WOODY SPECIES DIVERSITY AND CARBON STOCK POTENTIAL OF AGRI-SILVICULTURE OF FEDIS DISTRICT, EASTERN ETHIOPIA

MSc THESIS

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NOVEMBER 2022
HARAMAYA UNIVERSITY, HARAMAYA

Woody Species Diversity and Carbon Stock Potential of Agri-silviculture of Fedis District, Eastern Ethiopia

A Thesis Submitted to Africa Center of Excellence for Climate Smart
Agriculture and Biodiversity Conservation
Postgraduate Programs Directorate
HARAMAYA UNIVERSITY

In Partial Fulfillment of the Requirements for the Degree of MASTER OF SCIENCE IN BIODIVERSITY AND ECOSYSTEM MANAGEMENT

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November 2022
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BIOGRAPHICAL SKETCH

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ACKNOWLEDGEMENTS

First and foremost, I thank my God who has given me strength and health for the completion of my study. I would like to express my deepest gratitude to my advisors Dr. Sintayehu Workeneh and Dr. Samuel Feyissa for their consistent and stimulating advice, encouragement, guidance, comments, insight, and professional expertise during my study. Next, my thanks go to the School of Natural Resources Management and Environmental Sciences, Haramaya University for giving me the chance of joining the postgraduate program. I would like to thank the Africa Center of Excellence for Climate Smart Agriculture and Biodiversity Conservation for all financial support and quality education by outstanding scholars.

I would like to thank Fedis District agriculture experts Mr. Mahammad Abdukarim and Ramadan Hamido for providing full information about the study area. Words cannot express how grateful I am to my friend and colleague Mr. Mekonnen Keneni for his technical support, encouragement, and assistance, and for all the sacrifices that he has made for me during field data collection. I thank my fellow laboratory mates Mr. Girmaye Mekonnen, Yonas Sisay, and Bane Kebede for their special support on soil laboratory analysis. Thanks indeed to my friend Mr. Abdulbasit Hussein for sharing information, and providing moral and emotional support. My thanks also go to all my friends, and staff members who supported me with their advice, sharing of information, and cooperation. I am very thankful to my hand-right brother Dandu Diriba Balcha for your uncountable support, inspiration, and encouragement in every direction. I do not have a word for my father Diriba Balcha Tufa, and my mother Hirphe Bushi Gobena for their prayer and true love. Thank you all my sisters and brothers. I would like to thank the whole family of my wife for their inspiration and encouragement throughout my study.

Finally, my special thank goes to my lovely wife Ms. Keneni Bayisa Chala (Qanii koo), and my baby boy Raya Lenjisa for their kindness, patience, prayers, and encouragement throughout my study.

ACRONYMS AND ABBREVIATIONS

AGB	Aboveground Biomass
AGC	Above Ground Carbon
BA	Basal Area
BD	Bulk Density
BGB	Belowground Biomass
BGC	Below Ground Carbon
CSA	Central statistical agency
DBH	Diameter at breast height
DSH	Diameter at stump height
EC	Ecosystem Services
FAO	Food and Agricultural Organization
FWAO	Fedis Wored Agriculture Office
HLs	Herbs and Litters
GDP	Gross Domestic Product
GPS	Global Positioning System
Gts	Giga tons
H'	Shannon diversity index
Ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
ICRAF	International Center for Research in Agroforestry
IVI	Importance Value Index
LULCC	Land use and land cover change
mg	Milligram
Mg	Megagram
mm	Millimeter
OC	Organic Carbon
OM	Organic Matter
RBA	Relative Basal Area
RD	Relative Density
REDD	Reducing Emissions from Deforestation and Forest Degradation
RF	Relative Frequency
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
TBC	Total Biomass Carbon
TC	Total Carbon
t ha^{-1}	ton per hectare
UNFCCC	United Nations Framework Convention on Climate Change
USNETL	United State National Energy Technology Laboratory
REDD+	Reducing Emissions from Deforestation and Forest Degradation
WBISP	Woody Biomass Inventory and Strategic Planning Project
WD	Wood Density

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ABSTRACT

Previous vegetation studies and their ecosystem services have concentrated largely on natural ecosystems, with less emphasis on managed areas like agricultural systems. Moreover, the protection and conservation of vegetation would be not only successful in protected areas alone but also in the agriculture environment and surrounding it. More recently, human-altered ecosystems such as conventional agroforestry like agri-silviculture have become increasingly conscious of their ability to sustain woody species and ecological services like; mitigation of climate change. Thus, this study was conducted to assess woody species diversity and carbon stock potential of agri-silvicultural systems of Fedis District, Eastern Ethiopia. Fedis District was selected purposively since the agri-silvicultural system is widely practiced. Then two agri-silviculture systems practicing kebeles were identified. Each selected potential kebele was stratified into three villages. Furthermore, ten rectangular quadrats 100 m X 50 m or 0.5 ha were established at 100 m intervals between two quadrats Hence, a total of sixty quadrats were used for vegetation data and soil sample collection. DBH and height of each woody species found within each quadrat were recorded by the use of a caliper and hypsometer respectively. Woody species diversity analysis was carried out by the Shannon Weiner Diversity index by the use of the R software program. For soil sampling, 1 m X 1 m was laid out, four at the corner and one at the centre of each main quadrat. At each sampling point of 1 m X 1 m, a soil sample was collected at the depth of 0-30cm and thoroughly mixed in a plastic bag to produce a 1 kg composite sample. To determine soil bulk density, an undisturbed sample was collected from the centre of the central sub-quadrat of the main quadrat using a core-sampler auger. Therefore, a total of 60 composite and 60 undisturbed samples were collected. A total of 27 woody species representing 26 genera and 20 families were collected from the study site. Shannon Weiner diversity index and evenness have resulted in 2.12 and 0.64 respectively. With population structure, Cordia africana and Faidherbia albida together constitute about 54% of the total plant species in the study. Faidherbia albida was the most frequent encountered woody species following Cordia africana. The total basal area for the study area was about 66.77 m^2 for woody species having DBH ≥ 2.5 cm with a 300 value of IVI. The mean total carbon stock of the study area was 63.9 Mg C ha^{-1}, of which 8.6 Mg C ha^{-1}, 2.3 Mg C $ha^{-1}$and 53 Mg C ha^{-1} were contained above ground, below ground, and soil organic carbon, respectively. The results of the study showed that the agri-silviculture agroforestry practice has a large potential to deliver regulating ecosystem services like opportunities to mitigate the impending climate-changing through carbon sequestration and increasing the resilience of the agricultural system at Fedis District. Therefore, we recommend the inclusion of agri-silviculture in the Nationally Determined Contribution of Ethiopia.

Keywords: *Agroforestry, Biomass Carbon, Soil organic carbon, Agricultural land, and Climate change mitigation*

1. INTRODUCTION

The unique geological formation of Ethiopia resulted from great geographical diversity which in turn resulted in the formation of diverse ecological conditions that helped to have rich biodiversity (Bekele *et al.,* 1999; Masresha *et al.,* 2015). Previous studies (Bekele *et al.,* 1999; Woldu *et al.,* 1999; Masresha *et al.,* 2015) justified that the richness in biodiversity is the reflection of diverse ecological settings, climate & topography in the country. Thus, the flora of Ethiopia is estimated to possess about 6500 to 7000 species of higher plants, of which about 10% are endemic (Kelbessa *et al.,* 1992; Masresha *et al.,* 2015). However, the rich plant biodiversity resources, including forests, are being destroyed at an alarming rate largely due to human-related disturbances.

Land use and land cover change (LULCC), mainly deforestation and forest degradation, are responsible for 17–25% of annual anthropogenic greenhouse gas emissions that are a principal factor in global warming (Bernstein *et al.,* 2008; Quéré *et al.,* 2015). Although deforestation and forest degradation have declined, they are still serious in scope and quantity, especially in developing countries (Hansen *et al.,* 2013; Köthke *et al.,* 2013; Calle *et al.,* 2016). LU/LCC has become part of the global science agenda (Lambin *et al.,* 2001). It is driven by human activities (Teixeira *et al.,* 2014) and is associated with negative impacts on ecosystems observed at local, regional, and global scales (Girma and Hassan, 2014). The interaction between nature and humans has transformed the face of the earth for their demands as no other living species has ever done (Melese, 2016). Usually, the development of LU/LCC is relied on the two broader groups of man-made agents, i.e., proximate drivers and underlying causes. The proximate drivers explain the direct action of humans on local land covers and include expansion of agriculture, unsustainable exploitation of forest resources and infrastructure development (Geist and Lambin, 2002). Indirect forces as economical, institutional, technological, cultural and demographic changes accelerate the effect of proximate drivers on natural resource use (Geist *et al.,* 2006).

Ethiopia is among the countries characterized by diverse vegetation zones (Teketay et al., 2010). However, the high demand for agricultural land due to the growing human population has contributed to the deterioration and depletion of forest resources in the country (Ariti *et al.,* 2015; Betru *et al.*, 2019). Most recent studies reported the decline of natural vegetation including forests, shrubs, and woodlands due to conversion to agricultural and grazing lands, opening up settlements areas in different parts of the country (Alemu *et al.,* 2015; Gashaw and Dinkayoh 2015, Bessie *et al.,* 2016; Kibret *et al.,* 2016). For instance, FAO (2020) indicated that the forests of Ethiopia declined at the rate of 0.8% from 1990 to 2015.

However, as vegetation fragmentation continues, the world's supply of valuable products and ecosystem services from vegetation resources, especially in developing nations, is declining significantly (Aerts *et al.*, 2011; Hundera *et al.*, 2013; Tadesse *et al.*, 2014). On the other hand, the alternative land-use system is recommended for the role of biodiversity conservation, food subsistence, revenue generation, and the provision of ecological services in tropical ecosystems in the sense of vegetation resource degradation and global climate change.

According to Oke and Jamala, and McNulty (2013) biodiversity and ecosystem services have focused on the agro-ecological environment in most parts of the world, especially in tropical countries, because the managed agricultural landscape may contribute to the conservation of plant diversity and carbon sequestration. Agroforestry is emerging as an inexpensive option that will help smallholders conserve natural resources, primarily in tropical regions, maintain biodiversity, increase food management, and reduce greenhouse gas emissions.

Previous biodiversity studies have concentrated largely on undisturbed habitats, with less emphasis on biodiversity in managed areas (Perfecto *et al.*, 2003). The protected area model remains the world's topmost biodiversity conservation policy (Persha *et al.*, 2010). However, the protection of vegetation diversity would be successful not only in protected areas alone)(Perfecto *et al.*, 2003) but also in the agricultural environment surrounding it, with unique efforts to increase its ecological value (Chazdon *et al.*, 2009; López-del-Toro *et al.*, 2009; Tejeda-Cruz *et al.*, 2010). More recently, human-altered ecosystems such as conventional agroforestry like agri-silviculture have become increasingly conscious of their ability to sustain the biodiversity of taxa varieties (McNeely and Schroth, 2006; Hylander and Nemomissa, 2009; Perfecto *et al.*, 2014; Tadesse *et al.*, 2014).

Agri-silviculture system of agroforestry is a land-use type in which crop production is the primary purpose of land use, and tree on cropland is considered the secondary objective of the land-use system (Mafongoya *et al.*, 1998). Trees are an important part of and a common feature of many agricultural ecosystems, where they provide a variety of livelihood-supporting ecosystem services. Scattered trees have occurred in Ethiopia in various land-use systems, such as communal land, coffee plantations, crop fields, and roadside systems (Teklay, 2005; Gebrewahid *et al.*, 2018a). Some of these trees were left when the natural forest was converted to other land-use systems; others were regenerated after the land was cleared or were actively planted by farmers. For example, parkland agroforestry in the farmland of northern Ethiopia often contains local species like (*Faidherbia albida* (Del.) because farmers plant or maintain this species to provide soil quality and productivity (Teklay, 2005; Gebrewahid *et al.* 2018).

Farmers cultivate and keep trees for various goods and services on their agricultural land (Kuyah *et al.*, 2016), and maintain a combination of exotic and indigenous trees in various ways (Nyaga *et al.,* 2015). The main productive services of trees, such as timber, plywood, fuelwood, or charcoal, come from tree wood, food, medicines, livestock feed, and natural gums (Kuyah *et al.,* 2016). Agricultural landscape trees are also significant in strengthening the adaptive capacity of farmers and reducing the vulnerability of farming systems to the impacts of climate change (Gebrewahid *et al.*, 2018). In addition, trees have a wide variety of environmental benefits, such as erosion prevention, preservation of soil organic carbon, of a large amount of carbon both above and below the ground (Gebrewahid *et al.,* 2018). However, the carbon sequestration ability of farmland trees depends on the composition of woody plants, tree age, geographical location, agro-ecological conditions (climate, altitude, and wind), management regimes, and soil characteristics (Bunker *et al.*, 2005; Henry *et al.*, 2009; Newaj *et al.*, 2016).

Most studies have shown that even if trees on farmland or agri-silvicultural systems are not primarily intended for carbon sequestration, there is a unique opportunity to increase carbon stocks in the terrestrial biosphere (Albrecht and Kandji, 2003). Agri-silviculture contains less carbon than primary or maintained forests, but they contain far higher stocks of carbon than annual crops (Henry *et al.*, 2009). Agrisilviculture sequester 2.67–89.62 Mg C ha^{-1} and averaging 31 Mg C ha^{-1} (Gebrewahid *et al.*, 2018), which is within the range of tropical agroforestry 7.9–105 Mg C ha^{-1} (Montagnini and Nair, 2004). According to Tsedeke *et al.* (2021)' Minjar Shenkor parkland agroforestry stores a mean total biomass of 8.34 Mg C ha^{-1}. Furthermore, carbon storage in humid tropics of agri-silvicultural systems is comparatively higher compared to silvopasture systems and rangelands (Kaur *et al.*, 2002). In addition to rehabilitating degraded land and enhancing the livelihoods of rural people, studies have indicated that the integration and proper maintenance of trees on agricultural land have great potential to sequester carbon from the atmosphere (Kaur *et al.*, 2002; Gebrewahid *et al.*, 2018).

Climate change is the most challenging problem facing our current world. Nowadays high greenhouse gas, around 61% is emitted from agriculture in Ethiopia (CAIT, 2012). Consequently, global warming and biodiversity loss are increasing and changing dramatically in agriculture because of the impacts of climate change. The impact is and will be worst in agriculture, and such change has and will have an impact on our agriculture. On the other hand, agri-silviculture can play a role to mitigate climate change. That is why the role of agri-silvicultural systems in climate change mitigation and woody species conservation role was investigated. Most of the time the role of woody species conservation and their role in ecosystem service through regulating and supporting ecosystem services were focused only on the natural ecosystem (protected area) and, plantation areas. However, the role of different agroforestry systems and practices in the conservation of woody species, and their combating role in climate change mitigation through carbon sequestration is very significant. According to Nair *et al.* (2010), carbon storage in agri-silvicultural systems of agroforestry in the tropics was relatively higher compared to silvipasture systems and rangelands. So agri-silviculture systems play a great role in carbon sequestration both in vegetation biomass and soil as compared to mono-cropping agriculture.

Therefore, the potential of agri-silvicultural systems for carbon storage in tree biomass and soil system is investigated as part of a clean development mechanism to reduce the current global warming. Therefore, it is believed that this research was proposed to fill the knowledge gap on the woody species diversity, population structure, and potential carbon stock of the agri-silviculture system in the Fedis District. Because agri-silviculture agroforestry conserves more multipurpose vegetation, and stores a significant amount of carbon stock far greater than mono-cropping agriculture. So, it is very important to know the crucial role of this agroforestry system in the mitigation of climate change. In addition to this, the country has the plan to reduce greenhouse gas emissions by 65% mainly from agriculture (WRI, CAIT, 2012). So this study plays a great role in indicating the potential of agri-silviculture in the mitigation of climate change through carbon sequestration that can contribute to the climate-resilient green economy that our country Ethiopia planned from 2011-to 2030 (Yirdaw *et al.*, 2007).

The study helps to conceptualize the effect of woody species diversity, composition, and structure on the carbon stock potential in agri-silvicultural systems. The findings of the study encourage farmers and other concerned stakeholders in tree diversity conservation to have a great role in carbon storage and climate change mitigation in the agri-silviculture system, which contributes a great role to reducing global warming. It also generates information for future researchers, government and non-governmental organizations, and policymakers about the ecological services of woody species diversity and their role in climate change mitigation under the practice of agri-silvicultural systems.

The research questions of this study were:

- What is the woody species diversity; richness, and evenness of the study area?
- What is the population structure of woody species diversity; density, frequency, basal area, and importance value index of agri-silviculture?
- How much amount of carbon is stored in above-ground biomass, below-ground biomass, soil carbon, and total carbon stock of agri-silviculture of the site?

Therefore, this study was initiated with the general objective of assessing woody species diversity and carbon stock potential of agri-silviculture of Fedis District, Eastern Ethiopia. Moreover, the specific objectives were:

- ▪ To investigate woody species diversity; richness and evenness in the agri-silviculture system
- ▪ To assess the population structure of woody species in the agri-silviculture system
- ▪ To evaluate the carbon stock potential of the agri-silviculture system in the study area

2. LITERATURE REVIEW

2.1. Concepts of Agroforestry and Its Systems

Agroforestry is a new name for a set of ancient practices. The word and concept attained a fair level of acceptability in international land-use parlance in a rather short (Dagar and Tewari, 2017). In the beginning (during the 1970s and early 1980s), undoubtedly, a lot of ambiguity and confusion existed about the agroforestry concept (Nair, 1993). The situation was reviewed in an editorial, appropriately titled “What is Agroforestry?” in the inaugural issue of Agroforestry Systems (Vol 1, pp. 7–12, 1982) cited in (Dagar and Tewari, 2017) which contained a selection of “definitions” of agroforestry, proposed by various authors. In summarizing these definitions, (Lundgren, 1987) ICRAF is cited in (Dagar and Tewari, 2017) stated that two characteristics common to all forms of agroforestry and separate them from the other forms of land use, namely:

- The deliberate growing of woody perennials on the same unit of land as crops and/or animals, either in some form of spatial mixture or sequence.
- There must be a significant interaction (positive and/or negative) between the woody and non-woody components of the system, either ecological and/or economical (Dagar and Tewari, 2017a). These ideas were later refined through “in-house” discussions at ICRAF, and the following definition of agroforestry was suggested (www.icraf.org):

“*Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land management units as crops and/or animals, in some form of spatial arrangement or temporal sequence”*

This definition, though not perfect in all aspects but has been increasingly used in ICRAF and other publications. In agroforestry systems, there are both ecological and economical interactions between the different components (Lundgren and Raintree, 1982). Even the simplest agroforestry system is more complex, ecologically (structurally and functionally), and economically than a mono-cropping system.

Today, there is a consensus that agroforestry is practiced for a variety of objectives. It represents an interface between agriculture and forestry and encompasses mixed land-use practices. These practices by and large have been developed based on the special needs and ecological conditions of the farmers in developing countries (Dagar and Tewari, 2017). Social objectives are very important in their adaptations. It is based on the local people's direct participation in the process, either by growing trees themselves or by processing the tree products locally. Nowadays many self-help groups earn a livelihood by developing government-sponsored programs through value addition to agroforestry products. As characterized by ICRAF (2008), cited in (Dagar and Tewari, 2017) agroforestry helps in diversifying and sustaining the production of the broad spectrum of agricultural commodities for enhanced economic, environmental, and social benefits by integrating trees on farms and in the agricultural landscape. Today, agroforestry represents the modern, science-based approach to harnessing the sustainability attributes and production benefits of such time-tested practices, and its demonstrated role in sustaining crop yields, diversifying farm production, realizing ecosystem services, and ensuring environmental integrity in land use is receiving increasing attention in developing programs around the world (Pretty *et al.*, 2007; Dagar and Tewari, 2017).

Agroforestry systems are widely based on nature and arrangement of the components and ecological or socioeconomic criteria. But no single classification scheme can be accepted as universally applicable. Therefore, the classification of agroforestry systems has to be purpose-oriented. The complexity of the problem can be reduced if the structural and functional aspects of the systems are taken as the criteria for categorizing the systems and agro-ecological and socioeconomic aspects as the basis for further continuing. Since there are only three basic sets of components (woody perennials, herbaceous plants, and animals) to be managed, the first step of classification may be based on these components (Dagar and Tewari, 2017).

Numerous indigenous forms of growing trees and crops together, sometimes with animals, were brought under the realm of modern scientific land-use scenarios due to the efforts of local, national, and international organizations. Communities around the world have practiced diverse and evolving forms of agroforestry for time (Nair, 1989; Berkes *et al.*, 2000; Rhoades, 2012), and both indigenous and nonindigenous practitioners have taken advantage of indigenous and traditional ecological knowledge for developing improved practices of great value. Many workers (Nair, 1993; Dagar *et al.*, 2013; Rossier and Lake, 2014; Nair *et al.*, 2017) have mentioned the utilization of indigenous knowledge among the communities of Asia, Europe, Africa, American Indians, and Alaska Natives, the Caribbean, and Pacific Islanders, and other regions. Because indigenous groups have lived in the same areas for long periods of time, each generation has built on the knowledge of the previous generation through observation and experimentation and implemented in these local practices. In this manner, indigenous groups have evolved intricate ways to manage bio-culturally diverse ecosystems, which are time tested. These ecosystems are managed to provide food, fuel, building materials, agricultural and plant-tending tools, hunting and trapping equipment, baskets, medicines, and ceremonial spaces essential to life and maintaining cultural traditions. Many agroforestry practitioners across the globe have tried to learn from these complex systems and inculcated the useful information while developing the modern systems in many cases (Garrity, 2012; Dagar *et al.*, 2013).

There is a subtle difference between “system” and “practice.” A system is a specific local example of the practice. There are an enormously large number of agroforestry systems, but the specific practices that constitute them are few (Nair, 1985, 1989). These two terms that used to be distinguished in the early stages of agroforestry development are now used rather synonymously. According to Nair’s original classification scheme (Nair, 1985) the vast majority of agroforestry practices that have been discussed and researched fall under “conventional” categories (Nair, 2012). The three original major groups of systems included agri-silvicultural (crops + trees), silvopastoral (trees + pasture/animals), and agrosilvopastoral (crops + trees + pasture/animals) (Nair, 1985). In literature, particularly in India, some other terms referring to specific associations such as silvipasture, agri-horti, silvi-horti, horti-silvi, and so on have been found used. As stated above, traditional/ indigenous systems, which are time tested and have played a significant role in developing modern systems, are discussed in brief here explaining how these have helped in evolving modern agroforestry systems (Rao *et al.,* 2007; Dagar and Tewari, 2017a).

2.2. Agroforestry and Woody Species Diversity

2.2.1. Concepts of woody species diversity, richness, and evenness

Most people mix the concept of species diversity and species evenness as they are similar. However, the richness and evenness of the species are one of the diversity measurement techniques of a given area (Gebreselasse, 2011). They are also among the main techniques for measuring diversity. Species richness is the simplest concept of species diversity that involves the number of species in a community where evenness is a measure of equitability and attempts to quantify the unequal representation of species in a community against a hypothetical community in which all species are equally common (Vegetation ecology, 2005). The existence of more species is, therefore, an indicator of a strong or richer community in a given region. As (Kent and Coker, 1992; Whittaker, 1993) explain, in assessing the taxonomic, structural and ecological values of a given ecosystem, the species richness index is of great importance, while equality is a measure of the abundance of the different species that make up the richness of the environment (Tegegne and Workineh, 2017). The richness of species is a relative term that refers to the number of species in a community and is directly linked to the measurement of species diversity in a given region. Another dimension of diversity that determines the number of individuals from each species in the same region is a related concept, evenness (Petchey and Gaston, 2002). Nevertheless, the diversity of species is the result of the evenness and wealth of species. Indices of species diversity include data on species endemism, rareness, and commonality (Kuchler, 2015). If the area is to be said to have a high level of species, it should have the same composition of species in all habitats, while the area with a low spatial distribution of species is considered to be poor in evenness.

Whittaker (1993); Kent and Coker (1992) described that both species diversity and species evenness are often calculated using the Shannon diversity index (H'), which naturally varies between 1.5 and 3.5 and rarely, exceeds 3.5. The Shannon diversity index is the most appropriate and most widely used index for combining species richness and evenness (Krebs, 1999).

2.2.2. Role of agroforestry systems in the conservation of woody species diversity

Loss of biodiversity is being driven, mainly by human interference reinforced by inappropriate economic structures and activities that maximize short-term gain, without considering long-term consequences (Raven, 2002; Muruts and Birhane, 2017). Habitat destruction by humans becomes the primary source of the loss of species (Lugo, 1988; Muruts and Birhane, 2017). The destruction could be both temporal and spatial and could incorporate both natural and man-made ecosystems such as in agriculture and agroforestry.

Agroforestry systems like parklands incorporate several agroforestry tree species (Muruts and Birhane, 2017). Although frequently dominated by just one or a few species, parklands include a large number of woody species, often up to 40–50 in the cultivation cycle alone (Boffa, 1999; Muruts and Birhane, 2017). Most parkland species have a wide distribution range, occurring either in very localized or continuous patterns. They are, therefore, a very biodiverse agroecosystem with a high potential for biodiversity conservation (Muruts and Birhane, 2017). The parkland agroforestry practices have been described as good examples of traditional land-use systems and biodiversity management practices (Boffa, 1999; Muruts and Birhane, 2017). Remnant woody species in parkland agroforestry may play an important role in conserving biodiversity within farming systems because they provide habitats and resources that are otherwise absent from agricultural landscapes (Harvey and Haber, 1998; Muruts and Birhane 2017). They serve as critical nesting, feeding, and resting sites for a variety of bird and bat species. They also provide transient habitats for many migratory birds (Harvey and Haber 1998, Muruts and Birhane, 2017). The presence of woody species in agroforestry favors the survival of native forest plants. In addition, agroforestry trees often serve as a source of propagules for forest regeneration both because they produce seeds locally and because the birds that visit their canopies restate seeds of forest plants while perched in the trees. As a result, the seed rain beneath agroforestry trees is significantly higher than in open areas (Harvey and Haber, 1998; Muruts and Birhane, 2017)

A study from Sidama, Ethiopia, by (Asfaw, 2004) showed that the higher number of species at Hara may be attribu to its late stage of agricultural intensification, and the associated higher number of native remnant trees, particularly in places with relatively remote access to the market. Trees in agroforestry are deliberately preserved and managed on crop fields grown with annual crops such as teff, maize, barley, haricot bean, bean, and sweet potato. The number of trees preserved per hectare was on average 30 (Yeshimbet, 2011). Such agroforestry practices are common across the highlands of Ethiopia (e.g., (Poschen, 1986; Tolera *et al.*, 2008; Kassa *et al.*, 2010). Most farming systems in the highlands host large tree stems of different species that are deliberately left and managed by farmers. For instance, in the Tigray region of Northern Ethiopia, Kassa *et al.* (2010) noted a parkland agroforestry practice where the *Balanites aegyptiaca* tree was grown in association with sorghum. *Croton macrostachyus* and *Cordia africana* trees are also grown in association with annual crops such as *teff*, *maize*, sorghum, and haricot bean by the farmers in the Oromia region of Ethiopia. Farmers' objectives for maintaining trees in these systems are to provide products such as fodder, fruits, and fuelwood and to reduce risk (Rao *et al.,* 1997; Kalinganire *et al.,* 2007; Kuyah *et al.,* 2017).

Trees are sources of food, including fruits, fats, oils, leafy veges, nuts, etc., which complement s food crops in the local diet. Some of these foods are particularly important during the months when grains are in short supply and during years of intense drought (Kalinganire *et al.,* 2007). In addition, parkland trees and shrubs provide numerous traditional medicines that are essential for rural health care. Severe micronutrient deficiencies can be alleviated by consuming indigenous fruits and veges (Ruel *et al.,* 2005).

2.3. Ecosystem Services of Agroforestry Systems

The millennium ecosystem assessment framework identifies a variety of regulating ecosystem services (ES) delivered in ecosystems (Kuyah *et al.*, 2017). Regulating ES are the benefits obtained from the regulation of ecosystem processes (Kuyah *et al.,* 2017). These benefits occur both as intermediate services and final benefits, meaning some do not benefit humans directly, e.g., pollination, while others provide direct benefits to humans, e.g., flood regulation (Kumar and Wood, 2010a). Some of the ES is provided across ecosystems, while others are produced in specific ones. Most of the landscapes are managed to increase the supply of single provisioning ES such as timber in forestry or food in agriculture (Kuyah *et al.,* 2017). However, the importance of regulating services is becoming widely recognized, and landscapes are increasingly being managed for multiple ES (Kumar et *al.,* 2010; Harrison *et al.,* 2014). The range of ES can be delivered by incorporating trees in agriculture through different agroforestry practices (Sinclair, 1999; Kuyah *et al.,* 2017). The services can be provided at a small scale, e.g., enhancement of soil fertility through biological nitrogen fixation, or on a global scale, e.g., climate regulation through carbon sequestration (Schroth and Sinclair, 2003; Kuyah *et al.,* 2017).

The multifunctional role of trees makes agroforestry interventions good candidates for supplying multiple ES. This is underpinned by the ability of agroforestry to produce a variety of ES on the same land area as food or fodder crops while at the same time maintaining biodiversity (Kuyah *et al.,* 2017). Biodiversity is closely linked to the functioning of ecosystems, and studies show a positive relationship between biodiversity attributes and ES (Harrison *et al.*, 2014). Although recent developments in agriculture have to some extent increased productivity, negative impacts such as loss of biodiversity and associated ES have occurred because of landscape simplification and land-use intensification (Tscharntke *et al.*, 2005; Kuyah *et al.*, 2017). Agroforestry provides vegetation diversity that can enhance the delivery of regulating ES within agricultural landscapes. However, there are situations where agroforestry renders disservices, leading to trade-offs among ES (Kuyah et *al.*, 2016), and therefore there are prospects of optimizing agroforestry practices in the future for better multiple ES management.

The seven important regulating ES that has received significant attention in agroforestry research in both tropical and temporal regions: carbon sequestration and storage, soil fertility enhancement, prevention of soil erosion, water regulation, pest regulation, pollination, and wind regulation, and supported by some review papers regarding regulating ES and modification of agroforestry practices that aim to increase ES provision (Pumariño *et al.*, 2015, Kuyah et *al.*, 2016).

1. Ecosystem services that can be delivered by trees through agroforestry practices

L.N	Ecosystem Services	Descriptions
1	Soil fertility enhancement	Trees provide nutrient inputs into the soil through litter addition and biological nitrogen fixation and prevent nutrient loss
2	Pest regulation	Agroforestry systems regulate pests, weeds, and diseases by making conditions less beneficial for them, reducing their dispersal, or through the activities of predators and parasitoids
3	Water regulation	Agroforestry systems regulate water discharge and recharge within the landscape
4	Carbon sequestration	Trees remove carbon dioxide from the atmosphere and keep it in their tissues or the soil when they die and decompose
5	Prevention of soil erosion	Vegetation and litter provide ground cover to prevent soil loss
6	Wind regulation	Trees are used as windbreaks and shelterbelts to regulate wind speed
7	Pollination	Trees provide nesting habitat and food for insects, bats, and birds that transfer pollen from one plant to another
8	Microclimate	Trees provide shade and influence water availability locally
9	Climate regulation	Agroforestry systems regulate global climate by absorbing or emitting greenhouse gases into the atmosphere
10	Air-quality regulation	Trees absorb odors and sound, filter pollutants from the air, and release oxygen into the atmosphere
11	Water purification	Channels formed by the roots of trees allow water to trickle through the soil, filtering toxins, nutrients, and sediments
12	Bioremediation of soil	Woody vegetation removes nutrients and contaminants from the soil and can use these for growth
13	Moderation of extreme events	Trees stabilize slopes and create buffers against extreme weather events such as floods, storms, and landslides
14	Regulation of human disease	Trees regulate the incidence and abundance of some pests and vector-borne diseases that attack humans
15	Provision services	Sources food from different fruit trees
16	Aesthetic value	The landscape used as Eco-tourism

Source: (Kuyah *et al.,* 2016; Kuyah *et al*., 2017; Dagar and Tewari, 2017)

The Millennium Ecosystem Assessment identified four-pillar ecosystem services (provisioning, regulating, cultural, and supporting services) for various agroforestry methods such as parkland and homegarden agroforestry practices, which are mentioned in table 1(Kuyah *et al.,* 2017).

Food, fresh water, wood and fiber, fuel, and other goods and products produced through ecosystem services are provisioning services. Climate regulation, flood regulation, disease management, and water purification are some of the ecosystem services that are regulated by various agroforestry approaches. Nutrient cycling, soil formation, and primary photosynthetic production all provide supporting functions. Agroforestry methods deliver cultural benefits, including those that are educational, recreational, spiritual, and other, as the fourth ecosystem service. (Bekele, 2018; Achiso and Masebo, 2019;Sharma *et al.* 2022)

Parkland trees and homegarden agroforestry methods, which are quite popular in Ethiopia, are highly important resources for production, productivity, biodiversity protection, and other related benefits that are dependent on the system's existence. (Bekele, 2018; Achiso and Masebo, 2019; Sharma *et al.,* 2022)

2.3.1. Carbon sequestration services in agroforestry

Carbon sequestration involves the removal of carbon from the atmosphere and subsequent storage in vegetation; the carbon is transferred into the soil when the trees die and decompose forming soil organic matter (Kuyah *et al.,* 2017). Carbon is held in live vegetation as above- and belowground biomass, in dead wood, in the litter, and the soil. When trees are cut down and burned and the soil is tilled, the carbon stored is released back into the atmosphere, increasing atmospheric carbon dioxide (CO_2) concentration, a major contributor to the greenhouse effect responsible for global warming (Kuyah *et al.,* 2017).

Carbon sequestration was documented as the fourth most commonly reported regulating ES in agricultural landscapes of sub-Saharan Africa, after soil fertility enhancement, water regulation, and pest control (Kuyah et *al.,* 2016; Kuyah *et al.,* 2017). Due to the spatial extent of agricultural landscapes, trees in such landscapes store huge amounts of carbon (Zomer *et al.,* 2009). The duration carbon is stored in the systems can be prolonged by increasing the harvesting intervals and by conversion of harvested wood into durable products, e.g., sawn wood for use in buildings. Harvested wood products are considered a significant sink of carbon by the Intergovernmental Panel on Climate Change (IPCC) and considerably delay the release of CO_2 emissions into the atmosphere (IPCC, 2006) reported by (Eggleston *et al.,* 2006).

Scientific evidence shows that agroforestry practices in agriculture sequester larger amounts of carbon than monoculture field crops or pastures (Makumba *et al.,* 2007; Takimoto *et al.,* 2008; Gupta *et al.,* 2009; Saha *et al.,* 2009; Kuyah *et al.,* 2017). The carbon sequestered in agroforestry depends on the type of practice, its components (species), arrangement and density, age, and environmental conditions – which vary across agro-ecological zones (Nair *et al.*, 2009). For example, woodlots with mature trees stock more carbon in aboveground biomass compared to dispersed planting, live fences, and fodder banks (Takimoto *et al.*, 2008). An overview by Jose (2009) shows that agroforestry systems on fertile soils or in humid zones have higher carbon stocks than those on degraded soils or in arid and semiarid zones and that vegetation in temperate agroforestry systems has lower carbon storage potential than those in tropics.

2.3.1.1 Carbon sequestration in trees under different agroforestry

Carbon sequestration involves the net removal of CO_2 from the atmosphere and storage in long-lived pools of carbon. Such pools include the aboveground plant biomass; belowground biomass such as roots, soil microorganisms, and the relatively s forms of organic and inorganic carbon in soils and deeper subsurface environments; and the durable products derived from biomass (Soto-Pinto *et al.*, 2010). The significance of agroforestry concerning carbon sequestration and other CO_2 mitigating effects is now widely recognized. According to an estimate, 630 × 106 ha are sui for agroforestry in the world and have a strong potential to sequester carbon across the world (Jose, 2009; Nair *et al.*, 2009). A major portion of this area lies in the tropics and is currently under some or other agroforestry practices, which could be further efficiently utilized for carbon sequestration by intensifying management practices. The carbon sequestration potentials of tropical agroforestry systems are highly variable (Albrecht and Kandji, 2003).

Carbon storage in agri-silvicultural systems in humid tropics is relatively higher compared to silvipasture systems and range lands (Kaur *et al.*, 2002). According to a study, shifting from traditional fallow to traditional maize caused a total living biomass carbon loss of 94%, and shifting from traditional fallow to improved fallow, taungya, or coffee prototypes maintains carbon in living biomass averagely 50 Mg C ha^{-1} (Soto-Pinto *et al.*, 2010; Nair and Nair, 2014), whereas changing from pasture toward silvopastoral systems increased carbon in living biomass by 20 times. Similarly, the multi-strata complex systems in homegardens have an advantage of a higher number of components and could sequester more carbon as compared to less complex agri-silvicultural systems (Nair *et al.*, 2010). The agroforestry systems have more carbon than simple row crops and fallow lands. The potential of the agroforestry system (AFS) to accumulate carbon is estimated to be 12–228 Mg ha^{-1}, with an average of 95 Mg ha^{-1} (Albrecht and Kandji, 2003; Soto-Pinto *et al.,* 2010). Agroforestry systems in arid, semiarid, and degraded sites have a lower carbon sequestration potential than those in fertile humid sites; and the temperate agroforestry systems have relatively lower vegetation carbon sequestration potential than the tropical ones. A comparative account of carbon sequestration under different agroforestry practices is presented in Table 2.

One of the major issues of keeping the soil resource productive and in place could be accomplished using maintaining the levels of soil organic carbon. Agroforestry systems help in improving the status of organic carbon in the soil. Scientifically accep evidence to support the positive influence of trees in enhancing soil organic carbon is overwhelming (Swamy and Puri, 2005; Swamy and Mishra, 2014). It is a fact that soil factors (type, water content, pH, aeration, microflora, and so on), climatic conditions (temperature, rainfall), and litter fall (quantity) determine the soil resources. In this context, it is envisaged that the increased litter input and addition of root residues under agroforestry practices shall improve carbon storage in soil. According to a study conducted in humid tropics, agroforestry systems have the potential to sequester more than 70 Mg ha^{-1} in the top 20 cm of the soil (Soto-Pinto *et al.*, 2010).

Earlier studies showed that a significant increase in carbon was observed in the topsoil even after the short duration of the 5-year plantation. Soil organic carbon accretions through employing improved fallow are estimated to be between 1.69 and 12.46 Mg ha^{-1} (Soto-Pinto *et al.,* 2010). Many studies indicated that the most marked differences in soil organic carbon are in the upper soil layer in plantations (Fang *et al.,* 2007; Gupta *et al.,* 2009; Chauhan *et al.,* 2012). However, the deeper layer seems to be more s and responds to long-term sequestration. The higher amount of leaf litter and root residues in the surface soil layer could be attributed to a higher carbon pool as opined by many researchers (Swamy and Mishra, 2014). The amount of carbon sequestered largely depends on the agroforestry system put in place, the structure and function of which are, to a great extent, determined by environmental and socioeconomic factors. Other factors influencing carbon storage in agroforestry systems include tree species, the structure and function of different components, and system management (Nair and Nair, 2014).

Although most agroforestry systems are potential sinks, some practices like shifting cultivation, pasture maintenance by burning, manuring, nitrogen fixation, nitrogen fertilization, frequent disturbance in soil, and animal production can act as sources of greenhouse gases (Swamy and Tewari, 2017). Silvopastoral systems, improved fallow, taungya, and coffee systems (especially polyculture-shade coffee and organic coffee) also have the potential to sequester carbon by maintaining polyculture and an optimum number of trees (Soto-Pinto *et al.,* 2010). Agroforestry systems could also contribute to carbon sequestration and reduce emissions when burning, and frequent tillage is avoided. A study conducted in Zimbabwe showed that in an improved fallow-maize rotation system, N_2O emissions were found to be almost ten times to those of continuous unfertilized maize, but these levels were still extremely low when compared to the increase in the amount of carbon stored (Jat *et al.,* 2016). Therefore, there is a need to optimize the tree-crop-animal component combinations and adopt integrated management to help in minimizing the sources and enhance the sink potential for better adaptation and mitigation of climate change through agroforestry.

2. Carbon storage potential in agroforestry systems

Continents	**Eco-regions**	**Systems**	**Mg C ha^{-1}**
Africa	Humid tropical high	agri-silvicultural	29–53
South America	Humid tropical low dry lands	agri-silvicultural	39–102
			39–195
Southeast Asia	Humid tropical dry low lands	agri-silvicultural	12–128
			68–81
Australia	Humid tropical low	Silvopastoral	28–51
North America	Humid tropical high	Silvopastoral	133–154
	Humid tropical low dry lands	Silvopastoral	104–198
		Silvopastoral	90–175
Northern Asia	Humid tropical low	Silvopastoral	15–18

Source: Albrecht and Kandji (2003)

2.3.1.2 Soil organic carbon stock under agroforestry systems

World soils are the largest stores of terrestrial carbon. Sequestration of soil organic carbon (SOC) is naturally driven, encompasses humification of organic matter (OM), and formation of secondary carbonates which are stored in the soil profile (Lal *et al.,* 2007). Soil plays an important role in carbon sequestration, being able to store 1.5–3 times more carbon than vegetation (Young, 1997). Nair *et al.* (2010) estimated that the agroforestry systems can store approximately 30–300 Mg C ha^{-1} in a 1 m soil depth. The amount of carbon sequestered in the soil depends on a large number of factors, including the region, site quality, current land use, previous land use, and the portion of the soil profile in case of land-use changes, (Nair *et al.*, 2010). Generally, soil accounts for 60% of the total carbon stored in tree-based land-use systems (Lal, 2004a; Lorenz and Lal, 2005; Lal, 2008; Nair *et al.*, 2010). Soil carbon sequestration occurs in two different ways: (1) direct fixation of atmospheric CO_2, which transforms CO_2 into soil inorganic carbon compounds, (2) and indirect fixation of atmospheric CO_2, in which atmospheric CO_2 is incorporated in plant tissue through the photosynthetic process, and subsequently, part of plant biomass is indirectly sequestered as SOC during decomposition processes (Burras *et al.*, 2001).

On a global scale, the total soil carbon pool was estimated in the range of 2157–2296 Pg, of which 1462–1548 Pg is soil organic carbon and 659–748 Pg is soil inorganic carbon (Batjes, 1996). The total soil carbon pool is about three times the estimated atmospheric carbon pool, and 3.8 times the vegetation carbon pool (Lal, 2004a; Nair *et al.*, 2010); therefore, any variation in the soil carbon pool would have a significant impact on the global carbon budget. Among land uses, agricultural and degraded soil have a promising carbon sequestration potential: those soils were depleted of a significant part of their original organic carbon pool, and the adoption of specific management practices, such as the implementation of trees and permanent vegetation, could significantly increase their carbon sequestration potential (Albrecht and Kandji, 2003).

However, Soil physicochemical properties play a major role in the soil carbon sequestration of agroforestry systems. These factors alter plant productivity, and root growth, influence both the quantity and quality of litter and in turn affect the carbon dynamics in these systems (Laganiere *et al.,* 2010; Nair *et al.*, 2010). Kizito *et al.* (2006), Liste and White (2008) have also shown that the hydraulic uplift of water by the roots of a single tree will lead to enhanced water uptake by neighboring plants as well in the agroforestry system which will in turn positively affect carbon sequestration by way of increased productivity and enhanced decomposition of carbon. Surface horizons of intensively managed agricultural landscapes are highly prone to erosion which will be reduced drastically by incorporating trees into the system (Lorenz and Lal, 2005).

Soil carbon content in agroforestry systems can be enhanced by increased biomass additions along with the reduction in their decomposition rates. The decomposition rates of SOC in these systems can be decreased by adopting measures that reduce water and nutrient losses and soil management strategies that enable physical, chemical, and biological mechanisms of carbon stabilization (Follett *et al.*, 2009). Like agricultural systems, reduction in cultivation intensity along with soil supplementation with mineral fertilizers, irrigation, and residue incorporation will lead to enhanced carbon sequestration in agroforestry systems (Nair *et al.,* 2010). Soil management strategies such as manure additions will influence the formation and stability of soil micro- and macro-sized aggregates in agroforestry systems, hence carbon stabilization and sequestration. Agroforestry could offer a viable opportunity to deal with climate change issues, having the potential to sequester and store atmospheric CO_2 over long periods (Albrecht and Kandji, 2003; Lorenz and Lal, 2014). In sustainable-managed agroforestry systems, a large portion of organic carbon returns to the soil in the form of crop residues and tree litter (Oelbermann *et al.*, 2004). Those inputs can help to stabilize soil organic matter and decrease biomass decomposition rate and SOM destabilization, improving SOC stocks (Oelbermann *et al.,* 2004; Sollins *et al.,* 2007).

2.4. Agri-silviculture Systems

Agrisilviculture is a multiple-use concept whereby forest trees/crops are raised in combination with crops (Olawoye, 1975). Agrisilviculture system integrates annual food crops along with trees simultaneously or sequentially and mainly includes improved fallows, taungya, alley cropping, plantation crops, shelterbelts, woodlots, homegardens, etc. practiced in various ecological and socioeconomic situations (Rao *et al.,* 2007). The systems are designed for simultaneous production of food along with wood products, etc.

Several indigenous peoples in the tropics have developed s agri-silvicultural systems using annual plants, bushes, trees, and vines (Weaver, 2012). Such systems frequently simulate the natural forest in appearance, remain productive through the entire year, resist plagues and infestations and minimize soil erosion. Microclimates within them are modified by tree cover (Wilken, 1972), and minerals are recycled through natural processes that include organic material from dead plants and manure from livestock. Yields are both diverse and nutritious and include seeds, flowers, fruits, veges, leaves, medicines, resins, forage, firewood, and lumber.

The regular presence of well-grown trees distributed on cultivated or recently tilled fields is referred to as parkland agroforestry/scattered trees on agricultural practices. Because of their special utility, trees are purposely associated with the agricultural environment in this practice of agroforestry systems. (Achiso and Masebo, 2019). In parkland practices, managing selected trees for improving soil productivity through a mix of multipurpose selected trees and food crops on the same farmland is the major goal of practicing agroforestry systems. (Bekele, 2018; Achiso and Masebo, 2019). Parkland agroforestry is classified as multipurpose trees on farmlands in the ICRAF agroforestry systems list. According to this, woody species in parklands are frequently seen as a source of products and services critical to farmers' livelihood and welfare (Achiso and Masebo, 2019).

3. Some agri-silvicultural systems and practices in the tropics

Agri-silvicultural system	**Practices**	**Combination**	**Components**
	Shifting cultivation/ improved fallow	Trees are grown in non-crop Period	Fast-growing trees, agricultural crop
	Taungya	Intercropping in initial stages of establishment of trees	Plantation of tree species and crops
	Hedgerow intercropping	Perennial trees such as woody hedges and crops in alleys	Woody trees with coppicing ability and crops
	Tree gardens	Multiple species, dense mixed	Fruit trees shade tolerant
	Multipurpose trees on farmlands	Trees scattered on-field/ boundaries	Multipurpose trees and crops
	Plantation crops	Shade trees with plantation crops	Coffee, coconut, fruit trees, and shade-loving crops
	Shelterbelts, wind breaks, live fences	Trees/shrubs in single or multi-rows	Multipurpose trees on boundaries plus crops
	Homegardens	Multi-strata systems around homes	Multipurpose fruit, timber trees with crops
	Farm woodlots	Firewood and MPTs	Trees and crops in separate settings

Source: (Rao *et al.,* 2007; Nair, 1991b; Dagar and Tewari, 2017)

2.4.1. Greenhouse gas emissions from an agri-silviculture system

Human activities, including the clearing of land for agriculture and agricultural production systems themselves, have increased emissions of greenhouse gases to the extent that scientists are predicting an average increase in global temperature of 2-4°C by the middle of the 21st century (Gates 1992). Temperature increases are expected to vary over the globe, perhaps being as much as 8°C higher at northern latitudes in the wintertime. Precipitation is expected to increase globally by up to 15% (Rosenzweig, 1989) but predictions of future precipitation patterns are imaginary and often contradictory due to numerous uncertainties associated with the complexities of coupled atmosphere/ocean circulation models. Although climate change and its consequences are uncertain, its potential importance is such that much effort has been given to the assessment of the sources and radiative effects of greenhouse gases, and possible mitigation and adaptation strategies (Duxbury, 1994).

Assessments of climate forcing created by greenhouse gases evolved from agriculture have concentrated on carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_20) because these gases are considered to be the most important and their effects can be reasonably well quantified with present knowledge. Soil sources of nitric oxide (NO or NOx) and ammonia (NH_3) have potentially important, but less well understood, effects on climate forcing through their impacts on atmospheric chemistry and dispersal of nitrogen over landscapes. In general, we have a reasonable understanding of the processes and controls on the generation of all of these gases and their emissions at small scales. Emission estimates are less certain at regional and larger scales. We have much less information about the impact of agriculture on emissions of a range of sulfur-containing gases that have indirect radiative effects (Duxbury, 1994).

Agriculture and clearing of land for agriculture account for about 25%, 65%, and 90% of total anthropogenic emissions of CO_2, CH_4, and N_2O, respectively (Duxbury, 1994). Agriculture is also thought to be responsible for about 55% of the ammonia or ammonium hydroxide (NH_3,) 50% of the carbon monoxide (CO) (largely from biomass burning), and probably also makes an important contribution to nitrogen oxides (NOx) released into the atmosphere as a result of human activities (Isermann and Limburgerhof, 1993).

2.4.2. Climate change adaptation potential of agri-silviculture systems

Adaptation is believed to enhance the resilience of ecosystems against increasing climate variability. It is now increasingly accepted as a viable strategy to reduce the vulnerabilities of climate change. Adaptation refers to adjustments in ecological, social, or economic systems in response to actual or expected climatic change and its negative impacts (Swamy and Tewari, 2017). It mainly includes processes, practices, and structures to moderate potential damages or to benefit from opportunities associated with climate change. Adaptation to climate change has the potential to substantially reduce many of the adverse impacts on agriculture and enhance beneficial impacts though neither without cost nor without leaving residual damage (Swamy and Tewari, 2017).

Agrisilviculture practices offer the most viable opportunities for climate change adaptation and promote the maintenance of agricultural production by making a resilient agricultural system (Nair and Nair, 2014). The perennial tree component of the agroforestry system efficiently utilizes the scarce resources available in climate change scenarios and minimizes the risks involved in mono-cropping. In low-rainfall years, water availability may further decline, cause frequent droughts, and decrease food production. Agrisilviculture systems help in buffering crops against water deficiencies through ameliorating microclimate by influencing radiation flux, air temperature, wind speed, saturation deficit of understory crops all of which will have a significant impact on modifying the rate and duration of photosynthesis and subsequent plant growth, transpiration, and soil water (Lin, 2007). The shading of trees further reduces heat stress and controls wind storms, thus saving crop failure in the extremely hot dry season.

Climate change also poses a serious threat to agricultural systems by increasing the incidence of invasive weeds. The germination and growth of most weed species are usually stimulated by exposure to light. Thus, some control of weeds may be affected if a closed canopy can be maintained during the fallow period in an alley cropping system (Nair *et al.,* 2009). In agri-silviculture shading by trees suppresses weed proliferation and growth. Trees also suppress weed growth through the litter layer which forms from natural leaf fall and pruning residues.

2.4.3. Climate change mitigation potential of an agri-silviculture system

Agrisilviculture is an age-old practice that integrates trees and shrubs, with annual crop production to ensure a steady supply of food and/or income throughout the year; halt degradation and maintain soil fertility; diversify income sources; enhance the efficient use of soil nutrients, water, and radiation; and provide regular employment (Rao *et al.*, 2007). Agrisilviculture can both sequester carbon and produce a range of economic, environmental, and socioeconomic benefits (Jose, 2009). The perennial trees/shrubs are capable of absorbing large amounts of atmospheric CO_2 through photosynthesis and storing C in long-lived and short-lived biomass components in addition to enriching the soil productivity. For example, trees in agri-silviculture improve soil fertility through maintenance of soil organic matter and physical properties, increased N, extraction of nutrients from deep soil horizons, and promotion of more closed nutrient cycling (Montagnini and Nair, 2004).

Combined yields of the tree, and crop products from well-planned and well-managed agri-silviculture systems tend to be higher than those from sole systems due to increased and efficient use of scarce resources. Agrisilviculture systems therefore can enhance resilience by diversifying the production base and ensuring the risks involved in mono-cropping due to climate change. Promising agri-silviculture systems capable of ameliorating microclimate, arresting soil degradation and restoring soil fertility, and diversifying income-generating opportunities were evolved in the tropics in the last few decades (Rao *et al.,* 2007). Carbon storage in agri-silvicultural systems in humid tropics is relatively higher compared to silvopasture systems and rangelands (Kaur *et al.,* 2002). However, the potential of trees on farmlands to sequester carbon depends upon the woody species composition, ages of trees, geographic location, agro-ecological conditions (climate, altitude, and wind), management regimes, and soil characteristics (Henry *et al.,* 2009; Newaj *et al.,* 2016).

Tree on the agricultural landscape is also important in enhancing farmers' adaptive capacity and reducing the susceptibility of farming systems to climate change impacts (Boye and Albrecht, 2020). In addition, trees provide a wide range of environmental benefits such as control of erosion and storing a significant amount of carbon both above and below ground in the form of soil organic carbon. Therefore, trees on farmland must be included in the climate change programs and policies such as Reducing Emissions from Deforestation and Forest Degradation (REDD+). Most studies indicated that even if trees on farmland or agricultural landscape are not primarily designed to sequester carbon, it is a unique opportunity to increase carbon stocks in the terrestrial biosphere (Albrecht and Kandji, 2003). Tree on farmland contains less carbon than primary or managed forests but they contain significantly higher carbon stocks than annual crops (Henry *et al.,* 2009). Studies suggested that the integration and proper management of trees on farmland has a great potential to sequester carbon from the atmosphere, in addition, to rehabilitating degraded land and improving the livelihood of the rural communities.

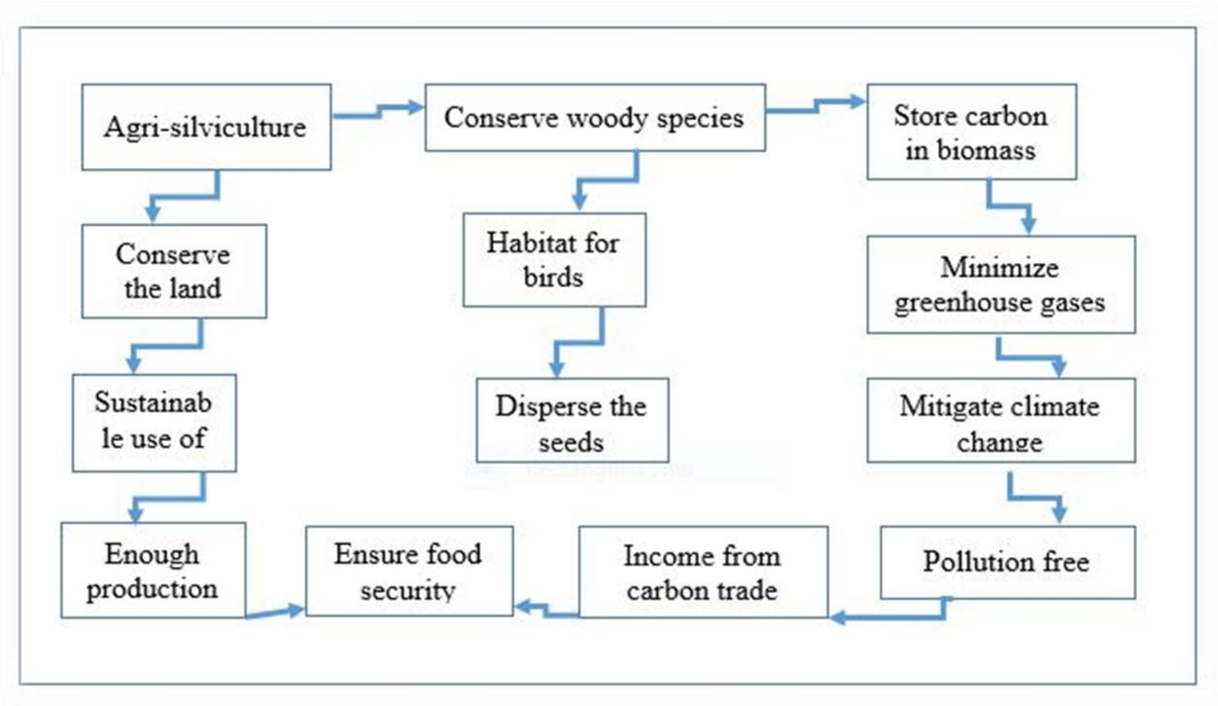


Figure 1. Framework shows role of agri-silviculture in woody species conservation and climate change mitigation (Lenjisa Direba, 2022)

3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1. Location

The study was conducted in Fedis district of Eastern Hararghe Zone, Oromia Regional State, eastern Ethiopia. It is located in the eastern part of the country at 550 km from Addis Ababa the capital city of Ethiopia, and 24 km from Harar town in the southern direction according to (Abdella *et al.*, 2020). The geographical location of the district is 9^0 6’ 0” and 9^0 15’ 0” N and 42^0 3’ 0” and 42^0 9’ 0” E (Figure 1). The altitude of the actual study area ranges from 1702-to 1818 meters above sea level. The district consists of 19 *kebeles* (the lowest administrative units in Ethiopia) and two rural towns with a total human population of the district was 149,664 of which 76,183 were males and 73,482 were females (Abdella *et al.*, 2020). The average family size is estimated to be 6 and 4 per household in rural and urban areas respectively. The total area of the district is 1105.2 km^2 (Abady *et al.*, 2019), and the area of the actual study site was 54.92 km^2 (EthioGIS, 2022)

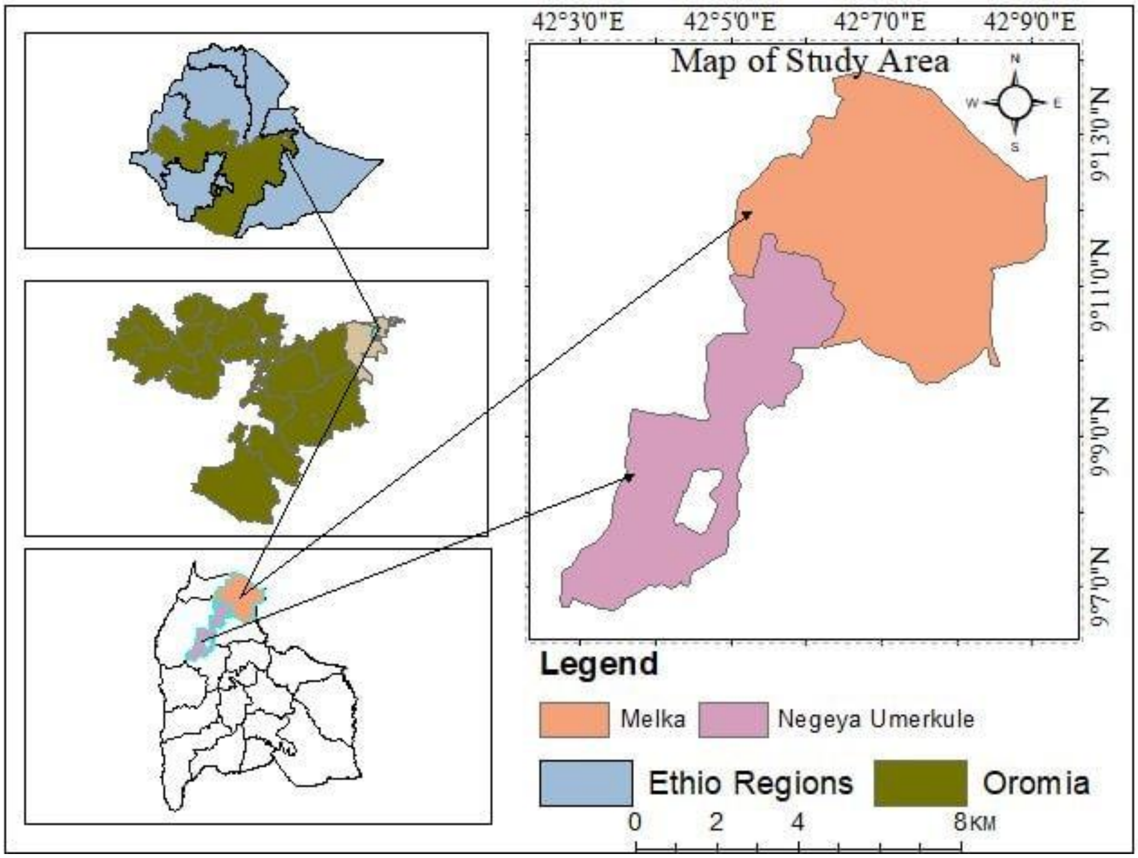
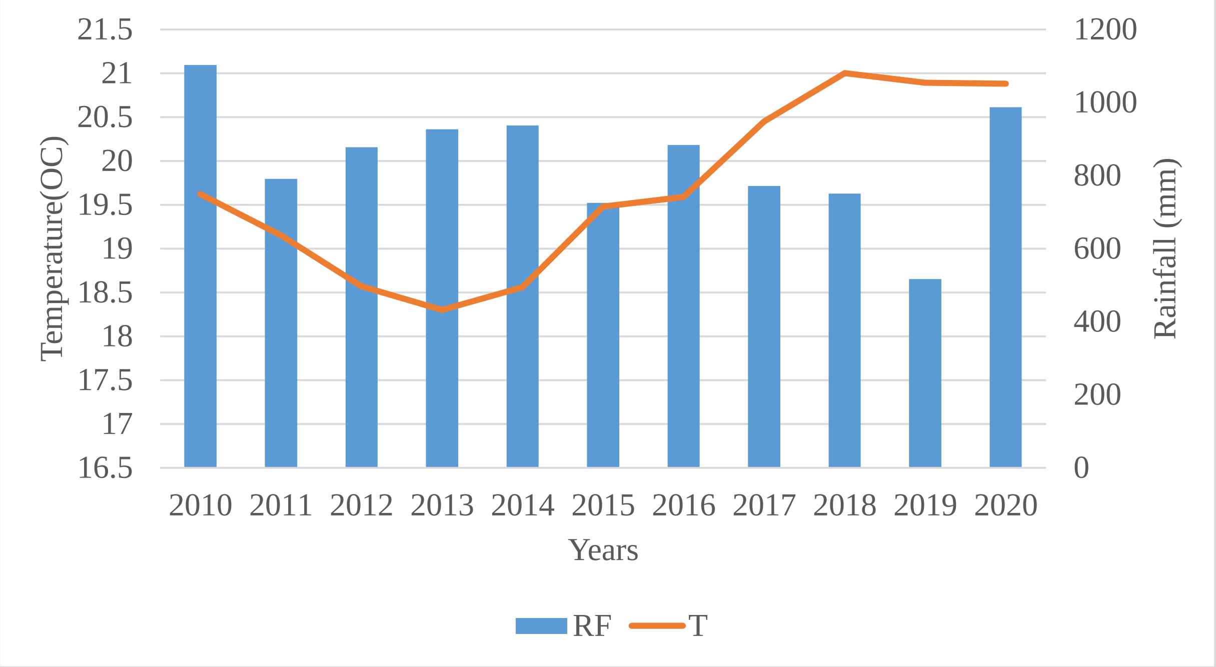


Figure 2. Map of the study area

3.1.2. Climate

The district has two basic agro-climatic conditions, namely Midland (39%), and lowland (61%). However, the study was only carried out in midland (Abdella *et al.*, 2020). The district experiences different mean annual rainfall and temperature (Figure 2). Accordingly, the district has a bimodal rainfall distribution pattern with high rains from April to June and long and erratic rains from August to October (Abady *et al.*, 2019).



RF= Rainfall, mm= Millimeter, T°= Temperature, °C= Degree Celsius

Figure 3. Shows the mean annual rainfall and temperature of the study area from 2010-to 2020

3.1.3. Topography and soil

The topographic feature of the district is 70% plain area, 28% plateau, and 2% mountain or hill (Abdella *et al.*, 2020). The soil of the area is dominantly sandy clay loam soils with moderately fine texture, and with 8.5 soil P^H (Abdella *et al.*, 2020). The soil of the study area is vertisols and leptosols (Hengl *et al.*, 2017).

3.1.4. Land use/ land cover

Cultivable land/cropland (21.02%), pasture (2.80%), grassland (38.01%), communal land (10.5%), and remaining (16.47%) are considered mountainous, valley and unusable land, forest (11.2%) patches of natural vegetation cover, plantation forests(Abdella *et al.* 2020). Beyond that, farmers incorporating trees on farmlands, boundary plantings, and woodlots agroforestry, etc (Abdella *et al.*, 2020). The most dominant tree species found in the area include; acacia species, *Croton macrostachyus*, *Cordia africana*, *Faidherbia albida*, *Eucalyptus camaldulences*, and many others (Abdella *et al.*, 2020)

3.1.5. Farm activities

Crop-livestock mixed farming is a common practice across the district (Abady *et al.,* 2019). Farmers are growing trees and/or shrubs in the agricultural landscape, and crop production is a leading economic activity in the area (Abdella *et al.,* 2020). Crop production is mainly based on rain-fed agriculture. Maize (Z*ea mays* L.), sorghum (S*orghum bicolor*), and haricot beans (*Phaseolus vulgaris*) are the major crops grown in the study area (Abady *et al.,* 2019). *Khat* (*Catha edulis*) is one of the cash crops grown predominantly in the study area. Besides fruits trees, veges, and tuber crops are the most common agricultural productions in the study area (Abdella *et al.,* 2020). Agroforestry like parkland trees/scattered trees on farm land have been highly practiced on the farm land with the dominance of multipurpose trees like *Faidherbia albida*, *Cordia africana*, and *Croton macrostachyus* (Abdella *et al.*, 2020). These trees were selected because farmers preferred for different socio-economic purposes and their ecosystem services like soil fertility management, and protection of soil from erosion (Abdella *et al.*, 2020)

3.2. Reconnaissance Survey

A reconnaissance survey was conducted in the study area to collect information on site, and to determine the type of sampling and sampling sizes.

3.3. Sampling Design

Fedis District was selected purposively since the agri-silvicultural system is widely practiced in the study area. Accordingly, a reconnaissance survey was conducted to uncover the history of agri-silvicultural system across the study area and identify the sampling sites. More relevant information was also obtained from Fedis District Agriculture and Natural Resource Office.

Then two agri-silviculture systems practicing *kebele's*, namely *Melka* and *Negeya Umerkule*, were identified purposively. Each selected potential *kebele* was stratified into three villages. Furthermore, ten rectangular quadrats (50 X 100 m or 0.5 ha) (Nikiema, 2005; Gebrewahid *et al.,* 2018) were established systematically in each selected *kebele* from which both vegetation data and soil samples were collected at 100 m intervals between two quadrats. Hence, a total of sixty quadrats (2 *kebeles* X 3 villages X 10 quadrats) were used for vegetation data and soil samples collection. The rectangular quadrat is preferred because it consists of more heterogeneous vegetation within the plot and, hence, is more representative than square or circular plots of the same area(Bonham, 1989).

3.4. Data Collection

3.4.1. Woody species data collection

Tree diameter and height measurements were taken by calliper and hypsometer respectively. Tree DBH measurement was taken at about 1.3 m from the ground using a caliper, and diameter tape. Trees with multiple stems or forks below 1.3 m height were treated as a single individual (Kent and Coker, 1992), and shrub diameter at stump height (DSH), about 30cm from the ground, was measured from each quadrat of the corresponding size (Atsbha *et al.*, 2019b). For a tree that was branched around the breast height, the diameter was measured separately and averaged them. For buttressed trees and/or shrubs, their DBH or DSH have been measured 5cm above the buttressed point (Snowdon *et al.*, 2002). Trees and shrubs on the border of the quadrat were included if more than 50% of their basal area falls within the quadrat and excluded if more than 50% of their basal area falls outside the quadrat (Bhishma *et al*., 2011). All the woody species encountered in each sample quadrats were recorded and coded with vernacular and local names. Woody species occurring outside sample quadrats but inside the study site were recorded only as present but not used in the subsequent vegetation data analysis. All collected woody species and the rest plant specimens were pressed and brought to the Haramaya Herbarium for taxonomic identification. Physiographic variables such as altitude, latitude and longitude were recorded in the study site for each sampled quadrat using GPS.

3.4.2. Soil sampling

Five 1 m by 1 m sub-quadrat were laid out, four at the corner and one at the centre from which five soil samples of each main quadrat. This is followed by five soil subsamples (four from the corner and one from the centre) from each were collected at the depth of 30 cm and thoroughly mixed in a plastic bag to produce a 1 kg composite sample (FAO, 2019) Moreover, to determine soil bulk density, an undisturbed sample was collected from the centre of the central sub-quadrat of the main quadrat using a core-sampler auger. Therefore, a total of 60 composite and 60 undisturbed samples were collected. The collected samples were properly packed in a plastic bag, labelled, and submitted to Haramaya University Laboratory for analysis of soil organic carbon content and bulk density following standard procedures.

3.5. Data Analysis

3.6. Woody Species Diversity and Population Structure

3.6.1. Woody species diversity

Species diversity was measured for each quadrat of all species and calculated as an index based on the number of species and their abundance. All woody species were considered for diversity analysis (Negash *et al.*, 2013). The diversity of species (species richness and evenness) was determined using the Shannon-Wiener Diversity Index (H') and Evenness or Equitability Index (E) (Krebs 1999b).

Shannon diversity index calculated by: (Krebs 1999b).

$$H' = -\sum_{i=1}^{s} pi \ln(pi) \text{…………………………………………………………………}8$$

where;
H'= Shannon diversity indices, S= the number of species, Pi=proportion of individual species
LnPi=log proportion of individual species

Species richness was undertaken from all species encountered in each quadrant.

$$\mathrm{S} = \frac{\text{Number of species}}{\text{quadrant}} \text{……………………………………..……………………………}9$$

Evenness (E) or equitability was a measure of similarity of the abundances of the different species in a given site (Krebs *et al.*, 2007). Species evenness (a measure of species balance) was a measure of the relative abundance of the different species making up the richness of an area. Equitability (E) was calculated as follows (Krebs *et al.*, 2007a):

$$E = \frac{H\prime}{Hmax} = \frac{H\prime}{\ln S} \text{……………………………………………………………………}10$$

where;

H’= Shannon diversity indices, S= the number of species

Hmax =lnS is the maximum level of diversity possible within a given population.

3.6.2. Vegetation structure

Density (relative density), frequency (relative frequency), basal area, and importance value index (IVI) are the measurements that were used to assess woody species' structure.

Density: Density is defined as the number of plants of a certain species per unit area (Kuchler, 2015). It is closely related to abundance but more useful in estimating the importance of a species (Kuchler, 2015). Counting was in quadrats placed several times into vegetation communities under study and the sum of individuals per species was calculated in terms of species density per convenient area unit such as a hectare (Kuchler, 2015).

$$\text{Density } = \frac{\text{Total number of all trees species}}{\text{Sampled size in hectare}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. 1$$

$$\text{Relative desnsity} = \frac{\text{Number of individuals of tree species}}{\text{Total number of individuals}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. 2$$

Frequency: Frequency is the chance of finding a species in a particular trial sample. Frequency was obtained by using quadrats and expressed as the number of quadrats occupied by a given species per number thrown or more often, as a percentage (Dereje Denu, 2007). The high-frequency value of a given plant species in the community indicates that it was widely distributed in the area under the study (Dereje Denu, 2007).

It was calculated with the formula below.

$$\text{Frequency} = \frac{\text{Number of plots in which species occur}}{\text{Total } number \text{ of plots}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. 3$$

The frequencies of the tree and shrub species in all quadrats were computed.

$$\text{Relative frequency } = \frac{\text{Frequency of tree species}}{\text{Frequency of all tree species}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. 4$$

Basal area (BA): There is a direct relationship between DBH and the basal area (Beyene, 2010).

Basal area was the area outline of a plant near the ground surface. It is the cross-sectional area of tree stems at DBH.

Basal area = Σ $(d/2)^2$, where D is the diameter at breast height (Kent, M. and Coker 1992; Beyene, 2010)

Basal area =.$(\pi D^2)\ /\ 4$, where π=3.14……………………………………………..… 5

Relative basal area= $\frac{\text{basal area of species}}{\text{Total basal rea}} \times 100$………………………………………. 6

Importance value index (IVI) of the species: It is used to calculate the percentage values of the relative frequency, relative density, and basal area of woody species (Kent, M. and Coker, 1992).

IVI=Relative density + Relative frequency + Relative basal area…………………..….7

3.7. Carbon Stock Estimation

3.7.1. Aboveground biomass and carbon stock estimation

Biomass carbon stocks for each quadrat (Mg C ha^{-1}) were calculated as the product of dry matter biomass and carbon content. Trees and/or shrubs biomass were calculated using the plot inventory data and allometric biomass functions. The following parameters were used to calculate above-ground biomass in carbon stock: DBH, tree height, a wood density factor, and a carbon fraction. According to Henry et *al.* (2010) equations that integrate more than one tree dimension improve the reliability of vegetation biomass estimation.

Therefore, the model of Chave *et al*. (2014) used by many studies was the best model for carbon stock assessment in Africa the then (CEFCC, 2016) based on climatic conditions, DBH of trees, and vegetation type of the study area to determine the biomass of tree species having ≥ 5 cm DBH.

$AGB = 0.0673 * (WD * DBH^{2} * H)^{0.976}$ ……………………………………………...11

Where:
AGB is above ground biomass (in kg dry matter), WD is wood density (g/cm^3)
DBH is diameter at breast height (in cm), H is total height of the tree (in m)

While for tree/shrub having < 5cm DBH, allometric equations given by (FAO, 1997) were engaged. The equations developed by the woody biomass inventory and strategic planning project (Parent *et al.,* 2000) for all woody species of Ethiopia were used for estimating woody carbon stocks.

$$AGB = (1.4277 \times DSH + (0.0088 \times (DSH^3))) \ldots\ldots 12$$

Where;
AGB is Above-ground sapling biomass (Kg), DSH is Diameter (cm) at stump height

To convert the above-ground dry biomass to carbon, 50% of all trees and shrubs biomass has been assumed to be the carbon stock. Then the tree biomass was converted into carbon by using Brown, (2002) formula.

$$AGC = AGB \times 0.5 \ldots\ldots 13$$

Whereas,
AGC is Aboveground carbon, AGB is Above ground biomass

So, an allometric equation developed by Chave *et al.* (2014) was used to estimate the aboveground biomass (stem plus bark, branches, and foliage) of the trees and/or shrubs. This equation was selected as it is appropriate to estimate a wide range of parameters ranging from DBH, height, and woody density to estimate aboveground biomass with the lowest prediction error value.

According to Chave *et al.* (2014), the inclusion of country-specific wood density in the equation significantly improves biomass estimation. Therefore, Ethiopia's ministry of environment, forest, and climate change conducted an extensive study on forest reference levels to determine the most appropriate wood density estimate for the country and the basic wood density of 421 indigenous and exotic tree species growing in Ethiopia the then (CEFCC, 2016). The overall average wood density for the species is 0.612 g cm^{-3}. This overall average wood density is comparable with the global average value and that of tropical Africa (IPCC, 2006; Chave *et al.*, 2009). The minimum value of wood density was 0.262 for *Moringa* species, and the maximum was 1.040 g cm^{-3} for *Dodonaea angustifolia* for trees found in Ethiopia (CEFCC, 2016).

3.7.2. Estimation of biomass and carbon stock of dead woods

For standing dead wood, which has branches, biomass was estimated in a similar manner using the Chave *et al.* (2014) allometric equation. As the deadwood does not have leaves, 5-6 percent subtracted for conifer species while 2-3 percent for broad-leaved species (Pearson *et al.*, 2005).

BDW = $0.0673 \times (\rho D^2 H)^{0.976} - 5.5\% \ (2.5\%)$..14

BDW is Biomass of Dead Wood, ρ is wood density, D is Diameter, H, is height

The total carbon stock in deadwood was computed by multiplying the total biomass of deadwood by 0.5 (Pearson *et al.*, 2005). AGB and AGC per hectare were calculated from the area of a single quadrat by conversion method. Finally, the area of each quadrat was converted to the hectare in order to get above ground biomass per hectare.

3.7.3. Belowground carbon stock estimation

To estimate the BGB carbon pool default values proposed by IPCC (2006) were applied. A root-to-shoot ratio of 27% was applied as suggested for tropical mountain systems (Chave *et al.*, 2014; CEFCC, 2016).

BGB = AGB $\times 0.27$ ………………………………………………………………….. 15

where BGB is Belowground Biomass, AGB is Aboveground Biomass, BGC is Belowground Carbon

Then BGC was computed by multiplying BGB by 0.5 using the (Brown, 2002) formula. Finally, BGB and BGC of a single quadrat were changed to per hectare by converting the area of the quadrat to hectare conversion method.

3.7.4. Estimation of soil organic carbon stock

Soil samples were air-dried, grinded, and sieved with a 0.5 mm size mesh weir, and the coarse fragments (> 0.5 mm) were removed. For the size fraction < 0.5 mm, soil organic carbon was taken to the laboratory for organic carbon determination. Soil organic carbon was analyzed by

Walkley and Black (1934) oxidation method. The bulk density of undisturbed soil was determined by the core method as described by (Kauffman *et al.*, 2012).

Moreover, the bulk density of a soil sample was calculated as follows:

$$\mathrm{BD}(\mathrm{g\ cm}\ -^{3}) = \frac{\text{Oven dry sample(g)}}{\text{Sample volume(cm3)}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 16$$

where;
BD (g cm^3) is bulk density of the soil

After soil bulk density and percentage of soil carbon (%C) were determined, soil organic carbon concentration was calculated by the following equation (FAO, 2019);

$$\mathrm{SOCi\ Stock} = \mathrm{OCi} * \mathrm{BDi} \times (1 - \mathrm{gGi}) * \mathrm{ti} * 0.1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 17$$

Whereas:
SOC_i is (Mg C ha^{-1}) is the soil organic carbon stock of depth increment
OC_i (mg C g^{-1} fine earth) is the organic carbon content of the fine earth fraction
(< 2 mm) of the depth increment, BD_i (g cm^{-3}) is the mass of soil per total volume of the soil sample of the depth increment
gG_i (g coarse fragment g^{-1} soil) is the mass fraction of coarse mineral fragment, thus
(1-gG_i) is the mass fraction fine earth (g fine earth g^{-1} soil) of the depth increment
t_i is the thickness (depth, in cm) of the depth increment i
0.1 is a factor for converting mg C cm^{-2} to Mg C ha^{-1}.
Soil organic carbon percent (OC%) was converted to mg C g^{-1}. 1 mg C g^{-1} = 0.1percent

3.7.5. Estimation of total carbon stocks

Total carbon stock was calculated by summing up the individual carbon pools following (Pearson *et al.*, 2005). The carbon stock density of the study area was:

$$\mathrm{TC} = \mathrm{AGC} + \mathrm{BGC} + \mathrm{SOC} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 18$$

Where,
TCis Total Carbon, AGCis Aboveground Carbon, BGCis Belowground Carbon, and

SOCis Soil Organic Carbon.

The atomic weight of carbon is 12 atomic mass units, while the weight of carbon dioxide is 44 because it includes two oxygen atoms that each weigh 16. So, to switch from one to the other, the following formula was used: One ton of carbon equals 44/12 = 11/3 = 3.67 CO_2 eq (Ginzburg and Ballas, 2000; Birhane *et al.,* 2020).

3.8. Statistical Data Analysis

Descriptive statistics such as mean, frequency, standard deviation, and percentages were used to discuss and present the result of the proportion of structural parameters of vegetation such as density, frequency, basal area, and important value index. Statistical analysis was carried out using the R software program (version 3.5.1.) for Shannon Weiner Diversity Index analysis, and Microsoft Excel was used for soil and carbon analysis.

4. RESULTS AND DISCUSSIONS

4.1. Woody Species Composition

In this study, a total of 27 woody species belonging to 26 genera and 20 families were recorded (Table 4). The collected species were composed of 80% (n=23 in number) trees and 20 % (n=4) trees/shrubs. Fabaceae is the most dominant family with 3 (11.54%) genera and 3 (11.11%) species followed by Myrtaceae which has 2 (7.69%) genera and 3 (11.11%) species, and Anacardiaceae, Boraginaceae, Euphorbiaceae each of them having 2 (7.69%) genera and 2 (7.41%) respectively (Table 5). Annonaceae, Araliaceae, Bignoniaceae, Bombacaceae, Caricaceae, Combretaceae, Cupressaceae, Moraceae, Moringaceae, Oleaceae, Rhamnaceae, Rutaceae, Sapotaceae, Ulmaceae, and Zygophyllaceae were represented by 1 (3.85%) genera each and 1 (3.70%) species.

The result of the current study area was nearly in line with (Wari *et al.*, 2019) who reported (25) woody species found in crop land fields. However, the number of wood species in the current study disagreed with (Guyassa and Raj 2013,), who reported that woody species found on the cropland were (n=15). Similarly, the farmland of Ghana reported that woody species found on the cropland was (21) as reported by (Chimsah *et al.*, 2013) and Benin (21) as reported by (Fifanou *et al.*, 2011; Alemu, 2012). This difference may be due to environmental factors and farmers' tree species preferences. The total number of individuals (976) found at the current study site was higher than the number of individuals (Gebrewahid and Abrehe, 2019). However, lower than the (Manaye *et al.*, 2021). However, the number of woody species (27) recorded in the current study area was less than that of trees on farmland of semi-arid East Shewa (77) as reported by (Endale *et al.*, 2017). Furthermore, woody species found in the study area were less than in the farmlands of Dellomenna District, Southeastern Ethiopia (55) as reported by (Molla and Kewessa, 2015) and Semi-Arid West Africa (Burkina Faso) (41) as reported by (Nikiema, 2005). This may be due to farmers managing their farmland to reduce shading effects competition with their crops, and shortage of land per household (Bobo *et al.*, 2006). Not only this, farmers are very selective on woody species, the current study was dominated by *C. africana* (30.74%) and *F. albida* (23.46%) individuals. So this may be a big reason why the number of woody species was lower than in the above studies.

Table 4. Family, genera, species scientific and local name (*Afan Oromo*), and habit species of the study site

Family	Genera	Species	Local name	Habit
Anacardiaceae	Mangifera	*Mangifera indica* var. mekongensis	*Mango*	T
	Schinus	*Schinus molle* L.	*Qundo barbare*	T
Annonaceae	Annona	*Annona senegalensis* Pers.	*Gishxa*	Sh/T
Araliaceae	Schefflera	*Astropanax abyssinicus* Seem.,	*Arfato*	T
Bignoniaceae	Stereospermum	*Stereospermum kunthianum* Cham.	*Gambello*	Sh/T
Bombacaceae	Ceiba	*Ceiba pentandra* (L.) Gaertn.	*Muka jibri*	T
Boraginaceae	Cordia	*Cordia africana* Lam.	*Wadesa*	T*
	Ehretia	*Ehretia cymosa* Thonn.	*Ulaga*	T
Caricaceae	Carica	*Carica papaya* L.	*Papaya*	T
Combretaceae	Terminalia	*Terminalia brownii* Fresen.	*Birensa*	T
Cupressaceae	Juniperas	*Juniperus procera* Hochst. ex Endl.	*Gatira*	T
Euphorbiaceae	Euphorbia	*Euphorbia tirucalli* L.	*Inciba*	Sh*/T
	Croton	*Croton macrostachyus* Hochst. ex Delile	*Bakanisa*	T
Fabaceae	Faidherbia	*Faidherbia albida* (Delile) A.Chev.	*Garbi*	T
	Erythrina	*Erythrina brucei* Schweinf.	*Walensu*	T
	Acacia	*Vachellia abyssinica* Kyal. & Boatwr.	*Lafto*	T
Moraceae	Ficus	*Ficus vasta* Forssk.	*Qilxu*	T
Moringaceae	Moringa	*Moringa oleifera* Lam.	*Moringa*	T
Myrtaceae	Eucalyptus	*Eucalyptus camaldulensis* Dehnh.	*Barzafi dima*	T
	Psidium	*Psidium guajava* L.,	*Zayituna*	Sh/T
	Eucalyptus	*Corymbia citriodora* subsp. citriodora	*Shito barzaf*	T
Oleaceae	Olea	*Olea europaea subsp*. cuspidata	*Ejersa*	T
Rhamnaceae	Ziziphus	*Ziziphus mucronata* Willd.	*Qurqura*	T
Rutaceae	Casimiroa	*Casimiroa edulis* La Llave & Lex.	*Amba*	T
Sapotaceae	Mimusops	*Mimusops kummel* Bruce ex A.DC.	*Oladi/Qoladi*	T
Ulmaceae	Celtis	*Celtis africana* Burm. f.	*Aroresa*	T
Zygophyllaceae	Balanites	*Balanites aegyptiaca* (L.) Delile,	*Badano*	T

T*= Tree, and Sh*= shrub

Identification was done at Haramaya University Hebarium by Lenjisa Direba, 2022.

Table 5. Percentage of each family's genera and species of the study site

L.N	Family	% of Genera	% of Species
1	Myrtaceae	7.69	11.1
2	Anacardiaceae	7.69	7.4
3	Fabaceae	11.54	11.1
4	Boraginaceae	7.69	7.4
5	Euphorbiaceae	7.69	7.4
6	Ulmaceae	3.85	3.7
7	Rutaceae	3.85	3.7
8	Combretaceae	3.85	3.7
9	Bignoniaceae	3.85	3.7
10	Annonaceae	3.85	3.7
11	Oleaceae	3.85	3.7
12	Cupressaceae	3.85	3.7
13	Rhamnaceae	3.85	3.7
14	Bombacaceae	3.85	3.7
15	Caricaceae	3.85	3.7
16	Moraceae	3.85	3.7
17	Zygophyllaceae	3.85	3.7
18	Araliaceae	3.85	3.7
19	Sapotaceae	3.85	3.7
20	Moringaceae	3.85	3.7
	Total	100	100

4.2. Woody Species Diversity

The value of Shannon -Wiener Diversity Index (H') of the whole vegetation of this study was 2.12 with the evenness or equitability value of 0.64 and 27 species richness. Shannon diversity index is considered as high when the calculated value is 3.0, medium when it is between 2.0 and 3.0, low between 1.0 and 2.0, and very low when it is 1.0 (Cavalcanti and Larrazábal 2004, Atsbha *et al.* 2019). So, the Shannon-wiener diversity index (H') of the study site was found in the medium range. The Shannon-wiener diversity index (H') of the study site was higher than the (Abreha *et al.,* 2014; Abate *et al.,* 2018; Gebre *et al.,* 2019; Gebrewahid and Abrehe, 2019; Gebrewahid and Meressa, 2020; Sintayehu *et al.,* 2020, Manaye *et al.,* 2021).

However, the result for Shannon's wiener diversity of woody species diversity of the study site was lower than the results recorded by (Molla and Kewessa, 2015; Wari *et al.,* 2019). The reason why the current study site Shannon diversity and species evenness was becoming lower may be because of the dominance of a few species like *F. albida and C. africana* (Abdella *et al.*, 2020) in the study site. Of the total quadrat, seven of them were only covered by both *F. albida and C. africana*, and again two quadrats had only a single species of both *F. albida* and *C. africana* individually, where their diversity became zero. Such a kind of dominance of a single or few species can minimize the value of diversity index and evenness (Kent, M., and Coker, 1992; Wilson *et al.*, 1996; Cavalcanti and Larrazábal, 2004; Atsbha *et al.*, 2019). Quadrat 56, 32, and 60 have high diversity than other quadrats with the value of 1.87, 1.75, and 1.69 respectively. Whereas quadrats 49 and 53 have no diversity; which means they have only one single species (Figure 4).

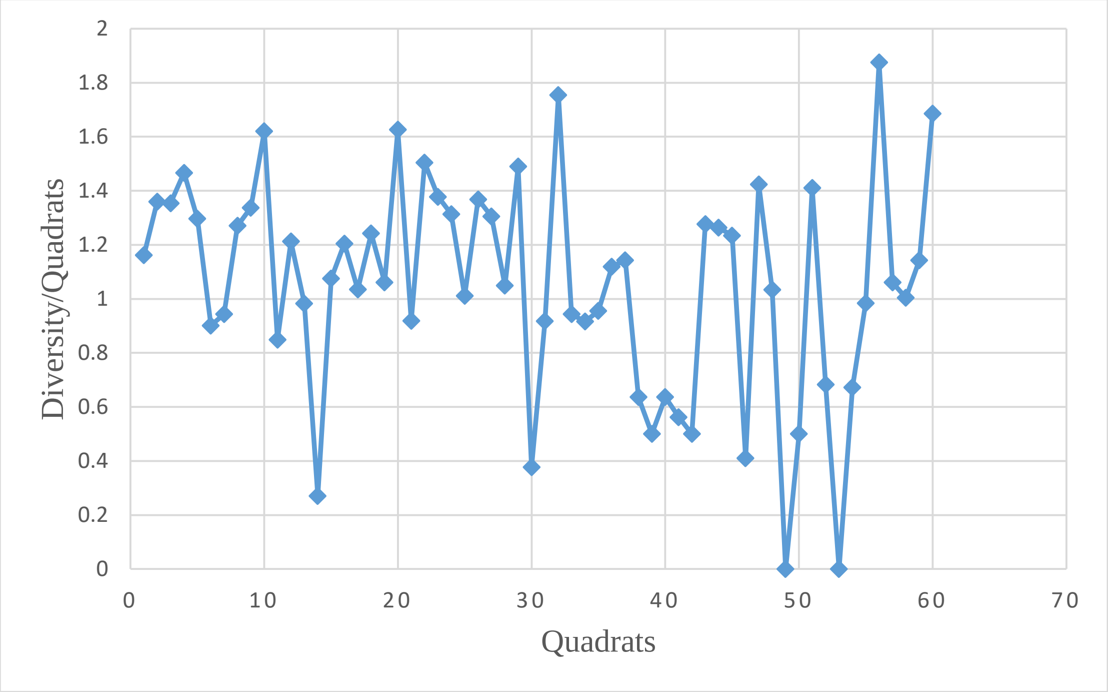


Figure 4. Diversity for each Quadrats

4.3. Woody Species Structure

4.3.1. The density of woody species

A total of 976 individuals, from 27 species, having DBH ≥ 2.5 cm were recorded within 60 quadrats in the study site (Table 6). *C. africana* was the dominant species in the study area covering 30.74% (300 individuals). *F. albida* is the second dominant species with 23.46% (229 individuals) coverage of the whole quadrats of the study site. The individual density of *F. albida* in the current study was almost agreed with (Manaye *et al.*, 2021) reported (239) individuals in the parkland agroforestry. M. *indica* covered 9.53% (93 individuals), both *E. cymosa and P. guajava* were 8.91% (87 individuals), *E. camaldulensis* 4.92% (48 individuals), *O. europaea* 2.87% (28 individuals), *C. macrostachyus* 1.95% (19 individuals), *E. tirucalli* 1.43% (14 individuals), both *T. brownii*, *A. senegalensis* were 1.23% (12 individuals), *E. brucei* 1.03% (10 individuals stems). *C.edulis* is 0.72% (7 individuals stems), *A. abyssinica* 0.51% (5 individuals), *S. kunthianum* 0.51% (5 individuals), *J. procera* 0.41% (4 individuals), *C. africana* 0.31% (3 individuals). *F. vasta*, *C. papaya*, *S. molle* have the same coverage of 0.20% (2 individuals). *Z. mucronata*, *C. pentandra*, *E. citriodora*, *B. aegyptiaca*, *S. abyssinica*, *M. kummel*, *M. oleifera* were the least with a value of 0.10% (1 stem). The density of dominant woody species found in the study area was higher than (Guyassa and Raj, 2013; Wari *et al.*, 2019) agri-silviculture agroforestry.

Table 6. Tree species, abundance, density, frequency, and species density per hectare

Plant Species	Abundance	Quadrats No. Spp. Occurs	D*	RD* (%)	F* (%)	RF* (%)	Indiv.*/ha
Acacia abyssinica	5	1	16.7	0.51	1.67	0.4	0.6
Annona senegalensis	12	4	40	1.23	6.67	1.6	1.3
Balanites aegyptiaca	1	1	3.33	0.1	1.67	0.4	0.1
Carica papaya	2	1	6.67	0.2	1.67	0.4	0.2
Casimiro edulis	7	4	23.3	0.72	6.67	1.6	0.8
Ceiba pentandra	1	1	3.33	0.1	1.67	0.4	0.1
Celtis africana	3	3	10	0.31	5	1.2	0.3
Cordia africana	300	54	1000	30.7	90	22	33
Croton macrostachyus	19	10	63.3	1.94	16.7	4.1	2.1
Ehretia cymosa	87	18	290	8.9	30	7.4	9.7
Erythrina brucei	10	7	33.3	1.02	11.7	2.9	1.1
Eucalyptus camaldulensis	48	8	160	4.91	13.3	3.3	5.3
Eucalyptus citriodora	1	1	3.33	0.1	1.67	0.4	0.1
Euphorbia tirucalli	14	8	46.7	1.43	13.3	3.3	1.6
Faidherbia albida	229	57	763.	23.4	95	23	25
Ficus vasta	2	2	6.67	0.2	3.33	0.8	0.2
Juniperas procera	4	1	13.3	0.41	1.67	0.4	0.4
Mangifera indica	93	21	310	9.52	35	8.6	10
Mimusops kummel	1	1	3.33	0.1	1.67	0.4	0.1
Moringa oleifera	1	1	3.33	0.1	1.67	0.4	0.1
Olea europaea	28	11	93.3	2.87	18.3	4.5	3.1
Psidium guajava	87	12	290	8.9	20	4.9	9.7
Schefflera abyssinica	1	1	3.33	0.1	1.67	0.4	0.1
Schinus molle	2	1	6.67	0.2	1.67	0.4	0.2
Stereospermum kunthianum	5	5	16.67	0.51	8.33	2.1	0.6
Terminalia brownii	12	8	40	1.23	13.3	3.3	1.3
Ziziphus mucronata	1	1	3.33	0.1	1.67	0.4	0.1

D = Density, RD = Relative Density, F = Relative Frequency, ha = Hectare, Indiv. *=Individual

4.3.2. Frequency of woody species trees

Frequency is the number of quadrats in which a given species occurred in the study area. Accordingly, the frequency distribution of species in the current study showed that *F. albida* (95%) and *C. africana* (90%) were the most frequently observed woody species respectively (Table 6). *M. indica* (35%), *E. cymosa* (30%), *P. guajava* (20%), *O. europaea* (18.3%), *C. macrostachyus* (16.7%). *T. brownii*, *E. tirucalli*, and *E. camaldulensis* were equally frequent with a percentage of (13. 3%). *E. brucei* (11.6%), *S. kunthianum* (8.3%), *A. senegalensis* (6.6%), *C. edulis* (6.6%), and *C. africana* (5%). *J. procera*, *S. molle*, *A. abyssinica*, *Z. mucronata*, *C. pentandra*, *E. citriodora*, *C. papaya*, *F. vasta*, *B. aegyptiaca*, *S. abyssinica, M. kummel, M. oleifera* were the least frequent woody species found in the study area. The frequency of the two (*F. albida and C. africana*) dominant woody species trees found in the study site was higher than (Guyassa and Raj, 2013; Abate *et al*., 2018; Wari *et al*., 2019) because farmers preferred these two trees as they have multiple uses. The domination of these two woody species in the Fedis District was also supported by (Abdella *et al*., 2020).

4.3.3. Basal area (BA)

The total basal area calculated for the study area was about 66.77 m^2 with an average of 2.2 m^2 ha^{-1} for woody plants ≥ 2.5 cm in DBH (Table 7). The maximum and minimum values BA were recorded in *F. albida* (36.42 m^2**)** with 54.55% and *Ceiba pentandra* (0.0024 m^2) with 0.0036% respectively. The basal area per hectare of the current study was higher than (Manaye *et al.*, 2021) who reported that (1.52 m^2 ha^{-1}) in parkland agroforestry in Northern Ethiopia.

The two species *F. albida* and *C. africana* together make up 50.5% of the total basal area. The basal area provides a better measure of the relative importance of the species than a simple stem count (Cain and Castro, 1959; Bekele, 1994).

Thus, the species with the largest contribution to BA can be considered the most important species. In this study, basal area analysis across individual species revealed as there was high domination by very few species. Accordingly, woody species that have high-value indexes were *F. albida* and *C. africana*, because of their higher relative density and frequency. *F. albida* data was the leading dominant in this regard. Although *C. africana* has high density and relative density than *F. albida*. But its basal area is not as high as *F. albida*. This also indicates that species with the highest basal area do not necessarily have the highest density, indicating size difference between species (Bekele, 1994; Teshager *et al.* 2018).

Table 7. Tree name, abundance, basal area, basal area per hectare, and relative basal area

Plant Species	Abundance	BA*	BA/ha	RBA*
Acacia abyssinica	5	0.03	0.0008	0.04
Annona senegalensis	12	0.25	0.008	0.367
Balanites aegyptiaca	1	0.35	0.01	0.53
Carica papaya	2	0.02	0.0008	0.04
Casimiro edulis	7	0.42	0.01	0.62
Ceiba pentandra	1	0.002	8E-05	0.004
Celtis africana	3	0.03	0.0009	0.04
Cordia africana	300	13.99	0.47	20.95
Croton macrostachyus	19	0.69	0.02	1.04
Ehretia cymosa	87	1.41	0.047	2.11
Erythrina brucei	10	1.46	0.05	2.19
Eucalyptus camaldulensis	48	0.72	0.02	1.08
Eucalyptus citriodora	1	0.006	0.0002	0.009
Euphorbia tirucalli	14	0.18	0.006	0.28
Faidherbia albida	229	36.42	1.2141	54.55
Ficus vasta	2	3.82	0.13	5.71
Juniperas procera	4	0.01	0.0005	0.02
Mangifera indica	93	2.38	0.08	3.56
Mimusops kummel	1	0.008	0.0003	0.01
Moringa oleifera	1	0.03	0.001	0.05
Olea europaea	28	1.87	0.06	2.80
Psidium guajava	87	1.16	0.04	1.74
Schefflera abyssinica	1	0.003	9E-05	0.004
Schinus molle	2	0.26	0.008	0.39
Stereospermum kunthianum	5	0.38	0.01	0.57
Terminalia brownii	12	0.67	0.02	0.99
Ziziphus mucronata	1	0.19	0.006	0.29

BA* = Basal Area, RBA* = Relative Basal Area, ha = hectare

The total tree individuals (n=976) found in the current study area was categorized in to five DBH classes. The distribution of woody species in different DBH classes was analyzed and classified into 5 classes were; (1) ≤15cm, (2) 15-30 cm, (3) 30-45 cm, (4) 45-60, (5) ≥60cm (Figure 5). DBH class distribution of all individuals in different size classes showed an inverted J- shape. The majority of the species had the highest number of individuals in the lowest DBH class distribution with a gradual reduction toward high DBH classes. Nearly half of woody species individuals having ≤15cm DBH were shows, trees found in the agri-silviculture system of the current study site were not enough young. This implies the presence of management practice behind the system. In the current study site DBH was the most contributor for total biomass carbon stock (figure 8). Individual trees having lower DBH shows, those woody species were store less carbon stock in their biomass than trees having higher DBH's. Out of the total woody species, 48.98, 24.20, 14.0, and 8.30, 4.51% were distributed in the first, second, third, fourth diameter, and fifth classes, respectively. This study's result was similar to the results of (Wari *et al.*, 2019).

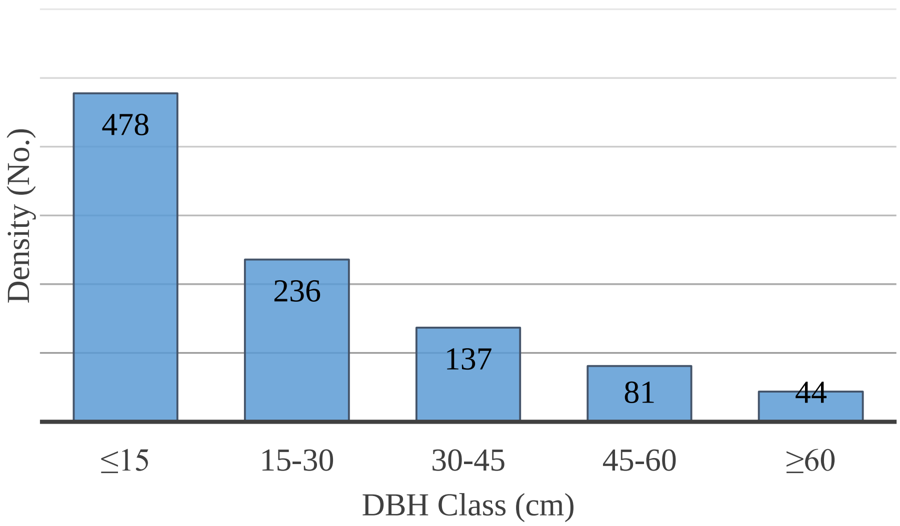


Figure 5. Diameter at breast height (DBH) class distribution of all woody species

The overall average DBH and height of the all woody species found in the current study were 25.4 cm and 10.7 m respectively. This result was higher than the (Manaye *et al.*, 2021) that reported (18.05 cm, and 5.65 m) respectively, in the parkland agroforestry in Northern Ethiopia. *F. vasta, B. aegyptiaca, Z. mucrnata, S. molle*, and *F. albida* were species that have high DBH with the value of 144.5, 67, 50, 41, and 40.39 cm respectively (Figure 6). Whereas, *C. pentandra, S. abyssinica*, and *J. procera* were species that had lower DBH respectively. Together, DBH and density have a high contribution to basal area determination of the vegetation.

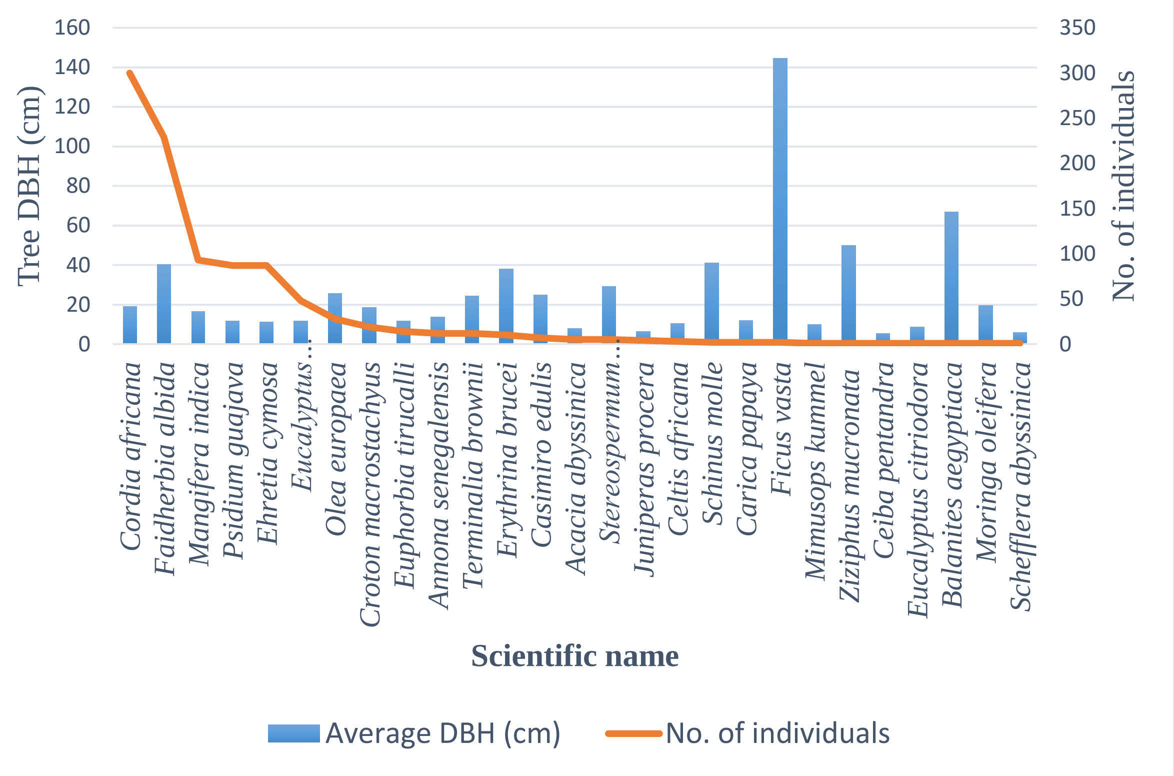


Figure 6. Woody species density with their average DBH

4.3.4. Importance value index

Based on Importance Value Index (IVI) values, the three dominant and those that had high IVI woody species in the entire study area were *F. albida*, *C. africana*, *M. indica*, (101%), (73.8%), (21.7%) respectively (Table 8). IVI combines data from three parameters which include RF, RD and RDO (Lamprecht, 1989; Kent and Coker, 1992) also noted that it is useful to compare the ecological significance of species (Neelo *et al.*, 2015). It was also stated that species with the greatest importance value index were the leading dominant of specified vegetation (Teshager *et al.*, 2018). The IVI of *F. albida* and *C. africana* were 101% and 73.8 respectively. The reason why they have a higher IVI value was that they had higher relative density, relative frequency, and relative abundance relative to other species in the study site. The leading dominant and ecologically most significant species might also be the most preferred woody species by farmers, pathogen resistance, used as the attraction of pollinators within the existing environmental conditions (Kenea, 2008).

Table 8. Tree species, abundance, density, frequency, basal area, and importance value index

Plant Species	Species Abundance	D*	RD* (%)	F*	RF* (%)	BA* (m^2)	RBA* (%)	IVI*
Acacia abyssinica	5	16.67	0.51	1.67	0.4	0.03	0.04	0.96
Annona senegalensis	12	40	1.23	6.67	1.6	0.25	0.37	3.24
Balanites aegyptiaca	1	3.333	0.1	1.67	0.4	0.35	0.53	1.04
Carica papaya	2	6.667	0.2	1.67	0.4	0.03	0.04	0.65
Casimiro edulis	7	23.33	0.72	6.67	1.6	0.41	0.62	2.98
Ceiba pentandra	1	3.333	0.1	1.67	0.4	0	0	0.52
Celtis africana	3	10	0.31	5	1.2	0.03	0.04	1.58
Cordia africana	300	1000	30.7	90	22	14	21	73.8
Croton macrostachyus	19	63.33	1.94	16.7	4.1	0.69	1.04	7.1
Ehretia cymosa	87	290	8.9	30	7.4	1.41	2.11	18.4
Erythrina brucei	10	33.33	1.02	11.7	2.9	1.46	2.19	6.09
Eucalyptus camaldulensis	48	160	4.91	13.3	3.3	0.72	1.08	9.29
Eucalyptus citriodora	1	3.333	0.1	1.67	0.4	0.01	0.01	0.52
Euphorbia tirucalli	14	46.67	1.43	13.3	3.3	0.19	0.28	5.01
Faidherbia albida	229	763.3	23.4	95	23	36.4	54.5	101
Ficus vasta	2	6.667	0.2	3.33	0.8	3.82	5.71	6.74
Juniperas procera	4	13.33	0.41	1.67	0.4	0.01	0.02	0.84
Mangifera indica	93	310	9.52	35	8.6	2.38	3.56	21.7
Mimusops kummel	1	3.333	0.1	1.67	0.4	0.01	0.01	0.53
Moringa oleifera	1	3.333	0.1	1.67	0.4	0.03	0.05	0.56
Olea europaea	28	93.33	2.87	18.3	4.5	1.87	2.8	10.2
Psidium guajava	87	290	8.9	20	4.9	1.16	1.74	15.6
Schefflera abyssinica	1	3.333	0.1	1.67	0.4	0	0	0.52
Schinus molle	2	6.667	0.2	1.67	0.4	0.26	0.4	1.01
Stereospermum kunthianum	5	16.67	0.51	8.33	2.1	0.38	0.57	3.14
Terminalia brownii	12	40	1.23	13.3	3.3	0.67	1	5.52
Ziziphus mucronata	1	3.333	0.1	1.67	0.4	0.2	0.29	0.81

D* = Density, RD* = Relative Density, F*= Frequency, RF*= Relative Frequency, BA*= Basal Area, RBA*= Relative Basal Area, IVI*= Importance Value Index

IVI analysis is used for setting conservation priority (Gurmessa *et al.,* 2013). Those species which receive lower IVI values need high conservation efforts while those with higher IVI values need monitoring management (Belayneh *et al.*, 2011; Mekonen *et al.*, 2015).

4.4. Biomass and Carbon Stock Estimation

4.4.1. Above and below-ground biomass

Generally, the result revealed that the mean above-ground biomass and below-ground biomass stored in the study area was 17.2 Mg ha^{-1}, and 4.6 Mg ha^{-1} respectively (Appendix 1). The result of the study site biomass was agreed with (Gebrewahid and Meressa, 2020), and greater than the (5.97 and 2.3 Mg C ha^{-1}) results of Minjar Shenkora recorded by (Tsedeke *et al.,* 2021), and Gununo watershed agroforestry, Wolayitta Zone (Bajigo *et al.,* 2015).

4.4.2. Biomass Organic Carbon Stock

The results show that the mean above and below-ground carbon stock of the study area was 8.6, and 2.3 Mg C ha^{-1} respectively (Appendix 1). The minimum and maximum above-ground carbon stocks were 1.6 and 35.4, and, the minimum and maximum below-ground carbon stocks were 0.4 and 9.5 Mg C ha^{-1} respectively (Appendix 1). So biomass organic carbon (AGC and BGC) results in the current study were almost agreed with the finding of Gebrewahid and Meressa, 2020 who reported 7.9 and 3.0 Mg C ha^{-1} of the tree species diversity and its relationship with carbon stock in the parkland agroforestry of Northern Ethiopia. The mean above and below ground carbon stock were relatively greater than the findings of Manaye *et al.,* 2021 who has reported 5.27, 2.38 Mg C ha^{-1} of total biomass carbon, 5.97 and 2.3 Mg C ha^{-1} Carbon Stock Potential of Parkland agroforestry practice in Minjar Shenkora, North Shewa finding of Tsedeke *et al.*, 2021, 0.57 and 0.13 Mg C ha^{-1} estimation of biomass carbon stored in agroforestry practices in Gununo watershed, Wolayitta Zone (Bajigo *et al.,* 2015) and greater than 7.1 Mg C ha^{-1} aboveground carbon stock of woody species diversity in tropical ecosystems of farmland of Babile Elephant Sanctuary, Eastern Ethiopia (Sintayehu *et al.,* 2020). However, above-ground carbon stocks of the agri-silviculture agroforestry were found to be lower than those reported in the southern Burkina Faso parkland agroforestry system (86.6 Mg C ha^{-1}) by (Dimobe *et al.,* 2018), and smallholder farming system of western Kenya (16 Mg C ha^{-1}) by (Henry *et al.,* 2009). Similarly, the belowground carbon stock of the study site was lower than those reported in the West Africa Sahel parkland agroforestry system (Takimoto *et al.*, 2008). The variation in such a result is because of the age of the trees; which has a direct effect on DBH, height, tree density, management practices, climate condition, and human and natural disturbances factors influence the aboveground and belowground carbon stored in an agroforestry system (Tilahun *et al.,* 2015).

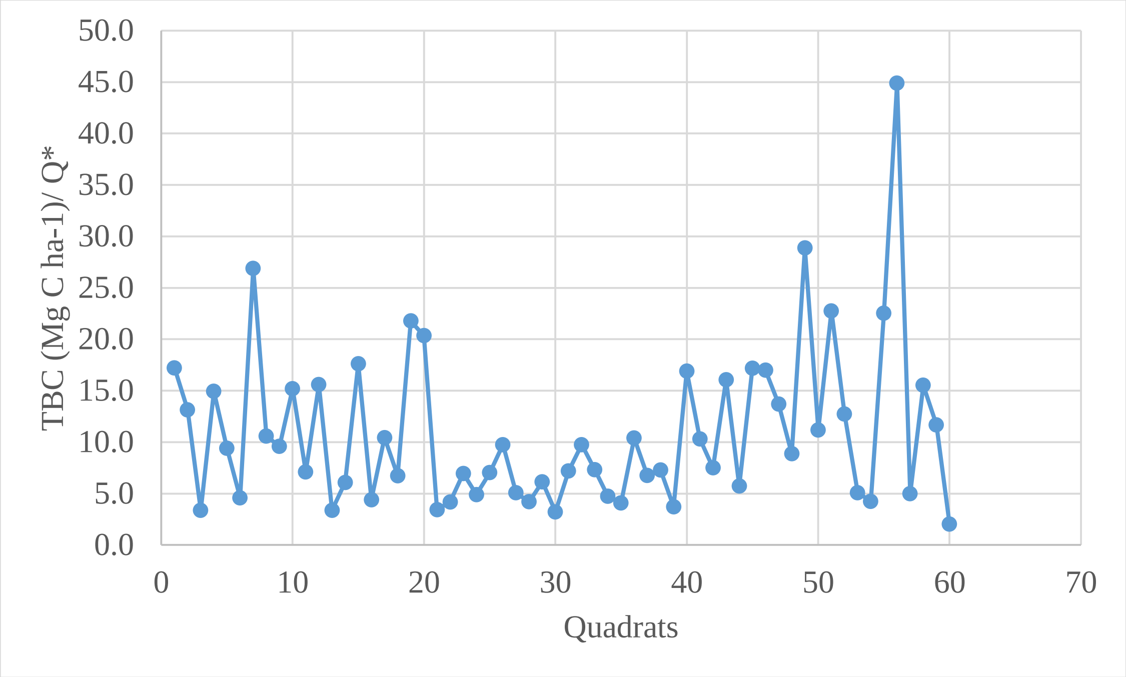


Figure 7. Total biomass carbon (TBC) Mg C ha^{-1} of all quadrates
Q* = Quadrat

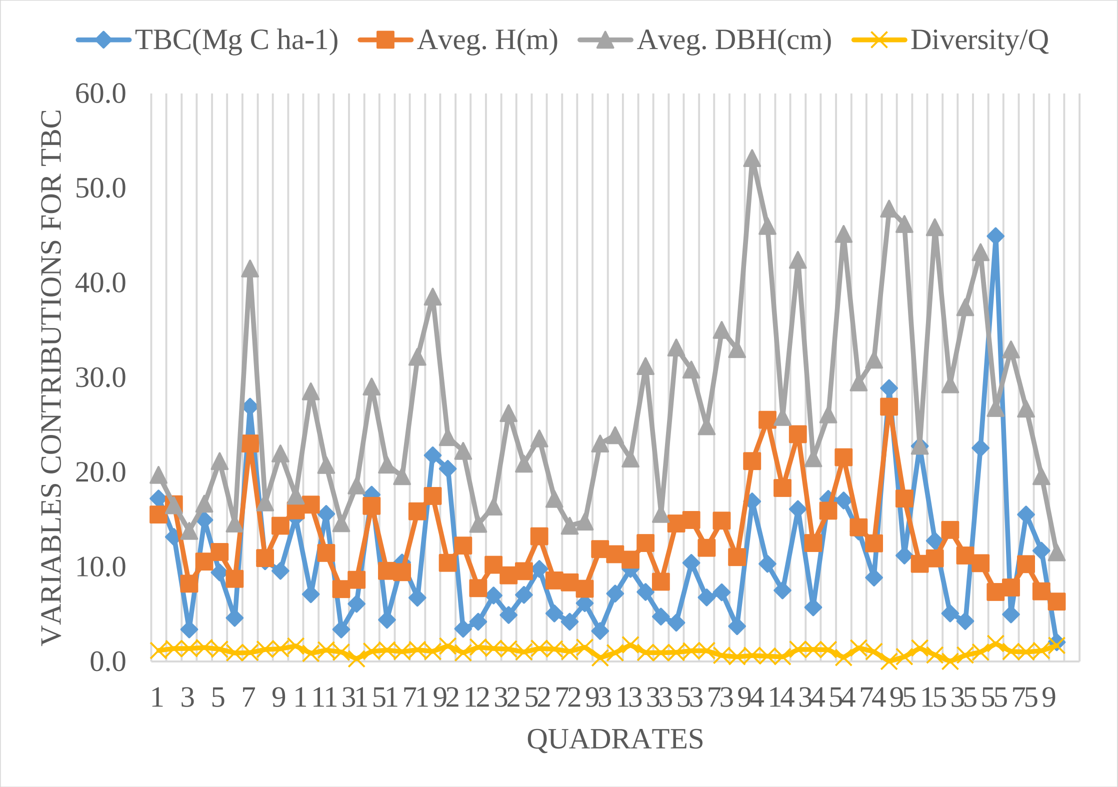


Figure 8. Contributions of diameter at breast height (DBH in cm), tree diversity, and height (H in m) of trees for total biomass carbon (TBC in Mg C ha^{-1}) in all quadrats (Q)

4.5. Soil Bulk Density and Organic Carbon

4.5.1. Soil bulk density

The lowest and highest bulk density values were 1.02 and 1.47, respectively with an average value of 1.26±0.098 gcm^{-3} (Appendix 2). Soil that has lower bulk density has higher carbon contents, and stocks because of the presence of organic matter, and soil with higher bulk density had lower soil organic contents and stocks (Abdella *et al.,* 2020). The result of bulk density of the study area was supported by 1.01 to 1.38, with an average of 1.21 gcm^{-3} bulk density of Minjar Shenkor parkland agroforestry (Tsedeke *et al.,* 2021).

4.5.2. Soil organic carbon contents and stock

Soil organic carbon (SOC) is a significant carbon pool because, it has the longest residence time among organic carbon pools (Lugo and Brown, 1993). The organic carbon content of the soil in the study area ranges from 0.70 to 3.08% with a mean value of 1.63%±0.49%. Quadrats 4, 6, and 7 had higher soil organic carbon contents with relatively low bulk density (Appendix 2). This shows how the soil bulk density influences the soil carbon content and stock of the soil. The result of soil organic carbon content was agreed with 1.14 to 3.38% of Minjar Shenkor parkland agroforestry (Tsedeke *et al.,* 2021).

Accordingly, the average soil organic carbon investigated in the current study area was 53±13.7-Mg C ha^{-1} with a minimum and maximum value of 25.2 and 94 Mg C ha^{-1}, respectively. The soil carbon stock of the study sites was in agreement with 41.75-81.25 Mg C ha^{-1} (Abdella *et al.,* 2020), the specified range for agroforestry soil carbon 13 to 300 Mg C ha^{-1} findings of Kumar and Nair (2011), Soil carbon of 28.2 to 98.9 Mg C ha^{-1} traditional agroforestry land use of southern Ethiopia (Demessie *et al.*, 2013), and 29.66 to 92.86 Mg C ha^{-1}, with the mean value 51.31 of Minjar Shenkor parkland agroforestry (Tsedeke *et al.*, 2021).

The result was higher than parkland agroforestry of Northern Ethiopia with the mean value of 20.07 Mg C ha^{-1} (Gebrewahid and Meressa, 2020), SOC of scattered trees on farmland in Tigray (Gebrewahid *et al.,* 2018), Gununo Watershed, Wolayitta Zone parkland agroforestry 49.05 Mg C ha^{-1} -ton ha^{-1} (Bajigo *et al.,* 2015). However, the SOC in the study area was remarkably lower as compared to results conducted in Cheha woreda, the Gurage zone for cultivated land 73 Mg C ha^{-1} (Semere, 2017) cited in (Tsedeke *et al.*, 2021), and 80–103 Mg C ha^{-1} of tropical agricultural land of (Lal 2004b)

Soil organic carbon stock studied in different agroecology has a significant difference. These are due to the composition, land-use history, management, and structure of vegetation along the agro-ecology zone, which may accumulate different amounts of organic matter due to high inputs from root biomass and above-ground (Sauer *et al.*, 2007; Jose, 2009). Diversified tree species have high fine root production and the SOC is high (Sauer *et al.*, 2007). Thinning and pruning of trees may reduce SOC sequestration by reducing litter-fall and accelerating decomposition due to changes in understory light, air/soil temperature, and soil moisture regimes (Lorenz and Lal, 2014; Tsedeke *et al.,* 2021).

4.6. Total carbon stock

The carbon stock distribution of all carbon pools within sampled quadrats ranged from a minimum of 27.2 Mg C ha^{-1} to a maximum of 138.9 Mg C ha^{-1}. However, the mean total carbon stock and CO_2 equivalent values of the study area were 63.9 Mg C ha^{-1} and 234.5, respectively (Appendix 1). The total carbon found in the study area was relatively higher than Gununo Watershed, Wolayitta Zone, parkland agroforestry 51 Mg C ha^{-1} (Bajigo *et al.* 2015), scattered trees on farmland in Tigray 31 Mg C ha^{-1} (Gebrewahid *et al.*, 2018), Minjar Shenkor parkland agroforestry 59.65 Mg C ha^{-1} (Tsedeke *et al.,* 2021), and parkland agroforestry of northern Ethiopia 31 Mg C ha^{-1} (Gebrewahid and Meressa, 2020). The average total carbon stock of the study area was within the range of tropical agroforestry 7.9–105 Mg C ha^{-1} (Montagnini and Nair, 2004), Cocoa-based agroforestry practiced in Nigeria ranged from 16–96.01 Mg C ha^{-1} (Oke *et al.,* 2011). The difference in carbon stock could be attributed due to DBH, the height of trees, management, socio-economic needs, species diversity, the age of trees, local climate, tree spacing among agroforestry systems (Kumar, 2011), higher levels of disturbance (pruning and damage), intensive management practices, and small land size that forces scattered trees on farmland not only having a higher density of wood perennials but also an accumulation of other plants and crops per unit area.

Another important observation in this study was about the contribution of each carbon pool to the total carbon stock. The trend of the total carbon stock shows that soil carbon stock contributed 83 percent more than vegetation biomass carbon stock (Figure 9). The contribution of above-ground and below-ground carbon contribution for the study area was 13 and 4 percent respectively. The contribution of SOC of the current study was relatively greater than 66% of soil carbon stock in traditional agroforestry systems of southeastern Ethiopia, (Tesemma *et al*., 2013), and 65% of soil carbon stock in parkland agroforestry of Northern Ethiopia (Gebrewahid and Meressa, 2020).

The total carbon stock observed in quadrats 5, 56, and 10 were higher respectively, with a minimum value of quadrat 60. This is due to the high amount of soil organic carbon being relatively high in those two quadrats (5 and 10), and above-ground carbon stock was the reason for the increment of total carbon stock in quadrat 56. On the other hand, the bulk density of those quadrats were relatively low when compared with other quadrats. Of course, soil that has low bulk density has high soil organic carbon content and stock.

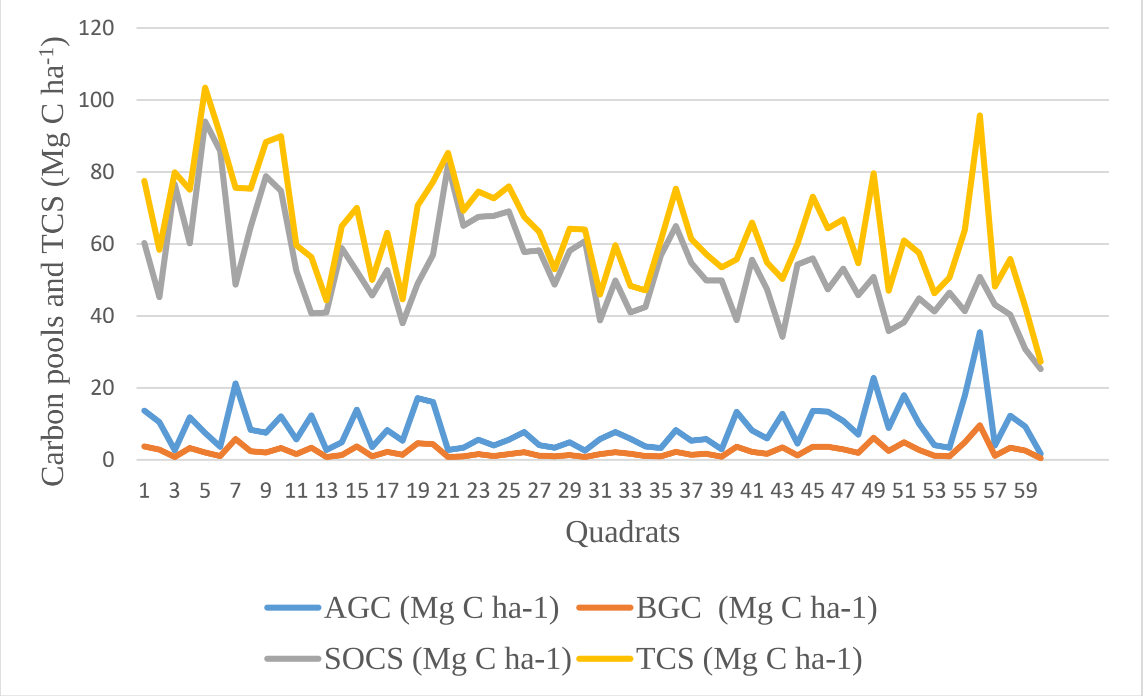


Figure 9. Values of Above ground carbon (AGC), Below ground carbon (BGC), Soil organic carbon stock (SOC) and Total carbon stock (TC)

Carbon stock in a different pool of the study site shows variation. Of the TCS of the study site the highest percentage of carbon stock was stored in the soil organic carbon by 83%, above-ground carbon stock was 13%, and below-ground carbon stock was the least contributor for TCS by 4%.

5. SUMMARY, CONCLUSION, AND RECOMMENDATIONS

5.1. Summary and Conclusion

This study was conducted in Agrisilviculture agroforestry of Fedis District of Eastern Hararghe, Oromia Regional State, Eastern Ethiopia after the rainy season from the beginning of November to the early weeks of December 2021. The objective of this study was to investigate the woody species diversity, population structure, and carbon stock potential of agri-silviculture agroforestry of Fedis District. Both woody species and soil parameters were collected from the study site. Accordingly, woody species parameters including tree and shrub species identification, height, and DBH were recorded in 60 quadrats. Finally, biomass values with their respective carbon stocks were exploited. Soil parameters were collected from the depth of 30cm for soil organic carbon determination, and one soil data were taken from the center of each quadrat by the use of a core sampler. The collected soils for carbon percentage determination and soil bulk density analysis were done at the Central Laboratory and Soil Physics Laboratories of Haramaya University respectively. The vegetation and soil data analysis were done using R software and micro soft excel. In composition, a total of 27 woody species in 26 genera and 20 families have been identified from Fedis agri-silviculture agroforestry.

Agri-silviculture system was the main land-use system in agri-silviculture practicing kebeles of Fedis District. These agroforestry practices played an important role in conserving different woody species of trees. However, *Faidherbia albida* and *Cordia africana* were the most dominant woody species with IVI of 101 and 73.8 respectively. The total number of individuals of *Cordia africana* was relatively higher than *Faidherbia albida.* But, *Faidherbia albida* was the most frequent woody species found in Fedis agrisilviculture. The Shannon diversity index of woody species was 2.12, with an evenness value of 0.64. This Shannon diversity index value is found in the medium range. Farmers prefer *Faidherbia albida* and *Cordia africana* because of their multipurpose services, on the other hand, this preference has a direct effect on species richness, diversity, and evenness.

However, there was an average of 8.6, 2.3, 53, and 63.9 Mg C ha^{-1} of AGC, BGC, SOC, and TC respectively, which suggests the significant potential of these production systems to store and enhance ecosystem carbon stocks. But, carbon stock was not influenced by woody species diversity but rather by tree diameter, height, and density. The contribution of the three-carbon pools was 13%, 4%, and 83% of AGC, BGC, and SOC respectively. Averagely, 234.5 CO_2 equivalents were sequestered per hectare. This carbon sequestration could be an attractive opportunity for farmers to benefit economically from agri-silviculture agroforestry if carbon sequestered is sold to developed countries. It will help the farmers to improve their farm economy besides securing environmental benefits for global communities. Additionally, agri-silviculture could be one of the good climate-smart agriculture practices and has a great contribution to the achievement of the green economy plan that the government has planned for ten years.

5.2. Recommendations

Based on the results of the study and observations made during the field study, the following recommendations were forwarded;

- We can sustain multipurpose native woody species by conserving and managing the agri-silviculture ecosystems.
- The most dominant multipurpose woody species like *Cordia africana* and *Faidherbia albida* found in the study site benefit the farmers if expand and planted in different parts of the country within the same agro-ecology
- Conservation of such important multipurpose native woody species in agri-silviculture should be delivered to other farmers in the parts of the country in the form of training and field visits.
- Better to integrate **the** carbon sequestration benefit of agri-silviculture with Reduced Emission from Deforestation and Degradation (REDD+) and the Clean Development Mechanism (CDM) carbon trading system of the Kyoto Protocol to benefit the farmers through monetary funds that intern initiate the farmers to conserve woody species in their agricultural land.
- It is good if the government considers agri-silviculture as climate-smart agriculture and also includes it in the plan for the green economy.
- Policy makers, different government and non-government organizations have to focus on the agrisilviculture systems to help the farmers, where farmers conserve and manage such beneficial woody species on their limited farmlands.
- Better, if Development Agents are establishing tree nurseries that can help farmers in the plantation of highly preferable woody species.

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7. APPENDIX

Appendix 1. Values Above ground carbon (AGC) Below ground carbon (BGC), Soil organic carbon stock (SOCS), Total carbon stock (TCS)

Quadrat No.	**AGB (Mg C ha^{-1})**	**AGC (Mg C ha^{-1})**	**BGB (Mg C ha^{-1})**	**BGC (Mg C ha^{-1})**	**SOCS (Mg C ha^{-1})**	**TCS (Mg C ha^{-1})**
1	27.1	13.6	7.3	3.7	60.2	77.5
2	20.7	10.4	5.6	2.8	45.2	58.4
3	5.3	2.6	1.4	0.7	76.6	79.9
4	23.5	11.8	6.3	3.2	60.1	75.1
5	14.8	7.4	4	2	94	103.4
6	7.2	3.6	1.9	1	85.8	90.4
7	42.4	21.2	11.4	5.7	48.7	75.6
8	16.7	8.3	4.5	2.3	64.7	75.3
9	15.1	7.5	4.1	2	78.8	88.3
10	23.9	12	6.5	3.2	74.7	89.9
11	11.2	5.6	3	1.5	52.5	59.6
12	24.5	12.3	6.6	3.3	40.7	56.3
13	5.3	2.7	1.4	0.7	40.9	44.3
14	9.6	4.8	2.6	1.3	58.8	64.9
15	27.7	13.9	7.5	3.7	52.4	70
16	6.9	3.5	1.9	0.9	45.6	50
17	16.4	8.2	4.4	2.2	52.7	63.1
18	10.6	5.3	2.9	1.4	37.9	44.6
19	34.3	17.1	9.3	4.6	48.9	70.6
20	32	16	8.7	4.3	56.9	77.2
21	5.4	2.7	1.5	0.7	81.9	85.3
22	6.6	3.3	1.8	0.9	65	69.2
23	10.9	5.5	3	1.5	67.5	74.5
24	7.7	3.9	2.1	1	67.8	72.7
25	11.1	5.5	3	1.5	69	76
26	15.4	7.7	4.1	2.1	57.7	67.5
27	8	4	2.2	1.1	58.2	63.3
28	6.6	3.3	1.8	0.9	48.7	52.9
29	9.7	4.8	2.6	1.3	58.1	64.2
30	5.1	2.5	1.4	0.7	60.8	64
31	11.3	5.7	3.1	1.5	38.7	45.9
32	15.4	7.7	4.1	2.1	49.8	59.6
33	11.5	5.8	3.1	1.6	40.9	48.3
34	7.4	3.7	2	1	42.4	47.1
35	6.4	3.2	1.7	0.9	56.8	60.9
36	16.4	8.2	4.4	2.2	64.9	75.3
37	10.6	5.3	2.9	1.4	54.7	61.4

Appendix 1. Values of the three-carbon pools and total carbon stock of all quadrats. Above ground carbon (AGC), Below ground carbon (BGC), Soil organic carbon (SOC), Total carbon (TC)

Quadrat No.	**AGB (Mg C ha^{-1})**	**AGC (Mg C ha^{-1})**	**BGB (Mg C ha^{-1})**	**BGC (Mg C ha^{-1})**	**SOCS (Mg C ha^{-1})**	**TCS (Mg C ha^{-1})**
38	11.5	5.7	3.1	1.6	49.8	57.1
39	5.8	2.9	1.6	0.8	49.8	53.5
40	26.6	13.3	7.2	3.6	38.8	55.7
41	16.2	8.1	4.4	2.2	55.6	65.9
42	11.8	5.9	3.2	1.6	47.3	54.8
43	25.3	12.7	6.8	3.4	34.2	50.3
44	9	4.5	2.4	1.2	54.3	60
45	27	13.5	7.3	3.6	56	73.1
46	26.8	13.4	7.2	3.6	47.3	64.3
47	21.6	10.8	5.8	2.9	53.1	66.8
48	14	7	3.8	1.9	45.7	54.6
49	45.5	22.7	12.3	6.1	50.8	79.6
50	17.6	8.8	4.8	2.4	35.8	47
51	35.8	17.9	9.7	4.8	38.2	60.9
52	20	10	5.4	2.7	44.8	57.5
53	8	4	2.2	1.1	41.2	46.3
54	6.7	3.3	1.8	0.9	46.4	50.6
55	35.5	17.8	9.6	4.8	41.3	63.9
56	70.7	35.4	19.1	9.5	50.8	95.7
57	7.8	3.9	2.1	1.1	43.1	48.1
58	24.4	12.2	6.6	3.3	40.3	55.8
59	18.4	9.2	5	2.5	30.7	42.4
60	3.2	1.6	0.9	0.4	25.2	27.2
Min	3.2	1.6	0.9	0.4	25.2	27.2
Max	70.7	35.4	19.1	9.5	94	138.9
Aveg.	17.2	8.6	4.6	2.3	53	63.9
STDEV	12.2	6.1	3.3	1.6	13.7	21.4

Appendix 2. Soil Bulk Density, Depth, Organic Carbon contents and Soil organic carbon stock

Quadrat No.	BD(g/cm3)	Depth (cm)	%C	%C to mg /g	1-frag (g fine)	Conversion factor	SOCS Mg C ha-1
1	1.26	30	2.17	21.7	0.73	0.1	60.2
2	1.07	30	2.11	21.1	0.67	0.1	45.2
3	1.09	30	3.06	30.6	0.77	0.1	76.6
4	1.08	30	2.05	20.5	0.91	0.1	60.1
5	1.2	30	3.08	30.8	0.85	0.1	94
6	1.11	30	2.81	28.1	0.92	0.1	85.8
7	1.04	30	1.99	19.9	0.78	0.1	48.7
8	1.18	30	2.44	24.4	0.75	0.1	64.7
9	1.47	30	2.34	23.4	0.76	0.1	78.8
10	1.23	30	2.5	25	0.81	0.1	74.7
11	1.12	30	1.83	18.3	0.85	0.1	52.5
12	1.25	30	1.31	13.1	0.83	0.1	40.7
13	1.3	30	1.4	14	0.75	0.1	40.9
14	1.25	30	1.97	19.7	0.8	0.1	58.8
15	1.27	30	1.79	17.9	0.77	0.1	52.4
16	1.27	30	1.56	15.6	0.77	0.1	45.6
17	1.18	30	1.66	16.6	0.9	0.1	52.7
18	1.31	30	1.37	13.7	0.7	0.1	37.9
19	1.22	30	1.5	15	0.89	0.1	48.9
20	1.24	30	1.85	18.5	0.83	0.1	56.9
21	1.31	30	2.26	22.6	0.92	0.1	81.9
22	1.43	30	1.62	16.2	0.94	0.1	65
23	1.38	30	1.72	17.2	0.95	0.1	67.5
24	1.28	30	1.87	18.7	0.94	0.1	67.8
25	1.3	30	1.97	19.7	0.9	0.1	69
26	1.23	30	1.66	16.6	0.94	0.1	57.7
27	1.25	30	1.66	16.6	0.93	0.1	58.2
28	1.23	30	1.44	14.4	0.92	0.1	48.7
29	1.2	30	1.7	17	0.95	0.1	58.1
30	1.37	30	1.56	15.6	0.95	0.1	60.8
31	1.3	30	1.05	10.5	0.95	0.1	38.7
32	1.4	30	1.25	12.5	0.95	0.1	49.8
33	1.32	30	1.13	11.3	0.91	0.1	40.9
34	1.41	30	1.09	10.9	0.92	0.1	42.4
35	1.25	30	1.62	16.2	0.93	0.1	56.8
36	1.24	30	1.85	18.5	0.94	0.1	64.9
37	1.31	30	1.46	14.6	0.95	0.1	54.7
38	1.37	30	1.31	13.1	0.93	0.1	49.8

Appendix 2. Soil Bulk Density, Depth, Organic Carbon contents and Soil organic carbon stock

Quadrat No.	**BD(g/cm3)**	**Depth (cm)**	**%C**	**%C to mg /g**	**1-frag (g fine)**	**Conversion factor**	**SOCS Mg C ha-1**
39	1.22	30	1.42	14.2	0.96	0.1	49.8
40	1.32	30	1.07	10.7	0.92	0.1	38.8
41	1.27	30	1.56	15.6	0.94	0.1	55.6
42	1.3	30	1.4	14	0.87	0.1	47.3
43	1.36	30	1.05	10.5	0.8	0.1	34.2
44	1.35	30	1.7	17	0.79	0.1	54.3
45	1.41	30	1.52	15.2	0.87	0.1	56
46	1.13	30	1.58	15.8	0.88	0.1	47.3
47	1.24	30	1.74	17.4	0.82	0.1	53.1
48	1.18	30	1.44	14.4	0.9	0.1	45.7
49	1.21	30	1.83	18.3	0.76	0.1	50.8
50	1.35	30	1.13	11.3	0.78	0.1	35.8
51	1.34	30	1.09	10.9	0.87	0.1	38.2
52	1.34	30	1.15	11.5	0.97	0.1	44.8
53	1.44	30	1.11	11.1	0.86	0.1	41.2
54	1.25	30	1.29	12.9	0.96	0.1	46.4
55	1.02	30	1.39	13.9	0.97	0.1	41.3
56	1.26	30	1.4	14	0.96	0.1	50.8
57	1.31	30	1.17	11.7	0.94	0.1	43.1
58	1.25	30	1.17	11.7	0.92	0.1	40.3
59	1.22	30	0.94	9.4	0.89	0.1	30.7
60	1.26	30	0.7	7	0.95	0.1	25.2
Min	1.02	30	0.7	7			25.2
Max.	1.47	30	3.08	30.8			94
Aveg	1.26	30	1.63	16.31			53
STDE	0.1	*0*	0.49	4.95			13.7