ASSESSMENT OF WOODY SPECIES DIVERSITY AND CARBON STOCK ESTIMATION ALONG ALTITUDINAL GRADIENT OF KULKAL BER NATURAL FOREST IN MAKSEGNET DISTRICT, NORTHWESTERN ETHIOPIA

MSc THESIS

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Assessment of Woody Species Diversity and Carbon Stock Estimation along Altitudinal Gradient of Kulkal Ber Natural Forest in Maksegnet District, Northwestern Ethiopia

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As research advisors, we hereby certify that we have read and evaluated this thesis entitled "Assessment of Woody Species Diversity and Carbon Stock Estimation along Altitudinal Gradient of Kulkal Ber Natural Forest in Maksegnet District, Northwestern Ethiopia" prepared under our guidance by Endawok Asmare. We recommend that it be submitted as fulfilling the thesis requirement.

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I would like to dedicate this Thesis to my parents for their motivation and support throughout my Study.

STATEMENT OF THE AUTHOR

By my signature below, I declare and affirm that this Thesis is my own work. I have followed all ethical and technical principles of scholarship in the preparation, data collection, data analysis and compilation of this Thesis. Any scholarly matter that is included in the Thesis has been given recognition through citations.

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BIOGRAPHICAL SKETCH

Endawok Asmare Belay was born in Gondar Azezo, in the Central Gondar administrative zone of Amhara National Regional State, Ethiopia, in 1998. She completed her elementary and secondary education in Azezo Keble 19 elementary and Azezo secondary and preparatory school respectively. She attended a BSc. degree in Forest management and utilization program at Hawassa University, Wondo Genet College of Forestry and Natural Resources from 2018 - 2021. She got a chance and joined Haramaya University, to pursue an MSc. degree program in Biodiversity and Ecosystem management at ACE-Climate SABC of College of agriculture and Environmental Sciences, Haramaya University in 2023.

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ACRONYMS AND ABBREVIATIONS

AGB	Above Ground Biomass
AGC	Above Ground Carbon
BGB	Below Ground Biomass
BGC	Below Ground Carbon
DBH	Diameter at Breast Height
DOM	Dead Organic Matter
DWB	Dead Wood Biomass
EBI	Ethiopian Biodiversity Institute
EFRL	Ethiopia Forest Reference Level
FAO	Food and Agricultural Organization
FBA	Forest Based Adaptation
GARC	Gondar Agricultural Research Center
GHGs	Green House Gases
GHL	Grass, Herb and Litter
GPS	Global Positioning System
GZDARDO	Gondar Zuria District Agricultural and Rural Development Office
IPCC	Intergovernmental Panel on Climate Change
NOAA	National Oceanic and Atmospheric Administration
PFM	Participatory Forest Management
SFM	Sustainable Forest Management
SOC	Soil Organic Carbon
SLM	Sustainable Land Management
UNEP	United Nations Environment Program
WCMC	World Conservation Monitoring Centre

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ABSTRACT

Forest ecosystems play a vital role in mitigating climate change and conserving biodiversity. Assessing their woody species diversity and carbon stocks along altitudinal gradient is essential for informing forest management strategies that enhance carbon sequestration in both vegetation and soil. This study aimed to establish baseline data on woody species diversity, structural attributes, and carbon stock potential along altitudinal gradient of the Kulkal Ber Natural Forest in Maksegnet District, Northwestern Ethiopia. Data collection was conducted using a stratified systematic sampling approach. Six transects, spaced 500 m apart along the altitudinal gradient, were established. A total of 60 plots (20 m × 20 m) were systematically placed at 200 m intervals along the transect lines. Additionally, five 5 m × 5 m subplots (positioned at the corners and center of the main plot) were used for sampling shrubs. Within each 5 m × 5 m subplot, a single 1 m × 1 m nested subplot was used to collect ground herbaceous layer (GHL) and soil samples. Woody species diversity was assessed using the Shannon-Wiener diversity index (H'), while hierarchical cluster analysis was performed to classify plant community types. Above and belowground biomass was estimated using general allometric models, and soil organic carbon (SOC) and grass, herb, and litter (GHL) carbon content were determined through laboratory analysis. A total of 36 woody species belonging to 26 families and 31 genera were identified. The overall Shannon-Wiener diversity index (H') was 1.801, with an evenness value of 0.48. The six most abundant species, in descending order of density, were Dodonaea angustifolia, Combretum molle, Rhus glutinosa, Millettia ferruginea, Rhus vulgaris, and Cordia africana. The forest's basal area was 6.53 m² ha⁻¹. ANOVA results indicated that altitudinal variation had no significant effect on species diversity. However, species composition, evenness value, and structural attributes highlighted the dominance of few species, with low importance value indices. Hierarchical cluster analysis identified three distinct plant community types, such as Ficus thonningii–Dodonaea viscosa, Olea europaea–Clausena anisata, and Myrsine africana–Euphorbia tirucalli. The total mean carbon stock of the forest was 150.76 t C ha⁻¹, with aboveground carbon (AGC) of 57.29 t C ha⁻¹, belowground carbon (BGC) of 15.47 t C ha⁻¹, grass, herb and litter (GHL) carbon of 3.21 t C ha⁻¹, deadwood carbon (DWC) of 2.86 t C ha⁻¹, and soil organic carbon (SOC) of 71.93 t C ha⁻¹. While AGC, BGC, and SOC showed no significant variation with altitude, GHL carbon was significantly higher at lower altitudes, suggesting that altitude influences ground herbaceous layer carbon accumulation. The forest's population structure exhibited a reversed J-shaped height class distribution in the two altitudinal gradients, dominated by small trees and shrubs, indicating good regeneration potential. These findings emphasize the importance of conservation measures and sustainable management strategies to safeguard the genetic resources and carbon sequestration capacity of Kulkal Ber Natural Forest.

Keywords: Aboveground Carbon, Belowground Carbon, Carbon Pools, Genetic Resources, Regeneration Potential, Sustainable Forest Management, Kulkal ber natural forest.

1. INTRODUCTION

Ethiopia's diverse agro-ecology, encompassing a wide range of agro-climatic zones, has fostered a wealth of habitats suitable for a remarkable variety of plant life **(**Dawson *et al*., 2009; Friis *et al*., 2010; Sebsebe *et al*., 2011). This rich biodiversity positions Ethiopia as a global hotspot (WCMC, 1994). The country is home to numerous endemic and endangered mammals and plants, many of which find refuge in its extensive forest and woodland ecosystems (Fashing *et al*., 2022)**.** Ethiopia boasts 6,027 species of vascular flora, with a remarkable 10% being endemic (Sebsebe *et al*., 2021). Woody plants, those with wood as their structural tissue, are particularly well represented, with over 1000 species, including 300+ tree species (Kelbessa and Demissew, 2014)**.** However, this impressive biodiversity faces significant threats: species abundance and diversity are in decline, with climate change emerging as a major culprit (Tesfay, 2017; Sintayehu, 2018; Thom *et al*., 2019). Human activities are the primary driver of global warming, accelerating it through the rapid release of greenhouse gases (GHGs) into the atmosphere. This, in turn, contributes to ecosystem degradation, leading to loss of biodiversity and increased carbon emissions. These environmental changes disproportionately impact the country, which often has weaker infrastructure and economies, limiting its ability to adapt to the consequences of climate change (Mahoo *et al*., 2013; Sintayehu, 2018)**.**

In this sense, forests play a crucial role in maintaining ecological balance and mitigating climate change. They act as reservoirs for biodiversity, harboring a wide variety of plant and animal species (Ahmed *et al*., 2023). Additionally, forests store significant amounts of carbon in their biomass, helping to regulate atmospheric carbon dioxide levels (Ahmad *et al*., 2023). Analyzing the diversity of woody species across various land use types is crucial for biodiversity conservation, which in turn plays a vital role in regulating the carbon cycle. According to the FAO (2022) report, forests store an estimated 62 billion metric tons of carbon. Unfortunately, global land use changes around the world have significantly contributed to the rising concentration of CO_2 in the earth's atmosphere (IPCC, 2007; Nair *et al*., 2010). Increasing the size of the global terrestrial carbon sink, such as forests, is a key strategy for mitigating the buildup of CO_2 in the atmosphere. Measuring forest carbon provides clear indications of how to support forest management and growth. This, in turn, mitigates climate change through enhanced soil and vegetation carbon sequestration. Additionally, carbon trading programs offer potential economic benefits for farmers participating in sustainable forestry practices. Beyond enhancing species diversity, promoting woody plants in various land use systems offers a range of additional benefits (Feyissa *et al*., 2014). However, unlike the industrialized world, Ethiopia lacks data banks and carbon inventories to track and improve the ability of various forests to sequester carbon (Siraj, 2019; Muluneh and Worku, 2022). Notably, very little has been done to evaluate the potential for small-scale carbon sequestration by soil and biomass (Feyissa *et al*., 2014).

The distribution pattern of plant species in Ethiopia varies at different scales and layers along the altitudinal gradient (Feyissa *et al*., 2014). This is because altitude affects the distribution of climatic elements, edaphic factors, and land suitability, which in turn affects the types of vegetation that can be cultivated, how quickly they grow, the types of natural vegetation that already exist, and the species diversity of those plants (Fekadu *et al*., 2018). There has been relatively little research on Ethiopia's forest carbon pool that considers environmental factors that influence both species diversity and carbon stock. Thus, understanding Ethiopia's ecological processes could help protect a few uncommon species that are vital to the ecosystem's wellbeing (Asefa *et al*., 2020).

While studies have explored how woody species diversity and carbon stocks vary with elevation in Ethiopian forests, such as Choke Mountain forest (Asrat *et a*l., 2022) and Hugumbrda Grat-kahsu forest (Abrha *et al*., 2024). However, no study has yet been conducted in Kulkal Ber Forest, indicating a critical knowledge gap exists for the vegetation type. Therefore, there is a need to generate more data specific to this area via research. Such data is crucial for developing targeted conservation and management strategies specific to Kulkal Ber's unique ecosystem and its role in Ethiopia's forest carbon pool. Regarding regional distribution, the Amhara National Regional State boasts a variety of ecosystems due to contrasting physiographic and climatic features and altitudinal ranges. The region is mostly known for its dry evergreen Afromontane forests and grassland complexes. However, because of a lengthy history of human disturbances, including demographic pressure, sedentary farming, and exotic tree planting, most of the forest area has degraded and been converted to agricultural land, dominated by patches of introduced tree species. This has resulted in the fragmentation of the forest, with only patch woods remaining in remote and protected locations, leaving the vegetation extremely threatened

(Masresha and Melkamu 2022; Alem, 2023). In addition, a lack of comprehensive data on the status and trends of forest resources in the region hinders effective planning and implementation for their improvement (Melesse and Abtew, 2016; Walle and Nayak, 2022;). This information gap is further compounded by poor environmental communication (Zikargae, 2018).

Based on the Ethiopian vegetation classification system of Friis *et al*. (2010), Kulkal Ber Natural Forest falls within the dry Afromontane Forest type, which is found in the Amhara Regional State of Ethiopia. In the same situation, Kulkal Ber forest also faces threats from unsustainable management practices, land use conversion to agriculture, excessive extraction of forest products, uncontrolled livestock grazing, a knowledge gap and lack of ownership among locals hindering conservation efforts, insufficient government investment, and inadequate enforcement contributing to the forest degradation (GIZ/SLM, 2015; Simegn, 2022). Previous studies in the Kulkal Ber forest, like that by Simegn (2022) recommend that future Participatory Forest Management (PFM) programs should be scaled up with research and should focus on providing data, information, and guidelines for efficient forest management practices and conservation strategies. Kidane *et al*. (2016) also recommend conducting future research on forest composition and carbon stock in relation to environmental variables that positively influence better management of the forest. Among these environmental variables, altitude plays a crucial role in shaping plant species diversity, floristic composition, and carbon stock.

While the function of forests in storing carbon is widely acknowledged (Kendie *et al*., 2021), there is a crucial knowledge gap about the particular carbon sequestration capacity of Kulkal Ber Natural Forest. Similarly, information about the variety and number of woody plant species in the forest is scarce. Investigating these ecological characteristics is crucial for several reasons. Diverse forests support complex webs of life, contributing to overall ecosystem health (Simegn, 2022). Documenting these species is essential for understanding and conserving Ethiopia's biodiversity. Furthermore, quantifying carbon stocks enhances our understanding of the forest's contribution to climate change mitigation (Prajapati *et al*., 2023) and provides essential data for developing effective conservation plans and contributing to national and international carbon accounting (Ware, 2022). This information can also inform strategies for mitigating global warming and potentially generating revenue through carbon trading, benefiting both the nation and local communities.

This research analyzed the contribution of woody natural vegetation to climate change mitigation by assessing the carbon stock in different carbon pools and woody plant species diversity, community types, and structure of Kulkal Ber Forest along the altitudinal gradients. The results provide baseline information for researchers, local experts, and the community to inform effective conservation and management strategies, biodiversity conservation, and sustainable resource use. Furthermore, these findings can inform policymaking contributing to climate change mitigation, including carbon credit programs and livelihood support, by providing scientific evidence for optimized species selection and management interventions. This research will also contribute to the implementation of the Kyoto Protocol's REDD+ (Reducing Emissions from Deforestation and Forest Degradation+) global agreement. Kulkal Ber Natural Forest was selected due to two key factors: projected increases in land cover change from anthropogenic pressure and the lack of existing data on aboveground and belowground biomass, grass, herbs, and litter (GHL) carbon, deadwood carbon (DWC), soil carbon stocks, and woody species diversity along the altitudinal gradient. Overall, these findings provide crucial data for developing effective management plans that balance biodiversity conservation with sustainable resource uses.

General Objective

- The general objective of this study is to investigate woody species diversity and carbon stock potentials along the altitudinal gradient of the Kulkal Ber natural forest in Maksegent district, Northwestern Ethiopia.

Specific Objectives

- To analyse species diversity, population structure, and community types of woody species along the altitudinal gradient in the study forest area,
- To estimate the carbon stock potential of the study area along the altitudinal gradients.

2. LITERATURE REVIEW

2.1. Woody Species Resource in Ethiopia

Ethiopia's diverse physical features, climatic types, topography, habitat, and vegetation types are all contributing to remarkable richness of woody species (Fris *et al*., 2010). Forest and woodlands provide goods such as timber, food, fuel, and other bio-products. Moreover, a healthy forest and woodland ecosystem functions as carbon storage and serves in nutrient cycling, water and air purification, and maintenance of wildlife habitat (EBI, 2022). However, the nation's once vast forests have significantly decreased in size because of activities including clearing land for cultivation and harvesting trees for firewood. Human-induced factors are the main cause of the decline in woody species found in natural forests. They include edge effects, habitat destruction and fragmentation, invasive species, population growth, deforestation, overexploitation, and climate change (Teklu, 2016). Due to this associated factors the amount of forest cover in the country has decreased, from 40% a century ago to an estimated 11.4% in 2012 (FAO, 2015).

The Afromontane Forest and grassland complex of the country is also threatened by habitat degradation and fragmentation because of anthropogenic pressure (Asefa *et al*., 2017). There are several remnant patches of Dry Evergreen Afromontane Forest and Grassland Complex in different parts of the country. According to Tesfay (2017), Ethiopia's incredibly diverse woody species face a web of complex threats; therefore, demanding stronger efforts for conservation and sustainable use is crucial. Studies have also determined that forests play a significant role in terms of reducing global warming (Muluneh and Worku, 2022)**.** However, most woody plant species in Ethiopia are used for several other purposes. The country tends to encourage the use of tree and shrub species in an unsustainable way. As a result, the elements of this categories of vegetation fall into the category of endangered species because of their excessive and unsustainable use, particularly for the production of fuel wood and lumber (Bellay, 2016).

Table 1: List of trees and other woody forest species considered to be threatened in Ethiopia

No	Species	Distribution in the country: widespread (W), rare (R) or local (L)	Threat categories
1	*Acacia pseudonigrescens*	R	Low
2	*Acacia venosa*	R	Medium
3	*Albizia malacophylla*	R	Medium
4	*Arundinaria alpine*	W	Medium
5	*Baphia abyssinica*	R	Medium
6	*Boswellia papyrifera*	R	High
7	*Cordia africana*	W	High
8	*Dicraeopetalum stipulare*	L	High
9	*Dracaena ambet*	R	High
10	*Hagenia abyssinica*	W	High
11	*Juniperus procera*	W	High
12	*Maytenus arbutifolia*	W	Medium
13	*Okotea kynensis*	R	Medium
14	*Oxytenanthera abyssinica*	W	Medium
15	*Podocarpus falcatus*	W	High
16	*Pouteria adolfi-frederici*	R	High
17	*Prunus africana*	W	High
18	*Teclea borennsis*	W	High
19	*Vitellaria paradoxa*	L	High

Source: Institute of Biodiversity Conservation (IBC) Country Report Submitted to FAO on the State of Forest Genetic Resources of Ethiopia, August 2012.

Effective conservation and management techniques, as well as ecological assessments, depend on the identification of both dominant and rare tree species in a forest, unique species of trees greatly enhance biodiversity (Berhe *et al*., 202). It is essential to comprehend the functions and patterns of distribution of both common and uncommon species to use sustainable forest management techniques and support climate change mitigation decision-making (Thompson *et al*., 2009). This is especially important in light of the need to conserve biodiversity, reduce global temperatures, and prevent the loss of forests (Basile, 2022; Tang *et al*., 2023). In view of this, the government of Ethiopia has made many efforts. The assessment of tree biomass and its carbon (C) stock at the local and regional level is considered a crucial criterion for understanding the impact of changing environments on the global carbon cycle (Tang *et al*., 2023).

2.2. Species Diversity Index Method

Different mathematical models have been developed to quantify species diversity in different habitats. While these models differ in the exact method of diversity estimation, they all include two important components: species richness and species evenness. Species richness is a measure of the number of different types of species in an ecosystem. Many different species in a habitat represent higher species richness and an overall more diverse ecosystem, whereas species evenness is a measure of the relative abundance of each species (Fekadu *et al*., 2023). More evenly represented species (evidenced by similar population sizes) illustrate higher species evenness and an overall more diverse ecosystem (Negi and Nautiyal, 2005). The species diversity index provides information about species rarity, endemism, and commonality. Measures of species diversity are usually seen as key indicators for the well-being of ecological systems (Bellay, 2016).

Accordingly, the recent review of Amenu (2016) indicated that understanding the richness, balance (evenness), presence of unique species (endemism), introduction of foreign species (exoticness), and changes in population size (enlargement or extinction) is crucial for developing effective conservation strategies. Ecologists and other researchers rely on various indices, like the Shannon-Wiener and Simpson indices, to calculate key diversity parameters. The Shannon-Wiener diversity index is one of the most used diversity indexes. It accounts for both the diversity and evenness of the species present in a community. This index takes into consideration species composition and evenness within the given land or community. The Shannon-Wiener diversity indices of diversity and evenness were used to look at the level of species diversity and evenness of species distribution (Kent and Coker, 1992).

2.3. An Overview of Global Climate Change

The increasing concentration of CO_2 and other greenhouse gases in the atmosphere is now widely recognized as the current issue around the globe due to the principal cause of global warming. Climate change is defined by comprehensive long-range temperature and precipitation trends and additional factors like the surrounding environment's pressure and humidity level (Abbass *et al*., 2022). The most well-known domestic and international repercussions of climate change are abnormal weather patterns, the retreating of global ice sheets, and the accompanying enhanced sea level rise (Murshed and Dao, 2020; Michel *et al*., 2021). Global climate change refers to the long-term alteration of temperature and weather patterns. It's primarily driven by human activities that release greenhouse gases like carbon dioxide (CO_2) into the atmosphere. The Earth's climate system currently exhibits a trend of increasing global mean surface temperature, a phenomenon recognized as global warming and presenting a critical environmental challenge. This warming is predominantly driven by the atmospheric accumulation of greenhouse gases (GHGs), primarily due to human activities. Carbon dioxide (CO_2) stands as the most significant GHG, contributing an estimated 76% of total emissions (US EPA, 2016).

Unequivocal global warming, driven by human activities like unsustainable energy use, land management, and consumption patterns, has caused a 1.1°C rise in average global surface temperature since the late 19th century; this warming disrupts weather patterns, leading to more extreme events like heat waves, droughts, floods, and storms (NOAA, 2024). Furthermore, this human-induced climate change is already disrupting weather patterns worldwide, leading to widespread consequences and harm to food and water security, human health, economies, and ecosystems (Chevuturi *et al*., 2022). The situation is urgent but not irreversible. However, by transitioning to cleaner energy sources, adopting sustainable practices, and reducing greenhouse gas emissions, we can mitigate the worst effects of climate change and build a more resilient future.

2.3.1. Greenhouse Gas and Climate Changes

The two most abundant gases in the atmosphere, nitrogen (78% of the dry atmosphere) and oxygen (21%), exert almost no greenhouse effect. Instead, the greenhouse effect comes from molecules that are more complex and much less common. Water vapor is the most important greenhouse gas, and carbon dioxide (CO_2) is the second-most important one. Methane, nitrous oxide, ozone, and several other gases present in the atmosphere in small amounts also contribute to the greenhouse effect (Treut *et al*., 2007). The potential for changes in atmospheric composition, in particular increased concentrations of GHGs (CO_2, N_2O, CH_4, and CFCs) that strongly absorb infrared radiation and allow solar short-wave radiation to enter the earth's surface, has been known for more than 100 years. Levels of these GHGs in the atmosphere are rising, causing the earth to warm. According to the IPCC's (2007) predictions, the earth's climate system shifts because of rising global mean temperatures and sea levels brought on by a rise in greenhouse gases in the atmosphere. This poses serious risks to both human survival and natural ecosystems. The effects are extremely detrimental, especially in tropical Africa, where there has historically been a high level of human suffering due to droughts, floods, and ensuing hunger because of climatic anomalies. However, the magnitude and rate of climate change and associated risks depend strongly on near-term mitigation and adaptation actions (Chevuturi *et al*., 2022).

Ethiopia has seen both climate fluctuation and change, as seen by the country's average annual temperature rise of 1.3^0C since 1960 and its corresponding rise of 0.28^0C each decade (UNDP, 2008). Precipitation differences in both space and time have increased, emphasizing how vulnerable the nation is to changes in the weather (Kobe, 2024). To combat global climate change and secure a livable and sustainable future for all, rapid and far-reaching transformations across all sectors are necessary. This requires significantly scaling up a diverse range of mitigation and adaptation options, many of which are already feasible, effective, and affordable, though with variations depending on specific systems and regions. By maintaining forest ecosystems in a healthy state, we take the most straightforward action to retain their resilience (Fuller and Quine 2016). Healthy forests are like strong and adaptable organisms; they can cope with stress, recover from damage, and even adapt to changing environmental conditions on their own (Gitz *et al*., 2016). In addition, species diversity tends to increase the resilience of natural and planted forests in the face of climate change and variability because it increases the likelihood that some of the species’ present will be able to cope as conditions change. As indicated by many scholars like Tolla (2010), the estimated carbon stock density in Addis Ababa Orthodox Churches varies between 129.8 tons/ha for above-ground biomass, 25.9 tons/ha for below-ground biomass, 17.8 tons/ha for litter layer and dead wood, and 135.9 tons/ha for mineral soil to a depth of 30 cm. These results provide insights into the contribution of forests to carbon emission reduction and enhanced conservation of biodiversity.

2.3.2. Process of Carbon Sequestration

Through photosynthesis, green plants use sunlight to sequester carbon from the atmosphere and accumulate organic carbon-based molecules in their plant tissue (leaves, flowers, stems, and roots) both in their above and below ground structures. Plants also respire; they use oxygen to break down the molecules they create through photosynthesis, and in the process, they emit CO_2

into the atmosphere (Hoover and Riddle, 2020). In this regard, forests play an important role in preserving global ecological balance. They not only maintain biodiversity, minimize soil erosion, and protect watersheds, but they also increase ecosystem services. Forests are global air cleaners that reduce greenhouse gas (GHG) emissions (Nandal *et al*., 2023). They can act as sinks through the process of tree growth and resultant biological carbon sequestration. According to Teklu Gebrestsadik (2016), deforestation contributes to atmospheric concentrations of greenhouse gases (GHGs), particularly carbon dioxide, and consequently results in environmental warming. Many researchers, non-governmental organizations, and governmental organizations have explained how appropriate forest management and conservation can minimize greenhouse gas emissions. Therefore, it is possible to view natural forests as an excellent carbon dioxide sink and thus support international efforts to slow down global warming.

2.3.3. Methods for Estimating Forest Carbon Stock

The distribution of biomass is central to understanding how trees store carbon because forest carbon stocks are generally assumed to be half of their biomass *(*Brown *et al., 2005;* Pearson *et al*., 2005; Vashum and Jayakumar, 2012). Estimating forest biomass is also critically important for both resource utilization and environmental stewardship. In terms of resource use, it provides insights into the potential for carbon emissions if the forest is cleared. Conversely, it also indicates the forest's capacity to sequester carbon from the atmosphere. In terms of environmental management, biomass estimation is crucial for determining forest productivity and long-term sustainability (Wakawa, 2016). A forest's capacity to sequester carbon is based on how much biomass it produces, and its ability to absorb CO_2 from the atmosphere and slow down global warming is indicated by its rate of biomass generation, or the amount of carbon it sequesters annually. Methods that exist for this purpose include field measurement-based, remote sensing-based, and GIS-based methods (Iqbal *et al*., 2014; Chave *et al*., 2014). Field-based biomass measurement methods are also classified as direct and indirect.

Destructive (direct) methods: The destructive method involves harvesting all the trees in the known area and measuring the weight of the different components of the harvested tree, like the tree trunk, leaves, and branches, and measuring the weight of these components after they are oven-dried (Singh *et al*., 2011). However, this method of biomass estimation is limited to a small area or small tree sample sizes. Although this method determines the biomass accurately for a particular area, it is time and resource consuming, strenuous, destructive, and expensive, and it is not feasible for a large-scale analysis (Schettini *et al*., 2022). Therefore, the destructive method does not apply to species that are threatened or endangered and large areas of forests, so a new method for determining biomass through an allometric equation is a non-destructive method (Iqbal *et al*., 2014).

Nondestructive (indirect) methods: The indirect method aims to construct a functional relationship between tree biomass and other tree dimensions, such as stem diameter, height, and wood density (López-López *et al*., 2017). Their efficiency makes them ideal for large-scale studies. However, the accuracy of the equations depends heavily on the quality and representativeness of the underlying destructive sampling data used for their development. A demerit of using allometric relationships as a tool is that they often show varying relationships for different tree species and sites. It is too laborious for researchers to weigh a number of trees to establish a series of allometric relationships for all tree species and sites (Iqbal *et al*., 2014). Thus, the need exists to identify a common allometric relationship that can be applied to various tree species within a wide geographical location of the forest.

Remote Sensing and GIS: Remote sensing and GIS techniques provide a synoptic view of the surface area of interest, thereby capturing the spatial variability in the attributes of interest. A major advantage of remote sensing technology is that it can obtain information about an area of interest that is difficult to access or inaccessible. Remote sensing has enabled us to monitor natural resources on a continental, even global, scale. It is also the only realistic and cost-effective way of acquiring data over a large area (Kuimi and Jayakumar, 2012). Remotely sensed data are useful for mapping and monitoring vegetation, land cover, and land-use change. The forest's carbon stocks can be evaluated using remote sensing technology. Several studies have been carried out in Ethiopia to estimate the forest biomass using remote sensing data collected from the field (Sisay *et al*., 2017; Amare *et al*., 2021; Moisa *et al*., 2023), and all of them found varying results. Spatial, temporal, and spectral resolutions are relevant for the selection of approaches such as radar, optical, and LiDAR for C stock assessment. The capacity of a spatial resolution is defined in terms of its ability to capture the smallest unit of a forest ecosystem (Nandal *et al*., 2023). Remote sensing has advanced the estimation of AGB and C stocks at the global level. However, Different kinds of spectral wavelengths and spatial resolutions can be used to obtain imagery of different resolutions (Masek *et al*., 2015). Numerous factors, such as the nature of the study, the availability of experts, the cost of the procedure, the urgency of the findings, and the study region, may influence the choice of a particular approach (Kuimi and Jayakumar, 2012; Chavez *et al*., 2014).

2.4. Carbon Stock Pools in the Forest Ecosystem

The forest ecosystem's carbon pools are reservoirs that can store or release carbon. The global terrestrial carbon pool exhibits marked spatial heterogeneity in its distribution across forest ecosystems. Tropical forests emerge as the primary carbon repository, holding an estimated 55% of the total carbon stock forest. Boreal forests contribute significantly as well, accounting for roughly 32%. Temperate forests, on the other hand, harbor a comparatively smaller share, estimated at 13% (Yadav *et al*., 2022; Nandal *et al*., 2023). Different authors classified them into different pools; this may be related to the type of forest and the objectives of the project. According to the IPPC (2006) and Vashum and Jayakumar (2012) reports, carbon pools in forest ecosystems comprise carbon stored in living trees aboveground and belowground (roots), in dead matter, including standing dead trees, down woody debris and litter, in non-tree understory vegetation, and in organic matter in the soil. Carbon stock assessment is one of the important steps to start with sustainable land use planning for low carbon emissions. The change in carbon stocks due to the dynamics of land use changes may result in either carbon emissions or sequestration. A global assessment of biomass and its dynamics is an essential input to climate change forecasting models and mitigation and adaptation strategies. The accumulated carbon is stored in five different pools in the forest ecosystem: aboveground biomass (leaves, trunks, and limbs), belowground biomass (roots), deadwood, litter (fallen leaves), and soils (Iqbal *et al*., 2014; Hoover and Riddle, 2020).

2.4.1. Aboveground Biomass Carbon

Aboveground biomass carbon stock is the carbon in all living biomass above the soil, including all woody stems, stumps, branches, leaves of living trees, bark, seeds, and epiphytes, as well as herbaceous undergrowth (FAO, 2010). Ravindranath and Ostwald (2008) mentioned that the aboveground biomass is the most important and visible carbon pool of the terrestrial forest ecosystem. It is primarily the largest carbon pool and is impacted directly by deterioration and deforestation.

2.4.2. Belowground Biomass Carbon

Belowground biomass carbon stock is the carbon pool in live root biomass. That comprises the entire live root system (IPCC, 2006), which plays an important role in the carbon cycle by transferring and storing carbon in the soil (Vashum and Jayakumar, 2012). Roots are important to carbon balance because they transfer large amounts of carbon into the soil. More than half of the carbon assimilated by the plant is eventually transported belowground via root growth and turnover, root exudates (of organic substances), and litter deposition. Depending on rooting depth, a considerable amount of carbon is stored below the plow layer and better protected from disturbances, which leads to longer residence times in the soil.

2.4.3. Humus and litter Carbon

The dead mass of litter and woody debris is not a major carbon pool, as they contribute merely a small fraction to the carbon stocks of forests (Ravindranath and Ostwald, 2008). The DOM litter carbon pool includes all non-living biomass with a size greater than the limit for soil organic matter (SOM), commonly 2 mm, and smaller than that of DOM wood, 10 cm in diameter. This pool comprises biomass in various states of decomposition prior to complete fragmentation and decomposition, where it is transformed into SOM. Local estimation of the DOM litter pool relies on the establishment of the wet-to-dry mass ratio. Where there are no default values available, which may vary by forest type and climate regime, the IPCC ranges from 2.1 tons of carbon per hectare in tropical forests to 39 tons of carbon per hectare in moist boreal broadleaf forests (IPCC, 2006).

2.4.4. Dead Wood Biomass Carbon (DWBC)

Whether it is in the form of a standing, lying, or soiled object, the term "deadwood" refers to surface-lying wood, dead roots, and stumps with a diameter of at least 10 cm or any other diameter recognized by the nation (Schroth, 2004). 10–20% of the carbon in the AGB pool in a mature forest may be found in this pool.

2.4.5. Forest Soil Carbon Stock

With an increasing threat of climate change to ecosystem functioning, soils are considered important to storage of carbon to mitigate the adverse impacts of climate change. Soil carbon stock refers to the amount of carbon captured from the atmosphere by plants and stored in the soil as organic matter (Lal, 2004). Forest soils contain plant roots, leaf litter, and other dissolved organic material. The amount of carbon stored in forest soils is variable, and how much carbon soil can sequester is dependent on many local factors like geology, soil type, climate, vegetation, plant-animal interaction, and environmental management (Aynekulu *et al*., 2014). In some forests, the soil holds more carbon than the trees, but in other forests, like the rainforest, the soil holds relatively little carbon, and the trees store more carbon. This is because some soil types, like clay soils, can bind up a large amount of carbon, whereas sandy soils are not able to bind much carbon. Soils with more organic material (bits of wood, decaying leaves, or dead creatures) can store more carbon because organic material easily binds loose carbon molecules, and the organic material itself is stored as carbon (Norman and Kreye, 2020), which indicates that the carbon sequestration capacity of forest ecosystems exhibits significant variation across different forest types.

Table 2: Global carbon stocks (Gt) in vegetation and soil carbon pools down to a depth of 1 m

Biome	Area (10^9 ha)	Vegetation (Gt)	Soil (Gt)	Total (Gt)
Tropical forests	1.76	212	216	428
Temperate forests	1.04	59	100	159
Boreal forests	1.37	88	471	559
Tropical savannas	2.25	66	264	330
Temperate grasslands	1.25	9	295	304
Deserts and semi deserts	4.55	8	191	199
Tundra	0.95	6	121	127
Wetlands	0.35	15	225	240
Croplands	1.60	3	128	131

Source: IPCC (2007).

2.5. Role of Forests for Climate Change Mitigation

According to the IPCC, climate change mitigation refers to the interventions conducted by human beings to minimize the adverse impact of climate change on the environment and the economy. Activities such as reducing the number of particulates in the atmosphere and addressing other sources of pollutants are crucial to mitigating the impact of climate change. These activities play a vital role in reducing or maintaining greenhouse gas concentrations in the environment (Cherinet and Lemi, 2023). Therefore, forest ecosystems are important elements in mitigating climate change globally. The significance of forests in mitigating greenhouse gas emissions was recognized by the Kyoto Protocol. It is known that 45% of the earth's terrestrial carbon is stored in forests. In 2005, forests covered 4 billion ha of the earth's surface (30%). Of this, African forests covered 635 million and accounted for around 16% of the world's forests (Pearson *et al*., 2005).

Similarly, Dibaba *et al*. (2019) assert that forests and soils are potential sinks for elevated CO_2 emissions and are being considered in the list of acceptable offsets. One of the key supporting services provided by forests is carbon removal from the atmosphere (carbon sequestration) and the long-term storage of this carbon in biomass, dead organic matter, and soil carbon pools (Sintayehu, 2018). Trees and soil have the capacity to store substantial amounts of carbon for extended periods, making forests a significant source of carbon sinks. This carbon sequestration function of forests aids in mitigating greenhouse gas emissions. Furthermore, forests also play a crucial role in helping communities adapt to the impacts of climate change by providing shade, reducing heat island effects in urban areas, and serving as windbreaks that protect against extreme weather events (Cherinet and Lemi, 2023). Nevertheless, choosing which trees to take down is only one aspect of carbon management; another is determining the best locations for planting and harvesting on the terrain. Young and established forests should be prioritized since they store and capture the most carbon, although it is beneficial to have a variety of tree ages and forest types (Norman and Kreye, 2020).

In addition to enhancing livelihoods and controlling environmental shocks, forests are extremely important for a country's overall development. Above all, wood is a useful resource and a smart way to manage environmental risks caused by humans and nature. Ethiopian culture is aware of this; since the 1400s, rulers have issued decrees encouraging the planting, conservation, and preservation of trees. But it's important to note that the nation's initiatives for forest growth have not advanced sustainable conservation, management, and utilization; rather, they have stayed centered on planting trees (Mahoo *et al*., 2013). Because they offer a variety of ecological services, protected areas have a significant impact on lowering susceptibility to climate change and unpredictability. In addition to providing additional food production (fruits, grains, and wild games), their multiple services also include forest products (timber and fuel), water for irrigation and drinking, improved groundwater recharge/discharge and storage, mitigation of erosion and climate risks, aesthetic and cultural heritage values for recreational and ecotourism activities, and ecosystem-level nutrient cycling (Ola, 2025).

However, this multi-functionality is unlikely to be sustained because the forests are under heavy human pressure from settlement, encroachment of small and large-scale farming and grazing, and excessive wood extraction (Mahoo *et al*., 2013). The IPCC report estimated that the global forestry sector represents over 50% of global greenhouse gas emissions. Therefore, forestry has become the focus of global climate change policy and is given a key position in international climate treaties. While sustainable management, planting, and rehabilitation of forests can conserve or increase forest carbon stocks, deforestation, degradation, and poor forest management can conversely reduce them (Dibaba *et al*., 2019). The recent report of the IPCC (2023) also recognizes the significant role that forest-based adaptation (FBA) strategies can play in mitigating the impacts of climate change. The report outlines a multifaceted framework encompassing several key practices: sustainable forest management (SFM), forest conservation and restoration, and reforestation and afforestation initiatives. This comprehensive approach, as highlighted by the IPCC, emphasizes the importance of conserving, protecting, and restoring a wide range of ecosystems, including terrestrial, freshwater, coastal, and even oceanic environments. It also underscores that these efforts, when coupled with targeted management practices, can significantly enhance the resilience of biodiversity and the ecosystem services it provides. By promoting adaptation to the unavoidable consequences of climate change, FBA safeguards the integrity and functionality of these crucial ecological systems.

In essence, FBA acknowledges the vulnerability of biodiversity and ecosystem services but emphasizes that proactive management and restoration can empower them to adapt more effectively to a changing environment. Therefore, the report serves as a powerful call to action for forest resource conservation. Regular assessments of species diversity and forest carbon stock potential are fundamental components of effective FBA strategies. By monitoring these vital indicators, forest managers can gain a deeper understanding of the health and resilience of their forests. This knowledge empowers them to implement targeted SFM practices, prioritize conservation and restoration efforts, and strategically plan reforestation and afforestation initiatives. Ultimately, a data-driven approach to forest resource conservation, as advocated by the IPCC, is vital for maximizing the role of forests in mitigating climate change and ensuring the continued provision of the ecological services upon which all life depends.

The woody plants of the Gantamie Natural Forest (table 3) accumulated the highest carbon stock, followed by the Wujig Mahgo Waren Forest. Conversely, the Hunase forest exhibited the lowest carbon stock per hectare. The discrepancy may be due to the different methods and tools applied, regional variability in soil, topography, and forest type, and the uncertainties associated with the methods used. Thus, management intervention is crucial to enhancing the carbon sequestration potential of forests.

Table 3: Carbon stock potential in tons/ha of different forest areas in Ethiopia

Study sites	Carbon stock C/ha	Source
Gantamie Natural Forest	320.34 ± 39.1	Getasew *et al*. (2025)
Wujig Mahgo Waren Forest	181.78 ± 27.06	Solomon *et al.* (2018)
Alemsaga Forest (South Gondar)	91.85 ± 70.51	Enyew *et al*. (2019)
Furi Forest (Central Highlands)	58.74 (mid-alt), 49.76 (upper alt)	Guluma (2020)
Entoto Mountain Forest (Addis Ababa)	≈ 53.73	Lemlem *et a*l. (2024)
Hunase forest	2.32 (AGC)	Tamirat (2019)

2.6. Correlation between Climate Change and Woody Species Diversity

Woody species diversity offers a valuable buffer against climate change. Forests with a wider range of tree and shrub species are considered more resilient to environmental disturbances like droughts and heat waves, which are becoming more frequent due to climate change (Anderegg *et al.*, 2015). This diversity also enhances a forest's ability to store carbon, a key strategy for mitigating climate change, as diverse forests tend to sequester more carbon than those with lower diversity (Malek *et al.*, 2012). Additionally, a wider variety of wood species provides a broader range of ecosystem services, such as improved water filtration and habitat provision, which can contribute to overall ecosystem health and adaptation to changing environmental conditions (Girma *et al*., 2021). It's important to acknowledge that different species will have varying responses to climate change, and maintaining diversity requires careful management practices. However, the potential benefits of woody species diversity for mitigating and adapting to climate change are undeniable. The relationship between woody species and climate change is complex. While some studies suggest potential benefits for certain woody species due to increased CO_2 concentrations and warmer temperatures promoting growth (Wu *et al*., 2019; Zhang *et al*., 2021), others highlight potential threats. Rising temperatures and changes in precipitation patterns can disrupt existing ecosystems, impacting seed dispersal, germination success, and competition with other plant life (Root *et al*., 2003). Additionally, woody species with slower migration rates may struggle to adapt to rapidly changing climates (Tian *et al*., 2023). Understanding these complex correlations is crucial for predicting future impacts on forests and developing effective conservation strategies.

2.7. Factors Influencing Forest Carbon Stock and Species Diversity

The forest's ability to store carbon, known as forest carbon stock, is a complex interplay of biological, physical, and climatic factors that is affected by different natural and anthropogenic factors (Dibaba *et al*., 2019). The carbon sequestration potential of woody tree species varies depending on soil conditions, water availability, altitude, and slope gradients. Altitude has a significant effect on temperature and precipitation. This strongly affects species composition, diversity, and the turnover ecosystem. Species diversity and tree size influence the amount of carbon captured through photosynthesis and stored in biomass (Dibaba *et al*., 2019). As forests mature, carbon storage increases until reaching a peak, which may decline with tree death and decomposition (Pascal *et al*., 2018). Researchers across the globe have investigated the pattern of species diversity and carbon storage in forest ecosystems at different elevations (Dar and Sundarapandian, 2015; Ensslin *et al*., 2015; Do *et al*., 2017). However, these studies have not reached a consensus. Some report a rise in carbon stock with increasing altitude, while others observe a decrease. Similarly, numerous investigations carried out in various locations in Ethiopia and other tropical areas have noted a decline in the biomass carbon stock as elevation increases (Simegn *et al*. 2014; Tesfaye and Negash 2018).

Wodajo *et al*. (2020) estimated that the aboveground biomass (AGB) carbon stock density of the Gara-Muktar Forest, West Hararghe zone of Eastern Ethiopia, ranged from 102.13 ± 31.16 to 214.73 ± 54.73 t C ha^{-1} in the higher and lower altitudinal gradients, respectively. Similarly, Abrha *et al*. (2024) indicate the Hugumbrda Grat-kahsu forest carbon stock was found to be 21.02 tons per hectare, whereas the carbon stocks in the highland and midland were found to be 15.6 and 22.92 tons per hectare, respectively. This discrepancy shows a significant influence of altitude on carbon stock, with the highland forest having a lower carbon stock than the midland. On the other hand, Zelalem *et al*. (2018) and Lemmi (2020) estimated that the mean carbons above and below ground increase with altitude; this might be attributed to anthropogenic disturbances and microclimate. In terms of species diversity, forests at lower elevations are characterized by greater diversity and a richer variety of plant species compared to higher-altitude forests (Abrha *et al.*, 2024). This indicates that a forest's botanical characteristics are influenced by several climatic conditions, including temperature, incoming solar radiation, humidity, and the frequency and presence of clouds and fog. These factors can alter the way carbon is stored along aspect gradients as well.

Environmental variability influenced the variation in tree diameter at breast height, height classes of trees and shrubs, and density of trees (Cherinet and Lemi, 2023). Soil also plays a critical role, with nutrient availability impacting plant growth and organic matter content influencing carbon storage and release. Additionally, factors like slope and disturbance regimes all influence carbon dynamics, but environmental elements, primarily altitudinal gradients, have a great impact on carbon sequestration in forest ecosystems (Hamere *et al.*, 2015). Natural disturbances like fires and insect outbreaks can cause carbon loss, while human activities like logging and land use change can have significant negative impacts. Climate, particularly temperature and precipitation, affects plant growth rates, decomposition processes, and nutrient cycling, all of which influence the long-term carbon storage potential of a forest. Therefore, understanding these interconnected factors is crucial for managing natural forests to maximize their role in mitigating and adapting to climate change. Adaptation is an adjustment in ecological, social, or economic systems in response to actual or expected climatic change and its negative impacts (Swamy and Tewari, 2017).

3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1. Location

The study was conducted in Kulkal Ber natural forest, which is found in Maksegent district, Central Gondar administrative zone of Amhara National Regional State (ANRS). Maksegnet district is located at 640 km to the northwest of Addis Ababa and geographically lies between 12º 7′ 23′′ to 12^0 39′ 35′′ North and 37^0 24′ 24′′ to 37^0 45′ 43′′ East (Ethiopian Mapping Agency, 2016). The district borders Wegera and west Belesa districts in the north, Lay Armachiho in the west, Dembia district and Lake Tana in the south, and Libo Kemikem district in the east. Maksegnet town is the seat of the district. The district is divided into 35 rural kebeles (the lowest administrative unit in Ethiopia) and 3 urban kebeles. It lies between 1800 and 2700 meters above sea level (m.a.s.l.) (GZDARDO, 2016). Kulkal Ber natural forest is approximately 50 km from Gondar and 10 km from Maksegnet town. Nearby is the main road from Bahrdar to Gondar. It has altitudinal range of 2000 to 2336 m.a.s.l. Kulkal Ber natural Forest is one of the state-protected natural forests of the region and covers a total area of 1350 ha (Simegn, 2022).

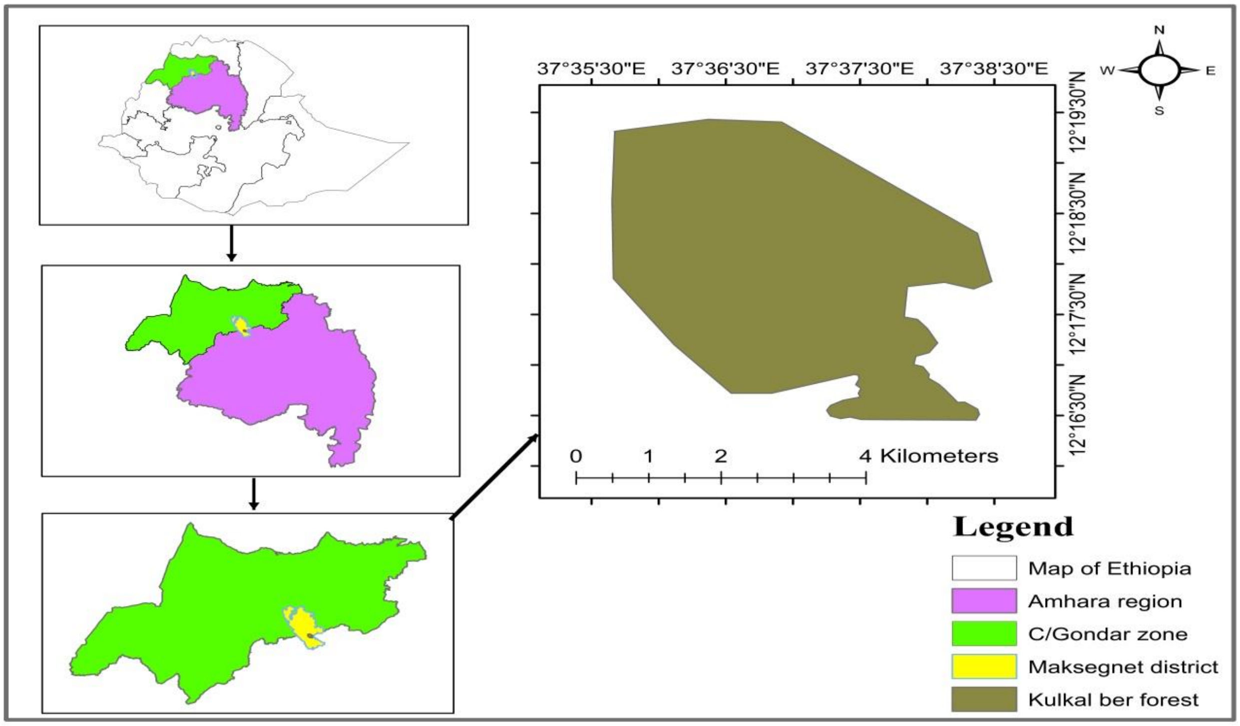

Figure 1: A locational map of the study area within the district

3.1.2. Climate

Rainfall and temperature are the major environmental factors that play a significant role in the growth and distribution of plants. Based on the traditional agro-ecological classification, the district consists of two agro-ecological zones, woina-dega (1500 – 2300) and dega (2300 – 3200) (GZDARDO, 2016). The temperature ranges between 14.1 – 29°C with a mean annual temperature of 20.9°C. Rainfall ranges between 1297 – 1721 mm, with a mean annual rainfall of 1457 mm (GARC, 2025). The district is also characterized by two main rainy seasons: the June-August major rainfall season and the March-May minor rainy season (Wossen *et al*., 2021).

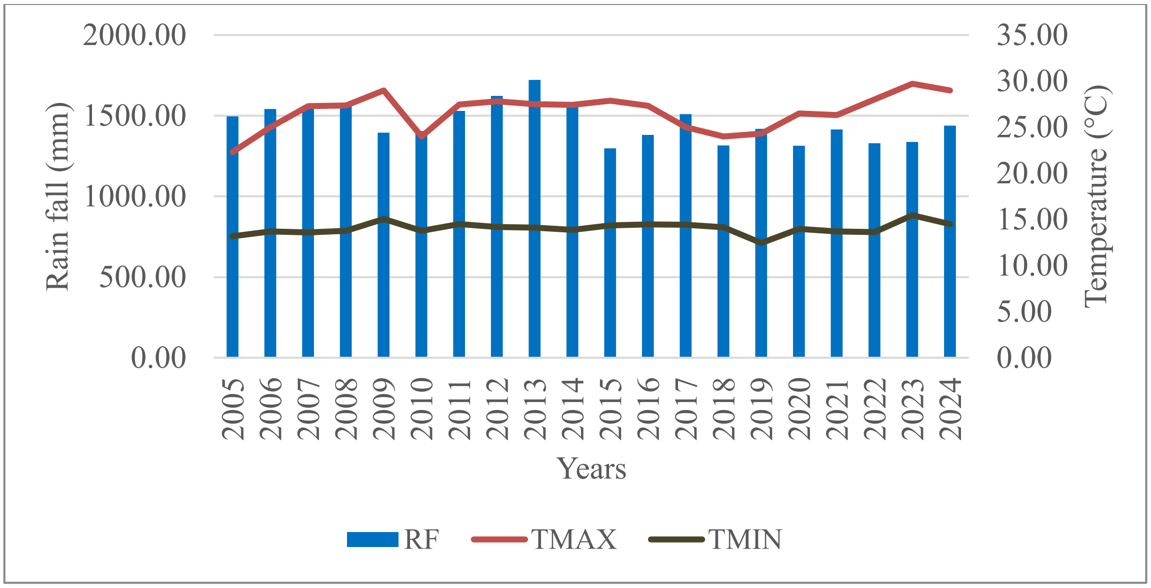

Figure 2: Climate condition of the study area from 2005 - 2024. Source: Gondar Agricultural Research Center (GARC) (2025).

3.1.3. Topography and soil type

The topography of the district's area is 65% flat land, 25% hilly, and 10% valley type (GZDARDO, 2016). The types of soil are red soil (nitosol) and black soil (vertisol) with clay loam to sandy clay loam textures (Worku, 2017).

3.1.4. Farming and Vegetation

Maize *(Zea mays* L.*),* sorghum (*Sorghum bicolor* (L.) Moench), *teff* (*Eragrostis teff* (Zucc.) Trotter), and other cereals, pulses, and oil crops are produced in the district (Wossen *et al*., 2021). The vegetation strata of the Kulkal Ber forest are disturbed and consist of mainly shrubs and bushes, with some tree species. The common tree species found in Kulkal Ber natural forest include *Combretum molle, Olea europaea, Olea welwitchii, Dodonaea angustifolia, Carisa edulis, Rhus vulgaris, Croton macrostachyus, Allophylus abyssinicus, Cordia africana, Ficus vasta, and Gardenia lutea,* which are dominant throughout the forest (Billa and Teshom, 2003). The forest is the habitat of numerous wild animals, including hyenas and Baboons. In addition to the wild animals, numerous bird species live within the forest.

3.1.5. Land use and Population

The major land use types in the district include cropland (722,050 ha), forest and shrubs (11,073 ha), settlements and buildings (8,643 ha), rivers, streams, and valleys (3,005 ha), and other land use types (2,065 ha) (GZDARDO, 2016)**.** Forest cover accounts for approximately 9.6% of the district. The total population of the district was 230,033 (51.3% males and 48.7% females) in 2017. Out of this, 87.8% live in rural settings, while the remainder reside within urban areas (CSA, 2017).

3.2. Sampling and Data Collection Methods

3.2.1. Reconnaissance survey

A discussion was held with Maksegnet district agriculture office experts and officials in the first week of January 2025 to create awareness and issuance of appropriate authorizations. Subsequently, an initial reconnaissance survey within the entire natural forest was conducted to gather general information about the study area and to select sampling sites. A preliminary site visit that was undertaken in the study area gave initial ecological context.

Before the actual field data collection, a second (pre-field) survey was conducted. The purpose of this survey was to refine the preliminary information obtained during the reconnaissance survey and to prepare the study area for sampling. During this second survey, the study area was carefully assessed to confirm accessibility, delineate altitudinal ranges, and identify major vegetation patterns. Based on this assessment, the area was stratified into distinct altitudinal strata which informed the subsequent sampling strategy design, optimizing the number and location of plots within the forest.

3.2.2. Data Sources

The data were collected from both primary and secondary data sources, which are relevant to the study objectives. Primary data, including field measurements, was conducted at the plot level to record data on woody species (trees and shrubs), and soil and GHL samples were collected for laboratory analysis. Secondary data like wood density data was taken from indigenous and exotic tree species in Ethiopia and other studies and databases.

3.2.3. Sampling Design

The study used a stratified systematic sampling method with a nested plot approach where the stratification was done based on the altitude gradient following Fekadu *et al*. (2018) since the area under study has an altitudinal variation ranging from 2000 to 2336 m.a.s.l. A stratified systematic sampling design across altitudinal gradients was used to investigate how altitude influences forest characteristics like carbon stock potential and woody species diversity, and to obtain homogenous units, and to increase the precision of measuring and estimating woody species diversity and carbon stock.

This approach divided the forest area into distinct altitudinal zones (strata). As a result, altitudinal variations were used as a predictive factor to analyze their relationship with both forest carbon storage and the diversity of woody plant species throughout the entire study area. Accordingly, the study site was classified into two altitudinal gradients: lower altitude (2000-2200 m.a.s.l.) and higher altitude (2201-2336 m.a.s.l.). The cutting point to determine the two strata was the altitude and topographical and plant distribution of the site, following (Negasi *et al*., 2024). Sampling sites from the forest were arranged by laying transect lines**.** The distance between transects, plots, and the number of sampling plots were determined based on vegetation density, spatial heterogeneity of vegetation, and the size of the forest (Tefera *et al*., 2005). To reduce edge effects, transect lines were laid 50 meters inside from the forest edges.

Plots were established along transect lines, with 200 m between adjacent plots, and transect lines spaced at 500 m intervals along the altitudinal gradient, following Hassan *et al*. (2013) and Muluken *et al*. (2015). For sampling trees and deadwood, 20 m × 20 m (400 m^2) main plots were established systematically. Within each main plot, four subplots measuring 5 m × 5 m were established in the four corners of the main plot and one 5 m × 5 m at the center and these were used for sampling shrubs. Diameter at breast height (DBH) was measured for trees and diameter at stump height (DSH) for shrubs. Additionally, within each 5 m × 5 m subplot, a single 1 m × 1 m nested subplot was established at the center for sampling grasses, herbs, litter, and soils (Muluken *et al*., 2015). Hence, a square-nested plot design makes sense and conveniently accommodates the different sizes of trees (Brown, 1997). In total, six transect lines and 60 main plots (30 per altitudinal gradient) were established. GPS coordinates were recorded to indicate the location and altitude of each sample plot. In this study, a total of 60 sub-plots were used for collecting ground herbaceous layer (GHL) samples. Similarly, 60 subplots were used for soil carbon sampling, and an additional 60 sub-plots were used for bulk density determination. For each parameter, samples from the respective subplots were composited to obtain representative values for analysis.

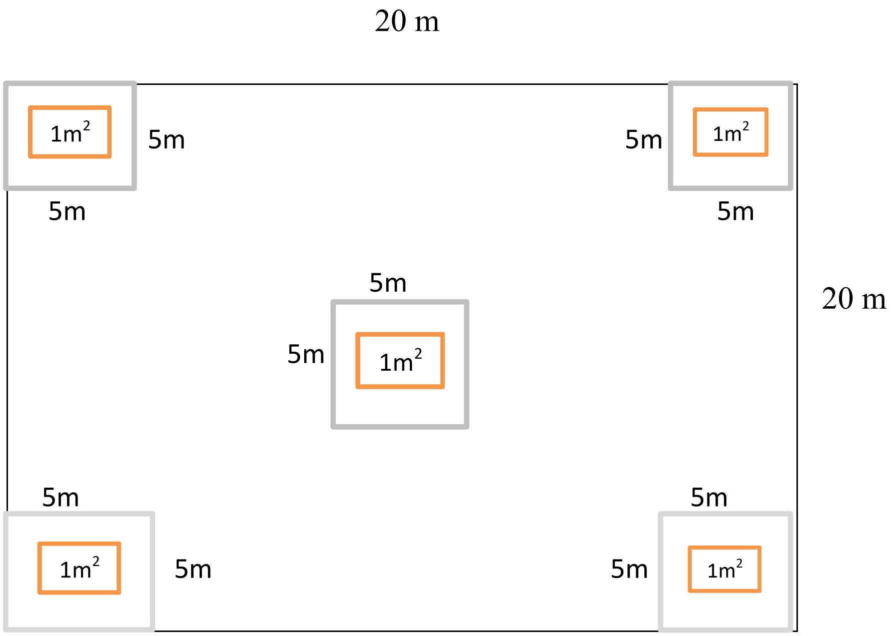

Figure 3: The 20 × 20 m (400 m²) main plot and subplots sampling design for data collection

3.2.4. Vegetation Data Collection

Vegetation data were recorded in each plot. Individuals of woody species were counted, and their diameter at breast height (DBH at 1.3 m) for trees, diameter at stamp height (DSH at 30 cm) for shrubs, and height from the ground were measured. Within the sample plot, all individuals of woody species with a DBH ≥ 5 cm and matured individuals for shrubs were measured and recorded. In case of trees with multiple stems below 1.3 m each stem was treated as different individuals, and the diameter was measured separately for each stem. Buttressed trees DBH measurements were undertaken from the point just above the buttresses. Trees with multiple stems above 1.3 m in height were also treated as one individual and DBH was measured through following Kent and Coker (1992).

Plant species were initially identified using local (vernacular) names with the assistance of experienced key informants (using the knowledge of local people) and specimens were collected for verification at the Haramaya University herbarium. Identification was further confirmed through relevant reference materials, including the Flora of Ethiopia and Eritrea (Hedberg *et al*., 1995; Edwards *et al*., 1997; Azene *et al*., 1993; Friis, 1992; Kelbessa and Demissew, 2014). A diameter tape was used to measure the diameter at breast height and woody species heights were measured by measuring sticks (for small individuals), and hypsometer for taller individuals.

3.2.4.1. Grass herbs and litter sampling

Grass, herbs, and litter samples were collected diagonally across a single 1 m nested subplot within 5 m × 5 m subplot. These subsamples were thoroughly mixed to create a homogenous sample. The mixed samples were then transported to a laboratory (for laboratory analysis).

3.2.4.2. Soil sampling

The concentration of soil carbon is expected to be highest at the top of the 30 cm layer of soil profiles, and for convenience and cost efficiency, it is advised to sample to a constant depth, maintaining a constant sample volume rather than mass. As suggested by Pearson *et al*., 2005 and IPCC, 2006, a 30 cm probe is an effective measurement tool, as observed in previous studies. Therefore, soil organic carbon pool samples were collected up to a depth of 30 cm for this study. Following the principles outlined by Pearson *et al*. (2005), soil samples for soil carbon determination were collected within a 1 square meter area (m^2) nested subplots established within 5 m × 5 m subplot. An auger was used to collect soil samples from the four corners and center of each subplot, reaching a depth of up to 30 cm. Additionally, a core sampler was used to collect undisturbed soil samples for bulk density (BD) determination from the center of the plot. To ensure homogeneity, the samples from each subplot were mixed thoroughly, taking an equal amount of soil from each location to create a composite sample and properly packed in a plastic bag, and labeled for soil laboratory analysis.

3.3. Data Analysis

3.3.1. Woody Species Diversity Analysis

The Shannon-Wiener diversity index was used to evaluate species diversity of the study area. Those diversity indexes are popular measures of species diversity and evenness that are not affected by sample size and can provide relevant information for the evaluation and quantification of woody species diversity (Michael *et al.*, 2019). Accordingly, the following equation was used:

$$H' = -\sum_{i=1}^{s} P_i \ln P\,i \tag{1}$$

where H′ is the Shannon-Wiener diversity index, S is the number of species,

Pi is the proportion of individual woody plant species, and ln: natural logarithm.

The equitability, or evenness, of the species in each plot was computed using the following formula:

$$\text{Evenness index (Equitability)} = J = \frac{H'}{H_{Max'}} = \frac{H'}{\ln S} \tag{2}$$

where J: Evenness, H′: Shannon-Wiener diversity index, and $H'max^{'}$ = ln S; S: the number of species. Evenness value is represented by the value of J, which ranges from 0 to 1 (Konopinski, 2020). There would be a high J value if the species were dispersed equally. In light of this, the J value enables us to determine how evenly a species' abundance is dispersed throughout the community (Mohammed, 2017).

3.3.2. Woody Species Structural and Community Type Analysis

All woody species recorded from the study forest were used in the structural analysis, including basal area, relative dominance, frequency, relative frequency, density, relative density, and importance value index (IVI). A recent study by Amanuel and Gemedo (2018) reported that IVI reflects a species' structural importance within a forest stand, so it was calculated for all woody species encountered during the surveys. Therefore, the vegetation structure was described. Diameter data was arranged in classes of ≤ 10cm, 10.1-20cm, 20.1-30cm, 30.1- 40cm, and >40.1cm and height classes of ≤ 5m, 5.1-10m, 10.1-15m, 15.1-20m >20.1m to determine the dominant diameter and height class of the woody species and the status of the forest. The following formulas were used to examine the structural parameters:

Density is defined as the number of individuals of a species in the plots, or it is the number of stems counts in the study area. It is also closely related to abundance but more useful in estimating the importance of a species. It was calculated by summing up all stems across all areas per hectare.

$$\text{Density} = \frac{\text{Total number of stem of a given species}}{\text{Sample size in ha}} \qquad (3)$$

Relative Density (RD)

Relative density is the density of a species as a percentage of total plant density. It was calculated as follows:

$$\text{Relative density} = \frac{\text{Density of species A}}{\text{Total density of all species}} \text{ X } 100 \qquad (4)$$

Basal Area: It is the cross-sectional area of all stems in a stand at breast height. The basal area of all woody species with DBH ≥5 cm was calculated using the following formula.

$$\text{Basal Area (m}^2\text{)} = \frac{\pi \text{DB}H^2}{4} \qquad (5)$$

Relative Dominance (RDM)

Relative dominance was measured using the following formula.

$$\text{Relative dominace } = \frac{\text{Basal area of species A}}{\text{Basal area of all species}} \text{ X } 100 \qquad (6)$$

Frequency: It is the number of times a plant species occurs in each study area. The more frequent the species, the wider their distribution in the study area.

$$\text{Frequency } = \frac{\text{Number of sample plots in which species recoreded}}{\text{Total number of sample plots}} \text{ X } 100 \qquad (7)$$

Relative Frequency (RF)

It refers to the percentage or proportion of times that species occur within a set of total numbers of species in the study area.

$$\text{Relative frequency } = \frac{\text{Frequency of species A}}{\text{Frequency of all species}} \text{ X } 100 \qquad (8)$$

where, A is type of species recorded in the plot and π is pi symbol

Importance Value Index (IVI)

It is a combination of relative frequency (RF), relative density (RD), and relative dominance (RDO) (Kent and Coker, 1992). If a species has the highest IVI value, it is relatively dominant in that ecosystem and ecologically more important. IVI was calculated as follows:

$$\text{Important Value Index (IVI)} = \text{Rel.F.} + \text{Rel.Den.} + \text{Rel.Dom.} \tag{9}$$

where, Rel. F is Relative frequency, Rel. Den is Relative density and Rel. Dom is the Relative dominance

Woody Plant Community Type Analysis

This study utilized a field-based methodology that focuses on dominant species and their frequency to identify and categorize the woody plant communities within the study area. Additionally, a hierarchical cluster analysis classification system was used to evaluate the frequency of occurrence for each species of woody plant encountered across all plots. Ward's method was used as a distance measure and group average as a group linkage method. The most prevalent and often observed tree species, which indicate the dominant species in each community, were discovered through the analysis of this data.

3.3.3. Estimation of Carbon in Above Ground Biomass

To estimate above- and below-ground biomass and carbon, a nondestructive approach using allometric equation was applied. Diameter at breast height (DBH at 1.3 m) and diameter at stump height (DSH at 30 cm) for trees and shrubs respectively were measured using diameter tape, while tree height was measured with a measuring stick for small trees and hypsometer for taller individuals. Wood densities of species were obtained from basic wood density of indigenous and exotic tree species in Ethiopia and other studies and databases (EFRL, 2016). However, for any species lacking a recorded wood density value, a default value of 0.6 g/cm^3 was used. This value reflects the average wood density reported for trees in tropical African ranges (Henry *et al*., 2010). To estimate carbon stock and generate a more accurate assessment of aboveground biomass (AGB) across the forest, most researchers prioritize the use of species-specific allometric equations if available. Due to the absence of a specific equation for the study site's forest type, a generic allometric equation was employed.

The allometric equations developed by Chave *et al*. (2014) was used, given their widespread adoption and success in tropical African carbon stock assessments. The model developed by Chave *et al*. (2014) was the primary choice. This equation was chosen because it was developed for calculating woody species biomass in tropical natural forests. Furthermore, the most critical biomass predictor factors, DBH, tree height, and wood density, are incorporated into this equation (Betemariyam *et al*., 2023). Equations that incorporate more than one tree parameter improve the reliability of forest biomass estimation (Henry *et al*., 2010). This equation's strength lies in its ability to incorporate three trees' parameters, which enhances the precision of the carbon stock estimates. The selection of the specific equation is ultimately considered based on factors such as tree species, geographic location, forest stand type, and climate, as well as whether it fits the biophysical condition of the study area (Vorster *et al*., 2020). The aboveground biomass was calculated using allometric equations.

$$AGBT = 0.0673 * (\rho DBH^2H)^{0.976} \quad (10)$$

$$AGBS = (1.4277 \text{ x } DSH + 0.0088 \text{ x } (DSH \exp 3.0)) \quad (11)$$

Where, AGBT is aboveground biomass of trees (kg),

AGBS is aboveground biomass of shrubs (kg), H is Height of tree or shrub (m),

DBH is diameter (cm) at breast height (1.3m), for trees

DSH is diameter (cm) at stump height (30cm) for shrubs

ρ is wood density (g/m^3), the African trees average wood density values (0.6 ton/m3) (Brown *et al*., 1997; Henry *et al*., 2010).

The tree/shrub biomass were converted into C by multiplying the above ground tree/shrub biomass by 0.47 (IPCC, 2006; Walker *et al*., 2016).

AGC = AGB X 0.47 where AGC is aboveground carbon. (12)

3.3.4. Estimation of Carbon in Below Ground Biomass

Below-ground biomass estimation presents a significantly greater challenge and requires more time than above-ground biomass estimation (Geider *et al*., 2001). This difficulty arises from the complexities of directly measuring root systems in the soil. Destructive methods, such as uprooting plants, that disrupt the soil structure are impractical for large-scale studies (Tadesse, 2015). Ultimately, scientists often rely on estimating belowground biomass using allometric equations that relate it to a proportion of aboveground biomass measurements. Root biomass is always estimated from root-shoot ratios (R/S) by taking aboveground biomass. Based on this, the BGB was calculated by considering 27% of the AGB (Chave *et al*., 2014).

$$BGB = AGB * 0.27 \tag{13}$$

$$BGC = AGC * 0.27 \tag{14}$$

Where BGB = belowground biomass and AGC = aboveground carbon content

3.3.5. Estimation of Carbon Stocks in Grass, Herb and Litter

The grass, herbs, and litter (GHL) sample was taken to the laboratory for oven drying at 105 °C for 48 hours and weighed for analysis of total carbon concentrations. The carbon content in GHLs biomass was calculated from the amount of biomass of GHLs by multiplying with 0.37 following Pearson *et al*. (2005) and IPCC (2006).

According to Pearson *et al*. (2005), the estimation of the amount of biomass in grass, herbs, and litter was calculated by:

$$\mathrm{GHLs} = \frac{\mathrm{Wfield}}{\mathrm{A}} * \frac{\mathrm{Wsub\_sumple(dry)}}{\mathrm{Wsub\_sumple(fresh)}} * \frac{1}{10{,}000} \tag{15}$$

Where: GHL = Biomass of grass, herb, and litter (ha^{-1})

W_{field} = weight of wet field sample of GHLs sampled within an area of size 1 m^2 (g);

A = size of the area in which GHLs will be collected (ha);

W sub-sample (dry) = weight of the oven-dry sub-sample of GHLs taken to the laboratory to determine moisture content (g), and

W sub-sample (fresh) = weight of the fresh sub-sample of GHLs taken to the laboratory to determine moisture content (g).

3.3.6. Estimation of Dead Wood Carbon Stock

For standing dead wood, which had branches, biomass was estimated using the allometric equation of aboveground biomass of deadwood. As the standing deadwood did not have leaves, 5% was subtracted (Pearson *et al.*, 2005).

$$DWB = 0.0673 * (\rho DBH^2H)^{0.976} \qquad (16)$$

Where DWB = Deadwood biomass D = Diameter at breast height

H = Height, ρ =Wood density.

The carbon content in the deadwood was calculated by multiplying the total biomass of deadwood with the default carbon fraction of 0.47 (IPCC, 2006).

3.3.7. Estimation of Soil Organic Carbon (SOC)

Soil samples were air-dried and passed through a 2 mm sieve to obtain the fine fraction for analysis. The coarse fragments (>2 mm) were then removed from the sample, and their percentage of stoniness and rockiness was calculated by comparing their mass with the total weight of the soil samples.

$$CFW = \text{Weight of coarse fraction/Weight of total soil} * 100 \qquad (17)$$

Where CFW is the percentage of coarse fragments by weight

Soil organic carbon stock was calculated using the equation of (Pearson *et al.*, 2005).

$$SOCS = [(BD\ (gcm^{-3}) * d\ (cm) * \%C) * (1\text{-}CFW)]\ 100 \qquad (18)$$

For %C determination, the loss on ignition method was used

$$\%C = (100 - Ash\ \%) * 0.58 \qquad (19)$$

where SOCS is soil organic carbon stock (ton ha-^{1}), BD = bulk density (g cm-^{3}),

d = Depth of the soil sample (cm), and %C = Carbon concentration in percent.

Bulk density (g cm^{-3}) = Mass of oven-dried weight of soil (gram) / Volume of core (cm^{-3}).

$V = h*\pi r^2$ where r is the internal radius of the cores (cm), and h is the height of the core. π is a constant that is equal to 22/7.

3.3.8. Total Carbon Stock Estimation

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

$$\text{Cdensity} = \text{CAGTSB} + \text{CBGB} + \text{CGHL} + \text{DWC} + \text{SOCS} \tag{20}$$

Where Cdensity = Carbon stock density for all pools (t C ha^{-1});

CAGTSB = Carbon in aboveground tree and shrub biomass (t C ha^{-1});

CBGB = Carbon in belowground biomass (t C ha^{-1});

CGHL= Carbon in grass, herbs, and litter biomass (t C ha^{-1});

DWC = Dead wood carbon (t C ha^{-1}) and SOCS = Soil organic carbon stock (t C ha^{-1})

Then, to estimate the amount of CO_2 sequestered in different carbon pools of the forest, the total carbon was multiplied by 3.67, where 3.67 means the ratio of the molecular weight of carbon dioxide to carbon. One ton of carbon stored in a tree represents the removal of 3.67 tons of CO_2 from the atmosphere and the release of 2.67 tons of oxygen back into the atmosphere (IPCC, 2006).

3.4. Statistical Analysis

The data collected from sample plots in two altitudinal gradients (strata) within the forest were meticulously organized using Microsoft Excel spreadsheets. This facilitated the application of appropriate biomass estimation equations and structural and biodiversity indices analysis. Woody species community types were analyzed using hierarchical cluster analysis in SPSS. Elevation ranges (strata) served as independent variables, while species richness, diversity, density, basal area, DBH, height, biomass carbon stock, soil organic carbon, and forest ecosystem carbon stock were treated as dependent variables. Data were tested for normality and homogeneity using the Shapiro-Wilk and Levene tests, respectively. To analyze the equality of means for species diversity and carbon stock in aboveground, belowground, grass, herbs, and litter (GHL), deadwood carbon (DWC), and soil organic carbon across the strata and also to determine the statistical significance of woody species diversity and carbon stock differences along the altitudinal gradient of the study area a one-way ANOVA was used. The significance level was set at $\alpha = 0.05$. Finally, all results were presented in clear graphs and tables for effective communication.

4. RESULTS AND DISCUSSION

4.1. Woody Species Composition

A total of 36 woody species belonging to 26 families and 31 genera were recorded across 60 plots within the study area. Among the recorded species, trees accounted for 60%, shrubs for 27.5%, and trees/shrubs for 12.5%, averaging the values across lower and higher altitudes (Figure 4). Among these, 33 woody plant species belonging to 24 families and 29 genera were identified at lower altitude (LA) and 29 woody plant species belonging to 22 families and 26 genera were identified at higher altitude (HA).

Sapindaceae and Moraceae were the most dominant families, each represented by three species (8.33%). Fabaceae, Euphorbiaceae, Malvaceae, Myrsinaceae, Oleaceae, and Anacardiaceae each had 2 species (5.56%) each, while the remaining families were represented by a single species (2.78%) (table 4).

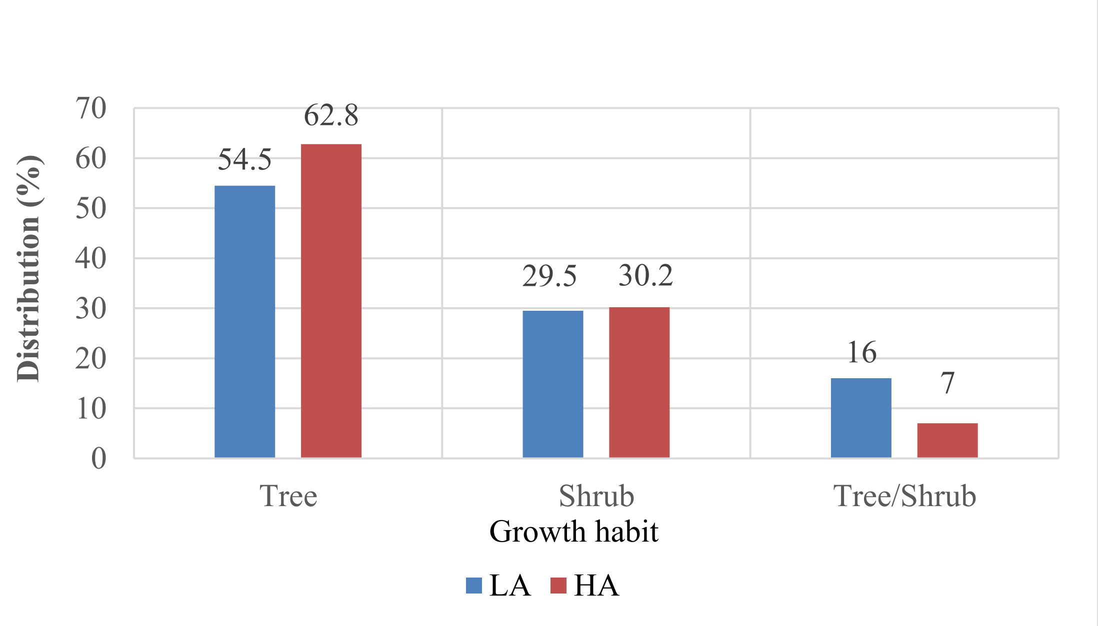

Figure 4: Distribution of woody species by their habits in Kulkal Ber forest (LA: Lower Altitude and HA: Higher Altitude).

Table 4: Dominated plant families recorded in the study area

Family	No of Genera	No of plant Species per family
Sapindaceae	2	3
Moraceae	1	3
Fabaceae	2	2
Euphorbiaceae	2	2
Malvaceae	2	2
Myrsinaceae	2	2
Oleaceae	1	2
Anacardiaceae	1	2

The observed total number of species (36) (table 5) was lower than that reported from some other dry Afromontane forests, such as Alemesaga Forest Reserve (66 species) in South Gondar (Enyew *et al*., 2019) and 68 species of woody plants in Seqela Forest (Liyew *et al*., 2025), Yemrehane Kirstos Church Forest (39 species) in North Wollo (Amanual, 2016), and Kurib Forest (39 species) in Awi Zone (Molla, 2016). However, the species richness in this study was very close to that of dry Afromontane forests of Awi Zone, northwestern Ethiopia (38) (Gebeyehu *et al*., 2019), and higher than Gezha Natural Forest, with a total of 29 woody species (Biruk, 2018) and Kella Natural Forest, with 22 woody species (Biruk, 2019). These variations in species richness may be attributed to differences in environmental factors and anthropogenic pressures.

Table 5: Species list, local name in Amharic language, family and habit of all woody species recorded in the study area

No	Scientific name	Local name in Amharic language	Family	Habit
1	*Acacia abyssinica/Vachellia abyssinica* (Hochst. ex. Benth.) Kyal. and Boatwr.	Bazra Girar	Fabaceae	T
2	*Acanthus pubescens* (Thomson ex Oliv.) Engl.	Kosheshile	Acanthaceae	S

3	*Allophylus abyssinicus* (Hochst.) Radlk.	Embies	Sapindaceae	T
4	*Bersama abyssinica* Fresen.	Azamir	Melianthaceae	S
5	*Calpurnia aurea* (Aiton) Benth.	Digita	Papilionoideae	S
6	*Carissa spinarum* L.	Agam	Apocynaceae	S
7	*Clausena anisata* (Willd.) Hook.f. ex Benth.	Limich	Rutaceae	S
8	*Combretum molle* R. Br. ex G. Don.	Abalo	Combretaceae	T
9	*Cordia africana* Lam.	Wanza	Boraginaceae	T
10	*Croton macrostachyus* Hochst. ex Delile	Bisana	Euphorbiaceae	T
11	*Dodonaea viscosa* (L.) Jacq.	Kitikita	Sapindaceae	T
12	*Dodonaea angustifolia* L.f.	Kitikita	Sapindaceae	T
13	*Dombeya torrida* (L.f.) A. Rich.	Wolkeffa	Malvaceae	T
14	*Dovyalis abyssinica* (A. Rich.) Warb.	Koshim	Flacourtiaceae	S
15	*Ekebergia capensis* Sparrm.	Teselimo	Meliaceae	T
16	*Euphorbia tirucalli L.*	Kinchib	Euphorbiaceae	T
17	*Ficus sur* Forssk.	Shola	Moraceae	T
18	*Ficus thonningii* Blume.	Chebaha	Moraceae	T
19	*Ficus vasta* Forssk.	Warka	Moraceae	T
20	*Grewia ferruginea* Hochst. ex A. Rich.	Lenkuata	Malvaceae	T
21	*Juniperus procera* Hochst. Ex Endl	Habesha tid	Cupressaceae	T
22	*Maesa lanceolata* Forssk.	Yeregna qolo	Myrsinaceae	T/S
23	*Maytenus arbutifolia* (A. Rich.) Wilczek	Atat	Celastraceae	S
24	*Millettia ferruginea* (Hochst.) Hochst. Ex Baker	Birbira	Fabaceae	T
25	*Myrsine africana* L.	Kechemo	Myrsinaceae	S
26	*Nuxia congesta* Br. ex Fresen.	Atquar	Buddleiaceae	T
27	*Olea europaea* L.	Ejersa	Oleaceae	T
28	*Olea welwitschii* (Knobl.) Gilg and Schellenb.	Weira/sigida	Oleaceae	T
29	*Osyris quadripartita* Salzm. ex Decne.	Keret	Santalaceae	T/S
30	*Rhamnus staddo* A. Rich.	Tedo	Rhamnaceae	T/S
31	*Rhus glutinosa* Hochst. ex A. Rich	Embus	Anacardiaceae	S
32	*Rhus vulgaris* Meikle.	Qummo	Anacardiaceae	T/S

33	*Rosa abyssinica* R.Br. ex Fresen.	Kega	Rosaceae	T/S
34	*Rumex nervosus* Vahl.	Embacho	Polygonaceae	S
35	*Schefflera abyssinica* (A. Rich.) Harms.	Getem	Araliaceae	T
36	*Vernonia amygdalina* Delile.	Grawa	Asteraceae	T

Note: T=Tree, S=Shrub, and T/S =Tree/ Shrub

4.2. Species diversity indices

The evenness value of the studied forest was 0.48, indicating relatively low evenness within the forest community. This suggests that a few species are likely dominant while others are less abundant and represented by few individual stands. The Shannon–Wiener diversity index (H') was 1.801, which falls within the low diversity category accordingly to Cavalcanti and Larrazabal (2004) who classify species diversity as high (≥ 3.0), medium (2.0-3.0), low (1.0-2.0), and very low (≤ 1.0). The combination of low diversity and low evenness indicates that a reasonable variety of species exists, but their distribution is skewed, suggesting the presence of a few dominant species like *Dodonia angustifolia, Combretum molle,* and *Croton macrostachyus* and a high number of less common species like *Juniperus procera, Maesa lanceolata,* and *Osyris quadripartita.*

Compared to other dry Afromountain forest, the diversity of woody species in the Kulkal Ber forest is lower than that in the Seqela dry Afromontane forest (H' 2.12 and evenness values of 0.92) (Liyew *et al*., 2025) and Kahitassa forest (H' 2.92 and evenness values of 0.72) (Workayehu *et al*., 2022). However, the Kulkal Ber forest exhibited a higher diversity index when compared to the Abebaye forest (H' 1.31) and evenness values of 0.31 (Zegeye, 2011). These comparisons indicate that the Kulkal Ber Natural Forest has a lower species diversity and evenness compared to other dry Afromontane forests in Ethiopia. Factors such as the size of the forests, human disturbances, habitat diversity, environmental conditions, and forest management practices might have contributed to the observed low diversity.

4.2.1. Woody species diversity along altitudinal gradient in the study area

The Shannon-Weiner diversity indices were 1.83 and 1.80 at lower (2000–2200 m.a.s.l.) and higher (2201–2336 m.a.s.l.) altitudes, respectively, indicating slightly higher diversity at the lower altitude. This discrepancy might be attributed to anthropogenic pressures, While Shannon diversity was slightly higher at the lower altitude, evenness was also slightly higher at the lower altitude (0.35) compared to the higher altitude (0.32), indicating richness slightly decrease with increasing altitude. This suggests a slightly more balanced, though still highly uneven, distribution of species abundance at the lower altitude. Several factors influence altitudinal gradients of diversity, including climatic variables (rainfall, temperature), area effect, and increased isolation with elevation. The area effect, where the total area decreases with increasing altitude (Körner, 2000).

Table 6: Woody species richness, diversity, and evenness (mean ± SE) along altitudinal gradients in Kulkal Ber Natural Forest

Altitudinal gradient	Species richness	Shannon diversity index (H') Mean ± SE	Evenness (J) Mean ± SE
LA (2000–2200 m)	33	1.83 ± 0.06^a	0.35 ± 0.01^a
HA (2201–2336 m)	29	1.80 ± 0.05^a	0.32 ± 0.01^a
P-value	> 0.05	> 0.05	> 0.05

Mean diversity values with the same letter are not significantly different at the 0.05 significance level. (LA: Lower Altitude and HA: Higher Altitude).

However, the ANOVA results (table 6) showed no significant difference in species diversity (H') between high and low altitudes ($F = 0.128$, $p = 0.722$). Since the p-value is much greater than the conventional significance level of the 0.05 threshold, altitude does not have a statistically significant effect on species diversity. While the descriptive statistics show slightly higher mean diversity at low altitude (1.83) compared to high altitude (1.80), this difference is not statistically significant. Therefore, based on this analysis, altitude does have a minor effect on the determining factor in species diversity within the studied area. Similar results were reported (Zerihun, 2020).

4.3. Analysis of the Vegetation Structure

Vegetation structure was assessed based on density (relative density), frequency (relative frequency), basal area, and importance value index (IVI) analyses of woody species

4.3.1 Density

A total of 252.08 stems ha^{-1} were recorded in the study area. The overall density of the study area forest was lower than reported in other dry Afromontane forests, including Seqela Forest

(Liyew *et al*., 2025) and Wof Ayzurish Forest (Tefera *et al*., 2024). These variations in density exhibited likely reflect differences in topographic, climatic, and anthropogenic factors across these sites. *Dodonia angustifolia*, *Combretum molle*, *Rhus glutinosa*, *Millettia ferruginea*, *Rhus vulgaris*, and *Cordia africana* exhibited the highest densities. Conversely, *Maesa lanceolata*, *Grewia ferruginea*, and *Rumex nervosus* had low densities. A total of 36 woody species were recorded.

Diameter classes were used to determine the population structure of 36 woody species (figure 5). Species were classified into five density classes: ≤10 cm, 10.1–20, 20.1–30, 30.1–40, and diameter with ≥40.1 cm.

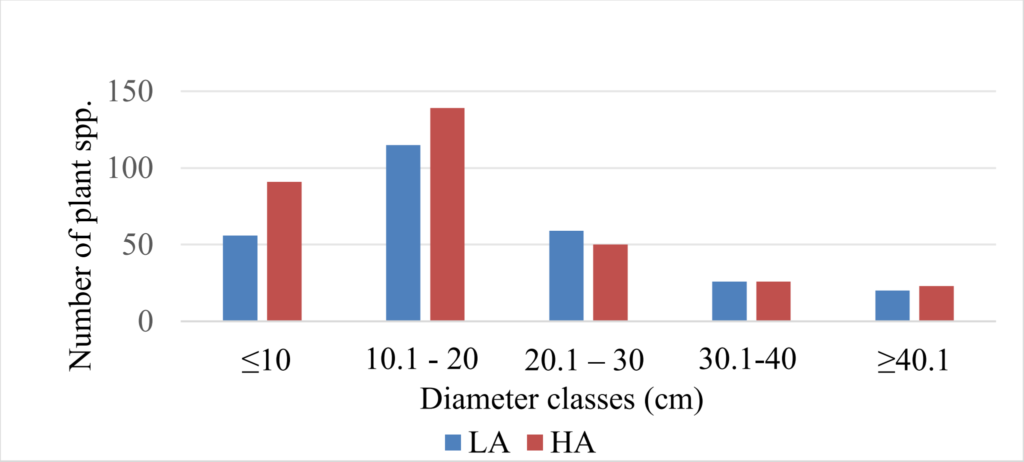

Figure 5: Diameter Classes and density distribution of woody plant species in the two altitudinal gradients (LA: Lower Altitude and HA: Higher Altitude).

A notable concentration of species in the 10.1-20 cm diameter class exists at both altitudinal ranges, with a slightly higher number at HA. While both altitudes show fewer species in (20.1–30 cm, 30.1–40 cm, and ≥ 40.1cm) diameter classes, HA generally exhibits a higher number of species across most categories, suggesting a broader distribution of tree sizes compared to LA.

4.3.2. Height Structure

The woody species in the study area were conveniently classified into 5 height classes: ≤5 m, 5.1–10 m, 10.1–15 m, 15.1–20 m, and ≥ 20.1 m. Density of woody species decreased with increasing height classes, showing a reversed J-shape (Figure 6). This means the forest had high density in the lower diameter class and lower density in the higher diameter class. The decrease in density of each height class towards the highest height classes reveals the dominance of small-sized individuals in the forest. Such a reversed J-shaped distribution pattern depicts that the forest is in the status of favorable regeneration and recruitment potential.

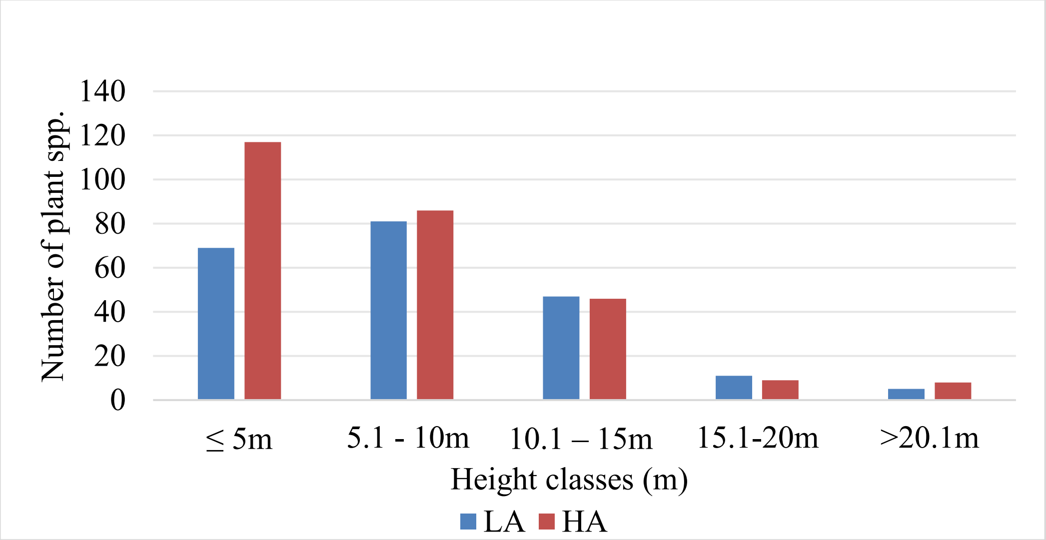

Figure 6: Height Classes and Density of woody species (LA: Lower Altitude and HA: Higher Altitude).

A notable feature is the dominance of shorter plants (≤ 5 m) at both altitudes, but significantly more so in the high-altitude areas. This suggests that higher altitude may favor the establishment of smaller, potentially cold-tolerant species. While both altitudes exhibit a considerable number of species in the mid-height ranges (5.1-10 m and 10.1-15 m), the high altitude shows a slightly higher count in the former, indicating a possible preference for this height range in these environments. Conversely, taller species (15.1-20 m and ≥20.1 m) are significantly less common at both altitudes, with remarkably similar numbers between the low and high-altitude locations. Overall, the data reveals the influence of altitude on plant species distribution, highlighting the prevalence of shorter plants, particularly at higher elevations, while demonstrating a diminished presence of taller species regardless of altitude.

4.3.3. Frequency

The woody species with the highest occurrence in the study area were *Dodonaea angustifolia, Combretum molle,* and *Rhus glutinosa,* followed by *Millettia ferruginea, Rhus vulgaris,* and *Cordia africana* (table 7) with density value of 46.34, 22.5, 21.34, 18.29, 19.51, and 14.63

respectively. The least frequent species in the study area were *Osyris quadripartita, Maesa lanceolata,* and *Juniperus procera, with density value of 0.61, 0.6, and 0.61 respectively.*

Table 7: Most frequent and less frequent species recorded in the study area

No	Scientific name	Frequency (%)
1	*Dodonia angustifolia*	16.38
2	*Combretum molle*	8.1
3	*Rhus glutinosa*	7.6
4	*Rhus vulgaris*	6.9
5	*Millettia ferruginea*	6.5
6	*Cordia africana*	5.2
7	*Myrsine africana*	0.43
8	*Osyris quadripartita*	0.2
9	*Maesa lanceolate*	0.2
10	*Juniperus procera*	0.2

4.3.4. Basal Area

The basal area of woody species in the Kulkal ber forest was 6.53 m^2/ha, which is extrapolated from DBH and DSH. Species with higher basal area could be considered as the most important species in the study forest, as they contribute more to stand biomass. *Ficus thonningii, Olea europaea, Euphorbia tirucalli, Croton macrostachyus, Combretum molle, Cordia africana,* and *Vernonia amygdalina* constitute a large basal area of the study site. Kulkal Ber natural forest exhibits a low basal area as compared to the basal area of Harego Forest in northeastern Ethiopia (9.66 m^2/ha) (Bogale et al., 2022), Wof Ayzurish Forest (18.03 m^2/ha) (Tefera *et al.*, 2024) and Seqela dry afro mountain Forest (27.4 m^2/ha) (Liyew et al., 2025). This reduced basal area could be caused by grazing pressure, severe human disturbance (fuelwood harvesting, logging), and resource scarcity, all of which diminish the total size and density of trees. Tree growth might have also been restricted by environmental factors, including soil fertility, moisture availability, and altitude, which would lead to smaller average diameters and, ultimately, a smaller basal area.

4.3.5. Importance Value Index (IVI)

In this study the highest IVI values (table 8) were recorded for *Dodonia angustifolia, Combretum molle, Croton macrostachyus*, and *Millettia ferruginea*.

Table 8: Ten top woody species that exhibited the highest IVI in Kulkal Ber natural forest

Scientific name	R. Den	R. Dom	RF	IVI **(%)**	Rank
Dodonia angustifolia	15.83	2.91	10.18	28.92	1
Combretum molle	7.71	4.67	6.55	18.93	2
Croton macrostachyus	4.38	5.66	4.36	14.4	3
Millettia ferruginea	6.25	3.77	4.36	14.38	4
Rhus glutinosa	7.29	0.86	6.18	14.34	5
Cordia africana	5	4.15	4.73	13.88	6
Rhus vulgaris	6.67	0.74	5.82	13.23	7
Olea welwitschii	3.75	2.98	3.64	10.37	8
Ficus thonningii	1.04	7.11	1.82	9.97	9
Vernonia amygdalina	2.2	5.09	2.5	9.79	10

Note: R. Den = relative density, R. Dom = relative dominance, RF = relative frequency, IVI = importance value index

However, *Maesa lanceolata, Juniperus procera, Myrsine africana, Rumex nervosus,* and *Osyris* quadripartita had low IVI values. This may be due to selective disturbance of humans for the available resource use and adverse environmental conditions (Tilahun, 2018). Low-frequency woody species which have lower ranks in IVI, are more threatened and need immediate conservation (Atsbha *et al*., 2019). However, it is important to note that in ecosystems subject to significant human disturbance, the Importance Value Index (IVI) may not accurately reflect the species' natural ecological niche or intrinsic role within the plant community. Instead, IVI values can be disproportionately influenced by anthropogenic factors such as, selective harvesting and/or land-use changes, which may artificially elevate the prominence of certain woody species while masking the ecological significance of others.

4.4. Plant Community Types of Kulkal Ber Forest

Three plant community types were identified using hierarchical cluster classification in SPSS (Figure 7). Two distinctive species with the highest mean cover abundance value in each community were used to name the plant community types. Accordingly, three plant community types were recognized.

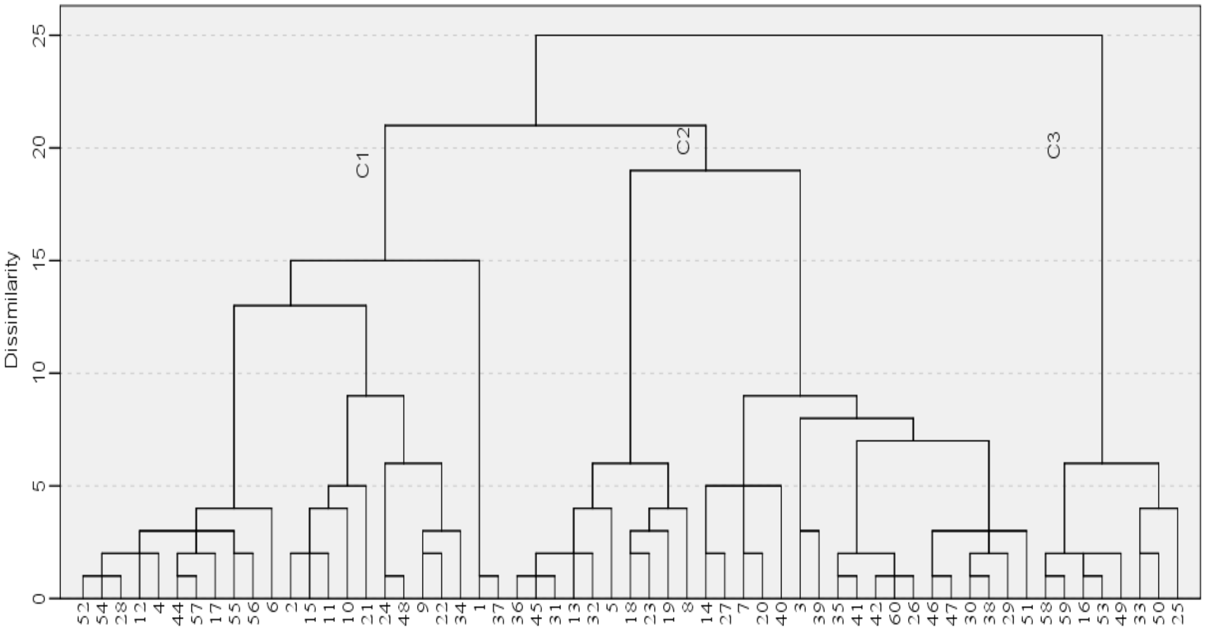

Figure 7: Dendrogram that represents plant community types of Kulkal ber natural forest using hierarchical cluster classification in SPSS, where C1 = community I, C2 = community II, and C3 = community III.

Community I the *Ficus thonningii–Dodonaea viscosa*:

This community is characterized by the co-dominance of *Ficus thonningii* and *Combretum molle*, each with a mean cover-abundance value of 0.14 and 0.43 respectively. It spans the broadest altitudinal range (2019–2311 m a.s.l.) and comprises 24 plots and consists of a mixture of species, indicating its adaptability across different elevations. Other significant species in this community include *Nuxia congesta*, *Carissa spinarum*, and *Rhus* species. The species composition suggests a transitional vegetation type influenced by environmental gradients, making this community an ecologically significant component of the forest.

Community II the *Olea europaea–Clausena anisata*:

This community is floristically defined by the dominance of *Olea europaea* and *Clausena anisata*, both with a cover-abundance value of 0.167. It occurs within a moderately high altitudinal range (2113–2300 m a.s.l.) and consists of 28 plots. Other important species include *Rosa abyssinica*, *Olea welwitschii*, and *Cordia africana*. The dominance of *Olea* species, known for their ecological resilience and role in forest recovery, indicates this community's potential significance for forest regeneration and biodiversity conservation efforts.

Community III the *Myrsine africana–Euphorbia tirucalli*:

This community is distinguished by multiple co-dominant species with equal or near-equal mean cover-abundance values: *Myrsine africana* (0.25), *Euphorbia tirucalli* (0.128), *Rumex nervosus* (0.128), *Acanthus pubescens* (0.128), and *Maytenus arbutifolia* (0.128). It occupies a narrower altitudinal range (2024–2249 m a.s.l.) and includes only 8 plots, making it the smallest in spatial coverage. This community is found across both lower and higher elevation zones, which reflects its ecological resilience and adaptability to varying environmental conditions. The high abundance of drought-tolerant and disturbance-adapted species such as *Euphorbia tirucalli* and *Myrsine africana* suggests that this community may be responding to anthropogenic disturbances or microclimatic stress.

4.5. Carbon Stock of the Different Carbon Pools

The carbon stock value of different pools in the study site showed variation. As depicted in Table 6, the soil organic carbon constituted the largest proportion of the total carbon pool in the study site, followed by aboveground and belowground biomass, whereas litter and dead wood contributed only a small fraction. This study indicates that soil serves as the most important carbon reservoir, while woody biomass components account for a considerable but smaller share compared to SOC. The percentage of carbon dioxide sequestered in respective carbon pools followed the same trend (Table 9), since it is converted by the same conversion factor. The highest percentage of carbon was stored in the soil organic carbon pool (47.55%), followed by the aboveground carbon pool (38%), which is a consistent result with Chinasho *et al*. (2015) and Dibaba (2019). The high amount of soil organic carbon in the study area can be attributed to continuous organic inputs and low disturbance under favorable climatic and soil conditions, consistent with other northern Ethiopian dry Afromontane forests. Belay *et al*. (2018) also reported high soil carbon stocks in Afromontane forests in the highlands of Ethiopia, resulting from long-lasting biomass accumulation.

Table 9: Summary mean of carbon density (t ha^{-1}) and distribution of each pool in the study site

Carbon pool	(t ha^{-1})	Percent (%)	Co_{2equv}
Aboveground carbon stock	57.29±3.73	38	210.3
Belowground carbon stock	15.47±1.04	10.26	56.77
GHL carbon stock	3.21±1.16	2.29	11.78
Dead wood carbon stock	2.86±1.46	1.9	10.49
Soil organic carbon stock	71.93±8.14	47.55	263.98
Total carbon stock	150.76	100	553.32

GHLs denote grass, herbs, and litter carbon stock.

The mean organic carbon stock of the study site was 150.76 t ha^{-1} with 553.32 Co_{2equv} (Table 6). The current finding is smaller compared to previous studies conducted in similar forest types of Ethiopia. Asersie and Motuma (2019) found 185.71 t ha^{-1} in the Sekele-Mariam dry evergreen mountain forest, and Dibaba *et al*. (2019) reported 508.9 t ha^{-1} for the Gerba-Dima Forest. Additionally, the current finding exceeds the national average of 113.0 Mg ha^{-1} (EFRL, 2017). But the mean carbon stock of 150.76 t ha^{-1} observed in the Kulkal Ber forest is higher than that reported in several other Ethiopian dry Afromontane forests. For instance, the Desa'a forest in northern Ethiopia has a mean total carbon stock of 92.89 t ha^{-1} (Negasi *et al*., 2024), and dry forests under community management in Tigray (Solomon, 2017) are below the national average of 113.0 Mg ha^{-1} (EFRL, 2017). These variations in carbon storage across different forests may result from factors such as forest management practices, disturbance levels, species composition, and environmental conditions (Gebeyehu *et al*., 2019).

4.5.1. Altitudinal Variation of Carbon and Carbon Dioxide Sequestration

The study examined the effect of altitude on carbon stock across four carbon pools: Above-Ground Carbon (AGC), Below-Ground Carbon (BGC), Grass, Herb, and Litter Carbon (GHLC), and Soil Organic Carbon stock (SOC). As compared to lower altitudes, the results indicated that both aboveground and belowground carbon stores were marginally smaller at higher altitudes (Table 7). Statistical analysis also revealed that these variations were not significant, indicating that these carbon reservoirs may not be much impacted by altitude. Similarly, except for the presence of slight variations, there were no discernible differences in soil organic carbon across the two altitudinal gradients (Table 7). In contrast, GHLC exhibited a significant difference, with higher values at lower altitude (3.9 t ha^{-1}) compared to higher altitude (2.58 t ha⁻¹), and a statistically significant effect of altitude ($p = 0.005$). These findings suggest that while most carbon pools remain unaffected by altitude, GHLC is significantly higher at lower altitude, possibly due to more favorable growth conditions. Similar results were reported in the dry evergreen montane forests of the Choke Mountain ecosystem (Asrat *et al.*, 2022).

AGC, BGC, and SOC did not show significant variation with altitude, indicating stability across altitude. However, GHLC is significantly higher at low altitude, suggesting that altitude influences ground herbaceous carbon accumulation. These findings align with studies conducted in Ethiopian dry Afromontane forests, where variations in carbon stock have been attributed to multiple environmental and ecological factors beyond altitude alone (Getaneh *et al.*, 2019).

Table 10: Altitudinal variations of carbon pools and their sequestration of carbon dioxide (CO_2)

Elevation Class	AGC (t ha⁻¹)	BGC (t ha⁻¹)	GHLC (t ha⁻¹)	DWC (t ha⁻¹)	SOC (t ha⁻¹)	TC (t ha⁻¹)	Total Co_2 eqv
Lower altitude	44.1	16.3	3.9	2.86	71.16	138.32	507.63
Higher altitude	39.66	14.67	2.58	0	72.65	129.56	475.48

Note: AGC = Aboveground carbon, BGC = Belowground carbon, GHLC = Grass, herbs, and litter carbon, SOC= Soil organic carbon stock, DWC = Deadwood carbon, and TC =Total carbon stock.

Table 11: The mean ± SD carbon stocks (ton/ha) along altitudinal gradient in Kulkal Ber natural forest

Carbon Pools (t ha⁻¹)	Lower Altitude (Mean ± SD)	Higher Altitude (Mean ± SD)	Significance (p-value)
Aboveground carbon	44.1 ± 16.11^a	39.66 ± 19.30^a	0.252
Belowground carbon	16.3 ± 6.03^a	14.67 ± 7.29^a	0.568
Grass, herbs, and litter carbon	3.9 ± 0.81^a	2.58 ± 1.39^b	0.005
Soil organic carbon	71.16 ± 3.23^a	72.65 ± 11.34^a	0.695

Mean values with the same letter are not significantly different at the 0.05 significance level according to LSD post-hoc test LA: Lower Altitude and HA: Higher Altitude).

A study in Ethiopia by Asersie (2019) on Sekele-Mariam dry evergreen mountain forest found that carbon stocks were higher at elevations between 2395 and 2460 m above sea level. However, differences along altitudinal gradients were not statistically significant, suggesting that altitude alone may not be a decisive factor in carbon distribution (Asresie, 2019). Conversely, Negasi *et al*. (2024) in the Desa'a forest observed that the middle altitudinal class had the highest carbon stock, while the upper altitudinal class had the lowest. The study highlighted that climatic and soil conditions at mid-elevations might optimize carbon sequestration (Negasi *et al*., 2024).

Research conducted in the Furi forest reported significantly higher aboveground and belowground carbon stocks at middle elevations than at upper elevations, further supporting the hypothesis that mid-altitudes provide favorable biomass accumulation conditions (Tolesa *et al*., 2023). Similarly, a study in the Sirso moist evergreen Afromontane Forest found that carbon stocks varied significantly with altitude, with higher values recorded at mid-elevations. This was attributed to variations in vegetation composition and environmental factors, suggesting that carbon storage is influenced by both biotic and abiotic factors (Tadesse *et al*., 2019). These comparisons suggest that while altitude can influence carbon stocks, other site-specific factors such as vegetation type, climate, soil fertility, and human activity also play crucial roles. The significant effect of altitude on GHLC in this study may be due to favorable conditions for herbaceous plant growth at lower elevations, including higher temperatures and nutrient availability. In contrast, the lack of significant differences in AGC, BGC, and SOC might imply the forest structure and soil processes are relatively stable across altitude.

These findings emphasize the possibility of carbon dynamics in Ethiopian dry Afromontane forests and highlight the need for further research to assess other ecological drivers of carbon stock variability. In the present study, fallen dead wood occurred only in two plots in LA. No dead wood plant was recorded in the HA. The lack of dead wood in HA and its sparseness in LA could be attributed to intense human disturbance, especially fuelwood collection, which eliminates dead material before it builds up. Furthermore, the supply of dead wood may be impacted by variations in tree mortality and forest structure among altitudinal zones. This deficit has several ecological consequences, including decreased habitat availability for decomposers and other forest-dwelling animals, decreased soil fertility and nutrient cycling, decreased carbon storage in the dead wood pool, and potential inhibition of natural regeneration. Overall, the low proportion of dead wood in the study area indicates both ecological fragility and high levels of human pressure, which indicates taking a necessitating actions for sustainable forest management.

5. SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1. SUMMARY

A total of 36 woody species belonging to 26 families and 31 genera were recorded across 60 plots in the Kulkal Ber natural forest, with trees representing 60%, shrubs 27.5%, and tree/shrubs 12.5% of the total species. Species richness was slightly higher at lower altitude (33 species) than at higher altitude (29 species). Sapindaceae and Moraceae were the most dominant families, each represented by three species, while other families such as Fabaceae, Euphorbiaceae, Malvaceae, Myrsinaceae, Oleaceae, and Anacardiaceae were represented by two species each. The forest exhibited low species diversity (Shannon-Wiener index $H' = 1.801$) and low evenness ($J = 0.48$), indicating dominance of a few species, including *Dodonaea angustifolia*, *Combretum molle*, and *Croton macrostachyus*, with many species being less abundant. Slightly higher diversity and evenness were observed at lower altitudes compared to higher altitudes, but these differences were not statistically significant ($p > 0.05$). Vegetation structure analysis showed a total density of 252.08 stems ha^{-1}, with higher densities recorded for *Dodonaea angustifolia*, *Combretum molle*, *Rhus glutinosa*, *Millettia ferruginea*, *Rhus vulgaris*, and *Cordia africana*, while species such as *Maesa lanceolata*, *Grewia ferruginea*, and *Rumex nervosus* exhibited low densities.

Diameter and height class distributions displayed a reversed J-shaped pattern, reflecting a higher proportion of small-sized individuals, particularly in high-altitude areas. Frequency and Importance Value Index (IVI) analyses identified *Dodonaea angustifolia*, *Combretum molle*, *Croton macrostachyus*, and *Millettia ferruginea* as the most ecologically significant species, whereas *Maesa lanceolata*, *Juniperus procera*, *Myrsine africana*, *Rumex nervosus*, and *Osyris quadripartita* had low IVI values. Hierarchical cluster analysis revealed three distinct plant communities: *Ficus thonningii–Dodonaea viscosa*, spanning the broadest altitudinal range and comprising 24 plots; *Olea europaea–Clausena anisata*, occurring across 28 plots at mid-high altitudes; and *Myrsine africana–Euphorbia tirucalli*, the smallest community with only 8 plots dominated by drought-tolerant species.

Carbon stock assessment indicated a total mean carbon stock of 150.76 t ha^{-1} (553.32 t CO_2 equivalent), with soil organic carbon contributing the largest share (47.55%), followed by aboveground biomass (38%), belowground biomass (10.26%), grass, herb, and litter carbon (2.29%), and dead wood (1.9%). While aboveground, belowground, and soil organic carbon did not vary significantly along altitudinal gradients, grass, herbs, and litter carbon were significantly higher at lower altitudes ($p < 0.05$). Dead wood was sparse, particularly at higher altitudes, reflecting intense human disturbance and low natural accumulation.

5.2. Conclusion

Kulkal Ber natural forest is one of the dry Afromountain Forest in Maksegent district, Northwestern Ethiopia. This study was conducted to assess woody species diversity and carbon stocks along altitudinal gradient. Through this study a total of 36 woody species were recorded. Species richness was found to be low, falling between other dry Afromontane forests. The Shannon-Wiener diversity index indicated low species diversity with uneven distribution. There was no statistically significant difference in species diversity between the lower and higher altitudes. Most trees belonged to the 10.1–20 cm diameter class, suggesting a young forest with ongoing regeneration. The highest IVI values were recorded for *Dodonia angustifolia*, *Combretum molle*, and *Croton macrostachyus*, while some species like *Maesa lanceolata, Juniperus procera, Myrsine africana, Rumex nervosus,* and *Osyris quadripartita* had low IVI, indicating conservation needs. The basal area (6.53 m^2/ha) was lower compared to other dry Afromontane forests.

The study revealed that the Kulkal Ber natural forest harbors a low level of woody species diversity, with 36 species from 26 families and 31 genera. The species richness observed was lower than some previously studied sites. The dominant families were Sapindaceae and Moraceae. The Shannon-Wiener diversity index (H' = 1.801) indicated low diversity; similarly, low evenness (0.48) suggested dominance by a few species. Altitudinal variations had no significant effect on species diversity, as evidenced by ANOVA results. The forest exhibited a reversed J-shaped height class distribution, indicating good regeneration potential. However, species composition and structural attributes revealed the dominance of a few species, while others had low importance value indices, suggesting potential conservation concerns. Three plant community types were identified in the Kulkal Ber forest: *Ficus thonningii–Dodonaea viscosa*, *Olea europaea–Clausena anisata*, and *Myrsine africana–Euphorbia tirucalli*. Their distribution varies with altitude, where the *Ficus thonningii–Dodonaea viscosa* community dominated broad altitudinal gradients with a mixture of transitional species, while the *Olea europaea–Clausena anisata* community was concentrated at moderately higher altitudes, reflecting stability and regeneration potential. The *Myrsine africana–Euphorbia tirucalli* community, composed of drought-tolerant and disturbance-adapted species, occurred in scattered plots across both strata, suggesting responses to microclimatic stress or disturbance. Overall, this altitudinal variation in community composition underlines the ecological diversity of the forest and the importance of altitude-specific conservation strategies.

Carbon stock study of forests is crucial to show forest potential and their role in mitigating climate change risk. Forests have the capability to store a substantial amount of carbon within their biomass and soil. In this study, the lower parts of the altitude were slightly high in aboveground, belowground, litter carbon stocks, while the higher parts of the altitude had high soil organic carbon stock and low carbon stock in other carbon pools. But aboveground, belowground and soil carbon pool density showed insignificant variation, whereas the litter carbon stocks pool was significantly different along altitudinal gradients.

Overall, the present study result revealed that the carbon stock potential showed the same patterns of altitudinal gradient except GHL. At the ecosystem level, the average carbon stocks in the study site were found good in which the result is comparable to some study results of forests in the country. This indicates the contribution of the forest for carbon sequestration and to enhance mitigation of climate changes. The Kulkal Ber natural forest was found to have a moderate amount of carbon reservoir potential compared to similar areas in the country and the continent. The forest has a remarkable capacity to store carbon. A contribution for the provision of a carbon sequestration potential of 553.32 CO_2 equivalents could be significantly contributed to the national and global climate change mitigation efforts. Hence, it has the potential to mitigate CO_2 concentration in the atmosphere besides its direct economical use for the livelihood of the local people. This highlights not only its ecological role in biodiversity conservation and climate change mitigation but also its potential for integration into carbon financing and carbon market initiatives that could support both conservation and local livelihoods.

Kulkal Ber Natural Forest, despite its low species diversity and basal area, while demonstrates a significant capacity for carbon sequestration, with an average carbon stock comparable to other Afromontane forests in Ethiopia. The forest's reversed J-shaped height distribution indicates good regeneration potential, a crucial factor for its long-term health and carbon storage capacity. While altitudinal gradients did not significantly influence woody species diversity, they did affect the distribution of plant communities and certain carbon pools, underscoring the importance of altitude-specific management strategies. These findings reveal the forest's vital ecological role in mitigating climate change and may provide a strong scientific basis for its inclusion in carbon financing and market initiatives, which would support both conservation efforts and local livelihoods. Generally, this study confirms Kulkal Ber's potential as a valuable natural resource that warrants focused on conservation to secure its future contributions to both local well-being and global climate change mitigation goals.

5.3. Recommendations

Based on the findings of this study, the following recommendations are proposed for the conservation and sustainable management of the Kulkal Ber natural forest:

1. Promote the conservation and natural regeneration of less abundant and low-importance value index species by protecting their seedlings and saplings from grazing and other disturbances and safeguarding their habitats. Where natural regeneration is insufficient, this may be by actively applying enrichment planting with native species to maintain the forest’s ecological balance without disrupting its natural structure, which supports the natural growth of woody species to enhance forest density and basal area.
2. Recognize the three identified plant community types as distinct ecological units and manage them to conserve their unique ecological roles and species composition.
3. Protect and enhance forest carbon stocks by minimizing soil disturbance, preventing forest degradation, and promoting native reforestation to maintain the forest’s contribution to climate change mitigation.
4. Establish long-term monitoring systems and engage the local communities to track changes in species composition, vegetation structure, and carbon stocks, while raising awareness of the forest’s ecological and economic benefits and promoting sustainable management practices.
5. This study was limited by the exclusion of regeneration status (seedlings and saplings) and other key environmental variables, which are all crucial for accurately assessing the

forest's carbon stock potential and long-term sustainability. We therefore recommend that future research address these and other pertinent factors.

6. REFERENCES

Abbass Kashif, Qasim Muhammad Zeeshan, Huaming Song, Murshed Muntasir, Mahmood, Haider and Ijaz Younis. 2022. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. *Environmental Science and Pollution Research*, *29*(28): 42539–42559.

Abel Girma, Teshome Soromessa and Tesfaye Bekele. 2014. Forest carbon stocks in woody plants of Mount Zequalla Monastery and its variation along altitudinal gradient: Implications of managing forests for climate change mitigation. *Science, Technology, and Arts Research Journal*, *3*(2): 132-140

Abrha Haftu, Dodiomon Soro, Ongoma Victor, Birhane Emiru and Manaye Ashenafi. 2024. Assessing structure, species diversity, and carbon stocks across altitudinal gradients in Hugumbrda Grat-kahsu forest, Tigray, Ethiopia: Implications for ecosystem service management. *Forest Science and Technology*, *20*(1): 67–77.

Adugna Feyissa, Teshome Soromessa and Mekuria Argaw. 2013. Forest carbon stocks and variations along altitudinal gradients in Egdu Forest: Implications of managing forests for climate change mitigation. *Science, Technology and Arts Research Journal*, *2*(4): 40 - 46.

Ahmad Muhammed Molen, Imtiaz Muhammed Ans, Rasheed Fareeha Jameel, Muhammed Asif, Asif Muhammed and Ahmad Haseb. 2023. The Crucial Role of Forests in Combating Climate Change. *Trends in Biotechnology and Plant Sciences*, *1*(1): 1–6.

Alefu Chinasho, Teshome Soromessa and Eyale Bayable. 2015. Carbon stock in woody plants of Humbo forest and its variation along altitudinal gradients: The Case of Humbo District, Wolaita Zone, Southern Ethiopia. *International Journal of Environmental Protection and Policy, 3*(4): 97-103.

Alem Demelash. 2023. Trend and Current Status of Forest Resources in the Amhara National Regional State, Ethiopia: A Review. *East African Journal of Forestry and Agroforestry*, *6*(1): 113–136.

Amare Bantider, Geta Zeleke, Weldeamlak Bewket and Tibebu Kassawmar. 2021. Mapping Aboveground Carbon Stocks and Emissions Induced by Land Use and Land Cover Changes in Ethiopia: A Remote Sensing Approach Working Paper, Addis Ababa University. *Water and Land Resource Centre*, *3*: 1–46.

Amanual Ayanaw. 2016. Woody species diversity, structure and regeneration status of Yemrehane Kirstos Church Forest of Lasta Wereda, North Wollo Zone, Amhara Region, Ethiopia. Thesis, Addis Ababa University.

Amanual Ayanaw and Gemedo Dalle. 2018. Woody species diversity, structure, and regeneration status of Yemrehane Kirstos Church Forest of Lasta Woreda, North Wollo Zone, Amhara Region, Ethiopia. *International journal of forestry research*. Https://doi.org/10.1155/2018/5302523.

Amenu Bekele Tona. 2016. Review of Woody Plant Species of Ethiopian High Forests. *Journal* *of Resources Development and Management*, *27*: 7–16.

Anderegg, W. R. L., Hicke, J. A., Fisher, R. A., Allen, C. D., Aukema, J., Bentz, B., Hood, S., Lichstein, J. W., Macalady, A. K., Mcdowell, N., Pan, Y., Raffa, K., Sala, A., Shaw, J. D., Stephenson, N. L., Tague, C. and Zeppel, M. 2015. Tree mortality from drought, insects, and their interactions in a changing climate. *New Phytologist*, *208*(3): 674–683. https://doi.org/10.1111/nph.13477.

Asefa, A., Davies, A. B., McKechnie, A. E., Kinahan, A. A. and van Rensburg, B. J. 2017. Effects of anthropogenic disturbance on bird diversity in Ethiopian montane forests. *The Condor: Ornithological Applications*, 119*(3): 416–430. https://doi.org/10.1650/CONDOR-16-81.1.*

Asefa Mengesha Cao, Min He, Yunynu Mekonnen, Euketu Song Xiayang and Yang Jie. 2020. Ethiopian vegetation types, climate and topography. *Plant Diversity*, *42*(4): 302–311.

Asersie Mekonnen and Motuma Tolera. 2019. Carbon Stock Estimation along Altitudinal Gradient in Sekele-Mariam Dry Evergreen Montana Forest, North-Western Ethiopia. *Agriculture, Forestry and Fisheries*, *8*(2): 48-53.

Asrat Fikirte, Teshome Soromessa, Tesefaye Bekele, Rama Mohan Kurakalva, Sravya Sai Guddeti, David Russel Smart and Kristine Steger. 2022. Effects of Environmental Factors on Carbon Stocks of Dry Evergreen Afromontane Forests of the Choke Mountain Ecosystem, Northwestern Ethiopia. *International Journal of Forestry Research* https://doi.org/10.1155/2022/9447946.

Atsbha Tesfay, Anteneh Belayneh Desta and Tessema Zewdu. 2019. Woody species diversity, population structure, and regeneration status in the Gra-Kahsu natural vegetation, southern Tigray of Ethiopia. *Heliyon*, *September 2018*: e01120. https://doi.org/10.1016/j.heliyon.2019.e01120

Aynekulu, E., Koala, J., Feyisa, K., Sawadogo, L. and Shepherd, K. 2014. Final Report Livelihood diversifying potential of livestock-based carbon sequestration option in pastoral and agro pastoral systems in Africa, BMZ project.

Azene Bekele. 1993. Use full trees and shrubs for Ethiopia identification, propagation and management for agricultural and pastoral communities. RSCU/SIDA.

Basile, M. 2022. Rare species disproportionally contribute to functional diversity in managed forests. *Scientific Reports*, *12*(1): 5897.

Belay Melese, Ensermu Kelbessa and Teshome Soromessa. 2014. Forest carbon stocks in woody plants of Arba Minch groundwater forest and its variations along environmental gradients. *Science, Technology and Arts Research Journa*l, *3*(2):141-147.

Belay Molla. 2016. Identification of Floristic Diversity and structure in Kurib Forest in Guagusa shekudad Woreda in Awi Zone of Amhara Region. MSc Thesis, Addiss Abeba University, Addiss Abeba, Ethiopia.

Belay Tefera, Morgan L., Ruelle Zemede Asfaw and Berhanu Abraha Tsegay. 2014. Woody plant diversity in an Afromontane agricultural landscape Debark District, northern Ethiopia, *Forests, Trees and Livelihoods*, *23*(4): 261-279.

Berhe, D. H., Retta, A. N., Tefera, A. S., Gidey, T., Negussie, A., Birhane, E., Hadgu, K. M. and Gebrehiwot, K. 2024. Ecological study and forest degradation of the Waldiba Monastery woodland in Tigrai, Ethiopia*, Discover Sustainability*.

Biruk Lulseged. 2019. Effects of Elevation on Carbon Stocks and Woody Species Diversity of Kella Natural Forests in Konso Zone, Southern Ethiopia. MSc Thesis, Hawassa University, Hawassa, Ethiopia

Betemariyam Mulugeta, Kefalew Tamiru and Tolera Motuma. 2023. Comparison of Woody Species Diversity and Carbon Stock along Natural Forest to Farmland Conversion Gradient in the Gura-Ferda District of Southwestern Ethiopia. *Journal of Sustainable Forestry*, *42*(6): 590–606.

Billa Getachew Desalegn and Teshome Akalu. 2003. Report on The Potential of the Tara-Gedam and Kulkual-Ber Forests, Gonder.

Birhanu Liyew, Moges Getaneh, Amsalu Nigussie and Balzter Heiko. 2025. Woody species diversity, structure and community distribution along environmental gradients of Seqela Dry Afromontane Forest in Northwestern Ethiopia. *PLoS ONE 20*(1): e0313020.

Bogale, B., Birhane, E. and Muhie, S. 2022. Diversity, structural, and regeneration analysis of woody species in the afromontane dry forest of Harego, Northeastern Ethiopia. *Int. J. Fores*, 1–20

Brown, S. 1997. Estimating Biomass and Biomass Change of Tropical Forests: A Primer. UN FAO Forestry 134. Food and Agriculture Organization, Rome.

Cavalcanti., E.A.H. and Larrazabal, M.E.L. 2004. Macrozoopl ancton da zona econ^o-mica exclusiva do nordeste do brasil (segunda expediç~ao oceanograficaerevi-zee/ne II) comenfase em CopepFicus sycomorous (Crustacea), *Rev. Bras. Zool*, *21*(3): 467-475.

Chave, J. 2005. Measuring tree height for tropical forest trees: A field manual. Pan – Amazonia.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B. C., Duque, A., Eid, T., Fearnside, P. M., Goodman, R. C., Henry, M., Martínez-Yrízar, A., Mugasha, W. A., Muller-Landau, H. C., Mencuccini, M., Nelson, B., Nogueira, E. M., Ortiz-Malavassi, E. and Vieilledent, G. 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, *20*(10): 3177–3190.

Cherinet, A. and Lemi, T. 2023. review on the Role of Forest Ecosystems for Carbon Sequestration and Poverty Alleviation in Ethiopia. *Hindawi International Journal of Forestry Research*.

Chevuturi, A., Klingaman, N. P. and Vidale, P. L. 2022. Projected Changes in the East Asian Hydrological Cycle for Different Levels of Future Global Warming. *Atmosphere*. *13*(3).

Chinasho, A., Soromessa, T. and Bayable, E. 2015. Carbon stock in woody plants of Humbo forest and its variation along altitudinal gradients: the case of Humbo district, Wolaita Zone, southern Ethiopia. *Int J Environ Prot Policy, 3*(4): 97–103

CSA (Central Statistical Agency). 2017. Population Statistical. Addis Ababa, Ethiopia: Central Statistical Agency.

Dar., J. V. and Sundara pandian, S. 2015. Variation of biomass and carbon pools with forest type in temperate forests of Kashmir Himalaya. *India. Environmental Monitoring and Assessment,* 187: 3–17.

Dawson, I. K., Lengkeek, A., Weber, J. C. and Jamnadass, R. 2009. Managing genetic variation in tropical trees: linking knowledge with action in agroforestry ecosystems for improved conservation and enhanced livelihoods. *Biodiversity and Conservation*, *18*(4): 969–986.

Dibaba Abiyot, Soromessa Teshome and Workineh Bikila. 2019. Carbon stock of the various carbon pools in Gerba-Dima moist Afromontane Forest, South-western Ethiopia. *Carbon Balance and Management*, *14*(1): 1–10.

Do., T. V., T. Sato, V. D. Hai, N. T. Thang, N. T. Binh, N. H. Son, D. V. Thuyet, B. T. Doi, H. V. Thang, T. and N. V. Cam. 2017. Aboveground biomass and tree species diversity along altitudinal gradient in Central Highland, Vietnam. *Tropical Ecology,* 58: 95–104.

Edwards, S., Demissew, S. and Hedberg, I., 1997. Flora of Ethiopia and Eritrea Hydrocharitaceae to Arecaceae. The National Herbarium, Addis Ababa University.

Ensslin., A., R. Gemma, P. Ulf, Z. and F. Markus. 2015. Effects of elevation and land use on the biomass of trees, shrubs and herbs at Mount Kilimanjaro. *Ecosphere*, 6: 1–15.

Enyew Esubalew, Kidane Giday, Hadigu Hishe and Gezahegn Goshu. 2019. Carbon stock of woody species along Altitude gradient in Alemsaga Forest, South Gondar, North Western Ethiopia. *International Journal of Environmental and Agriculture Research (IJOEAR)*, *5*(7): 13–21.

Eshetu Tegne, Muhamed Bedurzeman, Awol Merima, Kassa Zebie, Getu Mehabaw and Zeleke Ayalew Jejaw. 2022. Research Article A Retrospective Analysis of Malaria Trends in Maksegnit Health Center over the Last Seven Years, Northwest Ethiopia. *Hindawi Journal of Parasitology Research*.

EBI (Ethiopian Biodiversity Institute). 2022. National Ecosystem Assessment of Ethiopia: Syntheses of the Status of Biodiversity and Ecosystem Services, and Scenarios of Change. 672. www.ebi.gov.et.

EFRL (Ethiopia Forest Reference Level). 2017. Ethiopia's forest reference level submission to the UNFCCC (Annex II: Basic wood density table). UNFCCC REDD+

FAO (Food and Agriculture Organization of the United Nations). 2010. Global forest resources assessment. Main report, Forestry Paper 163. Rome, Italy.

FAO (Food and Agriculture Organization of the United Nations). 2015. Coping with climate change: The roles of genetic resources for food and agriculture. Rome.

FAO (Food and Agriculture Organization of the United Nations). 2022. The State of the World's Forest: Forest pathways for green recovery and building inclusive, resilient, and sustainable economies.

Fashing, P. J., Nguyen, N., Demissew, S. and Gizaw, A. 2022. Ecology, evolution, and conservation of Ethiopias biodiversity. *PNAS*.

Fekadu Nemera, Zewdu Tessema and Ebro, A. 2018. Effect of altitudinal gradient in the species diversity of woody plants of west shoa. International livestock Research Institute (ILRI), Addis Ababa, Ethiopia.

Fekadu, T., Raga, D. and Denu, D. 2023. Woody species diversity and structure of Aba Sena Natural Forest, West Wollega Zone*,* Ethiopia. *Ethiopian Journal of Environmental Studies and Management*, 16(*1*): 29-44.

Feyissa Adugna, Soromessa Teshome and Argaw Mekuria. 2014. Forest Carbon Stocks and Variations along Altitudinal Gradients in Egdu Forest: Implications of Managing Forests for Climate Change Mitigation. *Science, Technology and Arts Research Journal*, *2*(4): 40.

Friis, I. 1992. Forests and forest trees of north east tropical Africa: their natural habitats and distribution pattern in Ethiopia, Djibouti and Somalia. Kew. Bull. Add. Ser, 15: 396.

Friis Ib, Sebsebe Demissew and van Bruegel Paol. 2010. Atlas of the Potential Vegetation of Ethiopia. *The Royal Danish Academy of Science and letters*, *Det Kongelige Danske Videnskabernes Selskab. Biol. Skr.* 58: 1- 307.

Gashu Kassahune and Aminu Omer. 2019. Participatory forest management and smallholder farmers' livelihoods improvement nexus in Northwest Ethiopia. *Journal of Sustainable Forestry*, *38*(5): 413–426.

Gebeyehu Getaneh, Soromessa Teshome, Bekele Tesfaye and Teketay Demle. 2019. Carbon stocks and factors affecting their storage in dry Afromontane forests of Awi Zone, northwestern Ethiopia. *Journal of Ecology and Environment*. *8*: 1–18.

Gebretsadik Teklu. 2016. Causes for Biodiversity Loss in Ethiopia: A Review from Conservation Perspective. *Journal of Natural Sciences Research*, *6*(11): 32–40.

Geider, J.R., Delucia, H.E., Falkowsk, G.P., Grime, P.J., Grace, J., Kana, M.T. and Roche. 2001. Primary productivity of planet earth: biological determinants and physical constraints in terrestrial and aquatic habitats. *Global Change Biology,* 7: 849-882

Getachew Mulugeta. 2014. Vegetation Dynamics of Area Enclosure Practices: A Case of Gonder Zuria District, Amhara Region, Ethiopia. *Jornal of Natural Sciences reasearch*, *4*(7): 75–83.

Getaneh, G., Soromessa, T., Bekele, T. 2019. Carbon stocks and factors affecting their storage in dry Afromontane forests of Awi Zone, northwestern Ethiopia. *j ecology environ,* 43, 7.

Getasew Fisseha, Binega Dereb, Adamsew Marelign Melese and Kiroos Getachew. 2025. Evaluating carbon stock in Gantamie Natural Forest, bure Zuria district, northwestern Ethiopia: a climate change approach. *Environmental system research*, *14*(1): 20–34.

Girma, S., Patrica, R., Jan, H., Werner, H., Kristoffer, H., Feyera, S., Joern F. and Annik S. 2021. Woody plant species diversity as a predictor of ecosystem services in a social ecological system of southwestern Ethiopia. Landscape ecology, 36:373–391.

Gitz, V., Meybeck, A., Lipper, L., Young, C. and Braatz, S. 2016. Climate change and food security: Risks and responses. In Food and Agriculture Organization of the United Nations.

GIZ/SLM (Sustainable Land Management). 2015. Report on The Woody Vegetation Survey of Kulkal Ber Forest Gondar Zuriya District, North Gondar Administrative Zone, Amhara Regional State, Ethiopia.

Guluma Tolesa Negese. 2020. Woody Species Diversity, Regeneration Status and Carbon Stock Along an Elevation Gradient in Furi Forest, Central Ethiopia. MSc Thesis, Haramaya University, Haramaya, Ethiopia.

GZDARDO (Gondar Zuria District Agricultural and Rural Development Office). 2016. Annual report for 2016 fiscal year. Maksegnit, Ethiopia

Hamere Yohannes, Teshome Soromessa and Mekuria Argaw. 2015. Carbon Stock Analysis Along Altitudinal Gradient in Gedo Forest: Implications for Forest Management and Climate Change Mitigation. *American Journal of Environmental Protection*, 237-244.

Hassan Yusuf M., Treydte Anna C., Abule Elias and Sauerborn Jurgen. 2013. Predicting aboveground biomass of woody encroacher species in semi-arid rangelands, Ethiopia. *Journal of Arid Environments,* 96: 64–72.

Hedberg, I., Edwards, S., Sileshi, N. and Eds. 1995. Flora of Ethiopia and Eritrea the National p Herbarium Addis Abeba University, Addis Abeba and Department of Systematic Botany Uppsala University, *Uppsala*, *4* (1).

Henry, A., Besnard, W.A., Asante, J., Eshun, S., and Saint-Andre A. 2010. Wood density, phytomass variations within and among trees, and allometric equations in a tropical rainforest of Africa, *Journal of Forest Ecology and Management,* 260: 1375–1388.

Hoover, K. and Riddle, A. A. 2020. Forest Carbon Primer. *Congressional Research Service*, *12*(7): 1–34.

IPCC (Intergovernmental panel on climate change). 2006. Agriculture, forestry and other land use, Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. Institute for Global Environmental Strategies (IGES), Japan, pp. 20.

IPCC (Intergovernmental panel on climate change). 2007. Africa. Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

IPCC (Intergovernmental panel on climate change). 2007. Mitigation of climate change Special report. Cambridge University Press, Cambridge, USA

IPCC (Intergovernmental panel on climate change). 2023. *Climate Change 2023:* Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1–34.

Iqbal, K., Hussain, A. and Negi, A. K. 2014. An overview of Biomass Estimation methods*: Research Journal of Social Science and Management, 4*(6): 42–57.

Kelbessa Enserumu and Demissew Sebseba. 2014. Diversity of vascular plant taxa of the flora of Ethiopia and Eritrea. *Ethiop Journal of Biological Science,* 13: 37–45.

Kendie Getnet, Solomon Addisu and Abrham Abiyu. 2021. Biomass and soil carbon stocks in different forest types, Northwestern Ethiopia. *International Journal of River Basin Management*, *19*(1): 123–129. https://doi.org/10.1080/15715124.2019.1593183.

Kent, M. and Coker, P. 1992. Vegetation Description and Analysis, A practical approach Bent Haven Press, New York.

Kidane Leul, Nemomissa Silesh and Woldu Zerihun. 2016. The effects of disturbance on the population structure and regeneration potential of five dominant woody species–in Hugumburda- Gratkhassu National Forest Priority Area, North-eastern Ethiopia. *African journal of ecology*, *54*(1): 20–28.

Kobe Fekadu Tadeg. 2024. Understanding Climate Change in Ethiopia : Impacts and Solutions. *International Journal of Big Data Mining for Global Warming. January*, 5(2).

Konopinski, M.K., 2020. Shannon diversity index: a call to replace the original Shannon's formula with unbiased estima- tor in the population genetics studies. *PeerJ*, 8: 9391

Korner, C. 2000. Why are there global gradients in species richness? Mountains might hold the answer. Trends Ecol Evol, 15:513-514.

Kuimi T. Vashum and S. Jayakumar. 2012. Methods to Estimate Above-Ground Biomass and Carbon Stock in Natural Forests - A Review. *Journal of Ecosystem and Ecography*, *02*(04).

Lal, R. 2004. Soil carbon sequestration impacts on global change and food security. *Science, 304*: 1623-1627.

Lemlem Wondwossen Solomon, Noopol Arunrat, Thamarat Phutthai and Worachart Wisawapipat. 2024. Carbon stock potential of trees in selected urban un-conserved forest in Entoto Mount Forest, Addis Ababa, Ethiopia. *E3S Web of Conferences, 557.*

Lemmi Sisay Oumer. 2020. Woody Species Diversity, Biomass and Soil Carbon Stock along

Altitudinal Gradients And Topographic Aspects: The Case Of Kura- Chalte Natural Forest, Jimma Zone, Oromia Regional State, South West Ethiopia. Msc Thesis, Hawassa University, Hawassa, Ethiopia.

Liyew Birhanu, Getaneh Moges, Nigussie Amsalu and Heiko Balzter. 2025. Woody species diversity , structure and community distribution along environmental gradients of Seqela Dry Afromontane forest in Northwestern Ethiopia. *PLoS* ONE, *20*(1): e0313020.

López-López S. F., Martínez-Trinidad T., Garcia-Nieto M. and Santos- Posadas H. M. 2017. Non-destructive method for above-ground biomass estimation of Fraxinus uhdei (Wenz) Lingelsh in an urban forest. *Urban Forestry and Urban Greening 24*(1): 62-70.

Mahoo, H., Raden, M., Kinyangi, J. and Cramer, L. 2013. Climate change vulnerability and risk assessment of agriculture and food security in Ethiopia: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark, *59*: 1–294.

Malek-Mohammadi, S., Tachiev, G., Cabrejo, E. and Lawrence, A. 2012. Simulation of flow and mercury transport in Upper East Fork Poplar Creek, Oak Ridge, Tennessee. *Remediation*, *22*(2): 119–131. https://doi.org/10.1002/rem.21314.

Masek, J. G., Hayes, D. J., Joseph, M., Healey, S. P. and Turner, D. P. 2015. The role of remote sensing in process-scaling studies of managed forest ecosystems. *Forest Ecology and Management,* 355: 109–123.

Masresha Getnet and Melkamu Yirgalem. 2022. The Status of Dry Evergreen Afromontane Forest Patches in Amhara National Regional State, Ethiopia. *International Journal of Forestry Research*.

Mazarrasa, I., Marba, N., Garcia-Orellana, J., Masque, P., Arias- Ortiz, A. and Duarte, C.M., 2017. Effect of environmental factors (wave exposure and depth) and anthropogenic pressure in the C sink capacity of Posidonia oceanica meadows. *Limnology and Oceanography*, *62*(4): 1436–1450.

Melesse Assefa M. and Abtew W. 2016. GIS and Remote Sensing-Based Forest Resource Assessment, Quantification, and Mapping in Amhara Region, Ethiopia. Landscape Dynamics, Soils and Hydrological Processes in Varied Climate. 1–839. https://doi.org/10.1007/978-3-319-18787-7.

Mesfin Sahile. 2011. Estimating and mapping of carbon stocks based on remote sensing, GIS and ground survey in the Menagesha Suba state forest. MSc Thesis, Addis Ababa University, Addis Ababa, Ethiopia.

Michael Roswell, Jonathan Dushoff and Rachael Winfree. 2019. A conceptual guide to measuring species diversity. *Oikos, 128*(5): 659–667. https://doi.org/10.1111/oik.05876

Michel, D., Eriksson, M. and Klimes, M. 2021. Climate change and (in) security in trans and boundary river basins Handbook of Security and the Environment. *Edward Elgar Publishing*.

Mohammed Adefa and Giacomo Santini. 2017. A survey on species diversity, abundance and community structure of woody plants in burial sites in Gobeya Rural Administrative of Tehuledere District, South Wollo, Ethiopia. *Journal of Ecology and the Natural Environment*, *9*(4): 62-70.

Mohammed Gedefaw. 2015. Estimation of Above and Belowground Carbon Stocks of Forests: Implications for Sustainable Forest Management and Climate Change Mitigation: A Case Study of Tara Gedam Forest, Ethiopia. *Journal of Earth Science and Climatic Change*.

Moisa Mitiku Badasa, Dejene Indale Niguse, Deribew Kiros Tsegaye, Gurmessa Mengistu Muleta and Gemeda Desalegn Obsi. 2023. Impacts of forest cover change on carbon stock, carbon emission and land surface temperature in Sor watershed, Baro Akobo Basin, Western Ethiopia. *Journal of Water and Climate Change*, *14*(8): 2842–2860.

Molla Belay. 2016. Identification of Floristic Diversity and structure in Kurib Forest in Kurib Forest, Guagusa shekudad Woreda in Awi Zone of Amhara Region kurib forest.

Muluken Nega, Teshome Soromessa and Eyale Bayable. 2015. Carbon stock in Adaba-Dodola community forest of Danaba District, West-Arsi zone of Oromia Region, Ethiopia: An implication for climate change mitigation. *Journal of Ecology and the Natural Environment, 7*(1): 14-22.

Muluneh Melese Genete and Worku Belachew Bogale. 2022. Carbon storages and sequestration potentials in remnant forests of different patch sizes in northern Ethiopia: an implication for climate change mitigation. *Agriculture and Food Security*, *11*(1): 1-38.

Murshed, M., Dao, N.T.T. 2020. Revisiting the CO2 emission- induced EKC hypothesis in South Asia: the role of Export Quality Improvement. *GeoJournal*. https:// doi. org/ 10. 1007/ s10708- 020- 10270-9.

Nair, P. K. R., Nair, V. D., Kumar, B. M., and Haile, S. G. 2010. Soil carbon sequestration in tropical agroforestry systems: A feasibility appraisal. *Environmental Science, Policy.*12: 1099–1111

Nandal, A., Yadav, S. S., Rao, A. S., Meena, R. S. and Lal, R. 2023. Advance methodological approaches for carbon stock estimation in forest ecosystems: In Environmental Monitoring and Assessment. *Springer International Publishing*, 195(2).

Negasi Solomon, Emiru Birhane, Mulley Teklay, Aklilu Negussie and Tesfay Gidey. 2024. Exploring the role of canopy cover and environmental factors in shaping carbon storage in Desa'a forest, Ethiopia. *Carbon Balance and Management*, *19*(1). https://doi.org/10.1186/s13021-024-00277-x.

Negi, C.S. and S. Nautiyal. 2005. Phyto-sociological studies of a traditional reserve forest - Thal Ke Dhar, Pithoragarh, Central Himalayas (India). *Forest. 131*(4): 519-532.

NOAA (National Oceanic and Atmospheric Administration). 2024. Annual 2023 global climate Report. *Climate Change : Global Temperature*.

Norman, C. and Kreye, M. 2020. How Forests Store Carbon. *Penn State Extension*, 4–7.

Noulekoun, F., Birhane, E., Mensah, S., Kassa, H., Berhe, A., Gebremichael, Z.M., Adem, N.M., Seyoum, Y., Mengistu, T. and Hagazi, N. 2021. Structural diversity consistently mediates species richness effects on aboveground carbon along altitudinal gradients in northern Ethiopian grazing exclosures. *Science of the Total Environment*, 776: 145838

Ola, A. 2025. Multifunctional roles of forest ecosystem services in environmental sustainability and climate regulation. *Journal of Forestry Research, 14*: 555. https://doi.org/10.35248/2168-9776.25.14.555.

Pascal, A., Katherina, A. and Katrin, N. 2018. Tree species richness increases ecosystem carbon storage in subtropical forests. *Zurich Open Repository and Archive State Key Laboratory of Vegetation and Environmental Change, Institute of Botany.285*.

Pearson Timothy, Walker Sarah, Brown, and Sandra. 2005. *Sourcebook for Land use, Land*-use change and forestry Projects. Bosquet, Ringius.

Prajapati, S. K., Kumar, V., Dayal, P. and Srivastava, R. 2023. Carbon Sequestration : A key strategy for climate change mitigation towards a sustainable future. *Emerging Trends in Climate Change*, *2*(2): 1–14.

Rathod M.M. 2014. Vegetative species community, richness and diversity in Patnadevi Forest Maharashtra, India, *Journal of Environmental Research and Developmen*t.

Ravindranath, N.H. and Ostwald, M. 2008. Carbon inventory methods: Handbook for greenhouse gas inventory, carbon mitigation and round wood production projects Netherlands, *Springer. Science + Business Media*, 113-14.

Root, T., Price, J., Hall, K., Schneider, S., Rosenzweig, C. and Pounds, J. 2003. Fingerprints of obal warming on wild animals and plants. *Nature,* 421: 57–60.

Schettini, B. L. S., Jacovine, L., Eleto, C. M. M., Carneiro, A. C. O., Castro, R. V. O., Henrique, P. and Villanova, J. S. S. 2022. Use of Destructive and Non-Destructive Methodologies to Estimate Stem Biomass Accumulation and Carbon Stock in Eucalyptus Forest. *Revista Arvore*, *46*: 1–9.

Schroth, G., Fonseca, G.A.B., Havey, C.A., Vasconcelos, H.L. and Izac, A.M.N. 2004. Centre for Agriculture and Biodiversity in Tropical Land Scape Washington DC: Island Press.

Sebsebe, D., Friis, I. and Weber, O. 2011. Diversity and endemism of the flora of Ethiopia and Eritrea: state of knowledge and future perspectives. *Rendiconti Lincei*, *32*(4): 675–697.

Simegn Birhan Tessema. 2022. Analyzing the perceived prioritized forest ecosystem services under the participatory management: A case of Maksegnit District, Amhara Regional State, Ethiopia. *Trees, Forests and People*, *9* (August).

Simegn Tebebu Yelemfrhat and Bayable Tegene Eyale. 2014. Forest carbon stocks in lowland area of Simien Mountains National Park implication for climate change mitigation, *Science, Tech- nology and Arts Research Journal,* 3(3): 29–36.

Sintayehu Dejene Workeneh. 2018. Impact of climate change on biodiversity and associated key ecosystem services in Africa: a systematic review. *Ecosystem Health and Sustainability*, *4*(9): 225–239.

Singh, V., Tewari, A. and Kushwaha, D.V. 2011. Formulating allometric equations for estimating biomass and carbon stock in small diameter trees. *Forest Ecology and Management, 261*(11): 1945-1949.

Siraj Yimer Mammo. 2019. Forest carbon stocks in woody plants of Chilimo Gaji Forest, Ethiopia: Implications of managing forests for climate change mitigation. *South African Journal of Botany, 127*: 213-219.

Sisay Kibruyesfa, Thurnher Christopher, Belay Beyene, Lindne Gerland and Hasenauer Hubert. 2017. Volume and carbon estimates for the forest area of the amhara region in northwestern Ethiopia. *Forests*, *8*(4): 122.

Solomon, N., Birhane, E., Tadesse, T., Treydte, A. C. and Meles, K. 2017. Carbon stocks and sequestration potential of dry forests under community management in Tigray, Ethiopia. *Ecological Processes*, *6*(1). https://doi.org/10.1186/s13717-017-0088-2

Solomon Negasi, Opoku Pabi, Ted Annang, Isaac K. Asante and Emiru Birhane. 2018. The effects of land cover change on carbon stock dynamics in a dry Afromontane forest in northern Ethiopia. *Carbon Balance and Management*, *13*(1): 14. https://doi.org/10.1186/s13021-018-0103-7.

Swamy, S.L. and Tewari, V.P. 2017. Mitigation and Adaptation Strategies to Climate Change through Agroforestry Practices in the Tropics. *Universal Journal of Agricultural Research, 2*(8): 284–296.

Tadesse Woldemariam. 2015. GHG Emission Assessment Guideline Volume II: Aboveground Biomass Field Guide for Baseline Survey Federal Democratic Republic Of Ethiopia Ministry Of Agriculture Addis Ababa Ethiopia.

Tadesse Solomon and Aseffa Tekalign. 2019. Practices, challenges and opportunities of sustainable forest management in Nono Sele Woreda, Southwest Ethiopia. *International Journal of Current Research,* 11(05): 4172-4178.

Tamirat Ergogo. 2019. Woody species diversity and aboveground live carbon storage in different categories of Hunase natural forest. MSc Thesis, Jimma University, Jimma, Ethiopia.

Tang, R., Li, S., Lang, X., Huang, X. and Su, J. 2023. Rare species contribute greater to ecosystem multifunctionality in a subtropical forest than common species due to their functional diversity, *Forest Ecology and Management*, 538: 120981.

Tefera Mengistu, Demel Teketay, Hulten, H. and Yonas Yemshaw. 2005. The role of enclosures in the recovery of woody vegetation on degraded dry land hillsides of central and northern Ethiopia. *Journal of Arid Environments, 60*(2): 259-281.

Tefera Yirefu, Leulekal Erimias and Warkineh Bikita. 2024. Trees, Forests and People Composition and Structural Diversity of Woody Species in the Wof Ayzurish Forests, the Dry Afromontane Forest of the Northern Ethiopia. *Trees, Forests and People*, *16*(May): 100562.

Teklu Gebretsadik. 2016. Causes for biodiversity Loss in Ethiopia: A Review from conservation perspective. *Journal of natural sciences research*, *6*(11): 40.

Tesfaye, M. and Negash, M. 2018. Combretum-Terminalia vegetation accumulates more carbon stocks in the soil than the biomass along the elevation ranges of dryland ecosystem in Southern Ethiopia. *Jornal of arid environments*, *155*: 59–64.

Tesfay Atsbha Hailu. 2017. Woody Species Diversity and Carbon Sequestration Potentials of Gra-Kahssu Natural Vegetation in Southern Tigray, Ethiopia. MSc. Thesis, Haramaya University, Haramaya, Ethiopia

Thom, D., Golivets, M., Edling, L., Meigs, G.W., Gourevitch, J.D., Sonter, L.J., Galford, G.L. and Keeton, W.S. 2019. The climate sensitivity of carbon, timber, and species richness covaries with forest age in boreal–temperate North America. *Global Change Biology*, *25*(7): 2446–2458.

Thompson, I., Mackey, B., McNulty, S. and Mosseler, A. 2009. Forest Resilience, Biodiversity, and Climate Change: A synthesis of the biodiversity / resilience / stability relationship in forest ecosystems. Secretariat of the Convention on Biological Diversity, *Montreal*

Tian, P., Liu, Y. and Ou, J. 2023. Meta-analysis of the impact of future climate change on the area of woody plant habitats in China. *Frontiers in Plant Science*, *14*(March): 1–13. https://doi.org/10.3389/fpls.2023.1139739.

Tilahun Abiyou. 2018. Vegetation Ecology and Carbon Stock of Wof Washa Forest, North Shewa Zone, Amhara Region, Ethiopia. Doctoral dissertation, Addis Ababa University, Adiss Abeba, Ethiopia.

Tolesa Negese, Solomon Estifanos and Mengistu Mengesha. 2023. Comparison of Carbon Stocks along an Elevation Gradient in Furi Forest. *Central Ethiopia, Sustainability and Biodiversity Conservation*, *2*(1): 20–31. https://doi.org/10.5281/zenodo.8352342.

Tolla Tulu. 2010. Estimation of Carbon stock in church forests: Implications for managing church forests for carbon emission reduction. MSc. Thesis, Addis Ababa University, Adiss Abeba, Ethiopia.

Treut, L., Somerville, R., Cubasch, U., Ding, Y., Mauritzen, C., Mokssit, A. and Peterson, T. 2007. Historical Overview of Climate Change Science. *Earth*, *Chapter 1*: 93–127.

US EPA (United States Environmental Protection Agency). 2016. Inventory of U.S Greenhouse Gas Emissions and Sinks: 1990–2015. Report and Assessment.

Vashum, K. T. and Jayakumar, S. 2012. Review on Methods to Estimate Above-Ground Biomass and Carbon Stock in Natural Forests - A. *Journal of Ecosystem and Ecography*, *2*(04): 116.

Vorster, A. G., Evangelista, P. H., Stovall, A. E. L.and Ex, S. 2020. Variability and uncertainty in forest biomass estimates from the tree to landscape scale: The role of allometric equations. *Carbon Balance and Management*, *15*(1): 1–20

Wakawa, L. 2016. Biomass Estimation in Forest Ecosystems: A Review. *Journal of Research in Forestry, Wildlife and Environment*, *8*(2): 126–144.

Walker, S., Murray, L. and Tepe, T. 2016. Allometric equation evaluation guidance document. Winrock International, USA.

Walle Yibletal and Nayak Diptimayee. 2022. Factors determining the participation of natural resource cooperative members in forest management: A study of dry forest area in Ethiopia. *Trees*, *Forests and People*, *8*(1).

Ware Guduro Beriso. 2022. Climate change adaptation and mitigation measures in Ethiopia: Review. *International Journal of Agriculture and Food Science*, *4*(2): 40–46.

WCMC (World Conservation Monitoring Centre). 1994. Biodiversity Data Source book. World Conservation Press, Cambridge, UK.

Wodajo Asaminew, Mohammed Muktar and Tesfaye Mehari. 2020. Carbon stock variation along altitudinal and slope gradients in Gara–Muktar Forest, west Hararghe zone, Eastern Ethiopia, *Forestry Research and Engineering: International Journal*, 4(1).

Workayehu Baymot, Fitamo Daniel, Kebede Firew, Birhan Liyew and Fassil Amare. 2022. Floristic Composition, Diversity, and Vegetation Structure of Woody Species in Kahitassa Forest, Northwestern Ethiopia. *International Journal of Forestry Research 2022.*

Worku Hailu. 2017. Impact of physical soil and water conservation structure on selected soil physicochemical properties in Gondar Zuriya woreda. *Sci Acad publishing, 7*(2): 40-8.

Wossen Tesfaye, Tesfaye Kindie, Simane Belay and Ousman Yenus. 2021. Analysis of rainfall variability and trends for better climate risk management in the major agro-ecological zones in Ethiopia's northwestern region. *Research Square*, *10*(11): 1–23. https://ccafs.cgiar.org/donors.

Wu, D., Su, Y., Xi, H., Chen, X. and Xie, B. 2019. Urban and agriculturally influenced water contribute differently to the spread of antibiotic resistance genes in a mega-city river network. *Water Res,* 158: 11–21.

Yadav, V. S., Gupta, S. R., Meena, N. S. and Jhariya, M. K. 2022. Carbon sequestration potential and CO2 fluxes in a tropical forest ecosystem. *Ecological Engineering*.

Zegeye Haileab, Teketay Demel and Kelbessa Ensermu. 2011. Diversity and Regeneration Status of Woody Species in Tara Gedam and Abebaye Forests, Northwestern Ethiopia. ‖ *Journal of Forestry Research, 22*(3): 315–28. doi: 10.1007/s11676-011-0176-6.

Zelalem Teshager, Mekuria Argaw and Abeje Eshete. 2018. Variations in Forest Carbon Stocks along Environmental Gradients in Weiramba Forest of Amhara Region, Ethiopia:

Implications of Managing Forests for Climate Change Mitigation. *International Journal of Scientific and Engineering Research, 9*(3).

Zerihun Lakew Gebremariam. 2020. *Carbon Stock Estimation and Woody Species Diversity Along of public parks in Addis Abeba, Ethiopia*. Hawassa University

Zhang, J., Deng, L., Jiang, H., Peng, C., Huang, C., Zhang, M. and Zhang, X. 2021. The effects of elevated CO2, elevated O3, elevated temperature, and drought on plant leaf gas exchanges: A global meta-analysis of experimental studies. *Environmental Science and Pollution Research*, *28*(12): 15274–15289.

Zikargae Mekonnen Hailemariam. 2018. Analysis of environmental communication and its implications for sustainable development in Ethiopia. *Science of the Total Environment*, 634: 1593-1600.

7. APPENDIX

Appendix 1: list of species identified at lower altitude

Scientific Name	Family Name	Genus Name
Acacia abyssinica	Fabaceae	Acacia
Acanthus pubescens	Acanthaceae	Acanthus
Allophylus abyssinicus	Sapindaceae	Allophylus
Bersama abyssinica	Melianthaceae	Bersama
Calpurnia aurea	Papilionoideae	Calpurnia
Carissa edulis	Apocynaceae	Carissa
Clausena anisata	Rutaceae	Clausena
Combretum molle	Combretaceae	Combretum
Cordia africana	Boraginaceae	Cordia
Croton macrostachyus	Euphorbiaceae	Croton
Dodonaea angustifolia	Sapindaceae	Dodonaea
Dodonaea viscosa	Sapindaceae	Dodonaea
Dombeya torrida	Malvaceae	Dombeya
Dovyalis abyssinica	Flacourtiaceae	Dovyalis
Ekebergia capensis	Meliaceae	Ekebergia
Euphorbia tirucalli	Euphorbiaceae	Euphorbia
Ficus sur	Moraceae	Ficus
Ficus thonningii	Moraceae	Ficus
Ficus vasta	Moraceae	Ficus
Grewia ferruginea	Malvaceae	Grewia
Juniperus procera	Cupressaceae	Juniperus
Maytenus arbutifolia	Celastraceae	Maytenus
Millettia ferruginea	Fabaceae	Millettia
Myrsine africana	Myrsinaceae	Myrsine
Nuxia congesta	Buddleiaceae	Nuxia
Olea europaea	Oleaceae	Olea
Olea welwitschii	Oleaceae	Olea
Rhamnus staddo	Rhamnaceae	Rhamnus
Rhus glutinosa	Anacardiaceae	Rhus
Rhus vulgaris	Anacardiaceae	Rhus
Rosa abyssinica	Rosaceae	Rosa
Rumex nervosus	Polygonaceae	Rumex
Vernonia amygdalina	Asteraceae	Vernonia

Appendix 2: list of species identified at higher altitude

Scientific Name	Family Name	Genus Name
Olea welwitschii	Oleaceae	Olea
Rhus glutinosa	Rhamnaceae	Rhus
Nuxia congesta	Loganiaceae	Nuxia
Dodonia angustifolia	Sapindaceae	Dodonia
Rhamnus staddo	Rhamnaceae	Rhamnus
Schefflera abyssinica	Araliaceae	Schefflera
Rosa abyssinica	Rosaceae	Rosa
Rumex nervosus	Polygonaceae	Rumex
Vernonia amygdalina	Asteraceae	Vernonia
Grewa ferruginea	Malvaceae	Grewia
Allophylus abyssinicus	Sapindaceae	Allophylus
Cordia africana	Boraginaceae	Cordia
Euphorbia tirucalli	Euphorbiaceae	Euphorbia
Ficus sur	Moraceae	Ficus
Ficus thonningii	Moraceae	Ficus
Millettia ferruginea	Fabaceae	Millettia
Acacia abyssinica	Fabaceae	Acacia
Calpurnia aurea	Fabaceae	Calpurnia
Combretum molle	Combretaceae	Combretum
Dombeya torrida	Malvaceae	Dombeya
Osyris quadripartita	Santalaceae	Osyris
Croton macrostachyus	Euphorbiaceae	Croton
Carissa edulis	Apocynaceae	Carissa
Acanthus pubescens	Acanthaceae	Acanthus
Dovyalis abyssinica	Salicaceae	Dovyalis
Dodonaea viscosa	Sapindaceae	Dodonaea
Olea europaea	Oleaceae	Olea
Rhus vulgaris	Rhamnaceae	Rhus
Rhamnus staddo	Rhamnaceae	Rhamnus

Appendix 3: Species Composition and Structure summary data of Kulkal ber natural forest

No	Species Name	Freq.	BA	Density	Rela. Freq.	Rela. Density	Rela. Dominance	IVI
1	*Acacia abyssinica*	17.07	381.5	6.09	2.55	2.08	3.73	8.36
2	*Acanthus pubescens*	14.63	51.19	4.26	2.18	1.46	0.5	4.14
3	*Allophylus abyssinicus*	12.19	245.3	9.75	1.81	3.33	2.4	7.55
4	*Bersama abyssinica*	9.75	104.6	2.43	1.45	0.84	1.03	3.31
5	*Calpurnia aurea*	26.83	77.8	10.97	4	3.75	0.76	8.51
6	*Carissa edulis*	19.51	55.62	6.09	2.91	2.08	0.56	5.53
7	*Clausena anisata*	9.75	97.76	3.66	1.45	1.25	0.97	3.66
8	*Combretum molle*	43.9	477.2	22.56	6.55	7.72	4.69	18.93
9	*Cordia africana*	31.7	424.1	14.63	4.72	5	4.15	13.88
10	*Croton macrostachyus*	29.27	578.2	12.8	4.36	4.38	5.66	14.4
11	*Dodonaea viscosa*	14.63	398.7	8.53	2.18	2.92	3.9	9.1
12	*Dodonia angustifolia*	68.29	297.2	46.34	10.18	15.83	2.9	28.9
13	*Dombeya torrida*	14.63	240.1	4.87	2.18	1.67	2.35	6.19
14	*Dovyalis abyssinica*	7.31	45.51	2.43	1.09	0.83	0.44	2.36
15	*Ekebergia capensis*	7.31	370.8	3.04	1.09	1.04	3.63	5.76
16	*Euphorbia tirucalli*	12.19	420.9	3.65	1.8	1.25	4.12	7.18
17	*Ficus sur*	9.75	269.9	2.43	1.45	0.83	2.64	4.9
18	*Ficus thonningii*	12.19	725.8	3.04	1.81	1.04	7.17	9.97
19	*Ficus vasta*	12.19	368	4.87	1.82	1.67	3.64	7.9
20	*Grewa ferruginea*	19.5	202.9	5.48	2.91	1.87	1.98	6.77
21	*Juniperus procera*	2.43	254.3	0.61	0.36	0.21	2.49	3.06
22	*Maesa lanceolata*	2.4	28.26	0.6	0.36	0.21	0.27	0.88
23	*Maytenus arbutifolia*	19.51	41.6	5.48	2.91	1.88	0.4	5.19
24	*Millettia ferruginea*	29.26	384.5	18.29	4.36	6.25	3.76	14.37
25	*Myrsine africana*	2.43	84.87	1.2	0.36	0.42	0.83	1.61
26	*Nuxia congesta*	12.19	237	3.65	1.82	1.25	2.32	5.39
27	*Olea europaea*	17.07	603	4.26	2.55	1.46	5.91	9.91
28	*Olea welwitschii*	24.39	304.3	10.97	3.64	3.75	2.97	10.37
29	*Osyris quadripartita*	2.43	47.13	0.61	0.36	0.21	0.46	1.03
30	*Rhamnus staddo*	12.19	106.3	5.48	1.81	1.88	1.04	4.73
31	*Rhus glutinosa*	41.46	88.14	21.34	6.18	7.29	0.86	14.33
32	*Rhus vulgaris*	39.02	75.62	19.51	5.82	6.67	0.74	13.22
33	*Rosa abyssinica*	12.19	67.9	3.65	1.81	1.25	0.66	3.73
34	*Rumex nervosus*	7.31	47.62	1.82	1.09	0.63	0.46	2.18
35	*Schefflera abyssinica*	7.31	227.4	1.82	1.09	0.63	2.22	3.94
36	*Vernonia amygdalina*	17.07	524.9	5.48	2.54	1.87	5.13	9.56

Appendix 4: Synoptic Cover Abundance Values of Species in Each Community

Species	Community I	Community II	Community III
Ficus thonningii	**0.14**	0	0
Nuxia congesta	0.087	0	0
Carissa edulis	0.087	0	0
Ficus vasta	0.087	0	0
Combretum molle	0.13	0	0
Rhus vulgaris	0.087	0	0
Rhus glutinosa	0.087	0	0
Vernonia amygdalina	0.087	0	0
Dovyalis abyssinica	0.043	0	0
Olea europaea	0.087	**0.167**	0
Schefflera abyssinica	0.043	0	0
Croton macrostachyus	0.087	0.083	0
Grewia ferruginea	0.043	0	0
Maytenus arbutifolia	0.043	0	0.128
Myrsine africana	0.043	0.083	**0.25**
Allophylus abyssinicus	0.043	0	0
Ekebergia capensis	0.043	0	0
Millettia ferruginea	0.043	0	0
Dodonaea angustifolia	0.043	0	0
Calpurnia aurea	0.043	0.083	0
Clausena anisata	0	**0.167**	0
Rosa abyssinica	0	0.083	0
Olea welwitschii	0	0.083	0
Cordia africana	0	0.083	0
Rhamnus staddo	0	0.083	0
Dombeya torrida	0	0.083	0
Osyris quadripartita	0	0.083	0
Bersama abyssinica	0.043	0.083	0
Combretum molle	0	0.083	0
Ficus sur	0.043	0.083	0
Acacia abyssinica	0.015	0	0
Maesa lanceolata	0.043	0.083	0
Euphorbia tirucalli	0	0	**0.28**
Rumex nervosus	0	0	0.128
Acanthus pubescens	0	0	0.128
Dodonaea viscosa	**0.43**	0	0.2

Note: Bold values represent species with the highest mean cover-abundance values used in naming each community