decaying organic matter, which serves as the natural medium for the growth of vegetation (Hill, 1999). Organic matter in soil is predominately derived from dead plant parts: leaves, stem, and roots) but decaying dead microbial biomass and animals are also contributing to the formation of soil organic matter. Organic matter is generally regarded as a vital component of a healthy soil. It is an important part of soil physical, chemical, and biological fertility. According to Sparrow (2008) organic matter in its broadest sense, comprises all living soil organisms and all the remains of previous living organisms in their various degrees of decomposition. Forest plantation management can generally affect soil organic matter content. For instance, it may be removed from the soil during the removal of logs and organic matter may be burnt.

Science Daily (2001) suggests that organic matter levels are marginally higher in the plantation soil than agricultural land. The organic matter content in the soil is a result of a slow formation process, continuing over thousands of years where the leaf and woody litter and other organic materials are incorporated into the soils and slowly, by the action of microorganisms, converted it into precious organic matter (Singwane and Malinga, 2012). Normally, forests are relatively rich in organic matter compared to other land-uses.

According to Singwane and Malinga (2012), the impact of Pine and *Eucalyptus* forest plantations on the soil organic matter content is both positive and negative. For instance, as much as they increase soil organic matter content, they also increase soil acidity.

Lemma (2006) and Gebremeskel (2003) mention that forest plantations established on degraded lands in Ethiopia are mainly monocultures of exotic species belonging to either of the general Cupressus, *Eucalyptus* and Pinus. To achieve ecological restoration, species selection is very important because planting inappropriate tree causes land degradation (Lemenih, 2004). Even though most of the studies (e.g. Amare, 2002; Dessie and Erkossa, 2011; FAO, 1979, 1985, and 2005; Singwane and Malinga, 2012) encourage the tree plantation establishment, selecting appropriate tree species to improve soil quality is critical.

3. MATERIALS AND METHODS

3.1. Description of the study area

3.1.1. Location

The study area, Damot Sore, is one of the 13 districts in Wolaita Zone of Southern Nations Nationalities and Peoples' Regional State (SNNPR) in Ethiopia. The woreda is located Southwest of Addis Ababa at 336 km on the way to Hosanna main road and 18km away from Sodo town, the capital city of Wolaita zone. It is situated at 06° 91' 92.9'' and 07° 19' 21.6'' North latitude and 37° 43' 73.9'' and 37° 84' 77.2'' East longitude (Abebe *et al.*, 2013) (Figure 2). Damot Sore is bordered on the Southeast by Sodo Zuria, on the West by Kindo Koysha, on the Northwest by Boloso Bombe, and on the North by Boloso Sore Woredas, respectively.

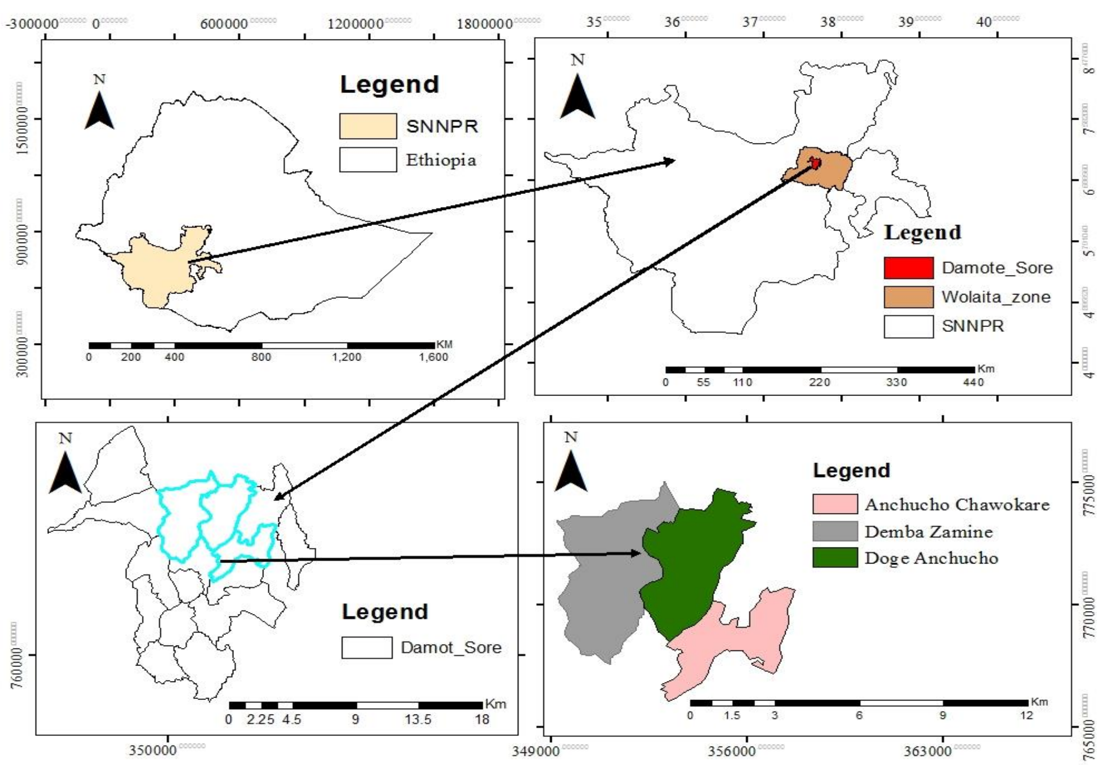

Figure 2 *Map of the study area*

3.1.2. Climate and topography

The altitude of the district varies from 1900 to 2010 masl with average annual temperature of 22.5°C and the rainfall of 1250 mm/yr. Agro-ecologically, the district has 74% weyna dega (warm to cool semi-humid), 15% dega (cool to cold humid) and 11 % kolla (semi-arid) (Abebe *et al*., 2013).

3.1.3. Soil

Nitisol is the dominant soil type in the area and actually considered fertile soils. They are deep, well drained, red, tropical soils and stable soils with favorable physical properties . In addition, the deep porous and stable soil structure permits deep rooting and make conducive environment for the production of various food crops and trees (Fekadu, 2009).

3.1.4. Demography

Based on the 2007 Census conducted by the CSA, the district had a total population of 100,683, of whom 49,047 are men and 51,636 women; 6,124 or 6.08% of its population are urban dwellers. According to Damot Sore Agricultural Development office (2017), the woreda has an estimated population of 134,804 , of whom 64,740 are men and 70,064 are women. The majority of the inhabitants were Protestants, with 62.47% of the population reporting that belief, 31.15% practiced Ethiopian Orthodox Christianity, and 5.47% were Catholic.

3.1.5. Vegetation and farming systems

The study site, Damot Sore, is situated in an *Enset* farming environment where livestock and crop production are integral part of the farming system (Fekadu, 2009). The cropping system in the district is mixed agriculture. The major annual crops grown commonly in the area are, Maize, Barely, teff, beans, Wheat, potato, Rape seed, and many other vegetables, spices, and fruits bearing shrubs and trees are cultivated throughout the study area. In spite of the fact that the diversified potential of crop productivity, farmers have widely planted *Eucalyptus* species computing croplands, it grows fast and requires less care. Tree planting niches identified in the study area are at woodlots, cropland boundary planting, homesteads, road sides, live fence, and churches under an agroforestry practice and plantations to fulfill the needs for fuel wood, construction and also to generate income.

3.2. Description of the species

Eucalyptus camaldulensis Dehnh. with common name river red gum is a tree of the genus *Eucalyptus*. It is one of around 800 in the genus in the family of Myrtaceae. It is a plantation species in many parts of the world, but is native to Australia, where it is widespread, especially beside inland water courses. In Ethiopia it is called *Key Bahir Zaf* or "red eucalypt" and one of the fifty-five introduced eucalypts and among the most widely adopted and used in plantations as well as smallholder farmers (Davidson 1995 and FAO 2001 cited in Zenebe, 2013).

Tree species reference and selection guide in Agroforestry Database tell us that *E. camaldulensis* botanically was described as a commonly grown plant that grows to a height of 20 m tall, occasionally reaching 50 m, with a trunk diameter of 1-2 m; in open formations has a short, thick bole and a large, spreading crown; in plantations has a clear bole of 20 m with an erect, lightly branched crown; bark smooth, white, grey, yellow-green, grey-green or pinkish grey, shedding in strips or irregular flakes; rough bark occupies the first 1-2 m of the trunk. Leaves is grey-blue, alternate, drooping, 8-22 cm long, 1-2 cm wide, often curved or sickle shaped, tapering, short pointed at base. Inflorescence axillary, solitary, 7-11 flowered; flower buds white, globular-rostrate or ovoidconical; operculum hemispherical, rostrate or conical, 4-6 x 3-6 mm, obtuse. Its fruit is very small capsules at the end of thin stalks, 5-8 mm, valves 4, and containing minute seeds (http://www.worldagroforestry.org/sea/products/afdbase/asp/SpeciesInfo.asp?SpID:760).

3.3. Methods

3.3.1. Data sources and collection techniques

During the study time, different qualitative and quantitative data were collected with sequential procedure (beginning with qualitative and followed by quantitative data collection). The qualitative data were assessed by the history of the study area regarding the practices of *Eucalyptus* tree management, different characteristics of trees, and field observation on the management of the farming system on farmers' woodlots. Combination of both primary and secondary data collection methods were used to obtain the required data to achieve the stated objectives of the study. The primary data were collected through preliminary survey followed by household survey using structured questionnaire through interviewing the household heads and measurements from the field. The secondary data were obtained from the District Office of Agriculture and Rural development documentations, reports related to *Eucalyptus* plantation activities and other relevant literature used to gather information about the study species.

3.3.2. Study site selection

Before the actual work started, informal discussions were conducted with the Department of Natural Resources Management team leader of Damot Sore District Office of Agriculture and Rural Development on the major trees grown and *Eucalyptus* plantation activities in the district. Reconnaissance surveys were carried out on farmers' *Eucalyptus* woodlots in the study kebeles prior to data collection to identify representative woodlots with Development

Agents (DAs). Discussions were also conducted with the Kebele leaders and Development Agents (DAs) to explain the aim of the study. According to the survey, all households within the study site have more or less intensive plantation of individually owned *E. camaldulensis* tree species on their own woodlots. As the result, three representative kebeles (i.e. Anchucho Chawokare, Demba Zamine, and Doge Anchucho) were randomly taken among 22 kebeles from the district.

3.3.3. Sampling techniques and sample size determination

Stratified random sampling technique was employed to collect data from the study site. The stratification of households into different woodlot size classes was done by using information gathered on *Eucalyptus* woodlot land holding size of households during preliminary survey conducted in the study area. Accordingly, three classes were identified, (Households having Large (≥ 0.2ha), Medium (≥ 0.1 to < 0.2), and Small (< 0.1) woodlot sizes). The number of plots were determined by the pragmatic approach, depending on available time and budget of the study. As a result, a 10% farmers from each woodlot size class were randomly selected by lottery method based on their relative proportion. Total of 62 households across the three woodlot size classes were selected, comprising 14, 26 and 22 sample plots were inventoried in large, Medium and small woodlot sized households farms respectively (Table 2).

Table 2. Summary of Kebeles and Households at each woodlot size class selected for the study

Study Kebeles	No. of villages	Villages selected	Total No. of HHs	HHs in each size class			Sampled HHs			Total sample
				Large	Medium	Small	Large	Medium	Small	
Ach	5	Gortancho	54	13	21	20	1	2	2	5
		Mehal Ach	68	17	27	24	2	3	2	7
		Dinkama	43	10	17	16	1	2	2	5
DA	8	Tayote	72	18	26	28	2	3	3	8
		Dukala	84	21	30	33	2	3	3	8
		Nazibo	118	32	42	44	3	4	4	11
DZ	6	Boko 1	67	9	34	24	1	3	2	6
		Waraza	58	6	29	23	1	3	2	6
		Boko 2	55	7	26	22	1	3	2	6
Total	19		619	133	252	234	14	26	22	**62**

Ach = Anchucho Chawokare, DA = Doge Anchucho, and DZ = Demba Zamine

3.3.4. Sampling design for biomass carbon stock estimation

Woody species inventory

In order to determine the above ground biomass and carbon stock of the individual woodlot, the woodlots were randomly selected in order to capture a representative mixture of size of woodlots. Studied woodlots were between the size ranged from 0.06ha to 1ha where a majority of woodlots were rectangular in shape. Sample plot with an area of 10mx10m ($100m^2$) were randomly located in each woodlots of the selected households using lottery method. Within this plot, the diameter at breast height (DBH ≥ 3cm) and total tree height of all *E.camaldulensis* trees encountered inside the plots were measured from two perpendicular sides using a Caliper graduated in Centimeter (cm) and Silva-Hypsometer, respectively. For larger shoots, measurements were made using diameter tape using the same unit. A stick marked at 1.3m from the point of sprout determined the heights for the diameter at breast height measurements respectively. Also, the plot centers were recorded using Global Positioning System (GPS).

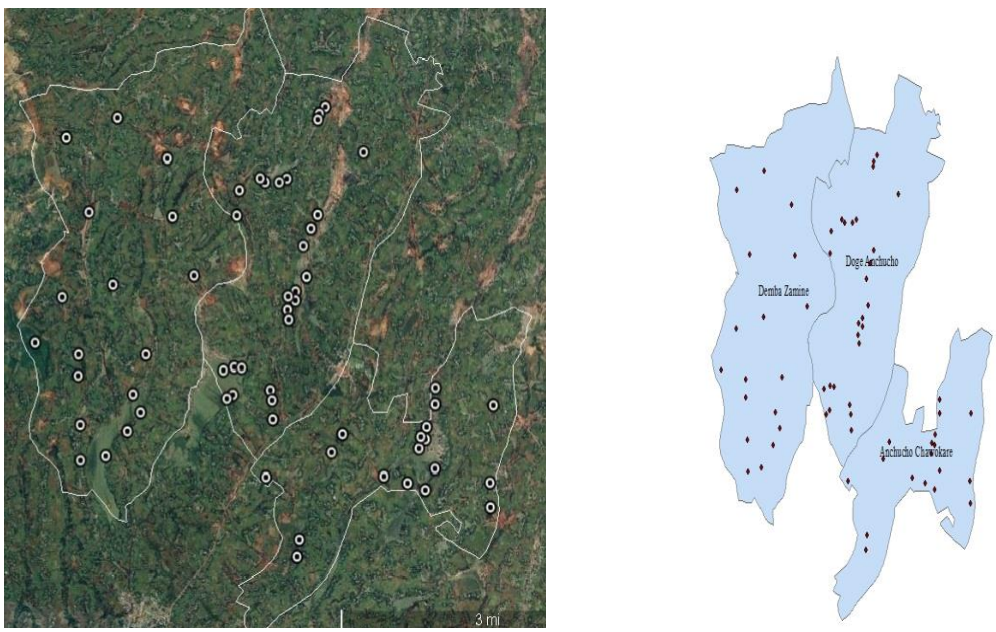

Figure 3 Location of sampled plots in study kebeles

3.3.5. Litter and soil sampling design

A. Litter sampling

Litter samples were taken randomly from a quadrat of 1m*1m laid down within the major plot with 3 replication per plot using a lottery method. After sub-samples from each plot were composited, the total fresh weight of litter sample of each plot was weighed and recorded on the site using spring balance and 100g sub-samples from each plot were taken to laboratory.

B. Soil sampling

Soil samples were taken from the default depth, which is 60cm (Bhishma *et al.,* 2010) from each of the sample woodlots in a 10m × 10 m (100m^2) plot to investigate the bulk density and the carbon stock in the soil.

In each soil sampling plot, the soil samples for SOC estimation were taken from the five sampling points with 'X' pattern with two replications by inserting soil augur 0 - 30 and 30 - 60 cm depths. Samples from each soil depths were carefully extract from the augur and thoroughly mixed in a large bucket to form composite soil samples for the plot. Undisturbed soil samples for bulk density determination were taken from the centre of each woody species sampling plot with above mentioned depths using soil core sampler with height of 10 cm and diameter of 7.2 cm (see appendix 7). Therefore, the total of 248 samples (i.e. 124 for SOC and 124 for bulk density) from two depths were taken. All soil samples were labeled individually and taken to soil laboratory of Wondo Genet College of Forestry and Natural Resources for further analysis (i.e. to determine SOC as well as bulk density of the soil). Since the height of core sampler is 10 cm, samples taken three times for the first depth and the same procedure followed for the depth 30 - 60cm.

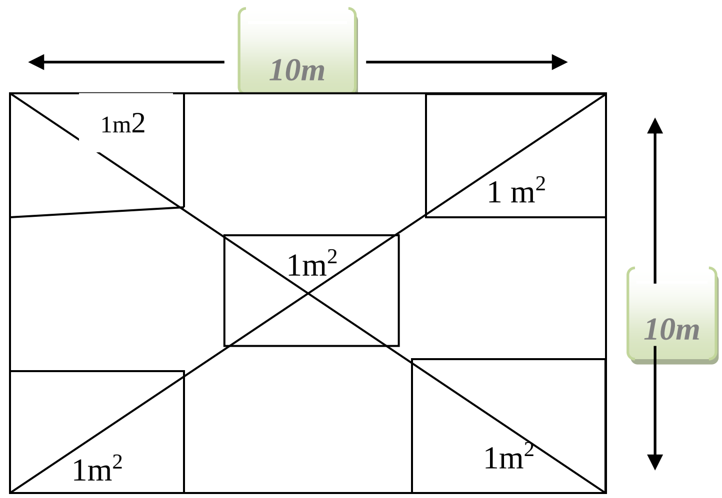

Figure 4 Layout of soil sampling plots

3.4. Data analysis

3.4.1. Woody biomass estimation

Above ground biomass was determined through taking the measured value of DBH of individual trees by using allometric equation developed for *E. camaldulensis* by Hailu (2002) in the Central and Northwestern Highlands of Ethiopia.

$AGB=0.0155\times d^{2.5823}$..Equation (2)

Where, *AGB* is above ground biomass in Kg, and d is diameter at breast height in cm.

Above ground carbon stock of each tree biomass conversion to carbon stock was based on (Pearson *et al*., 2005; Brown, 2002; IPCC, 2006).

$AGBC= AGB * 0.47$ .... Equation (3)

Where, AGBC = Above ground biomass carbon stock (kg/tree) and AGB = Above ground biomass (kg/tree).

Below ground biomass is estimated by using the globally averaged simple root to shoot ratio which varies 20 to 50% depending on species. Accordingly, for tropical dry forest, below ground biomass is estimated to be about 27% of the above ground biomass estimates (IPCC, 2006).

$$BGB = AGB * 0.27 \text{ ………………………………………………… Equation (4)}$$

Where, AGB = Above Ground Biomass (kg/tree), BGB = below ground biomass, 0.27 is conversion factor (or 27% of AGB). To estimate the carbon content in BGB, the same procedure was applied like that of AGB.

BGC = BGB * 0.47 .... Equation (5)

Where, BGC = carbon content of below ground biomass, BGB= below ground biomass

In order to make comparison of results of Hailu, 2002, aboveground total biomass determination equation developed by Kuyah *et al.* (2012) were used by considering all trees ≥3cm DBH and total height of the tree: AGB = $0.091*dbh^{2.472}$: Where; AGB = Aboveground biomass per tree (kg), dbh = diameter at breast height (cm).

3.4.2. Litter carbon stock estimation

The collected litter samples were air-dried and oven-dried for 24 hours at 70^0C to constant weight. Then, the samples were weighed and ground. The dry biomass of litter was calculated using the equation below (Pearson *et al*., 2005).

$$LB = \frac{W\ field}{A} \times \frac{W\ sub\text{-}sample(dry)}{W\ sub\text{-}sample\ (fresh)} \times \frac{1}{10000} \text{ .... Equation (6)}$$

Where: LB is Litter biomass (Mg ha^{-1}), W field is weight of wet field sample of litter sampled within an area of 1m^2 (g), A is size of the area from which litter was collected (ha), W sub-sample dry is weight of the oven-dried sub-sample of litter that was taken to the laboratory to determine moisture content (g), and W sub-sample fresh is weight of the fresh sub-sample that was taken to the laboratory to determine moisture content (g).

The loss on ignition (LOI) method was used to estimate the percentage of carbon in the litter biomass. From the oven-dried ground sample, 3 gram from each litter subsamples were taken in pre-weighted crucibles, and then put in the muffle furnace at 550 ^{0}C for two hours to ignite (Allen *et al*., 1986). Then, the crucibles were cooled slowly for two hours inside the furnace. After cooling, the crucibles with ash were weighed and percentage of organic carbon storage from the dry ash in the litter carbon pool was calculated as follows (Allen *et al*., 1986):

$$\%Ash = \left(\frac{W3-W1}{W2-W1}\right) * 100 \qquad \text{Equation (7)}$$

Where, W_1 is weight of crucible; W_2 is weight of the oven-dried ground sample and crucible, and; W_3 is weight of ash and crucible.

Percentage carbon content was estimated as 50% of OM (Pearson *et al*., 2005),

$$\%C = (100 - \%Ash) * 0.5 \qquad \text{Equation (8)}$$

The carbon content in litter biomass was calculated by the following formula given by (Pearson *et al.*, 2005).

$$CL = LB \times \%C \qquad \text{Equation (9)}$$

Where, CL is total carbon stocks in the dead litter in Mg ha^{-1}, %C is carbon fraction determined in the laboratory (Pearson *et al.,* 2005).

3.4.3. Soil organic carbon estimation

In the laboratory, the collected soil samples were air-dried by placing in a well-ventilated, dust and wind free area for three days. After three days, the soil samples were mixed well, ground in pestle and mortar and sieved through a 2mm mesh size sieve for the analysis of all parameters except SOC which were passed through 0.5 mm sieve. Three gram (3g) of each air-dried and sieved soil samples was taken separately to determine percentage of carbon in the soil through indirect method which uses the chemical oxidation agents such as potassium dichromate ($K_2Cr_2O_7$) in acidic medium (H_2SO_4) (Walkley-Black, 1934). Soil samples were analyzed for texture or particle size using hydrometer method as described by Day (1965) and Sahlemedhin and Taye (2000). The soil pH was determined using glass electrode pH meter in 1:2.5 soil to water suspension following the procedure outlined by Sahlemedhin and Taye (2000).

Bulk density was estimated using oven dried samples at 105^0C for 48 hours and weighed them. The weight of the soil was divided by the volume of the core sampler. The weight of the coarse fraction above 2 mm diameter was subtracted from oven-dried ground soil samples to determine the bulk density of the soil samples since the presence of rock fragments complicates determination of soil bulk density, leading to over or underestimation of the SOC stock (Throop *et al.,* 2012). This requires accurate estimation of the amount of rock fragments for SOC stock calculation (Mehler *et al.*, 2014). Coarse fragments were obtained after the oven-dried soil samples were ground with a mortar and pestle where each soil sample was washed by clean water and passed through 2mm sieve to separate rock fragments >2mm in size. The volumetric content of the coarse fraction was calculated from the gravimetric contents of >2mm material in the soil samples and an assumed density of solids value of 2.65 g cm^{-3} (Mehler *et al.,* 2014).

To determine the SOC, firstly determine the bulk density using the formula (Pearson *et al.*, 2007):

$$\rho = \frac{ODW}{CV - \frac{RF}{PD}}$$ .... Equation (10)

Where, ρ= Bulk density of the < 2mm fraction, (g/cm^3),

CV = Core volume in cm^3 ($V = h * \pi r^2$: Where, V is volume of the soil in the core sampler in cm^3, h is the height of core sampler in cm, and r is the radius of the core sampler in cm (Pearson *et al.*, 2007).

ODW = Oven-dried mass of fine fraction (<2 mm) in g,

RF = Mass of coarse fragments (>2 mm) in g and,

PD= Density of rock fragments (g/cm^3). This is often given as 2.65 g/cm^3, (Pearson *et al.,* 2007).

Therefore, the soil organic carbon stock pool was calculated using the formula (Pearson *et al.,* 2007).

SOC = %C x BD x d x100 ....Equation (11),

where, SOC= soil organic carbon stock (Mg ha^{-1}), BD = soil bulk density (g cm^{-3}), d = depth at which the sample was taken (cm), and %C = % Carbon fraction.

3.4.4. Total carbon stock estimation

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

$$\text{CT} = \text{AGC} + \text{BGC} + \text{CL} + \text{SOC} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation (12)}$$

Where, CT= Carbon stock for all pools (Mg ha^{-1}), AGC= Carbon stock in aboveground tree biomass (Mg ha^{-1}), BGC=Carbon stock in belowground tree biomass (Mg ha^{-1}), CL=Carbon stock in litter biomass (Mg ha^{-1}) and SOC = Soil organic carbon (Mg ha^{-1}).

To convert carbon into CO_2 equivalent, the tones of carbon are multiplied by the ratio of the molecular weight of carbon dioxide to the atomic weight of carbon (44/12), or 3.67 (Pearson *et al.*, 2007).

3.5. Statistical analysis

Qualitative data from informal survey was interpreted, analyzed, and synthesized using descriptive statistical analysis. The quantitative data (DBH, height, fresh and dry weights of litter and soil) collected from the field were fed into a computer and organized on the excel data sheet for the further analysis of the data. The size and variation in the carbon stocks for each households woodlot were described by the mean and standard deviation. To test for differences in biomass and soil organic carbon stock (0-60 cm) and total carbon stock in woodlots among the three size classes, one-way ANOVA was performed (α = 0.05). To find out the effect of woodlot size and soil depths on soil organic carbon stock two-way ANOVA was performed. The quantitative data from the household questionnaire survey were subjected to statistical analysis and the results were presented in a summarized form using descriptive statistics such as means, percentages and Tables. All statistical tests were performed by using Statistical Package for Social Science (SPSS) software version 20.

4. RESULTS AND DISCUSSION

4.1. Tree stand characteristics of the studied woodlots

Eucalyptus was planted by all of the 62 surveyed households. The majority of households had first planted *E. camaldulensis* during the previous 35 years according to the response of farmers from studied kebeles . Since the ages, stock/density of trees, and size of *Eucalyptus* woodlot stand were different, samples were taken based on all this under consideration. The overall mean landholdings of the respondents in the study area was 0.77 ha and the mean woodlot size of 0.19 ha which shows about 25% of their total landholdings occupied by farm woodlots. According to preliminary woodlot survey, woodlots in the study area categorized between newly planted three years plantations to up to 27 age stages (Appendix 3). About 81% of mean tree diameter were below 10cm DBH within each of the sampled woodlots from kebeles studied as indicated in appendix 3. As interviewed farmers responded, the dominance of young trees with smaller diameters in the woodlot is indicative of the high occurrence of afforestation of lands which is previously been under agriculture. In addition, most of the old stands were selectively and intensively harvested either for home use or sell. The descriptive statistics for household land use management are found in Table 3 below.

Table 3. Descriptive statistics for studied woodlots in three kebeles of Damot Sore district (n=62)

Stand characteristics	Size class			Overall Mean (n= 62)
	Large (n=14)	Medium (n=26)	Small (n=22)	
Landholding size (ha)	1.09 ± 0.88	0.68 ± 0.53	0.5 ± 0.25	0.77 ± 0.59
Woodlot size (ha)	0.38 ± 0.23	0.14 ± 0.03	0.07 ± 0.01	0.19 ± 0.16
DBH (cm)	7.57 ± 2.89	6.55 ± 2.39	7 ± 2.72	7.04 ± 2.61
H (m)	8.5 ± 3.05	7.49 ± 2.46	7.72 ± 2.47	7.90 ± 2.59
BA (m2 ha-1)	0.244 ± 0.203	0.064 ± 0.055	0.0352 ± 0.032	0.1146 ± 0.03
Tree density (stems ha^{-1})	3629 ± 2300	1072 ± 388	512 ± 158	1738 ± 1269

The values are significant at the p, since 0.000 < 0.05, DBH = Diameter at Breast Height, H = Height, and BA=Basal area

4.2. Biomass carbon stocks

The above and belowground carbon stocks in the studied woodlots among the three woodlot class categories are shown in figure 5. The above and belowground biomass carbon stocks for the study area were ranged from 1.09 to 70.31 Mg C ha^{-1} and 0.29 to 18.98 respectively. Mean AGB carbon stock was higher in large (≥0.2ha, 20.01±19.72 Mg C ha^{-1}, *n*=14) woodlots and statistically different ($p< 0.05$) compared to medium (≥0.1 to <0.2 ha, 9.78±7.66 Mg C ha^{-1}, *n*=26) and small woodlots (<0.1 ha, 7.43±5.08 Mg C ha^{-1}, *n*=22) whereas no significant differences are found between medium and small size woodlots (Figure. 5). Carbon stored in the litter also accounted for 1.58 ± 0.63, 1.15 ± 0.34, and 1.28 ± 0.45 Mg ha^{-1} (Mean ± SD) for large, medium and small woodlot sized households, respectively with a mean values of 1.293 ± 0.48 Mg C ha^{-1}.

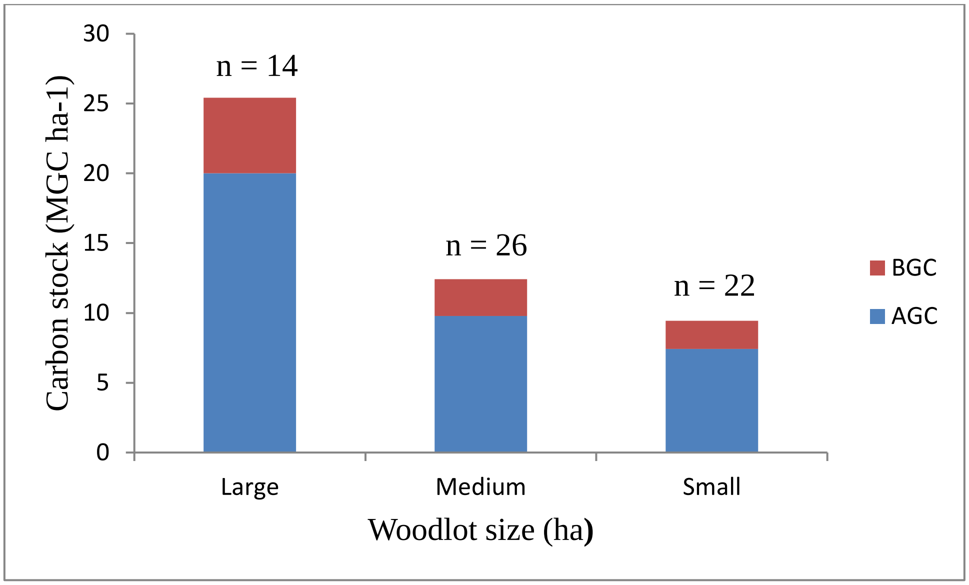

Figure 5 Mean above and belowground biomass carbon stocks among the three woodlot size classes of the studied woodlots

The results of the study has revealed that *E. camaldulensis* woodlot has a great significance as carbon store since it stores a large amount of carbon in biomass and soil, and can significantly contribute to the climate change mitigation in addition to other socio-economic benefits. The highest value of mean tree biomass carbon (AGC and BGC) of the species on woodlot of the study area is associated with high stand density/number of individuals per hectare and associated structural parameters such as basal area and crown cover due to dense *Eucalyptus* planting. In addition, this could be attributed with high efficiency of *Eucalyptus* in carbon sequestration than native species as it is faster in its growth (Gil *et al.*, 2010). The results of the current study are in line with those of Asfaw (2003); Mukutar (2006); Worku (2011); Yakob *et al.*, 2014; Haile *et al.*, 2017. Similar results were observed also in Western Kenya and indicated that woodlots of fast growing species contained the highest amount of AGC stock as compared to other agroforestry practices (Henry *et al.*, 2009; Yadava, 2011).

4.3. Soil organic carbon stocks

The mean total bulk density of the soil was determined to be 0.89 ± 0.095g/cm^3 which falls under the category of soils with a low bulk density (BD < 1.5 g/cm^3) (Cresswell and Hamilton, 2002). This the low value of bulk density indicates that most of farmers undertake the different management practices. As indicated in table 4, bulk density tends to increased with depth which from 0.93 g/cm^3 to 0.95 g/cm^3 due to the decrement of pore spaces among soil particles.

The mean soil texture under different areas of the study was clay loam with average values of Sandy (36.28%), Clay (35.44%), and Silt (28.28%) which might indicate the comparability of the site with respect to the soil (Appendix 5).

The result of the current study indicated that the mean total SOC (Mg ha^{-1}) in *E. camaldulensis* woodlots was found to be 73.43 ± 19.02 (Mean ± SD) which is higher than what was reported by Bajigo *et al* (2015) for woodlots in Gununo watershed in Wolaita Zone (48.57±0.3Mg ha^{-1}). This might be due to the management system of the woodlot in the current study area, where there was little crop resides on the woodlots and since the households used the fallen leaves for fuel, which might resulted in lower OC. Liang *et al.*, 2016; Nair, 1993; and Young, 1989 revealed that litter fall contributes to the return of organic carbon through decomposing in soil. Also the management practices of farmers' like burning can have an effect on carbon availability as burning remove carbon to atmosphere and might result in lower value of OC on woodlot. Similar result was observed in studies conducted in other areas (Blanco and Lal, 2008; Hazelton and Murphy, 2007).

The result of present study also indicated that soil organic carbon content decreases with soil depth. This might be due to the presence of lower accumulation of organic matter resulting from lower below-ground root biomass in the sub-surface layer (Yimer *et al.*, 2015). The result was consistent with other studies conducted in the different parts of Ethiopia (Bajigo *et al.*, 2015; Negash and Starr, 2015).

Table 4. Mean values of Soil pH, Bulk density, and SOC

Parameter	**Soil depth (cm)**	**Size class**			**Overall Mean (n=62)**
		Large (n=14)	**Medium (n=26)**	**Small (n=22)**	
Soil pH	0 - 30	5.07±0.21	5.46 ±0.59	5.10 ±0.61	5.21 ± 0.56
	30 - 60	5.25 ±0.26	5.62 ±0.61	5.23 ±0.57	5.37 ± 0.56
BD (g cm^{-3})	0 - 30	0.92± 0.13	0.94 ±0.09	0.91 ±0.09	0.93 ± 0.081
	30 - 60	0.96 ±0.07	0.95 ±0.08	0.92 ±0.09	0.95 ± 0.107
SOC (Mg ha^{-1})	0 - 30	45.23± 14.33^{bB}	45.11 ±15.48^{bB}	48.40 ±15.12^{aB}	46.25 ± 16.92^{B}
	30 - 60	25.68 ±13.86^{bA}	24.61± 15.75^{bA}	31.26 ±11.49^{aA}	27.18 ± 17.21^{A}

Within each soil layer, Similar letters shows not significant differences and different letters indicate significance differences among groups in row at 5 % level of significance and between soil depths different capital letters shows significant differences among groups in column at 5 % level of significance.

4.4. Total carbon stock

Total carbon stock (AGC + BGC + LC + SOC) in farmers' woodlots of the study area was determined to be 89.013 Mg ha^{-1} and CO_2 equivalents mean total value of 326.68 ton/ha. (Table 5).

It did not significantly differ between woodlots of large and small sized households but both of them significantly varied from the medium sized households ($p<0.05$). The highest total woodlot carbon stock was recorded for large (97.9 Mg C ha^{-1}), followed by small (90.38 Mg C ha^{-1}) and medium households (83.29 Mg C ha^{-1}). The soil organic carbon stock accounted for 72%, 84% and 88% of the total C stock (biomass plus soil) for the woodlots of large, medium and small sized households, respectively (Table 5). The total carbon stock in the studied woodlot was lower than the reports of Gunnuno watershed in Wolaita Zone (Bajigo *et al*., 2015) which is 448±43 ton/ha for woodlot agroforestry practice. This might be due to the replacement of old stands by the newly planted or coppiced ones annually and this might have resulted in the reduction of carbon stored in the woody biomass of the stand tree.

Table 5. Total carbon stock (AGC + BGC + LC + SOC) in farmers' woodlots of the study area

Carbon Pools	Size class			Overall mean
	Large	Medium	Small	(Mean ± SD)
AGC (Mg ha^{-1})	20.01 ± 19.72	9.78 ± 7.66	7.43 ± 5.08	11.25 ± 11.12
BGC (Mg ha^{-1})	5.40 ± 5.32	2.64 ± 2.07	2.01 ± 1.37	3.04 ± 2.92
LC (Mg ha^{-1})	1.58 ± 0.63	1.15 ± 0.34	1.28 ± 0.45	1.293 ± 0.48
SOC (Mg ha^{-1})	70.91 ± 17.05	69.72 ± 18.61	79.66 ± 15.85	73.43 ± 19.02
Total C (Mg ha-1)				89.013

4.5. The relationship between woodlot sizes and tree densities

The size of woodlots owned by each of the households were strongly related (R^2 = 0.75 and 0.5) to the densities of trees in both large and small woodlot sized households due to the total land holding areas and using narrow spacing during the time of planting respectively. But, as indicated in the figure 6, those households having medium sized woodlots shown weak relationships (R^2 = 0.023) between trees number and size since most of individually owned woodlots were exposed to illegal theft as well as cattle interference.

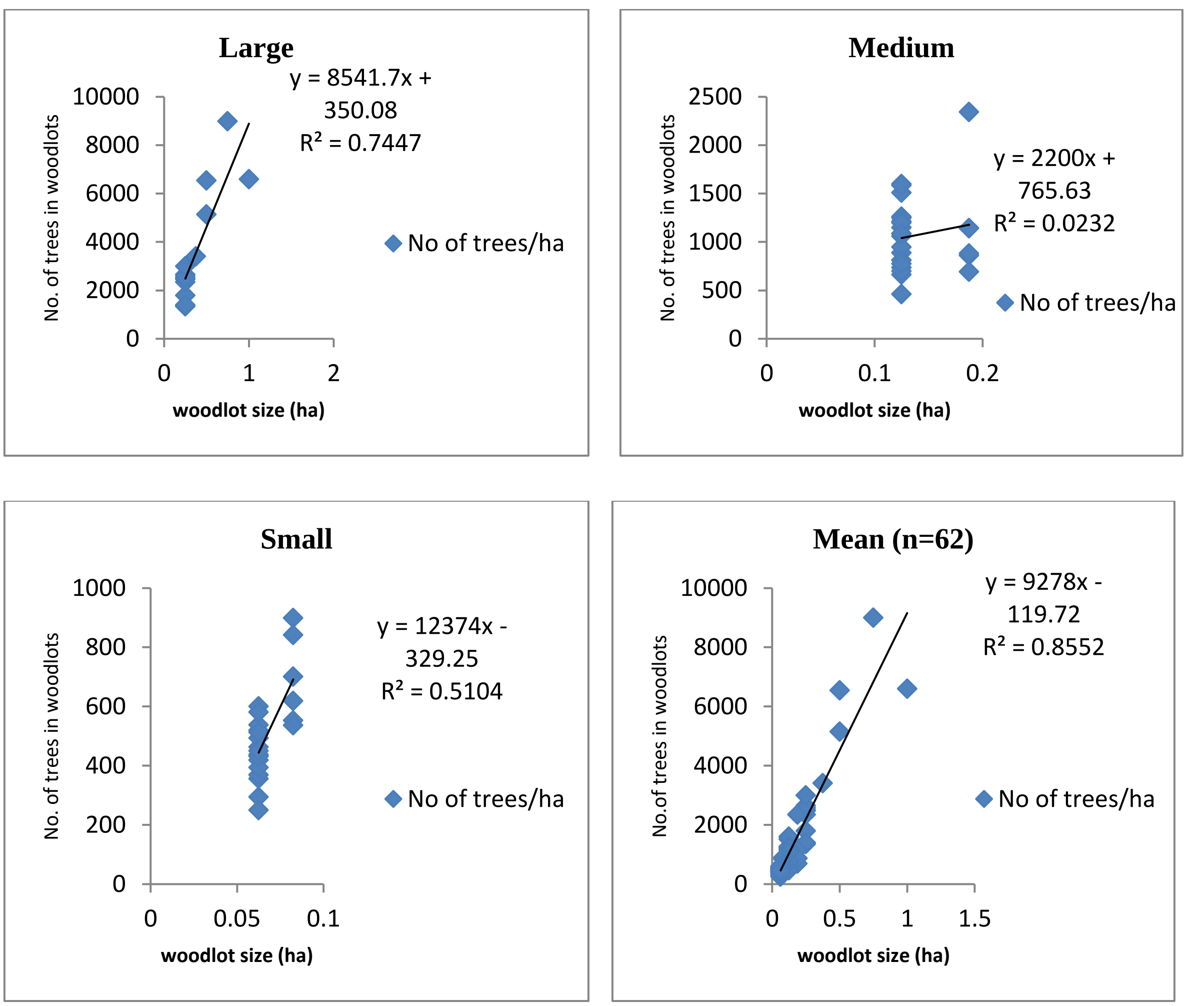

Figure 6 The relationship between number of trees per woodlot and the woodlot size in the large, medium, and Small woodlot sizes and across 62 sampled woodlots

4.6. The relationship between woodlot size class and carbon stocks

The total biomass carbon stock and total woodlot (biomass plus soil) carbon stocks were significantly correlated to woodlot size classes of households (Appendices 6). Similar trend was observed for SOC stock in the studied *Eucalyptus* woodlots. Different woodlot size category showed strongest significant correlation with total biomass carbon stocks (i.e. AGBC + BGBC) and the least with total woodlot (biomass plus soil) carbon stock (respectively r= 0.864 and r=0.753, $p<0.01$). The positive relationship between woodlot size class and carbon stocks in the present study might be due to wealth status of households related to stand characteristics (e.g. density/stocking of trees) and, size of the land holding (Getahun, 2011). The mean size of land holding in the present study area was higher for those who have large woodlot sizes and medium households than small.

Large and medium woodlot sized households having large farms and capital allocate more resources (e.g., space, labor and capital) for maintaining a sufficient amount of seedlings for *E. camaldulensis* trees. Hence, the more land a household owns, the higher the chance is to grow more trees and associated biomasses (Haile *et al*., 2017). Several studies from different parts of Ethiopia also reported the positive relationship between land holding and woodlot size of the households and stand characteristics including stem number, species richness and diversity (Worku, 2011; Agidie *et al*., 2013; Yakob *et al.*, 2014; Haile *et al*., 2017).

4.7. Importance and management practices of *Eucalyptus* in woodlots

4.7.1. Importance of *Eucalyptus* trees on farmers' woodlots

Eucalyptus trees identified in the study area were supporting the local people in several ways. Household respondents indicated that benefits being driven from *Eucalyptus* woodlots by the communities include cash income that can be used to cover various costs, construction material, fuelwood, shade, farm implements, and environmental services. The respondents also indicated that *Eucalyptus* woodlots have important role in the control of soil erosion particularly in Demba Zamine kebeles specially farms on sloppy areas.

They also indicated that when planted on soils that are unproductive from cereal production, *Eucalyptus* woodlots act as an asset and money saved in book account. This is consistent with the report of Lemenih (2010). Moreover, the respondents indicated that *Eucalyptus* woodlots contributing to the economic resilience of the communities against climate change. In addition to the environmental and economic benefits, they also indicated that some parts of the *Eucalyptus* such the tip of the young shoots could be used for the treatment of human ailments such as stomachache and also as preservative over.

According to the respondents in study areas, almost all of the farmers don't appreciate the role of trees to improve soil productivity but they said "if planted in the appropriate place, *Eucalyptus* have not negative effect on the crop. They even stressed that "living without *Eucalyptus* is nothing". This finding is in line with the findings of a number of researches conducted in Ethiopia and elsewhere (Jagger and Pender, 2003; Teshome, 2007; Munishi, 2007; Gemechu, 2010)

4.7.2. Management practices of woodlots

Farmers in the study area traditionally managed *Eucalyptus* trees in woodlots to get multiple benefits. They carry out different types of management activities for the species they have in their woodlots based on their indigenous knowledge either to improve the benefits obtained from the tree or to reduce the negative effects on it.

Interviewed respondents indicated that pruning, thinning (27.19%), composting, weeding and cultivation (38.60%), burning stump after harvest, application of commercial fertilizer, and watering are the most common management practices in the area (Figure 7). The management practice of the study area (thinning, pruning, coppicing, bark pollarding and others) are in line with the commonly used managements in tropical agroforestry (Badege and Abdu, 2003; Tengnas, 1994; Nair, 1993). These management practices were shown to vary in intensity, frequency they required and different age stages they needed. The application of any management scheme in the area is linked with the indigenous knowledge of the people in the area. They perceive how well the tree species (i.e. *E. camaldulensis*) react to different managements and its effect on different biophysical settings.

As indicated in the figure 7, majority of the respondents choose weeding and cultivation (38.60%) as the most common management practice in the woodlots during the time of early stage of trees after harvested or newly planted until the first three to four years annually during rainy seasons (i.e. June and July) to remove trees with undesirable characteristics from the woodlot. In addition, they also undertake such practices to make the rain water easily enter into the soil in-depth and also to undertake replacement plantings either on those newly planted dead ones or dead stumps. Thinning is the second most common (27.19%) management practice since most of the interviewed respondents agreed on selective low thinning as their best practice at the early age stages of woodlots to generate their daily fuelwood for home consumption. The finding of the present study indicated that, most of the respondents did not rate pruning as a best management practice for trees on their woodlot. This is because they left it for self-pruning. Burning stump after harvest, application of commercial fertilizers, and watering were also among the management practices indicated by the respondents although to a lesser extent as compared to the first three rated as very common ones. Better application of prescribed burning was given for woodlot to increase release of nutrients to soil, promoting the growth of grasses that can be harvested as feed for domestic animals and facilitate the vibrant shoots from the stamp. The respondents indicated that less attention was given for woodlot in fertilizer application and watering as *Eucalyptus* is deep rooted and can get nutrients and water from deeper soil horizons. But, instead they use type of management practices such as stocking control, removing dried stumps, bark pollarding, composting or application of manure, enrichment planting, terracing to control soil erosion, and removing epiphytes which may compete for nutrients.

The indigenous knowledge of the farmers is not only about the different *Eucalyptus* tree management practices, but they also know in which month it should be harvested. For example, they believed that July is a month not recommended for harvesting *Eucalyptus* trees it may result in complete death of trees locally named as 'Chegena' in local language.

In general, variation in the management intensity was observed in woodlot systems, and this is also true in different areas and eco regions (Badege and Abdu, 2003; Tengnas, 1994; Nair, 1993). The variation can be attributed to difference in socio economic, cultural and biophysical and environmental settings/criteria (RWEDP, 1995). In addition, it could be related with some of the factors affecting adoption of agroforestry technologies like woodlots in tropics such as sex, age, livestock population, education level, growing of trees, species preference, market, family size, farm size, etc (RWEDP, 1995; Bongers, 2010; Muhammad *et al.*, 2011; and El Tayeb, 2008).

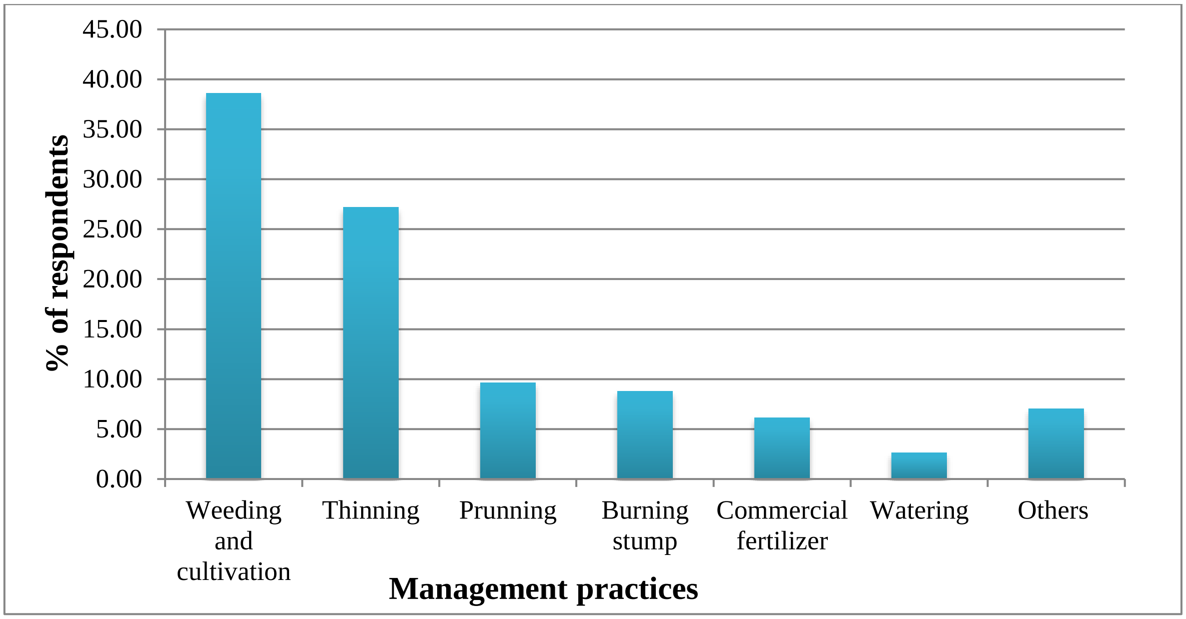

Figure 7 Eucalyptus tree management practices undertaken by the farmers in study area

The respondent households also undertake those management practices for their own woodlots for different purposes. As they responded , the major objective for managing *E. camaldulensis* woodlots were mainly for production (86.32 %, 81.46%, and 76.79% for large, medium, and small sized woodlots respectively) either for fuelwood consumption, construction materials and cash income generation. Others such as soil and water conservation, cure for stomachache etc. are also common ones raised by households from the interviewed respondents why they plant and manage *E. camaldulensis* trees on their own woodlots. In addition to this, households at the study area also provide different management activities to woodlot stands of different age stages which are planted annually during the rainy seasons i.e. June to July. This might indicate that there is sustainable management of stands to meet those objectives due to the presence of different age gradations within each household woodlot.

The seedling of the *Eucalyptus* species collected from different sources to increase number of trees on their woodlots. The interviewed respondents indicated that 38.71%, 19.35% , and 41.94% seedlings of the studied species planted in the area was obtained from self raised (own nursery), market place (purchased from local markets), and both respectively (Table 6).

Table 6. Seedling sources for *E. camaldulensis* woodlots

Source of seedlings	**Number of respondents**	**% of respondents**
Own nurseries	24	38.71
Market place	12	19.35
Both	26	41.94
Total	**62**	**100**

The result indicated that most of the respondents use their own nurseries as a seedling source due to the preparation of *Eucalyptus* seedlings were discontinued in government nursery sites. As result, they collect seeds from the area where the matured trees were harvested either for house construction or other purpose. This is an opportunity to improve density of only *E. camaldulensis* trees in woodlot based on the farming system adopted by the farmer and to increase the direct and indirect benefits of trees for the local community. This finding is in agreement with Gemechu (2010) on continued expansion of farmers' *Eucalyptus* plantations expansion either by preparing their own *Eucalyptus* seedlings or through purchase.

4.8. Constraints encountered in *Eucalyptus* woodlot management in the study area

There is also a challenge and constraints in the management of *Eucalyptus* trees on farmers woodlots (Table 7). Some of the main problems in study area encountered by the farmers include illegal cut by theft (34.84%), insect pest attacks (14.84%), and free grazing animals (13.55%) (Table 7). The respondents also mentioned other factors such as changes in the weather condition, drying of newly planted seedlings due to prolonged dry season.

Eucalyptus on farmers woodlots were highly affected by insect pests in Anchucho Chawokare than other kebeles. The result also indicated that Doge Anchucho and Demba Zamine kebeles are highly exposed to illegal cut of trees by thief because their *Eucalyptus* woodlots were far away from their home. This result agreed with Verheij (2003), he says "parklands and woodlots are best developed near the villages, as they can be well protected and managed" and management intensity levels decrease as distance from the compound increases (Boffa, 1999).

Drying of trees is also another problem in all of the study kebeles that affected the management of trees. Some farmers said it is because of natural cases like 'Dadda' (local name) which mean to 'the action from Gods messenger from the above', but they don't know the exact reasons. Local farmer of the study area has also raised others like drying of stump if harvested on unrecommended month 'July' according to their response which is called 'Chegena' in local language, and the presence of old stand near to another's woodlot as a constraints to manage *Eucalyptus* trees on their woodlots. Animal damage at saplings stage during free grazing and water shortage (during long dry season) are also constraints that affect management of woodlot trees in study area.

Table 7. Frequency and percentage of problems encountered by farmers in *Eucalyptus* woodlot management in the sampled kebeles (N = 3)

Constraints	Frequency for each kebele 1	2	3	Frequency total	% of respondents affected
Animal damage	9	7	5	21	13.55
Insect pest	12	7	4	23	14.84
Theft	1	40	13	54	34.84
Whether condition	5	2	4	11	7.1
Drying	4	2	3	9	5.81
Others	14	10	13	37	23.87

1 = Anchucho Chawokare, 2 = Doge Anchucho, 3 = Demba Zamine

Most of respondents (13.55%) agreed on constraints raised either from domestic animals such as cattle, goats, sheep, Donkey or wild animals such as monkey especially on Demba Zamine kebeles. Such damage and control majors are not restricted to the study area. For example, in Bangladesh major problem that faced the farmers in tree establishment and management were the damage caused by animals, storms, and insect pests (Alam *et al.*, 2005; Zaman *et al.*, 2010). Since there was insect pest attack on *E*. camaldulensis caused by red gum lerp psyllid also known as *Glycaspisbrimblecombeion* (Figure 8), most of the farmers responded it as a serious problem for managing *Eucalyptus* tree species.

Figure 8 Insect pest (red gum lerp psyllid known as Glycaspisbrimblecombeion) attack on E. camaldulensis trees in the study area (photo by Tadewos Tesfaye on Jan, 2018)

However, local farmers traditionally use practices such as fencing, guarding and application of insecticides to solve the problems (Table 8). Fencing was an effective means of solving animal damage on woody species especially at seedling stages in all kebeles. *Eucalyptus* trees grown in the Doge Anchucho and Demba Zamine kebeles are highly affected by theft for that guarding (21.05%) ranked a second means to solve the problem (Table 8).

Table 8. Techniques through which local farmers solve the problems of managing *Eucalyptus* species in woodlots and % of respondent uses at each kebele

Type of solution	Study kebeles 1	2	3	Frequency total	% of respondents uses
Fencing	9	7	3	19	33.33
Insecticides	1	4	3	8	14.04
Guarding	1	7	4	12	21.05
Terracing	1	1	4	6	10.53
Others	2	2	3	7	12.28

1 = Anchucho Chawokare, 2 = Doge Anchucho, 3 = Demba Zamine

4.9. The effect of different management practices on biomass carbon stocks

There were different kinds of management practices observed in *Eucalyptus* based woodlot of the district studied. Those management practices might have effect on the amount of carbon stored in both biomass and soil. As indicated on the result, the mean above and belowground biomass carbon stocks were high in households having large landholdings as well as large woodlot area on which *E. camaldulensis* were growing. This is due to the stands with normal growing stocks than medium and small sized woodlots and the wide application of other management practices such as cultivation and prescribed burning since the households have potential to cover costs to apply those practices. The results were consistent with others studies conducted in different parts of Ethiopia (Tadesse and Tafere, 2017; Hailu, 2002). In addition, Farmers who own small landholdings and woodlot size has stands dominated with small diameter trees due to narrow spacing between trees resulted in low carbon stocks were stored in tree biomass. Soil organic carbon were high on small woodlot sized households since the soil under woodlots were not exposed to management practices such as weeding and cultivation which might affect physical soil properties and resulted in high bulk density values. Similar result was observed in studies conducted in other area (Tadesse and Tafere, 2017).

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The *E. camaldulensis* based woodlot systems of the study area is not only providing the benefit of fuel wood for home consumption and protective services for smallholders but also have promising potential to contribute to mitigation of climate change as carbon sinks. The findings of this study indicated that households differ by size of woodlots in the study area influence biomass and soil organic carbon stocks that woodlots accumulate. The woodlots of large and medium sized households had higher biomass carbon stock but lower soil organic carbon stock than small woodlot sized households. The variation in carbon stocks (biomass and soil) between large and medium households is not significant, but small woodlot sized households are significantly different from both large and medium households. This is in association with high stem number and woodlots dominated with large diameter sized trees, which results in high accumulation of litter fall and biomass production in the woodlots of large and medium households. Carbon stocks were found to be strongly correlated with size of *E. camaldulensis* woodlots owned by each of the households in the study area. Moreover, biomass carbon stocks were found to be strongly correlated with management practices experienced by the farmers. To conserve and sustainably use the *Eucalyptus* in woodlots, weeding and cultivation, thinning, and pruning were the most common local woodlot management practices applied by the farmers in all the study kebeles. Thus, both sizes of *Eucalyptus* woodlots and management practices experienced by households might have effect on the amount of carbon stored in both biomass and soil.

5.2. Recommendations

Based on the results and conclusions, the following recommendations are forwarded:-

- As indicated on the result of this study, *E. camaldulensis* woodlots store high carbon stocks which indicate that it has a significant carbon sequestration and climate change mitigation role so, farmers should be benefited from carbon credit schemes in addition to other benefits of *Eucalyptus* woodlot based farming to maintain the system through the implementation of payment for environmental services.
- Site specific biomass equations for the studied tree species will need to be developed in the future to reduce possible error in biomass carbon estimation.
- Further research should be conducted on other factors other than size of woodlots that may affect the carbon stocks in the existing woodlot system.
- Farmers should be encouraged to use their knowledge in every aspect (for example, management of woodlots) and the researchers and extension practitioners should further work on enhancing the awareness about the role of *Eucalyptus* based woodlot farming system on climate change adaptation and mitigation.
- Since *E. camaldulensis* species was highly interrelated with the livelihood of society in the study area, further research should be carried out to assess the effect of the recent insect pest attack on the yield of the tree species as it could decimate the local and national economy.
- It is recommended that there should be a means through which the farmers' knowledge in managing their *Eucalyptus* woodlots should be systematically documented and information is kept to educate the young people.

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APPENDICES

Appendixes 1 Questionnaire for assessment of socio-economic parameters and management practices.

Part I: Household Survey Questionnaire

Background Information

PA/Kebele:....................................,Village(Mender):...

Enumerator's name:...,Date of interview:.............................

1. Household Characteristics

1.1. Name of the respondent:.., Sex: Male ☐ Female ☐ Age:....

1.2. Marital status: Single ☐ Married ☐ Divorced ☐ Widowed ☐

1.3. Family size: ....

1.4. Family composition

No.	Age group (Years)	Male	Female	Total
1	Children (<5yrs)			
2	Youth (6-14yrs)			
3	Adults (15 - 64yrs)			
4	Old age (> 65yrs)			

1.5. Educational background of the household head.

No.	Educational status	Remark
1	Illiterate (No schooling)	
2	Primary level (I - V)	
3	Secondary level (VI - X)	
4	College/University	

1.6. How many years lived in the village?:................

1.7. Responsibility in the village/Social position in the Kebele

a. Kebele Leader   b. Edir Leader   c. Religious leader   d. Cabinet member

e. Ordinary dweller   f. Others (specify):...

1.8. A means of livelihood: ....

Part II: Questionnaire for Assessment of Woodlot Tree Management Practices

1. Land use systems

1.1. Land holding size (ha): ....

1.2. Type of land use and its` size (timad=0.25 hectares) at each categories.

No	Land use type	Size/area	Site type	Trees growing	Remark
1	Homegarden				
2	Cropland				
3	Woodlots				
4	Coffee land				
5	Fallow / bare land				
6	Grazing land				
7	Settlement				
8	Others (Specify)				

Key for Site type: Degraded sloppy land, fertile plain area, virgin unutilized land, etc

2. Woody species in Woodlots

2.1. When do you start to grow *Eucalyptus* species on your woodlot (yrs)? ....

2.2. What is your objective for planting these trees in your woodlots?

Tree species in woodlot	Purposes									
	1	2	3	4	5	6	7	8	9	10

Key for purposes: 1- Fuel wood 2- Construction materials 3- Household tools 4- Fodders 5- Shade 6- Fencing 7- Soil fertility 8- Fruit 9- Timber 10- Others (For income generation, For soil and water conservation, To drain marsh land, For climate change mitigation, charcoal,).

2.3. If mostly used for selling or income generation (Q.2.2), which parts and at what stage (year) you sell?

3. Silvicultural Practices

3.1. Which seedling type do you prefer for planting and what is the reason for your choice? a. Potted b. Bare rooted c. Other (specify)

3.2. If your answer for question No.3.1 above is 'bare rooted', from where you obtain seedlings for planting i.e. seedling source?

Species name	Seed/Seedling source						
	1	2	3	4	5	6	7

Key for source of seed/seedlings: 1- Own nurseries/Self raised, 2- Government nurseries, 3-NGOs, 4- Market place, 5- Naturally regenerated, 6- Wild/Forest, 7- Other (Specify)

3.3.When is the proper time for: Seeding......................... ; Site preparation........................; and for planting............................

3.4. How do you establish your woodlot?

a. all at once b. Planting smaller units annually c. Other (specify):...........................

3.5. Have you got extension services in relation to tree planting? a. Yes b. No

3.6. If yes, who has given you the extension services? ....

and what services you got?...

3.7. Spacing used? Too narrow ☐ Medium ☐ Too wide ☐

3.8. Why you used the current spacing for planting *Eucalyptus*? ....

3.9. How many seedlings you were used to plant usually per hectare?

3.10. What type of management practices do you use to increase the productivity of woodlot woody species

No	Types of Woody Species	Management	Reason	Intensity	Season

Key for management: 1=Thinning, 2= Pruning, 3= Composting or Application of manure,4=,Weeding and Cultivation, 5= Watering, 6= Others(e.g. Commercial fertilizer, Stocking control, fertilizing, Lopping): Keys for season: 1= Kiremit, 2= Meher, 3= Bega, 4= Belig: Key for reason: 1= For growth, 2= To reduce competition, 3= To reduce shade, 4= For fuelwood, 5= For fodder, 6= Others(Specify)

3.11. Which weeding regime do you use for your woodlot?

a. Whole weeding b. Spot weeding c. Slashing d. Other (specify)....................

3.12. Why do you prefer the method under question 3.11?..........................

3.13. Have you got any training in forestry with regarding to woodlot tree management practices? a. Yes b. No

3.14. What problems did you encounter in managing woody species in your woodlot and how did you solve them i.e. Constraints to manage woodlot trees and solutions taken?

Species	Problem encountered	Solution undertaken

Key for problems: 1- Damage by animal, 2- Insect-pest, 3- Disease, 4- Thieves, 5- Others

(Shortage of land, Lack of seedlings, Lack of market for forest products, Lack of labor)

Key for solutions: 1- Fence, 2- Insecticides, 3- Guarding, 4- Others

3.15. What are the main forest product types (assortments) that could be harvested from a woodlot?-----------------

3.16. Would you please assign a respective rotation age for each assortment identified as a main product under question No.3.15?

No.	Assortments	objective	Rotation age
1			
2			
3.			
4			

3.17. Do you decide harvesting in accordance with your plantation objective? a. yes b. no

3.18. If your answer for question No.3.17 above is 'No', what is the reason?

a. Lack of knowledge b. Poverty

c. High market demand for wood products d. Other (specify).......

3.19. What criteria do you use to make harvesting decision?

a. Immediate need for cash b. Attractive market availability

c. Considering coppice d. Other (specify)............

3.20. What harvesting system do you use to utilize your woodlot stand?

a. Selective system b. Clear felling system c. Other system (specify)........

3.21. Who is responsible for making harvesting decision?.............

3.22. How many years *Eucalyptus* needed to provide outputs after the first plantation?

3.23. How many years *Eucalyptus* takes to give the first yield starting from the first coppicing?

Appendixes 2 Field format for vegetation and soil data collection in the study area.

1. Vegetation Data Collection Format sheet for *Eucalyptus* trees ≥2.5 cm DBH and total tree height for Plot of 10 m * 10 m area.

Owner's full name ……………………………………..

PA/Kebele/……………………….......Village………….......Plot area (ha):10x10m (100m^2)

Woodlot number……………....... Woodlot area (ha) .... Stand age ....

Name of data collector/ Surveyor /………………………… Surveying date.........................

Location (GPS Coordinate): Northings (X) .... Easting(Y) ....

Elevation .... Slope (%) ....

Tree No.	Species name		DBH (cm) (at 1.3m above the ground level and trees ≥2.5 cm DBH)	Total Height (m) (≥ *1.5*)	Remark
	Scientific Name	Vernacular (Local) Name			

2. Data format sheet for soil sampling

PA/Kebele/……………………….......Village…………....... Sub-sample size: 1mx1m (1m^2)

Name of data collector/ Surveyor /………………………… Surveying date.........................

Location (GPS Coordinate): Northings (N)....................... Easting(E)...............Accuracy....

Elevation (m) .... Slope (%)..........................point description.................................

PA /Kebele/	Woodlot No.	Soil depth for SOC	Sample ID	Soil depth for BD	Sample ID	Remark
		0 - 30cm		0 - 30cm		
		30 - 60		30 - 60cm		

NB: Composite soil samples which are mixed properly in their respective depths were taken to determine soil organic carbon stock. Soil samples for BD were taken from the centre of each sample plot with above mentioned depths using core sampler.

3. Data format sheet for litter sampling

PA/Kebele/	Woodlot number	Sample ID	Total Fresh weight (g)	Remark

NB: For litter samples, from each of the sub-plots samples were combined for each major sampling plot and measured in the field for fresh weight in the site with the help of String balance and then 100gm was taken to laboratory for further analysis.

Appendixes 3 Number of stems, DBH, Height and Basal area per plot and hectare basis for each of the 62 woodlots in the study kebeles.

Woodlot size	Woodlot No.	Trees/plots	Mean DBH	Mean height	Basal area/plot	Trees ha^{-1}	Basal area ha^{-1}	Stand age
Large (≥ 0.2ha)	1	54	6.3	7.0	0.0034	1350	0.0854	5
	2	66	10.9	11.5	0.0100	6600	1.0020	11
	3	120	5.3	5.9	0.0024	9000	0.1834	5
	4	99	6.9	8.1	0.0046	2475	0.1155	9
	5	72	7.7	8.3	0.0055	1800	0.1366	14
	6	131	5.3	6.2	0.0025	6550	0.1250	8
	7	94	4.6	6.0	0.0018	2350	0.0447	4
	8	100	4.4	5.5	0.0017	2500	0.0414	3
	9	106	11.0	12.3	0.0110	2650	0.2756	16
	10	56	11.1	12.8	0.0132	1400	0.3296	22
	11	91	6.5	7.2	0.0040	3413	0.1514	12
	12	103	5.0	5.9	0.0022	2575	0.0545	4
	13	120	7.0	7.6	0.0046	3000	0.1158	8
	14	103	13.4	14.8	0.0152	5150	0.7589	22
Medium (≥ 0.1ha to < 0.2ha	1	46	3.8	4.2	0.0011	863	0.0215	3
	2	65	5.3	5.5	0.0023	813	0.0291	6
	3	121	5.1	5.9	0.0023	1513	0.0287	4
	4	59	7.9	9.2	0.0054	738	0.0679	9
	5	92	5.1	6.1	0.0024	1150	0.0296	19
	6	128	5.4	6.3	0.0027	1600	0.0339	6
	7	127	5.3	6.0	0.0026	1588	0.0327	6
	8	53	6.8	7.8	0.0042	663	0.0530	12
	9	71	6.0	7.0	0.0032	888	0.0394	7
	10	37	15.5	16.1	0.0209	694	0.3924	27
	11	85	5.8	6.8	0.0030	1063	0.0377	5
	12	61	6.2	7.1	0.0036	1144	0.0677	6
	13	76	4.1	5.3	0.0015	950	0.0190	4
	14	61	8.7	10.7	0.0067	1144	0.1261	10
	15	87	9.2	10.0	0.0070	1088	0.0875	7
	16	101	6.6	7.6	0.0040	1263	0.0505	8
	17	100	6.0	6.8	0.0032	1250	0.0396	6
	18	125	6.4	7.3	0.0043	2344	0.0813	20
	19	65	5.4	6.3	0.0026	813	0.0325	6

	20	97	3.8	4.8	0.0012	1213	0.0149	3
	21	37	7.7	8.6	0.0057	463	0.0714	10
	22	47	9.4	10.8	0.0073	881	0.1377	13
	23	96	6.6	7.6	0.0043	1200	0.0533	9
	24	56	8.1	9.2	0.0055	700	0.0689	15
	25	87	5.3	6.3	0.0024	1088	0.0298	4
	26	62	4.7	5.5	0.0020	775	0.0248	8
Small (< 0.1ha)	1	47	5.8	6.1	0.0028	294	0.0178	4
	2	96	5.5	6.0	0.0026	600	0.0164	6
	3	109	5.7	6.2	0.0028	899	0.0230	6
	4	74	5.3	5.8	0.0024	463	0.0153	6
	5	67	5.3	5.9	0.0024	553	0.0196	4
	6	83	5.5	6.3	0.0027	519	0.0166	4
	7	65	4.9	6.4	0.0020	536	0.0168	4
	8	79	4.9	5.5	0.0021	494	0.0129	4
	9	40	5.6	6.9	0.0028	250	0.0176	6
	10	57	8.5	9.8	0.0065	356	0.0404	9
	11	86	6.2	7.2	0.0036	538	0.0224	7
	12	102	4.7	5.6	0.0019	842	0.0158	3
	13	85	8.2	9.5	0.0075	701	0.0616	17
	14	82	5.1	6.5	0.0023	513	0.0144	4
	15	67	15.0	13.0	0.0301	419	0.1880	18
	16	59	11.0	12.5	0.0098	369	0.0615	11
	17	75	6.0	7.0	0.0033	619	0.0269	8
	18	93	9.1	9.2	0.0069	581	0.0429	7
	19	63	7.1	7.3	0.0043	394	0.0269	11
	20	70	5.3	6.0	0.0025	438	0.0159	4
	21	69	12.4	13.5	0.0128	431	0.0798	19
	22	72	6.6	7.5	0.0036	450	0.0227	5

Appendixes 4 Bulk density and soil organic carbon.

Woodlot size class	Plot No.	Bulk density 0 - 30 cm	Bulk density 30 - 60 cm	SOC 0 - 30 cm	SOC 30 - 60 cm	Woodlot size class	Plot No.	Bulk density 0 - 30 cm	Bulk density 30 - 60 cm	SOC 0 - 30 cm	SOC 30 - 60 cm
Large (≥ 0.2ha)	1	1.0907	0.9517	36.8	14.4		18	0.9135	0.8405	30.2	5.4
	2	0.9506	0.8508	66.4	26.4		19	0.8004	0.7363	18.5	1.0
	3	0.8490	0.8415	38.9	12.8		20	0.9189	0.8454	27.4	2.4
	4	0.6009	0.8525	57.9	30.0		21	0.9661	0.8889	19.9	9.8
	5	0.8570	0.8931	56.8	40.8		22	1.0092	0.9286	49.2	22.0
	6	0.9223	0.9611	66.3	54.3		23	0.9366	0.8617	46.5	21.2
	7	0.8439	0.8794	20.5	20.2		24	1.0055	0.9252	28.0	0.7
	8	0.8091	0.8432	33.9	18.7		25	1.1024	1.0144	9.7	0.9
	9	0.8818	0.8476	46.4	30.8		26	0.8837	0.8130	61.0	37.2
	10	0.8988	0.9367	54.2	39.2	Small (< 0.1ha)	1	1.1330	0.8358	29.7	27.1
	11	0.8013	0.8351	42.0	27.9		2	0.9394	1.0259	46.1	31.9
	12	1.1706	1.0772	26.5	3.0		3	0.8868	0.7734	30.0	23.7
	13	0.9194	0.8459	33.7	8.8		4	0.8881	0.8623	51.1	33.7
	14	0.9494	0.8701	53.0	32.1		5	0.9389	0.8865	63.6	24.6
Medium (≥ 0.1ha to < 0.2ha)	1	0.9473	0.8560	46.1	30.8		6	0.8576	0.9127	37.2	25.0
	2	0.8995	0.8735	44.5	26.6		7	0.7801	0.8130	15.9	15.7
	3	0.9091	0.8892	51.9	18.5		8	0.9466	0.9864	65.1	50.3
	4	0.7297	0.8748	64.4	42.6		9	0.8736	0.9104	58.1	44.2
	5	0.8973	0.8965	62.6	24.5		10	0.9194	0.9581	72.9	59.5
	6	0.8395	0.8099	43.2	17.2		11	1.1053	0.8484	66.1	39.6
	7	0.8371	0.7613	59.7	13.1		12	0.9307	0.9699	42.0	24.9
	8	0.9647	0.9279	62.1	42.7		13	0.8642	0.9609	39.6	25.0
	9	0.6349	0.6618	58.4	48.8		14	0.8701	0.9068	50.1	35.3
	10	0.8784	0.9154	58.7	44.7		15	0.9304	0.9696	31.7	16.3
	11	0.8528	0.8888	33.3	17.0		16	0.8760	0.9129	48.6	33.3
	12	0.9306	0.9697	49.9	36.3		17	0.8794	0.8091	29.3	8.8
	13	0.8861	0.9234	35.8	19.0		18	1.0120	0.9312	68.9	41.7
	14	0.8574	0.9045	44.1	27.3		19	0.9265	0.8524	52.8	27.8
	15	0.7807	0.8136	54.9	42.9		20	0.8015	0.7373	54.2	32.7
	16	0.9139	0.9524	63.4	49.0		21	0.9374	0.8625	61.1	35.9
	17	0.8061	0.8400	49.6	38.3		22	0.7386	0.6794	50.58	30.712

Appendixes 5 Textural classes and pH of soil samples.

Woodlot size class	Plot No.	Depth (cm) 0 - 30 % Sand	% Clay	% Silt	Textural class	Soil pH	30 - 60 % Sand	% Clay	% Silt	Textural class	Soil pH
Large (≥ 0.2ha)	1	28	46	26	Clay	5.52	28	54	18	Clay	5.55
	2	38	32	30	Clay loam	5.22	26	54	20	Clay	5.6
	3	24	32	44	Clay loam	5.06	24	36	40	Clay loam	5.67
	4	46	24	30	Loam	4.97	26	24	50	Silt loam	5.32
	5	36	30	34	Clay loam	4.93	42	30	28	Clay loam	4.96
	6	28	36	36	Clay loam	4.77	40	24	36	Loam	4.9
	7	28	22	50	Silt loam	5.03	32	24	44	Loam	5.29
	8	54	26	20	Sandy clay loam	4.85	28	40	32	Clay	5.02
	9	40	28	32	Clay loam	5.17	28	36	36	Clay loam	5.22
	10	34	34	32	Clay loam	5.29	30	34	36	Clay loam	5.38
	11	52	34	14	Sandy clay loam	5.17	42	28	30	Clay loam	5.21
	12	34	52	14	Clay	5.3	26	64	10	Clay	5.42
	13	36	48	16	Clay	4.87	30	24	46	Loam	4.98
	14	52	36	12	Sandy clay	4.87	38	46	16	Clay	4.96
Medium (≥ 0.1ha to <0.2ha)	1	38	30	32	Clay loam	4.93	36	38	26	Clay loam	5.24
	2	34	42	24	Clay	5.97	34	32	34	Clay loam	5.99
	3	48	26	10	Sandy clay	4.98	28	42	46	Loam	5.34
	4	30	42	28	Clay	7.42	28	44	28	Clay	7.51
	5	38	32	30	Clay loam	6.14	34	38	28	Clay loam	6.54
	6	36	46	18	Clay	4.76	42	30	28	Clay loam	4.81
	7	24	34	42	Clay loam	5.53	28	44	28	Clay	5.58
	8	40	34	26	Clay loam	5.25	34	28	38	Clay loam	5.28
	9	38	34	28	Clay	6.37	40	32	28	Clay loam	6.73
	10	34	30	26	Clay loam	5.98	32	40	28	Clay	6.22
	11	56	18	26	Sandy loam	5.21	38	32	30	Clay loam	5.26
	12	38	30	32	Clay loam	4.93	36	34	30	Clay loam	4.96
	13	34	34	32	Clay loam	5.25	34	34	32	Clay loam	5.5
	14	38	28	34	Clay loam	5.27	26	34	40	Clay loam	5.65
	15	38	48	14	Clay	5.42	34	36	30	Clay loam	5.48
	16	42	34	24	Clay loam	5.12	32	28	40	Clay loam	5.13
	17	34	36	30	Clay loam	5.43	28	46	26	Clay	5.48
	18	38	32	30	Clay loam	5.11	42	30	28	Clay loam	5.25
	19	42	16	42	Loam	5.19	42	22	36	Loam	5.52
	20	40	24	36	Loam	5.43	46	32	22	Sandy clay loam	5.53

	21	34	46	20	Clay	5.72	28	58	14	Clay	5.78
	22	38	44	18	Clay	4.94	32	48	20	Clay	4.97
	23	36	48	16	Clay	5.25	42	38	20	Clay loam	5.3
	24	46	32	22	Sandy clay loam	6.21	42	36	22	Clay loam	6.28
	25	38	44	18	Clay	5.12	24	52	24	Clay	5.34
	26	46	30	24	Sandy clay loam	5.13	32	38	30	Clay loam	5.32
Small (<0.1ha)	1	26	44	30	Clay	5.61	24	38	38	Clay loam	5.65
	2	24	38	38	Clay loam	4.45	24	32	44	Clay loam	4.7
	3	44	38	18	Clay loam	4.83	38	38	24	Clay loam	4.91
	4	34	34	32	Clay loam	4.84	26	40	34	Clay	4.93
	5	38	34	28	Clay loam	4.65	40	28	32	Clay loam	4.89
	6	36	48	16	Clay	7.23	30	42	28	Clay	7.27
	7	48	30	22	Sandy clay loam	4.97	36	34	30	Clay loam	5.13
	8	28	36	36	Clay loam	4.34	34	32	34	Clay loam	4.72
	9	44	26	30	Loam	5.36	60	14	26	Sandy loam	5.49
	10	48	36	16	Sandy clay	4.76	56	24	20	Sandy clay loam	4.78
	11	60	22	18	Sandy clay loam	4.89	44	24	32	Loam	5.23
	12	36	32	32	Clay loam	5.78	28	34	38	Clay loam	5.81
	13	26	36	38	Clay loam	4.94	34	42	24	Clay	4.97
	14	50	16	34	Loam	5.21	24	32	44	Clay loam	5.44
	15	52	34	14	Sandy clay loam	5.41	34	24	42	Loam	5.63
	16	46	38	16	Sandy clay	4.76	30	46	24	Clay	4.9
	17	54	28	18	Sandy clay loam	4.87	38	34	28	Clay loam	4.91
	18	34	26	40	Loam	4.54	34	26	40	Loam	4.61
	19	32	34	34	Clay loam	5.35	24	50	26	Clay	5.47
	20	28	48	24	Clay	4.78	28	60	12	Clay	4.94
	21	34	46	20	Clay	5.23	28	46	26	Clay	5.38
	22	44	32	24	Clay loam	5.31	56	40	4	Sandy clay	5.39

Appendixes 6 Spearman correlations between woodlot size class and carbon stocks

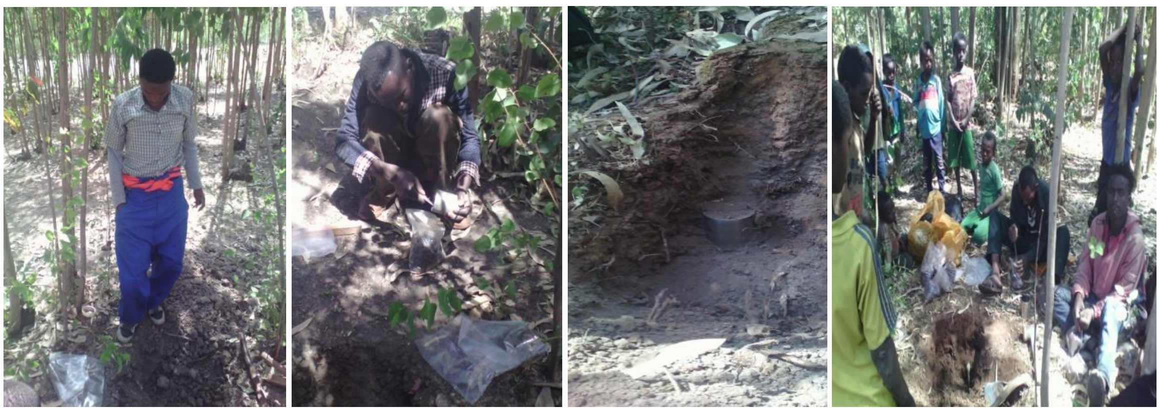
Carbon stock components	Correlation coefficient (r)
Biomass carbon (above and belowground)	0.864**
SOC	0.79**
Total carbon	0.753**
p-value	<0.01

**. Correlation is significant at the 0.01 level

Appendixes 7 Photos showing activities undertaken both in field and laboratory.

Tree inventory and litter sampling in the field (photo by Tadewos Tesfaye on Jan, 2018).

Litter sample analysis in the laboratory (photo by Tadewos Tesfaye on Feb, 2018).



Soil sampling in the field (photo by Tadewos Tesfaye on Jan, 2018).

Soil preparation for SOC, soil pH, texture and Drying soil for BD determination (photo by Tadewos Tesfaye on Feb, 2018).

Determination of soil pH (photo by Tadewos Tesfaye on Feb, 2018).

Soil organic carbon determination (photo by Tadewos Tesfaye on Feb, 2018).

Determination of soil texture (photo by Tadewos Tesfaye on Feb, 2018).

Household survey with questionnaires (photo by Tadewos Tesfaye on Jan, 2018).

BIOGRAPHICAL SKETCH

Tadewos Tesfaye Chare was born on November 21, 1990 GC in Gununo, Damot Sore district, SNNPR state, Ethiopia. He attended his elementary school (1 - 6) at Doge Mashido and junior school (7 and 8) at Shayamba Kilena from 1997 to 2004. He also completed secondary and preparatory school education (9 to 12) at Sodo General Secondary and Preparatory School from 2005 to 2009. In October 2009, he joined the higher institution and attended a Bachelor of Science degree in Forest Management and Utilization program at Hawassa University, Wondo Genet College of Forestry and Natural Resources from October 2009 - July 2012. After graduation, he was employed and worked in both Graduate assistant and Assistant Lecturer position from October 2012 to September 2016 at Hawassa University, Wondo Genet College of Forestry and Natural Resources. In October 2016, he joined again Hawassa University, Wondo Genet College of Forestry and Natural Resources for his study of Master of Science degree in Forest Resource Assessment and Monitoring which is newly launched by MRV project in the year 2017 G.C.