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*Research Article*

# Effects of Environmental Factors on Carbon Stocks of Dry Evergreen Afromontane Forests of the Choke Mountain Ecosystem, Northwestern Ethiopia

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The purpose of this research was to quantify and compare carbon stocks in two selected dry evergreen montane forests of the Choke Mountain ecosystem that are under different management regimes. The study also attempted to assess the carbon stock along environmental gradients. The average carbon stock throughout the whole plots investigated in Anshirava forest (protected) was 180.18 $t{\cdot}ha^{-1}$ (53%) in AGB, 111.43 $t{\cdot}ha^{-1}$ (33%) in soil, 36.43 $t{\cdot}ha^{-1}$ (11%) in BGB, 6.09 $t{\cdot}ha^{-1}$ (2%) in USB, 2.69 $t{\cdot}ha^{-1}$ (1%) in litter, and 1.36 $t{\cdot}ha^{-1}$ (less than 1%) in DW. In Ziba forest (high human intervention), the average carbon stock was 106.71 $t{\cdot}ha^{-1}$ (44%) in AGB, 100.07 $t{\cdot}ha^{-1}$ (42%) in soil, 21.34 $t{\cdot}ha^{-1}$ (9%) in BGB, 5.41 $t{\cdot}ha^{-1}$ (2%) in USB, 4.82 $t{\cdot}ha^{-1}$ (2%) in litter, and 2.00 $t{\cdot}ha^{-1}$ (1%) in DW. The AGB had the greatest carbon share in both forests, followed by soil. In Anshirava and Ziba forests, the mean total carbon stocks (TCS) were 338.18 $t{\cdot}ha^{-1}$ and 240.36 $t{\cdot}ha^{-1}$, with $CO_2$ equivalents of 1241.14 $t{\cdot}ha^{-1}$ and 882.12 $t{\cdot}ha^{-1}$, respectively. The study indicated a significant variation between the two forests. Anshirava forest has larger total carbon stocks than Ziba forest. For lower, medium, and higher altitudes, the total carbon stock variation along an altitudinal gradient was 289.67 $t{\cdot}ha^{-1}$, 347.93 $t{\cdot}ha^{-1}$, and 414.89 $t{\cdot}ha^{-1}$ in Anshirava forest and 270.99 $t{\cdot}ha^{-1}$, 204.24 $t{\cdot}ha^{-1}$, and 224.82 $t{\cdot}ha^{-1}$ in Ziba forest, respectively. As a result, a greater amount of carbon was stored at higher altitudes in Anshirava and at lower altitudes in Ziba, with no significant difference in both forests. The total carbon stock variation along slope gradient was 392.60 $t{\cdot}ha^{-1}$, 344.59 $t{\cdot}ha^{-1}$, and 295.49 $t{\cdot}ha^{-1}$ in Anshirava forest and 258.74 $t{\cdot}ha^{-1}$, 222.46 $t{\cdot}ha^{-1}$, and 171.46 $t{\cdot}ha^{-1}$ in Ziba forest for flat, intermediate, and steep slopes, respectively. This resulted in higher carbon being stored in flat slopes in both forests. Also, only at the Ziba site, a significant difference was found along the slope gradient. In each forest, eight distinct aspect facings were observed, with the western (W) aspect containing the highest value of total carbon stock in both forests. Lower values, on the other hand, were recorded in the south (S) and flat (F) aspects of Anshirava and Ziba forests, respectively. The slope aspects of both forests varied significantly. As a result, the research reveals that environmental factors have a significant impact on carbon stock value of Choke Mountain forest ecosystem, but the impact is not consistent among carbon pools.

## 1. Introduction

Nature has supplied us with natural carbon sinks just like the terrestrial environment and the oceans. Forest ecosystem is one of the maximum essential carbon sinks of the terrestrial ecosystem. Through the process of photosynthesis, trees, shrubs, and other vegetation components of the forest ecosystem take up the carbon dioxide from the atmosphere and store in their biomass, forest litter, and soil [1]. Forest ecosystems cover approximately 4.1 billion hectares globally

[2], and they play a major role in international carbon (C) cycle [2, 3] due to the fact that they store 80% of the worldwide aboveground C of the plants and approximately 40% of the soil C and have interaction with atmospheric processes via the absorption and respiration of $CO_2$ [4–6]. Tropical forests preserve huge stores of carbon [7] and play a prime role in the global carbon cycle, storing as much as 46% of the world's terrestrial carbon pool and approximately 11.55% of the world's soil carbon pool, performing as a carbon reservoir, and functioning as a regular sink of atmospheric carbon [8–11]. The overall forest ecosystem C inventory is huge and in dynamic equilibrium with its environment. Because of the wide areas involved at regional/international scale, woodland soils play an essential position in the global C cycle [12–15].

Atmospheric carbon dioxide has been growing progressively since 1958 [16]. The concentration of atmospheric carbon dioxide ($CO_2$), which is the essential constituent of GHG, has accelerated from 278 ppm in 1970 to 379 ppm in 2005 at an average of 1.9 ppm per year [17, 18]. According to Vashum and Jayakumar [1], the growing level of carbon dioxide in the atmosphere is particularly because of anthropogenic activities. In the 19th century, with the appearance of commercial revolution, human beings were burning a large quantity of fossil fuels, releasing the carbon saved in it that returned back into the atmosphere as carbon dioxide. Other human activities including deforestation actually have a great effect at the capacity of the terrestrial biosphere to emit or eliminate carbon dioxide from the atmosphere. Deforestation results in emission of carbon dioxide via burning of vegetation's biomass and decomposition of plant components and soil carbon. This degradation of forests has increased and contributed to a long-time period upward push in atmospheric carbon dioxide level. As a result, the natural stability of carbon dioxide sequestration and release that take place between sink and sources has been disturbed, and the yearly worldwide net emission exceeds the yearly sequestration resulting in unnatural gradual accumulation of greenhouse gases in the atmosphere and consequently causes climate change [19–23].

With the growing concern about the upward push in atmospheric carbon dioxide ($CO_2$) concentration and its implications for global climate, the function of tropical forest management in mitigating $CO_2$ emissions is receiving attention [24]. According to Deo [18], the quantity of carbon stored in the biomass has received special attention as a result of the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol. Under these agreements, countries are required to estimate and document $CO_2$ emissions and removals by forests. Therefore, understanding the function of terrestrial ecosystems in the global carbon (C) cycle has come to be increasingly essential, as policy makers take into account alternatives to cope with the problems related to global climate change [25–27]. Thus, figuring out the quantity of changes in vegetation biomass has come to be crucial for understanding the global C budget, such as the amount of $CO_2$ produced through burning of fossil fuels and forest clearing [12, 28] and management of existing carbon pools on the terrestrial ecosystem to mitigate $CO_2$ emission [4]. According to Munishi and Shear (2004), understanding the forest carbon inventory is also essential to become aware of and enhance natural sinks for carbon sequestration to mitigate the climate change. Therefore, this study aimed towards investigating the carbon stock of the forest vegetation in keeping with its environmental factors.

The global carbon cycle is influenced by biomass and carbon. Assessments of the magnitude of these sources and sinks necessarily require accurate estimates of forest biomass density and change over time [25]. However, reliable estimates are scarce [25]. The same is true that assessment and quantification of the carbon stock of forests are inadequate in Ethiopia as well as in the study area. As mountainous areas cover approximately 24 percent of total global land area [29] and there have been rapid climate changes in mountain areas throughout the past few decades [17], understanding shifts in forest carbon storage and allocation along altitudinal gradients in mountain regions will allow us to better predict regional and global carbon balance responses to future climate change. The forests of the Choke Mountain ecosystem play a complex and necessary role in the day-to-day life of the surrounding community. However, it is hard to obtain information on amount of carbon stock of the study area.

As a result, the proposed study will fill this gap by providing a quantitative description of the study area's carbon stock and evaluating its distribution along different environmental gradients. Therefore, the objectives of this study are (1) to assess and compare the carbon stocks of two high-biomass forests in the ecosystem that were managed differently, (2) to estimate the carbon stocks of two high-biomass forests in different pools, (3) to evaluate forest biomass and soil carbon stocks along an altitudinal gradient, (4) to determine the effect of slope on forest biomass and soil carbon stocks, (5) to analyze the effect of aspect orientation on forest biomass and soil carbon stocks, and (6) to provide baseline information for future forest management.

## 2. Methodology

### *2.1. Description of the Study Area*

*2.1.1. Location and Topography.* This research was carried out in the Choke Mountain Ecosystems of Amhara National Regional State in northwestern Ethiopia. Choke Mountain and its associated watersheds are located in Ethiopia's Blue Nile Highlands region [30] (Figure 1). Despite its location in the Ethiopian Highlands and a peak elevation of more than 4000 m, the mountain's watersheds drain in three directions to the Blue Nile Gorge, where elevation drops to less than 1000 m, within a radius of less than 70 kilometers [31]. The area is located at 9° to 11°N and 37° to 38°E. Over a shorter distance, one can find hot, dry valleys, gently rolling, deeply soiled midland plains, and cool, wet alpine zones. Because of the complexity of the topography, there are strong local gradients in precipitation, temperature, and soil properties [32]. Choke Mountain is the region's water tower, serving as

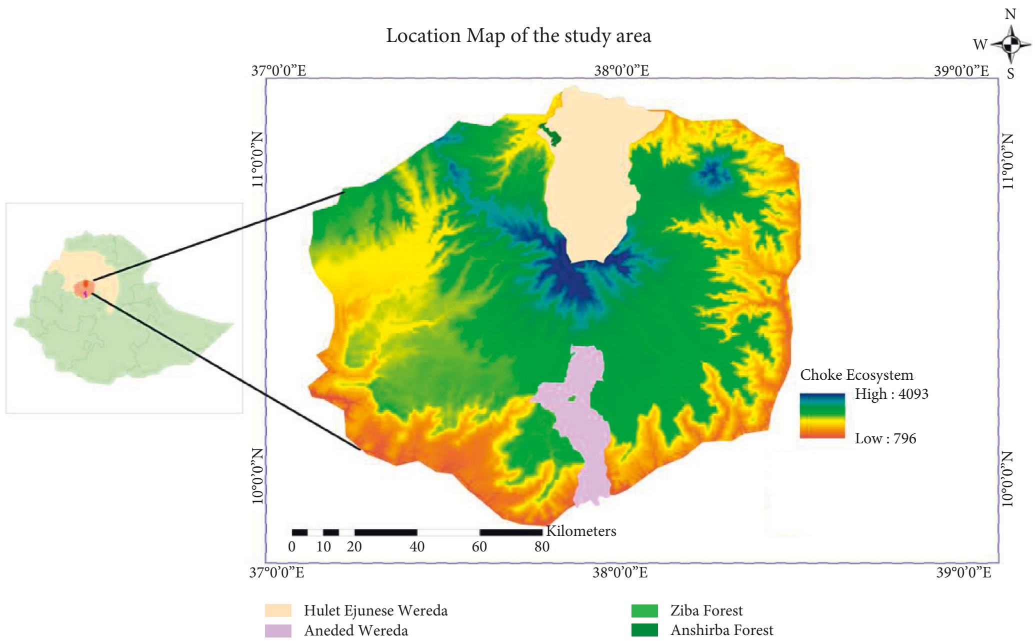


Figure 1: Location map of Choke Mountain ecosystem.

the upper Blue Nile basin's headwater. This mountain range is the source of the majority of Blue Nile river tributaries. These mountains are the source of four major rivers: Muga, Chemoga, Abeya, and Techma, as well as numerous smaller tributaries of the Blue Nile (Abay) [33].

Friis et al. [34] defined the afroalpine and subafroalpine zones as being higher than 3,200 m.a.s.l. on average. The dry evergreen montane forest is a very complex vegetation type found in an altitudinal range of 1500–2700 m. As a result, the Choke Mountain ecosystem is divided into two ecosystems: afroalpine and subafroalpine ecosystems, as well as dry evergreen ecosystems.

*2.1.2. Climate.* The majority of rain falling season of Choke Mountain ecosystem is between May and October [31]. The average annual precipitation ranges from 600 to 2000 mm·year$^{-1}$, with significant local variability due to topographic gradients. Precipitation events are convective in nature and are characterized by short, sometimes intense erosive bursts with notably large raindrops [35]. Precipitation distribution across the mountain is also not uniform. The western slopes are typically wetter than the eastern slopes, with the Blue Nile Gorge having the driest conditions. For instance, the areas where the studied forests were found, Hulet Eju Enesie and Aneded district, receive a mean annual rainfall of 1144.8 mm and 1031.2 mm, respectively (ARMA, 2019 (Amhara region meteorology agency data. Unpublished. East Gojjam Zone, Ethiopia)). Since the average annual temperature and rainfall vary with elevation, the annual temperature of the ecosystem ranges from 7.5°C to 28°C on average [31].

*2.1.3. Soil.* Existing soil types are volcanic in origin, derived from Mio-Pliocene shield volcano lavas and, at lower elevations, Oligocene flood basalts [36]. Types of soil dominate in the area are Leptosols, Cambisols, Vertisols, Nitosols, Alisols, Luvisols, Andosols, and Phaozems which support range of agricultural uses [32, 37, 38]. Under undisturbed conditions, soils tend to be deep: natural depths can extend to several meters, with rooting depths in this portion of the Ethiopian Highlands extending to one meter. These deep, weathered tropical soils are highly susceptible to erosion [39].

*2.1.4. Agriculture and Vegetation.* Subsistence farming with a low-input mixed crop-livestock agriculture dominates the ecosystem, with cultivation stretching from the Blue Nile Gorge to nearly the mountain's summit, practiced by independent farmers on small plots [32]. Choke Mountain watershed farms have an average size of 0.5 hectares [40, 41]. Sorghum, maize and teff, durum wheat, barley, chickpea, a variety of pulses, and potatoes are all growing in accordance with their agroecological system [32, 37]. Cows, oxen, sheep, and horses are among the animals found in the area. Overgrazing and deforestation have also contributed to the area's erosion and soil fertility decline [31].

The area was historically known for dense forest but now it is highly degraded with overgrazing and crop cultivation and the only few forests observed within the ecosystem [31, 40]. The major remaining natural habitats are moisture moorland, sparsely covered with giant lobelia Jibbra (*Lobelia* spp.), lady's mantle (*Alchemilla* spp.), Guassa grass (*Festuca* spp.), and other grasses [40]. The species *Juniperus procera, Erica arborea, Hagenia abyssinica, Hypericum revolutum, Olea europaea, Oxytenanthera abyssinica, Acacia* spp., *Prunus africana, Arundinaria alpina, Erythrina brucei* (commonly grown as border demarcation plant), and *Eucalyptus globulus* are the dominant Spps. grown in plantation, and some of the residents have become dependent on it for their livelihoods [37, 40].

*(1) The Vegetation of the Studied Forests.* According to Friis [42] criteria, Ziba forest is categorized under the dry evergreen afromontane forest in Ethiopia's northwestern highlands. It covers a total area of 362 ha and is composed of natural forest and established plantation forest (Table 1). Of this, 1793 ha are plantation forest with exotic and indigenous tree species in monoculture and mixed forms, while 1461 ha are natural forest. The Ziba natural forest's vegetation is dominated by *Cupressus lusitanica, Acacia abyssinica, Albizia gummifera, Maytenus obscura, Vernonia amygdalina, Nuxia congesta, Rosa abyssinica, Maytenus arbutifolia, Rhus glutinosa, Buddleia polystachya, Carissa spinarum*, and *Juniperus procera* tree and shrub spp. (Self-Survey, 2021). Plantation efforts have been carried out by various exotic and native tree species in and around the Ziba natural forest region since the Derg regime in the 1970s, according to information obtained from community and expert interviews. However, despite the fact that they assign a skimpy guard, Ziba forest has recently undergone anthropogenic disruptions due to human and animal encroachment. Not only is planting frequent in the forest but so is the harvesting of old trees, particularly by local youngsters for the sake of charcoal and lumber manufacture. The government organizes harvesting and planting activities. In contrast, Anshirava forest is a protected natural forest that has been closed since the Derg government in the 1970s. Initially, it was protected by the government and more recently by guards hired by the community. The local communities are allowed to use only the dead woods and the litterfall from the forest. The forest area is around 1300 ha (Table 1). The forest is dominated by *Dodonaea viscosa*, *Juniperus procera*, *Vernonia amygdalina*, *Rosa abyssinica*, *Mimusops kummel*, *Acacia abyssinica, Carissa spinarum, Dombeya torrida, Erythrococea trichogyne*, and *Maytenus arbutifolia* tree and shrub species (Self-Survey, 2021).

*(2) Reconnaissance Survey and Sampling Design.* A reconnaissance study was undertaken in the dry evergreen montane forest ecosystem of the mountain range to gather baseline information, assess vegetation distribution, and identify possible sampling sites as well as to decide the number of transect lines to be laid across the forests. Based on their level of management, two natural forests (Anshirava and Ziba) were selected from the dry evergreen montane forest ecosystem. Anshirava forest is well protected, and Ziba forest has a high level of human interference. The forests' altitudinal range and area coverage were then determined. For boundary demarcation, GPS tracking was employed, and then eight and seventeen transect lines were set following elevation gradients in Ziba and Anshirava forests, respectively. These lines radiate from the mountain's summit in a number of different directions, each with a different number of plots depending on the length of the transect line. 20 m ∗ 20 m sample plots were placed every 200 meters in Ziba forest and every 400 meters in Anshirava forest in each transect line. The first plots in each transect were placed 50 meters away from the edge to avoid the edge effect.

Table 1: Stand characteristics of the studied forests (source: Author 2021).

| Study site | Anshirava forest | Ziba forest |
|---|---|---|
| Mean annual rainfall (mm) | 1144.8 | 1031.2 |
| Area (ha) | 1300 | 362 |
| No. of tree spp. | 47 | 33 |
| Age of the stand (yrs) | | 35 |
| Average tree height (m) | 13.37 | 16.91 |
| Average tree DBH (cm) | 32.46 | 31.50 |
| Density (trees/ha) | 340.52 | 494.27 |
| Mean basal area ($m^2$/ha) | 44.58 | 29.2 |

Both forests are found in the Choke Mountain ecosystem. Specifically, the Anshirava forest is found in Hulet Eju Enesie district, Amhara Region, Ethiopia. It is located 370 kilometers northwest of Addis Ababa, 200 kilometers northeast of Debre Markos, and 120 kilometers southeast of Bahir Dar. It is bounded on the east by Goncha Siso Enesie, on the south by Enarge Enawega, on the southwest by Debay Telate, on the west by Sinan Bibugne, and on the north by South Gondar. The elevation ranges from 1290 to 4036 meters above sea level [43], with temperatures ranging from 13°C to 28°C with an annual rainfall of 1144.8 mm (see Figures 2 and 3) (ARMA, 2019). Agroecologically, the district is divided into three areas: 52 percent midland, 18 percent highland, and 30 percent lowland [43]. Agricultural crops account for 71.85 percent of the total land area, and agriculture is the primary source of livelihood for the inhabitants [44]. Ziba forest is located in Aneded district, which is one of the woredas of Ethiopia's Amhara Region. Aneded, which is part of the Misraq Gojjam Zone, is bounded on the south by the Abay River, which divides it from the Oromia Region, on the north by Sinan, on the east by Awabel, on the southwest by Baso Liben, and on the northwest by Guzamn. The district is located 283 km away from Addis Ababa, Ethiopia's capital city, 305 kms from Bahir Dar, the capital city of the Amhara Region, and 40 kms from Debre Markos, the capital city of the East Gojjam Zone [45]. The site has an altitude range of 1663–2570 meters above sea level [46] with a temperature of 11°C–28°C and a mean annual rainfall of 1031.2 mm per year (ARMA, 2019) (Figures 2 and 3). Agroecologically, the district has 3.3 percent highland, 81.1 percent midland, and 15.6 percent lowland [46]. According to the two districts' agricultural office report, both districts are characterized by subsistence mixed farming of rain-fed crops and animal production, along with tree plantation and management systems. Teff, maize, wheat, millet, beans, peas, and oil crops are commonly cultivated in the districts.

*(3) Sample Plot Design.* There are varieties of sample plot designs that are applicable in forest inventory for the purposes of biomass or carbon assessments. The two general designs are single plot design, which is appropriate for monoculture plantations which are homogenous in tree size and distribution and are in most cases single story, and nested plot designs, which are suitable for inventory in natural forests where tree size, distribution, and structure are variable. Forest carbon assessments usually use nested plot designs that present variable size subplots for the

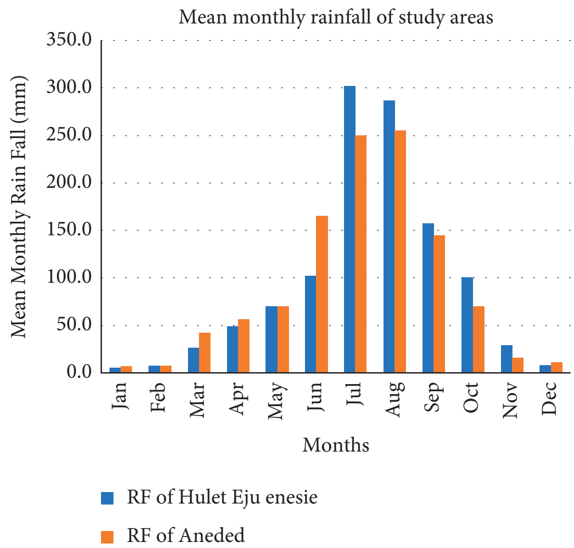


Figure 2: Mean monthly rainfall of the study areas. Source: ARMA (2019) for climatic data.

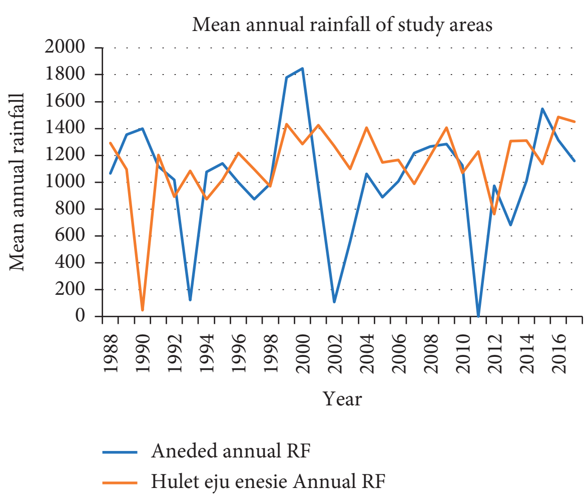


Figure 3: Mean annual rainfall of the study areas. Source: ARMA (2019) for climatic data.

different tree size classes and also for the different forest carbon pools [47, 48]. Thus, based on the vegetation and topographic variability, a nested plot design was used. So, the major plot 20 m ∗ 20 m was laid as it is used by different researchers [49–51]. Totally, 58 major plots in Anshirava forest and 48 major plots in Ziba forest were laid. The difference in number of plots is due to the difference in the size of the forests. Since the Ziba forest is smaller than the Anshirava forest in size, the transect lines to be laid were minimized. In each major quadrate, all woody plants which are ≥5 cm DBH and height >1 m were botanically identified, measured, and recorded. Then, one 5 m × 5 m plot for shrubs and five subplots (1 m × 1 m) within each corner and one at the center were laid inside the major plot to gather soil, litter, and vegetation sample on grasses and herbaceous plants (Figure 4).

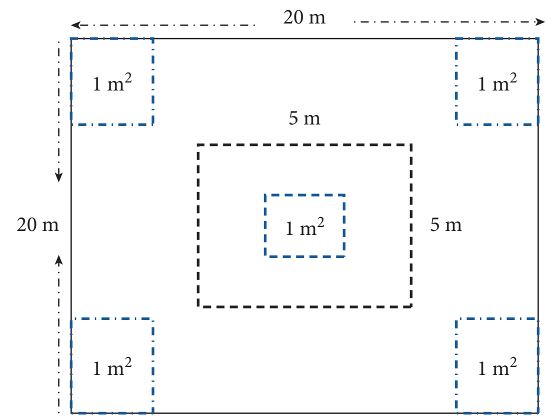


Figure 4: Sampling design used in data collection.

### 2.2. Data Collection

*2.2.1. Method of Data Collection.* The data were gathered from both primary and secondary sources. The primary data were collected through identification of tree species and field measurements to estimate carbon stock of the soil and vegetation of the study area. Carbon stock was estimated by using standard carbon inventory principles and techniques [48, 52]. The procedures were based on data collection and analysis of carbon stocks in aboveground biomass, belowground biomass, leaf litter, dead wood, and forest soil carbon. Secondary data such as meteorological data and other information that describe the forest sites were gathered from a variety of sources, including books, journals, published and unpublished materials, prior research studies, and electronic websites.

*2.2.2. Vegetation Data Collection and Identification.* Garmin GPS was used to measure altitude and geographical coordinates in the midst of the major plots. The diameter was measured using a caliper, and the total height of individual trees was measured using a Suunto hypsometer, whereas smaller individuals with a height of <10 m were directly measured using a marked stick. Skovsgaard [53] recommended that direct measurement is practical only for trees shorter than 10–15 m. All individuals of trees and shrubs with a diameter at breast height (DBH) of ≥5 cm and height of >1 m were measured for DBH and height in each plot. Individuals with height ≤1 m and DBH <5 cm were counted as seedlings, and plants with height >1 m and DBH <5 cm were counted as saplings. Plants with multiple stems below 1.3 m height were treated as a single individual. The DBH of all the stems was measured, and then the average of the diameter was used for basal area calculation. If a tree is buttressed and abnormal at 1.3 m, the diameter was measured just above the buttress where the stem assumes near-cylindrical shape.

The diameter and height of stumps in the main plot were measured using a diameter tape and measuring tape, respectively. The stumps were identified to the species level. If it is difficult to identify the species, local people were asked for the local name of the species and then that name was checked in botanical books. Plant species identification was made in the field using azene [54]. Voucher specimens of plant species difficult to identify in the field were collected, pressed, and identified in the National Herbarium of Ethiopia, Addis Ababa University. The nomenclature of plant names was done following different volumes of the published Flora of Ethiopia and Eritrea [55–62].

*2.2.3. Biomass and Carbon Stock Data Collection.* Carbon stock was measured in the following five pools: aboveground biomass, belowground biomass, litter, dead wood, and soil.

*(1) Aboveground Biomass Measurement.* Aboveground biomass carbon of trees (AGBC): first, the dominant species (≥5 cm DBH) was identified and then diameter at breast height (DBH) was measured using calipers and height of trees was measured using Suunto clinometers in the major plots. In addition, species type was recorded as this can help improve the estimates of wood density. Understory biomass carbon (USBC): fresh weight of all the undergrowth (<5 cm DBH) was measured and a small sample of (300 g) weight was taken for subsequent oven-drying.

*(2) Belowground Biomass Carbon (BGBC).* It was estimated using root-to-shoot ratio (4 : 1), using a conversion factor as it is recommended by Noordwijk and Mulia [63].

*(3) Dead Wood Carbon (DWC).* The dead organic matter pool (necromass) includes dead fallen trees, other coarse woody debris, litter, and charcoal (or partially charred organic matter) above the soil surface [19]. All trunks (unburned part), dead standing trees, dead trees on the ground, and stumps were sampled that have a diameter of >5 cm and a length of >0.5 m. Their height (length) and diameter (halfway the length included) were recorded. The type of wood was identified for estimating specific density.

*(4) Litter Carbon (LC).* Litter was collected in two steps by establishing 0.5 m ∗ 0.5 m quadrants in 1 m ∗ 1 m subplot and weighed. Any tree necromass <5 cm diameter and/or <50 cm length, nondecomposed plant materials or crop residues, all unburned leaves and branches, roots, and partly decomposed dark litter were collected in 0.5 m × 0.5 m quadrants (0.25 $m^2$), on a randomly chosen location (in the same plot where understory sample was taken). All nondecomposed materials were collected to a sample handling location.

*(5) Soil Carbon Stock.* Soil samples were taken from four corners and one from the center of main plot at three different depths (0–15 cm, 15–30 cm, and 30–45 cm) by using a soil coring auger. Then, the samples were pooled with their corresponding depth, and 0.5 kg composite soil sample from each plot was taken for the organic carbon (%OC) test. Additionally, separate representative soil samples were collected from each plot at 0–15 cm, 15–30 cm, and 30–45 cm using a 10 cm diameter core sampler for bulk density (BD) measurement.

*2.3. Data Analysis.* The data collected through field measurement were calculated through their respective allometric equations and subjected to statistical analysis.

*2.3.1. Basal Area.* Basal area of each woody plant species that have DBH ≥5 cm was computed using the following formula because there is direct relationship between DBH and basal area [64–66].

Basal area was calculated using the following formula:

$$\mathrm{BA} = \pi\left(\frac{\mathrm{DBH}}{2}\right)^2, \tag{1}$$

where BA is basal area, $\pi$ is 3.14, and DBH is diameter at breast height (at 1.30 m). Then, the value will be changed to $m^2$.

*2.3.2. Biomass Estimation and Carbon Stock Determination*

*(1) Aboveground Biomass.* AGB of trees: equations are different for different forest types. The following allometric equation is developed for trees having 5–156 cm DBH, which is used by many studies and has been the best general model for carbon stock assessment in Africa [67]. Based on this reason, the following equation which is developed by Chave et al. [68] and subjected for dry forests was selected for this study:

$$\mathrm{AGB}\,(\mathrm{kg}) = 0.0673 \times \left(\rho D^2 H\right)^{0.976}, \tag{2}$$

where AGB is the aboveground biomass of trees, H is the tree height (m), $D$ represents DBH (cm), and $\rho$ represents wood density (g/$cm^3$).

While DBH and tree height were directly measured, wood density of species was also obtained from [69] and the Global Wood Density database [70]. The authors also suggested that, for species with no wood density, the average wood density value (0.612) of the known species was utilized.

*(2) Understory Vegetation Biomass (USB).* All vegetation in the quadrant was cut and weighed immediately in the field to get fresh weight (FW) (kg/0.25 $m^2$). The leaves and stem were separated prior to obtaining subsamples, and the fresh weight of each would be measured. Before taking subsamples, all samples were chopped and mixed well. Then, a known weight of subsample (300 g) was taken from each and placed in a paper bag. For 48 hours, the subsample was put in an oven set to 85°C. The dry weight (DW) of the leaves and stem was then measured and computed as shown in the study of Hairiah et al. [52].

$$\mathbf{USB}\left(\mathrm{kg/m^2}\right) = \left(\frac{\mathrm{TFW\ (kg)}}{A} \times \frac{W\mathrm{subsample,\ dry\,(g)}}{W\mathrm{subsample,\ wet\,(g)}}\right), \tag{3}$$

where USB = understory vegetation biomass, TFW = total fresh weight, *W*subsample, dry = weight of the oven-dried subsample of the biomass (g), *W*subsample, wet = weight of fresh subsample of the biomass (g), and $A$ = size of the area in which the fresh biomass is collected.

*(3) Belowground Biomass (BGB).* Belowground biomass is also computed using the default values for the root-to-shoot ratio of 1 : 5 [71]. According to the abovementioned author, the following equation was employed to calculate belowground tree biomass:

$$\text{belowground tree biomass} = \text{AGB} * 0.2. \quad (4)$$

Since the research location is in the tropical zone, the carbon content in the biomass was calculated by multiplying 0.47, as suggested by IPCC Guidelines for National Greenhouse Gas Inventories [72], because dry biomass in the tropical and subtropical regions contains 47 percent organic carbon, which is widely accepted and used by different researchers [49, 73–76]. Also, the multiplication factor 3.67 was used to calculate $CO_2$ equivalent [77]. Total AGB and BGB carbon were determined for each quadrat by adding the carbon obtained from all trees. Carbon stocks were calculated for each quadrant and extrapolated to ton per hectare.

*(4) Dead Wood Carbon.* The biomass of dead wood was calculated using the following equation: as live trees, an allometric equation was employed for the dead trees with branching structures. For dead wood with unbranched cylindrical structures, an equation based on cylinder volume was used:

$$\text{biomass} = \frac{\pi D^2 h \rho}{40}, \quad (5)$$

where biomass is expressed in kg, $h$ represents length (m), $D$ represents tree diameter (cm), and $\rho$ represents specific gravity ($g{\cdot}cm^{-3}$) of wood.

The wood density is estimated at $0.612\,g{\cdot}cm^{-3}$ as the default value, as suggested by the UNFCCC [69], and is comparable to the average value recorded for wood density of trees in Africa, which ranges between 0.58 and $0.67\,g{\cdot}cm^{-3}$ [67]. The carbon content of dead wood was determined by multiplying total dead wood biomass by the default carbon fraction of 0.47 as suggested by the IPCC Guidelines for National Greenhouse Gas Inventories [72].

*(5) Litter Carbon.* Coarse and fine litter including dead roots and live root material were collected. After the coarse and fine litter collection measuring was done on the site, a known weight (300 g) subsample was obtained for oven-drying (oven at 80°C). The total dry weight was then calculated using the following equation:

$$\text{TDWL}\left(\text{kgm}^2\right) = \frac{\text{total fresh weight (kg)} * \text{subsample dry weight (g)}}{\text{subsample fresh weight (g)} * \text{sample area}\left(\text{m}^2\right)}, \quad (6)$$

where TDWL is the total dry weight of litter, and the carbon content is estimated to be 50% of the litter's dry mass [78]. As a result, the estimated carbon content was proportionately converted to the 1 m ∗ 1 m subplot and subsequently to hectare levels.

*(6) Soil Carbon Stock Analysis.* A 100 g composite soil sample was placed in clothed bags, labeled, and brought to the laboratory, where it was air dried, ground, and sieved through a 2 mm sieve. Then, SOC was determined by the wet oxidation method of Walkley and Black [79] as outlined in the study of Juo [80]. The representative soil sample taken by using a core sampler from each layer was weighed and put on an oven at 103°C for 24 hours. Soil bulk density was determined by using the core-volume method by dividing the weight of oven-dry soil in the core (g) to the volume of the soil in the core ($cm^3$). Soil carbon stocks (SCS) of 0–15 cm, 15–30 cm, and 30–45 cm soil layers were worked out separately as follows:

$$\text{SCS} = \%\text{OC} \times \text{BD} \times \text{depth}, \quad (7)$$

where SCS ($t{\cdot}ha^{-1}$) is the soil carbon stock of the sample plot, % OC represents carbon concentration (%), and depth (cm) is the depth at which the sample was taken.

Then, the data for the three depths were later pooled to represent SCS ($t{\cdot}ha^{-1}$) of 0–45 cm soil layer. Also, soil carbon stocks within each sample plot were calculated and converted to area bases.

*(7) Total Carbon Stock.* Finally, the total organic carbon stock in the forest was calculated as follows:

$$\text{TCS}\left(t \cdot ha^{-1}\right) = \text{AGBC} + \text{BGBC} + \text{USBC} + \text{DWC} + \text{LC} + \text{SCS}, \quad (8)$$

where TCS is the total carbon stock in the forest, AGBC is the total carbon in the aboveground biomass, BGBC is the total carbon in the belowground biomass, USBC is the total carbon stock in the understory biomass, LC is the total carbon stock in the litter, DWC is the total dead wood carbon, and SCS is the total carbon in the soil. Then, the total carbon stock was converted to $t{\cdot}ha^{-1}$ of $CO_2$ equivalent by multiplying it with 44/12 [71].

*2.4. Statistical Analysis.* All data were arranged for each study site. Then, Microsoft Office Excel 2010 and Paleontological Statistics software package for education and data analysis (PAST version 3.22) were used for descriptive statistics, graphs, and charts. In addition to this, analysis of variance (ANOVA) was employed by using OriginPro 8 version 8.0725 statistical software to analyze the difference of the means between the two sites. Multivariate analysis of variance was done by using SPSS statistical software version 25.0 to analyze the relationship between geographical factors and carbon stock in different pools. Finally, Tukey's honestly significant test at a $P$ value of <0.05 significant level was employed for mean comparisons.

## 3. Result

### 3.1. Carbon Stock Potential of the Ecosystem

*3.1.1. Carbon Stock in the Aboveground and Belowground Biomass.* The minimum value for AGB carbon stock recorded per tree species was in *Ricinus communis* and *Grewia ferruginea* in Anshirava and Ziba, respectively, while the maximum value was recorded for *Juniperus procera and Cupressus lusitanica tree* spp. in Anshirava and Ziba, respectively. The mean aboveground biomass carbon stock per tree was $3.82 \pm 1.77\,\mathrm{t{\cdot}ha^{-1}}$ in Anshirava forest and $4.92 \pm 1.98\,\mathrm{t{\cdot}ha^{-1}}$ in Ziba forest. Trees in the study sites captured on average 0.76–0.98 $\mathrm{t{\cdot}ha^{-1}}$ of carbon stock in their belowground biomass (Tables 2 and 3).

The average carbon stock in aboveground biomass was $180.18 \pm 17.19\,\mathrm{t{\cdot}ha^{-1}}$ in Anshirava forest and $106.71 \pm 7.64\,\mathrm{t{\cdot}ha^{-1}}$ in Ziba forest. Also, the mean carbon stock captured in the belowground biomass was $36.43 \pm 25.83\,\mathrm{t{\cdot}ha^{-1}}$ in Anshirava forest and $21.34 \pm 10.59\,\mathrm{t{\cdot}ha^{-1}}$ in Ziba forest (Table 4 and Figure 5).

*3.1.2. Dead Wood Biomass Carbon Stock.* One of the five carbon pools listed by the Intergovernmental Panel on Climate Change as needing to be quantified and monitored for carbon accounting is carbon stored in the dead wood of a forest stand [81]. Accurate accounting of these pools is critical for mitigating climate change [82]. The results indicated that the mean dead wood biomass carbon (DWC) stock comprised $2.0 \pm 0.48\,\mathrm{t{\cdot}ha^{-1}}$ and $1.36 \pm 0.33\,\mathrm{t{\cdot}ha^{-1}}$ in Anshirava and Ziba, respectively (Table 4 and Figure 5).

Plots AT15Q2 and ZT4Q1 in Anshirava and Ziba, respectively, had maximum carbon stocks of $10.95\,\mathrm{t{\cdot}ha^{-1}}$ and $14.49\,\mathrm{t{\cdot}ha^{-1}}$. The highest carbon storage in these plots might be attributed to the presence of large DBH size standing and fallen dead wood trees.

*3.1.3. Litter Biomass Carbon Stock.* Litterfall is an important component of the nutrient cycle in forest ecosystems, which regulates the buildup of soil organic matter, nutrient input and output, nutrient replenishment, biodiversity conservation, and other ecosystem processes [83]. In Anshirava, the mean carbon stock in the dead litter was $2.69 \pm 0.25\,\mathrm{t{\cdot}ha^{-1}}$, while in Ziba, it was $4.82 \pm 0.38\,\mathrm{t{\cdot}ha^{-1}}$ (Table 4 and Figure 5). In Anshirava and Ziba, the lowest values were observed in plots AT18Q1 and ZT4Q9, while the highest values were found in plots AT2Q3 and ZT6Q1.

*3.1.4. Understory Biomass Carbon Stock.* In Anshirava and Ziba forests, the mean USB carbon stock was $6.09 \pm 0.36\,\mathrm{t{\cdot}ha^{-1}}$ and $5.62 \pm 0.57\,\mathrm{t{\cdot}ha^{-1}}$, respectively (Table 4 and Figure 5). Plot AT17Q1 and ZT6Q1 in Anshirava and Ziba forests, respectively, had the highest USBC stock values. The minimum carbon stock value of Anshirava was observed at plot AT17Q8, whereas the minimum value of Ziba was revealed at ZT4Q1.

*3.1.5. Soil Organic Carbon.* The mean soil carbon stock at 45 cm depth showed $111.43 \pm 2.57$ SE $\mathrm{t{\cdot}ha^{-1}}$ and $100.07 \pm 2.99$ SE $\mathrm{t{\cdot}ha^{-1}}$ in Anshirava and Ziba forests, respectively (Table 4 and Figure 5). The lower SCS values were observed at plots AT8Q2 and ZT1Q3 in Anshirava and Ziba forests, respectively. The maximum SCS value of Anshirava was observed at plot AT15Q5, whereas the maximum value of Ziba was revealed at ZT4Q10. The mean $CO_2$ equivalent was estimated to be $408.96 \pm 9.42\,\mathrm{t{\cdot}ha^{-1}}$ in Anshirava forest and $367.27 \pm 10.97\,\mathrm{t{\cdot}ha^{-1}}$ in Ziba forest.

*3.1.6. Total Carbon Stock.* Anshirava forest total carbon stock varied from $85.78\,\mathrm{t{\cdot}ha^{-1}}$ to $655.84\,\mathrm{t{\cdot}ha^{-1}}$, and Ziba forest total carbon stock ranged from $105.29\,\mathrm{t{\cdot}ha^{-1}}$ to $432.95\,\mathrm{t{\cdot}ha^{-1}}$. The corresponding $CO_2$ equivalent value ranged from $314.82\,\mathrm{t{\cdot}ha^{-1}}$ to $2406.93\,\mathrm{t{\cdot}ha^{-1}}$ in Anshirava forest and $386.40\,\mathrm{t{\cdot}ha^{-1}}$ to $1588.91\,\mathrm{t{\cdot}ha^{-1}}$ in Ziba forest (Figure 6 and Table 4).

By adding the carbon stocks found in each carbon pool, the total mean carbon stock of the forests was calculated. As a result, the average TCS in Anshirava was estimated to be $338.18 \pm 170.80\,\mathrm{t{\cdot}ha^{-1}}$, with a mean $CO_2$ equivalent of $1241.14 \pm 81.20\,\mathrm{t{\cdot}ha^{-1}}$. In Ziba, however, the total mean carbon stock was $240.36 \pm 66.08\,\mathrm{t{\cdot}ha^{-1}}$, with a mean $CO_2$ equivalent of $882.12 \pm 36.24\,\mathrm{t{\cdot}ha^{-1}}$ (Figure 6 and Table 4).

*3.1.7. Percent Share of Carbon Pools.* The carbon stock distribution and percent share of each carbon pool were investigated, and the greatest carbon stock was recorded in the AGB in both forests, which is $180.18\,\mathrm{t{\cdot}ha^{-1}}$ (53%) in Anshirava forest and $106.71\,\mathrm{t{\cdot}ha^{-1}}$ (44%) in Ziba forest. The next largest carbon share is stored in soil, which is 33% in Anshirava and 42% in Ziba (Figures 7 and 8).

*3.2. Correlation between Different Carbon Pools.* Correlations between different carbon pools were tested using Pearson's correlation coefficient. In Ziba forest, AGBC exhibited statistically strong positive correlation with BGBC. SCS also revealed strong positive relationship with USBC and LC. LC also exhibited statistically strong positive correlation with USBC ($P < 0.05$). However, DWC exhibited negatively strong correlation with AGBC and BGBC (Table 5). Then, again in Anshirava forest, except DWC, all carbon pools exhibited strong positive correlation with each other, whereas DWC exhibited strong negative relationship with the other carbon pools (Table 6).

*3.3. Carbon Stocks in response to Topographical Factors.* Topographic features of the environment, such as elevation, slope, and aspect, are known to determine patterns of tree species distribution and affect forest carbon stock in different plant communities [84–86]. Thus, a detailed

Table 2: Mean, maximum and minimum value of aboveground and belowground biomass, carbon stock, and carbon dioxide equivalent per tree spp. in Anshirava forest.

| | AGB ($t{\cdot}ha^{-1}$) | AGB C ($t{\cdot}ha^{-1}$) | AGB $CO_2$ ($t{\cdot}ha^{-1}$) | BGB ($t{\cdot}ha^{-1}$) | BGB C ($t{\cdot}ha^{-1}$) | BGB $CO_2$ ($t{\cdot}ha^{-1}$) |
|---|---|---|---|---|---|---|
| N | 48.00 | 48.00 | 48.00 | 48.00 | 48.00 | 48.00 |
| Min | 0.01 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 |
| Max | 173.35 | 81.47 | 299.01 | 34.67 | 16.29 | 59.80 |
| Sum | 390.00 | 183.28 | 672.74 | 78.00 | 36.65 | 134.54 |
| Mean | 8.13 | 3.82 | 14.02 | 1.63 | 0.76 | 2.80 |
| Std. error | 3.76 | 1.77 | 6.49 | 0.75 | 0.35 | 1.30 |
| Stand. dev | 26.06 | 12.25 | 44.95 | 5.21 | 2.45 | 8.99 |

Table 3: Mean, maximum and minimum value of aboveground and belowground biomass, carbon stock, and carbon dioxide equivalent per tree spp. in Ziba forest.

| | AGB ($t{\cdot}ha^{-1}$) | AGB C ($t{\cdot}ha^{-1}$) | AGB $CO_2$ ($t{\cdot}ha^{-1}$) | BGB ($t{\cdot}ha^{-1}$) | BGB C ($t{\cdot}ha^{-1}$) | BGB $CO_2$ ($t{\cdot}ha^{-1}$) |
|---|---|---|---|---|---|---|
| N | 33.00 | 33.00 | 33.00 | 33.00 | 33.00 | 33.00 |
| Min | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Max | 129.14 | 57.53 | 211.13 | 24.48 | 11.51 | 42.23 |
| Sum | 351.96 | 162.27 | 595.49 | 69.07 | 32.43 | 119.13 |
| Mean | 10.67 | 4.92 | 18.05 | 2.09 | 0.98 | 3.61 |
| Std. error | 4.38 | 1.98 | 7.25 | 0.84 | 0.40 | 1.45 |
| Stand. dev | 25.14 | 11.36 | 41.68 | 4.83 | 2.27 | 8.34 |

Table 4: ANOVA of mean carbon stock in different pools ($t\ ha^{-1}$).

| Forest site | AGB | BGB | Total biomass | AGB C | BGB C | DW C | USB C | Litter C | Soil C | TCS |
|---|---|---|---|---|---|---|---|---|---|---|
| Anshirava | 387.55 | 77.51 | 465.06 | 180.18 ± 130.93 | 36.43 ± 25.83 | 1.36 ± 2.53 | 6.09 ± 2.77 | 2.69 ± 1.94 | 111.43 ± 19.55 | 338.18 ± 170.80 |
| Ziba | 227.05 | 45.41 | 272.46 | 106.71 ± 52.93 | 21.34 ± 10.59 | 2.00 ± 3.31 | 5.62 ± 4.22 | 4.82 ± 2.61 | 100.07 ± 20.71 | 240.36 ± 66.08 |
| F value | | | | 13.29 | 14.36 | 1.28 | 0.47 | 23.14 | 8.40 | 13.93 |
| Prob > F | | | | 0.00 | 0.00 | 0.26 | 0.49 | 0.00 | 0.004 | 0.00 |

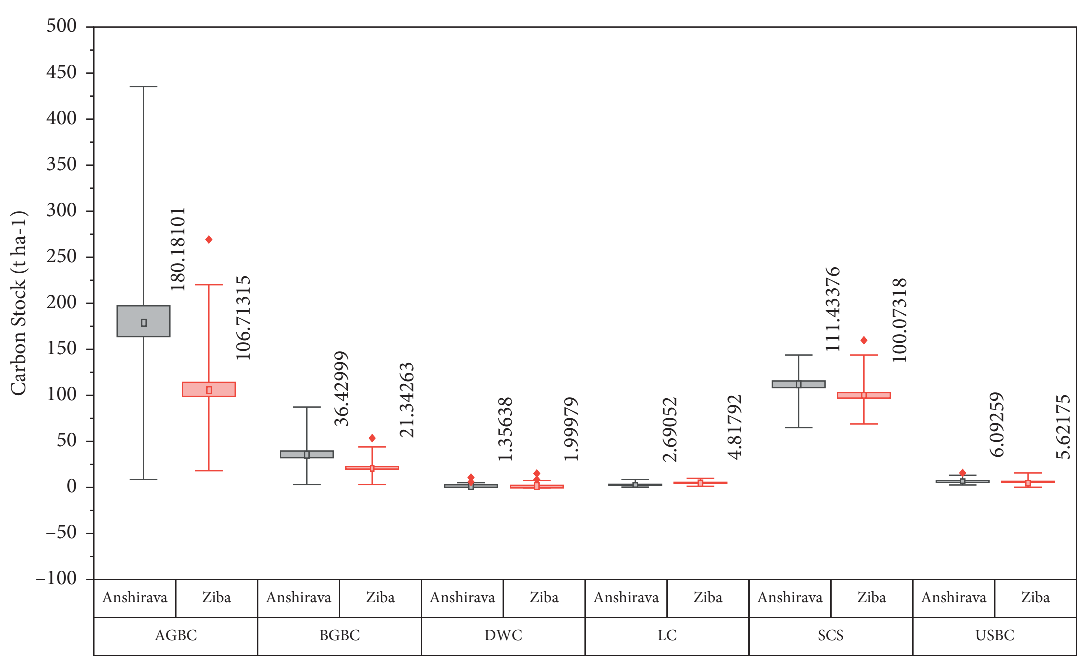


Figure 5: Carbon stock distribution of different carbon pools in studied forests.

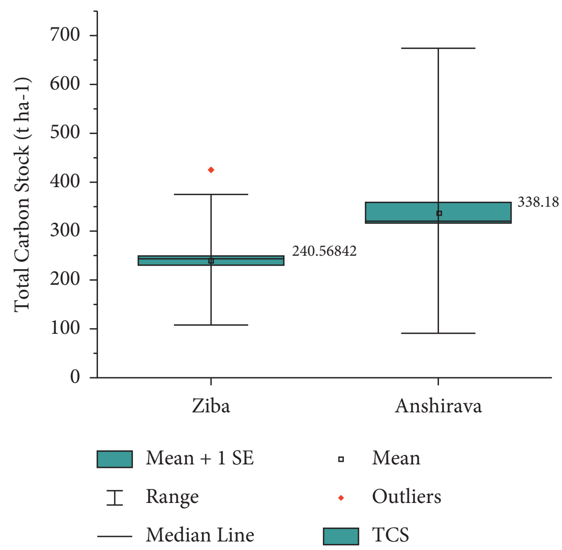


FIGURE 6: Total carbon stock of the studied forests.

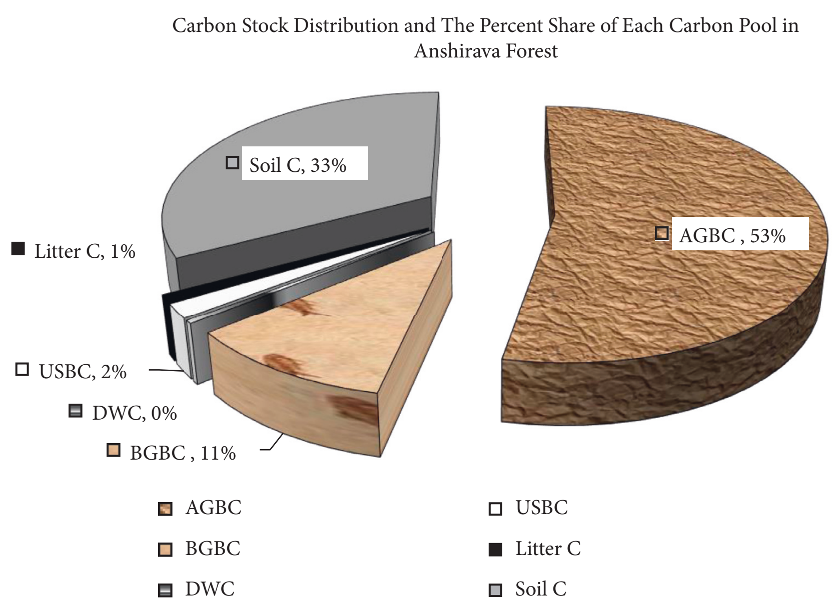


FIGURE 7: Carbon stock distribution and percent share of each carbon pool in Anshirava forest.

assessment of forest carbon stock potential in respect to environmental gradients is critical.

*3.3.1. Carbon Stocks in response to Altitude.* Altitude has a significant influence on the biomass and carbon stock in forest ecosystems [87, 88]. Based on the multivariate analysis result, except for DWC, the carbon stocks in the aboveground, belowground, understory biomass, litter biomass, and soil in Anshirava forest exhibited significant variation throughout the altitudinal gradient at $P < 0.005$ (Table 7). The higher mean AGBC, BGBC, USBC, DWC, and LC were exhibited at the highest altitude, while the lowest mean values were exhibited at the lower altitude. Moreover, the highest SCS was observed at the middle altitude, and the lowest value was observed at the lower altitude. In Anshirava forest, the maximum total carbon stock (TCS) was recorded in the higher altitude range, whereas the lower altitude class had the lowest value. Thus, the total carbon stock of the study site showed an increasing trend along the altitudinal gradient (Table 8).

In Ziba forest, the AGBC, BGBC, USBC, DWC, SCS, and LC exhibited variations in response to altitude. The higher mean AGBC and BGBC were exhibited at the lower altitude, whereas the higher mean values of USBC, DWC, and SCS were revealed at the higher altitude. At the middle altitude, however, the higher value of LC was observed. The lowest mean values of AGBC and BGBC were exhibited at higher altitudes, respectively, whereas the lowest mean values of USBC, DWC, SCS, and LC were observed at the lower

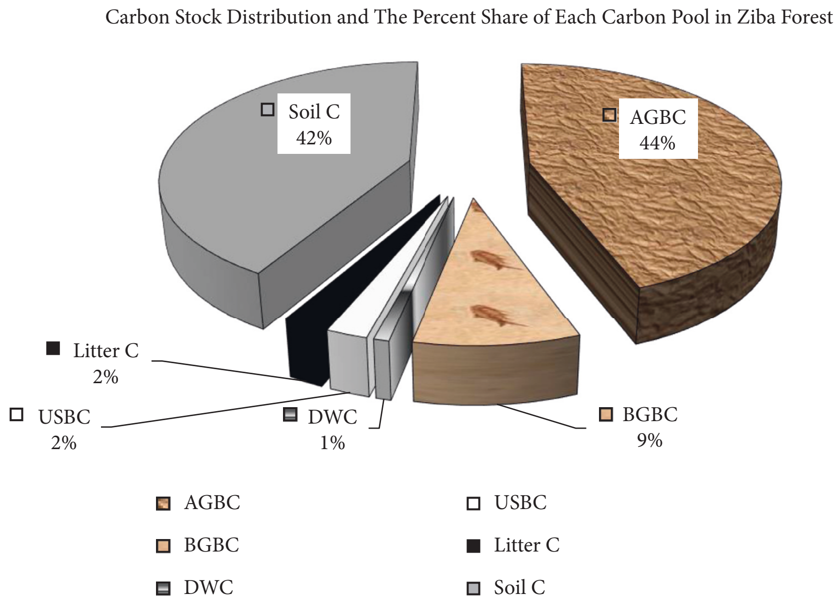


Figure 8: Carbon stock distribution and percent share of each carbon pool in Ziba forest.

Table 5: Pearson's product moment correlation coefficient and $P$ value between carbon pools in Ziba forest.

| | DWC | USBC | LC | AGBC | BGBC | SCS |
|---|---|---|---|---|---|---|
| DWC | | | | | | |
| USBC | 0.09* | | | | | |
| LC | −0.19 | 0.38* | | | | |
| AGBC | −0.53* | −0.01 | 0.14 | | | |
| BGBC | −0.53* | −0.01 | 0.14 | 1.00* | | |
| SCS | −0.05 | 0.47* | 0.61* | 0.00 | 0.00 | |

*Significant at $P < 0.05$.

Table 6: Pearson's product moment correlation coefficient and $P$ value between carbon pools in Anshirava forest.

| | DWC | USBC | LC | AGBC | BGBC | SCS |
|---|---|---|---|---|---|---|
| DWC | | | | | | |
| USBC | −0.59* | | | | | |
| LC | −0.58* | 0.97* | | | | |
| AGBC | −0.43* | 0.52* | 0.52* | | | |
| BGBC | −0.43* | 0.52* | 0.52* | 0.99* | | |
| SCS | −0.73* | 0.68* | 0.71* | 0.61* | 0.61* | |

*Significant at $P < 0.05$.

altitudes (Table 9). Besides, the differences between the means of AGBC, BGBC, and DWC were statistically significant along the altitudinal gradient, $P < 0.05$. However, USBC, SCS, and LC were not significantly correlated to altitude, $P = 0.123$, 0.072, and 0.478, respectively (Table 10). The maximum total carbon stock (TCS) was recorded in the lower altitude class, while the higher altitude class had the lowest value. Contrary to Anshirava, the total carbon stock of the Ziba site showed a decreasing trend along the altitudinal gradient. However, there is no statistically significant difference between the means of TCS at different levels on both sites (Table 10).

*3.3.2. Carbon Stocks in response to Slope.* All the biomass and soil carbon pools exhibited variations in response to the slope in Anshirava forest. The higher mean AGBC, BGBC, USBC, and LC were exhibited on the flat slope, while the highest mean values of DWC and SCS were presented on the steep and intermediate slopes, respectively. Moreover, the lowest mean values of all the carbon pools except DWC were observed on the steep slope (Table 11). The differences between means of all the carbon pools along the slope gradient were statistically significant at $P < 0.05$ as well (Table 11). Similar to other pools, the maximum total carbon stock (TCS) was recorded in the flat slope class, whereas the steep slope class had the lowest value (Table 11). However, there is no statistically significant difference between the means of different slope classes in total carbon stock, $P = 0.305$ (Table 7).

Alike Anshirava, all the biomass and soil carbon pools exhibited variations in response to slope in Ziba forest. Except DWC, the higher mean values of all the carbon pools were demonstrated at the flat slope. However, the higher mean value of DWC was exhibited on the steep slope and the lowest mean value of DWC was presented on the flat slope. Moreover, the lowest mean values of all the other carbon pools were observed at the steep slope (Table 12). The difference between the means of DWC and LC is not significant. However, the difference between means of AGBC, BGBC, USBC, SCS, and TCS were statistically significant along the slope gradient at $P < 0.05$ (Table 10). The maximum total carbon stock (TCS) was also recorded in the flat slope class, while the steep slope class had the lowest value. Then, the total carbon stock of the Ziba site showed a decreasing trend along slope classes (Table 12).

*3.3.3. Carbon Stocks in response to Aspect.* According to Bayat [89], because of differences in solar radiation receipt and soil properties in different aspect facings, there is a

Table 7: Tests of between-subject effects in Anshirava forest.

| Source | Dependent variable | Type III sum of squares | df | Mean square | F | Sig. | Partial eta squared |
|---|---|---|---|---|---|---|---|
| Corrected model | SCS | 18019.730[a] | 35 | 514.849 | 2.999 | 0.004 | 0.827 |
| | AGBC | 761137.455[b] | 35 | 21746.784 | 2.215 | 0.026 | 0.779 |
| | BGBC | 30855.926[c] | 35 | 881.598 | 2.703 | 0.008 | 0.811 |
| | LC | 202.650[d] | 35 | 5.790 | 10.485 | 0.000 | 0.943 |
| | USBC | 425.259[e] | 35 | 12.150 | 20.740 | 0.000 | 0.971 |
| | DWC | 332.922[f] | 35 | 9.512 | 6.359 | 0.000 | 0.910 |
| | TCS | 1315060.564[g] | 35 | 37573.159 | 2.377 | 0.018 | 0.791 |
| Intercept | SCS | 379218.959 | 1 | 379218.959 | 2209.243 | 0.000 | 0.990 |
| | AGBC | 917628.752 | 1 | 917628.752 | 93.473 | 0.000 | 0.809 |
| | BGBC | 37318.601 | 1 | 37318.601 | 114.441 | 0.000 | 0.839 |
| | LC | 226.261 | 1 | 226.261 | 409.736 | 0.000 | 0.949 |
| | USBC | 1199.936 | 1 | 1199.936 | 2048.212 | 0.000 | 0.989 |
| | DWC | 87.508 | 1 | 87.508 | 58.500 | 0.000 | 0.727 |
| | TCS | 3334107.530 | 1 | 3334107.530 | 210.889 | 0.000 | 0.906 |
| Altitude | SCS | 519.375 | 2 | 259.687 | 4.249 | 0.020 | 0.148 |
| | AGBC | 5714.355 | 2 | 2857.177 | 4.125 | 0.001 | 0.402 |
| | BGBC | 261.518 | 2 | 130.759 | 4.125 | 0.001 | 0.402 |
| | LC | 13.631 | 2 | 6.815 | 12.342 | 0.000 | 0.529 |
| | USBC | 35.464 | 2 | 17.732 | 30.267 | 0.000 | 0.733 |
| | DWC | 6.985 | 2 | 3.492 | 2.335 | 0.120 | 0.175 |
| | TCS | 13703.261 | 2 | 6851.630 | 0.433 | 0.654 | 0.038 |
| Slope | SCS | 3435.938 | 2 | 1717.969 | 10.008 | 0.001 | 0.476 |
| | AGBC | 18590.741 | 2 | 9295.371 | 5.078 | 0.002 | 0.293 |
| | BGBC | 702.943 | 2 | 351.471 | 5.078 | 0.002 | 0.293 |
| | LC | 82.263 | 2 | 41.131 | 74.485 | 0.000 | 0.871 |
| | USBC | 184.679 | 2 | 92.340 | 157.618 | 0.000 | 0.935 |
| | DWC | 79.211 | 2 | 39.605 | 26.476 | 0.000 | 0.706 |
| | TCS | 39658.268 | 2 | 19829.134 | 1.254 | 0.305 | 0.102 |
| Aspect | SCS | 1301.588 | 7 | 185.941 | 1.083 | 0.407 | 0.256 |
| | AGBC | 179865.101 | 7 | 25695.014 | 2.617 | 0.040 | 0.454 |
| | BGBC | 7095.321 | 7 | 1013.617 | 3.108 | 0.019 | 0.497 |
| | LC | 7.152 | 7 | 1.022 | 1.850 | 0.128 | 0.371 |
| | USBC | 9.974 | 7 | 1.425 | 2.432 | 0.052 | 0.436 |
| | DWC | 39.548 | 7 | 5.650 | 1.299 | 0.278 | 0.197 |
| | TCS | 288456.068 | 7 | 41208.010 | 2.606 | 0.040 | 0.453 |
| Altitude*slope | SCS | 274.124 | 3 | 91.375 | 0.532 | 0.665 | 0.068 |
| | AGBC | 130950.667 | 3 | 43650.222 | 4.446 | 0.014 | 0.377 |
| | BGBC | 5238.026 | 3 | 1746.009 | 5.354 | 0.006 | 0.422 |
| | LC | 14.016 | 3 | 4.672 | 8.461 | 0.001 | 0.536 |
| | USBC | 47.677 | 3 | 15.892 | 27.127 | 0.000 | 0.787 |
| | DWC | 1.916 | 3 | 0.639 | 0.427 | 0.736 | 0.055 |
| | TCS | 197143.960 | 3 | 65714.653 | 4.157 | 0.018 | 0.362 |
| Altitude*aspect | SCS | 1773.747 | 8 | 221.718 | 1.292 | 0.298 | 0.320 |
| | AGBC | 15854.477 | 8 | 1981.810 | 0.202 | 0.987 | 0.068 |
| | BGBC | 542.727 | 8 | 67.841 | 0.208 | 0.986 | 0.070 |
| | LC | 6.143 | 8 | 0.768 | 1.390 | 0.255 | 0.336 |
| | USBC | 9.130 | 8 | 1.141 | 1.948 | 0.103 | 0.415 |
| | DWC | 8.912 | 8 | 1.114 | 0.745 | 0.652 | 0.213 |
| | TCS | 22607.051 | 8 | 2825.881 | 0.179 | 0.992 | 0.061 |
| Slope*aspect | SCS | 2050.553 | 8 | 256.319 | 1.493 | 0.216 | 0.352 |
| | AGBC | 85784.406 | 8 | 10723.051 | 1.092 | 0.405 | 0.284 |
| | BGBC | 3218.378 | 8 | 402.297 | 1.234 | 0.326 | 0.310 |
| | LC | 4.407 | 8 | 0.551 | 0.998 | 0.465 | 0.266 |
| | USBC | 11.441 | 8 | 1.430 | 2.441 | 0.047 | 0.470 |
| | DWC | 29.905 | 8 | 3.738 | 2.499 | 0.042 | 0.476 |
| | TCS | 129779.616 | 8 | 16222.452 | 1.026 | 0.446 | 0.272 |

Table 7: Continued.

| Source | Dependent variable | Type III sum of squares | df | Mean square | F | Sig. | Partial eta squared |
|---|---|---|---|---|---|---|---|
| Altitude*slope*aspect | SCS | 410.074 | 2 | 205.037 | 1.194 | 0.322 | 0.098 |
| | AGBC | 3497.274 | 2 | 1748.637 | 0.178 | 0.838 | 0.016 |
| | BGBC | 139.891 | 2 | 69.946 | 0.214 | 0.809 | 0.019 |
| | LC | 0.499 | 2 | 0.249 | 0.451 | 0.642 | 0.039 |
| | USBC | 4.096 | 2 | 2.048 | 3.496 | 0.048 | 0.241 |
| | DWC | 1.153 | 2 | 0.577 | 0.385 | 0.685 | 0.034 |
| | TCS | 8574.512 | 2 | 4287.256 | 0.271 | 0.765 | 0.024 |
| Error | SCS | 3776.324 | 22 | 171.651 | | | |
| | AGBC | 215975.931 | 22 | 9817.088 | | | |
| | BGBC | 7174.103 | 22 | 326.096 | | | |
| | LC | 12.149 | 22 | 0.552 | | | |
| | USBC | 12.889 | 22 | 0.586 | | | |
| | DWC | 32.909 | 22 | 1.496 | | | |
| | TCS | 347814.232 | 22 | 15809.738 | | | |
| Total | SCS | 742010.103 | 58 | | | | |
| | AGBC | 2860094.808 | 58 | | | | |
| | BGBC | 115004.380 | 58 | | | | |
| | LC | 634.654 | 58 | | | | |
| | USBC | 2591.085 | 58 | | | | |
| | DWC | 472.538 | 58 | | | | |
| | TCS | 8296252.643 | 58 | | | | |
| Corrected total | SCS | 21796.054 | 57 | | | | |
| | AGBC | 977113.387 | 57 | | | | |
| | BGBC | 38030.029 | 57 | | | | |
| | LC | 214.798 | 57 | | | | |
| | USBC | 438.147 | 57 | | | | |
| | DWC | 365.832 | 57 | | | | |
| | TCS | 1662874.796 | 57 | | | | |

The mean difference is significant at 0.05 level. [a]$R$ squared = 0.827 (adjusted $R$ squared = 0.551); [b]$R$ squared = 0.779 (adjusted $R$ squared = 0.427); [c]$R$ squared = 0.811 (adjusted $R$ squared = 0.511); [d]$R$ squared = 0.943 (adjusted $R$ squared = 0.853); [e]$R$ squared = 0.971 (adjusted $R$ squared = 0.924); [f]$R$ squared = 0.910 (adjusted $R$ squared = 0.767); [g]$R$ squared = 0.791 (adjusted $R$ squared = 0.458); [h]computed using alpha = 0.05.

Table 8: Estimated marginal means of altitude in Anshirava forest.

| Dependent variable | Altitude | Mean | Std. error | 95% confidence interval | |
|---|---|---|---|---|---|
| | | | | Lower bound | Upper bound |
| SCS | Low | 104.943[a] | 3.386 | 97.920 | 111.965 |
| | Medium | 115.106[a] | 2.726 | 109.453 | 120.760 |
| | High | 114.017[a] | 4.202 | 105.302 | 122.732 |
| AGBC | Low | 146.679[a] | 25.609 | 93.569 | 199.789 |
| | Medium | 185.367[a] | 20.616 | 142.612 | 228.122 |
| | High | 239.006[a] | 31.780 | 173.098 | 304.915 |
| BGBC | Low | 30.374[a] | 4.667 | 20.694 | 40.054 |
| | Medium | 37.073[a] | 3.757 | 29.281 | 44.866 |
| | High | 47.801[a] | 5.792 | 35.789 | 59.813 |
| LC | Low | 1.858[a] | 0.192 | 1.460 | 2.256 |
| | Medium | 2.813[a] | 0.155 | 2.492 | 3.133 |
| | High | 3.615[a] | 0.238 | 3.121 | 4.109 |
| USBC | Low | 5.325[a] | 0.198 | 4.915 | 5.736 |
| | Medium | 5.901[a] | 0.159 | 5.571 | 6.231 |
| | High | 7.883[a] | 0.246 | 7.374 | 8.392 |
| DWC | Low | .494[a] | 0.316 | −0.162 | 1.149 |
| | Medium | 1.664[a] | 0.254 | 1.137 | 2.192 |
| | High | 2.568[a] | 0.392 | 1.754 | 3.381 |
| TCS | Low | 289.673[a] | 32.499 | 222.275 | 357.071 |
| | Medium | 347.925[a] | 26.162 | 293.667 | 402.182 |
| | High | 414.891[a] | 40.330 | 331.252 | 498.531 |

[a]Based on modified population marginal mean.

Table 9: Estimated marginal means of altitude in Ziba forest.

| Dependent variable | Altitude | Mean | Std. error | 95% confidence interval | |
|---|---|---|---|---|---|
| | | | | Lower bound | Upper bound |
| DWC | Low | .911[a] | 0.726 | −0.600 | 2.422 |
| | Medium | 2.963[a] | 0.529 | 1.862 | 4.063 |
| | High | 4.194[a] | 0.829 | 2.470 | 5.918 |
| USBC | Low | 2.989[a] | 0.879 | 1.162 | 4.816 |
| | Medium | 5.077[a] | 0.640 | 3.746 | 6.408 |
| | High | 8.408[a] | 1.003 | 6.323 | 10.493 |
| LC | Low | 4.966[a] | 0.578 | 3.765 | 6.168 |
| | Medium | 4.645[a] | 0.421 | 3.770 | 5.521 |
| | High | 5.129[a] | 0.659 | 3.757 | 6.500 |
| AGBC | Low | 145.456[a] | 13.436 | 117.514 | 173.398 |
| | Medium | 81.424[a] | 9.789 | 61.067 | 101.782 |
| | High | 88.084[a] | 15.334 | 56.196 | 119.972 |
| BGBC | Low | 29.091[a] | 2.687 | 23.503 | 34.680 |
| | Medium | 16.285[a] | 1.958 | 12.213 | 20.356 |
| | High | 17.617[a] | 3.067 | 11.239 | 23.994 |
| SCS | Low | 87.585[a] | 4.974 | 77.241 | 97.930 |
| | Medium | 93.847[a] | 3.624 | 86.310 | 101.384 |
| | High | 101.384[a] | 5.677 | 89.578 | 113.190 |
| TCS | Low | 270.999[a] | 14.360 | 241.137 | 300.862 |
| | Medium | 204.242[a] | 10.462 | 182.485 | 225.998 |
| | High | 224.816[a] | 16.388 | 190.735 | 258.896 |

[a]Based on modified population marginal mean.

Table 10: Tests of between-subject effects in Ziba forest.

| Source | Dependent variable | Type III sum of squares | df | Mean square | F | Sig. | Partial eta squared |
|---|---|---|---|---|---|---|---|
| Corrected model | DWC | 405.857[a] | 26 | 15.610 | 3.012 | 0.006 | 0.789 |
| | USBC | 679.541[b] | 26 | 26.136 | 3.449 | 0.003 | 0.810 |
| | LC | 250.569[c] | 26 | 9.637 | 2.940 | 0.007 | 0.784 |
| | AGBC | 94469.919[d] | 26 | 3633.458 | 2.050 | 0.049 | 0.717 |
| | BGBC | 3778.797[e] | 26 | 145.338 | 2.050 | 0.049 | 0.717 |
| | SCS | 15062.046[f] | 26 | 579.309 | 2.384 | 0.023 | 0.747 |
| | TCS | 170014.052[g] | 26 | 6539.002 | 3.230 | 0.004 | 0.800 |
| Intercept | DWC | 159.280 | 1 | 159.280 | 30.738 | 0.000 | 0.594 |
| | USBC | 518.633 | 1 | 518.633 | 68.441 | 0.000 | 0.765 |
| | LC | 372.658 | 1 | 372.658 | 113.695 | 0.000 | 0.844 |
| | AGBC | 172590.744 | 1 | 172590.744 | 97.373 | 0.000 | 0.823 |
| | BGBC | 6903.630 | 1 | 6903.630 | 97.373 | 0.000 | 0.823 |
| | SCS | 153682.543 | 1 | 153682.543 | 632.565 | 0.000 | 0.968 |
| | TCS | 893498.839 | 1 | 893498.839 | 441.340 | 0.000 | 0.955 |
| Altitude | DWC | 52.199 | 2 | 26.099 | 5.037 | 0.016 | 0.324 |
| | USBC | 146.491 | 2 | 73.246 | 2.246 | 0.123 | 0.127 |
| | LC | 5.010 | 2 | 2.505 | 0.764 | 0.478 | 0.068 |
| | AGBC | 20079.670 | 2 | 10039.835 | 5.664 | 0.011 | 0.350 |
| | BGBC | 803.187 | 2 | 401.593 | 5.664 | 0.011 | 0.350 |
| | SCS | 2093.937 | 2 | 1046.968 | 2.865 | 0.072 | 0.156 |
| | TCS | 15688.879 | 2 | 7844.440 | 2.686 | 0.081 | 0.121 |
| Slope | DWC | 8.708 | 2 | 4.354 | 0.840 | 0.446 | 0.074 |
| | USBC | 87.016 | 2 | 43.508 | 5.742 | 0.010 | 0.354 |
| | LC | 69.760 | 2 | 34.880 | 2.312 | 0.113 | 0.106 |
| | AGBC | 6713.679 | 2 | 3356.840 | 1.894 | 0.045 | 0.283 |
| | BGBC | 268.547 | 2 | 134.274 | 1.894 | 0.045 | 0.283 |
| | SCS | 4287.598 | 2 | 2143.799 | 8.824 | 0.002 | 0.457 |
| | TCS | 31691.394 | 2 | 15845.697 | 7.827 | 0.003 | 0.427 |

Table 10: Continued.

| Source | Dependent variable | Type III sum of squares | df | Mean square | F | Sig. | Partial eta squared |
|---|---|---|---|---|---|---|---|
| Aspect | DWC | 80.500 | 7 | 11.500 | 2.219 | 0.074 | 0.425 |
| | USBC | 104.158 | 7 | 14.880 | 1.964 | 0.109 | 0.396 |
| | LC | 46.474 | 7 | 6.639 | 2.026 | 0.100 | 0.403 |
| | AGBC | 32171.086 | 7 | 4595.869 | 2.593 | 0.043 | 0.464 |
| | BGBC | 1286.843 | 7 | 183.835 | 2.593 | 0.043 | 0.464 |
| | SCS | 1678.741 | 7 | 239.820 | 0.987 | 0.467 | 0.248 |
| | TCS | 45387.673 | 7 | 6483.953 | 3.203 | 0.018 | 0.516 |
| Altitude*slope | DWC | 0.638 | 2 | 0.319 | 0.062 | 0.940 | 0.006 |
| | USBC | 23.745 | 2 | 11.873 | 1.567 | 0.232 | 0.130 |
| | LC | 12.250 | 2 | 6.125 | 1.869 | 0.179 | 0.151 |
| | AGBC | 2450.070 | 2 | 1225.035 | 0.691 | 0.512 | 0.062 |
| | BGBC | 98.003 | 2 | 49.001 | 0.691 | 0.512 | 0.062 |
| | SCS | 223.487 | 2 | 111.744 | 0.460 | 0.638 | 0.042 |
| | TCS | 2243.456 | 2 | 1121.728 | 0.554 | 0.583 | 0.050 |
| Altitude*aspect | DWC | 17.513 | 5 | 3.503 | 0.676 | 0.646 | 0.139 |
| | USBC | 163.318 | 5 | 32.664 | 4.310 | 0.007 | 0.506 |
| | LC | 58.053 | 5 | 11.611 | 3.542 | 0.018 | 0.458 |
| | AGBC | 10524.463 | 5 | 2104.893 | 1.188 | 0.349 | 0.220 |
| | BGBC | 420.979 | 5 | 84.196 | 1.188 | 0.349 | 0.220 |
| | SCS | 265.955 | 5 | 53.191 | 0.219 | 0.950 | 0.050 |
| | TCS | 18355.722 | 5 | 3671.144 | 1.813 | 0.154 | 0.302 |
| Slope*aspect | DWC | 45.161 | 3 | 15.054 | 2.905 | 0.059 | 0.293 |
| | USBC | 4.413 | 3 | 1.471 | 0.194 | 0.899 | 0.027 |
| | LC | 30.631 | 3 | 10.210 | 3.115 | 0.048 | 0.308 |
| | AGBC | 4095.179 | 3 | 1365.060 | 0.770 | 0.524 | 0.099 |
| | BGBC | 163.807 | 3 | 54.602 | 0.770 | 0.524 | 0.099 |
| | SCS | 19.614 | 3 | 6.538 | 0.027 | 0.994 | 0.004 |
| | TCS | 5791.594 | 3 | 1930.531 | 0.954 | 0.433 | 0.120 |
| Altitude*slope*aspect | DWC | 1.571 | 1 | 1.571 | 0.303 | 0.588 | 0.014 |
| | USBC | 1.912 | 1 | 1.912 | 0.252 | 0.621 | 0.012 |
| | LC | 10.148 | 1 | 10.148 | 3.096 | 0.093 | 0.128 |
| | AGBC | 1386.239 | 1 | 1386.239 | 0.782 | 0.387 | 0.036 |
| | BGBC | 55.450 | 1 | 55.450 | 0.782 | 0.387 | 0.036 |
| | SCS | 271.619 | 1 | 271.619 | 1.118 | 0.302 | 0.051 |
| | TCS | 3062.261 | 1 | 3062.261 | 1.513 | 0.232 | 0.067 |
| Error | DWC | 108.821 | 21 | 5.182 | | | |
| | USBC | 159.134 | 21 | 7.578 | | | |
| | LC | 68.832 | 21 | 3.278 | | | |
| | AGBC | 37221.975 | 21 | 1772.475 | | | |
| | BGBC | 1488.879 | 21 | 70.899 | | | |
| | SCS | 5101.977 | 21 | 242.951 | | | |
| | TCS | 42514.820 | 21 | 2024.515 | | | |
| Total | DWC | 706.638 | 48 | | | | |
| | USBC | 2355.670 | 48 | | | | |
| | LC | 1433.592 | 48 | | | | |
| | AGBC | 678301.290 | 48 | | | | |
| | BGBC | 27132.052 | 48 | | | | |
| | SCS | 500866.825 | 48 | | | | |
| | TCS | 2990440.701 | 48 | | | | |
| Corrected total | DWC | 514.678 | 47 | | | | |
| | USBC | 838.675 | 47 | | | | |
| | LC | 319.401 | 47 | | | | |
| | AGBC | 131691.893 | 47 | | | | |
| | BGBC | 5267.676 | 47 | | | | |
| | SCS | 20164.023 | 47 | | | | |
| | TCS | 212528.872 | 47 | | | | |

The mean difference is significant at 0.05 level. [a]$R$ squared = 0.789 (adjusted $R$ squared = 0.527); [b]$R$ squared = 0.810 (adjusted $R$ squared = 0.575); [c]$R$ squared = 0.784 (adjusted $R$ squared = 0.518); [d]$R$ squared = 0.717 (adjusted $R$ squared = 0.367); [e]$R$ squared = 0.717 (adjusted $R$ squared = 0.367); [f]$R$ squared = 0.747 (adjusted $R$ squared = 0.434); [g]$R$ squared = 0.800 (adjusted $R$ squared = 0.552).

Table 11: Estimated marginal means of slope in Anshirava forest.

| Dependent variable | Slope | Mean | Std. error | 95% confidence interval | |
|---|---|---|---|---|---|
| | | | | Lower bound | Upper bound |
| SCS | Flat | 119.446[a] | 2.644 | 113.962 | 124.931 |
| | Intermediate | 125.125[a] | 4.632 | 115.519 | 134.731 |
| | Steep | 94.579[a] | 3.240 | 87.860 | 101.298 |
| AGBC | Flat | 217.245[a] | 19.999 | 175.769 | 258.720 |
| | Intermediate | 174.358[a] | 35.031 | 101.710 | 247.007 |
| | Steep | 159.759[a] | 24.500 | 108.949 | 210.569 |
| BGBC | Flat | 43.449[a] | 3.645 | 35.890 | 51.008 |
| | Intermediate | 34.872[a] | 6.385 | 21.631 | 48.112 |
| | Steep | 32.830[a] | 4.465 | 23.570 | 42.091 |
| LC | Flat | 4.154[a] | 0.150 | 3.843 | 4.466 |
| | Intermediate | 3.132[a] | 0.263 | 2.588 | 3.677 |
| | Steep | 0.816[a] | 0.184 | 0.434 | 1.197 |
| USBC | Flat | 8.309[a] | 0.154 | 7.989 | 8.630 |
| | Intermediate | 6.814[a] | 0.271 | 6.253 | 7.375 |
| | Steep | 3.446[a] | 0.189 | 3.053 | 3.838 |
| DWC | Flat | 0.000[a] | 0.247 | −0.512 | 0.512 |
| | Intermediate | 0.290[a] | 0.432 | −0.607 | 1.187 |
| | Steep | 4.065[a] | 0.302 | 3.438 | 4.693 |
| TCS | Flat | 392.604[a] | 25.379 | 339.971 | 445.237 |
| | Intermediate | 344.591[a] | 44.455 | 252.398 | 436.785 |
| | Steep | 295.495[a] | 31.091 | 231.015 | 359.974 |

[a]Based on modified population marginal mean.

Table 12: Estimated marginal means of slope in Ziba forest.

| Dependent variable | Slope | Mean | Std. error | 95% confidence interval | |
|---|---|---|---|---|---|
| | | | | Lower bound | Upper bound |
| DWC | Flat | 2.288[a] | 0.487 | 1.276 | 3.300 |
| | Intermediate | 2.131[a] | 0.771 | 0.529 | 3.734 |
| | Steep | 4.214[a] | 1.018 | 2.097 | 6.331 |
| USBC | Flat | 6.475[a] | 0.589 | 5.252 | 7.699 |
| | Intermediate | 5.493[a] | 0.932 | 3.556 | 7.431 |
| | Steep | 1.400[a] | 1.231 | −1.160 | 3.960 |
| LC | Flat | 5.567[a] | 0.387 | 4.762 | 6.372 |
| | Intermediate | 5.359[a] | 0.613 | 4.085 | 6.634 |
| | Steep | 2.176[a] | 0.810 | 0.492 | 3.860 |
| AGBC | Flat | 116.086[a] | 9.001 | 97.368 | 134.804 |
| | Intermediate | 101.326[a] | 14.251 | 71.689 | 130.963 |
| | Steep | 77.111[a] | 18.828 | 37.956 | 116.266 |
| BGBC | Flat | 23.217[a] | 1.800 | 19.474 | 26.961 |
| | Intermediate | 20.265[a] | 2.850 | 14.338 | 26.193 |
| | Steep | 15.422[a] | 3.766 | 7.591 | 23.253 |
| SCS | Flat | 105.110[a] | 3.332 | 98.180 | 112.040 |
| | Intermediate | 87.880[a] | 5.276 | 76.907 | 98.852 |
| | Steep | 71.140[a] | 6.971 | 56.644 | 85.637 |
| TCS | Flat | 258.743[a] | 9.619 | 238.739 | 278.748 |
| | Intermediate | 222.455[a] | 15.231 | 190.780 | 254.129 |
| | Steep | 171.463[a] | 20.122 | 129.617 | 213.310 |

[a]Based on modified population marginal mean.

significant relationship between aspect and forest carbon stock. Carbon stocks varied across different aspects of Anshirava forest. The western (W) aspect has the highest mean AGBC, BGBC, and SCS stocks (Table 13), whereas the highest mean USBC was observed in the east (E), followed by the west (W) and north (N) aspects. Besides, the highest LC was recorded in the south (S), followed by the west (W). The highest DWC was observed in the south (S). The mean AGBC, BGBC, and SCS stocks were lowest in the south (S) aspect, whereas the lowest USBC and LC were recorded in

Table 13: Estimated marginal means of aspect in Anshirava forest.

| Dependent variable | Aspect | Mean | Std. error | 95% confidence interval | |
|---|---|---|---|---|---|
| | | | | Lower bound | Upper bound |
| SCS | N | 117.143[a] | 4.632 | 107.537 | 126.749 |
| | NE | 102.935[a] | 5.513 | 91.502 | 114.369 |
| | NW | 109.247[a] | 4.115 | 100.714 | 117.781 |
| | S | 90.227[a] | 5.913 | 77.964 | 102.490 |
| | SE | 107.100[a] | 6.905 | 92.780 | 121.420 |
| | SW | 115.132[a] | 4.759 | 105.262 | 125.002 |
| | E | 122.446[a] | 13.102 | 95.275 | 149.617 |
| | W | 122.945[a] | 5.003 | 112.569 | 133.322 |
| AGBC | N | 165.270[a] | 35.031 | 92.621 | 237.919 |
| | NE | 98.483[a] | 41.695 | 12.014 | 184.953 |
| | NW | 206.431[a] | 31.118 | 141.895 | 270.966 |
| | S | 63.298[a] | 44.719 | −29.443 | 156.039 |
| | SE | 140.720[a] | 52.220 | 32.422 | 249.019 |
| | SW | 191.100[a] | 35.990 | 116.461 | 265.740 |
| | E | 138.249[a] | 99.081 | −67.233 | 343.731 |
| | W | 333.821[a] | 37.837 | 255.351 | 412.290 |
| BGBC | N | 33.054[a] | 6.385 | 19.813 | 46.295 |
| | NE | 22.552[a] | 7.599 | 6.792 | 38.311 |
| | NW | 41.286[a] | 5.671 | 29.524 | 53.048 |
| | S | 12.660[a] | 8.150 | −4.243 | 29.562 |
| | SE | 28.144[a] | 9.517 | 8.406 | 47.882 |
| | SW | 38.220[a] | 6.559 | 24.617 | 51.824 |
| | E | 27.650[a] | 18.058 | −9.800 | 65.100 |
| | W | 66.764[a] | 6.896 | 52.463 | 81.066 |
| LC | N | 3.329[a] | 0.284 | 2.741 | 3.918 |
| | NE | 1.494[a] | 0.313 | 0.846 | 2.143 |
| | NW | 2.407[a] | 0.233 | 1.923 | 2.891 |
| | S | 4.141[a] | 0.263 | 3.596 | 4.686 |
| | SE | 2.823[a] | 0.392 | 2.011 | 3.636 |
| | SW | 2.202[a] | 0.270 | 1.643 | 2.762 |
| | E | 1.517[a] | 0.335 | 0.821 | 2.212 |
| | W | 4.100[a] | 0.743 | 2.559 | 5.641 |
| USBC | N | 7.170[a] | 0.292 | 6.564 | 7.776 |
| | NE | 4.218[a] | 0.345 | 3.502 | 4.935 |
| | NW | 5.989[a] | 0.240 | 5.491 | 6.488 |
| | S | 4.648[a] | 0.322 | 3.980 | 5.315 |
| | SE | 5.768[a] | 0.403 | 4.932 | 6.605 |
| | SW | 5.478[a] | 0.278 | 4.902 | 6.055 |
| | E | 8.318[a] | 0.271 | 7.757 | 8.880 |
| | W | 7.670[a] | 0.765 | 6.083 | 9.257 |
| DWC | N | 1.239[a] | 0.432 | 0.342 | 2.136 |
| | NE | 1.383[a] | 0.515 | 0.315 | 2.450 |
| | NW | 1.113[a] | 0.384 | 0.316 | 1.909 |
| | S | 5.708[a] | 0.552 | 4.564 | 6.853 |
| | SE | 2.267[a] | 0.645 | 0.930 | 3.604 |
| | SW | 0.992[a] | 0.444 | 0.070 | 1.913 |
| | E | −8.882E-16[a] | 1.223 | −2.536 | 2.536 |
| | W | 0.757[a] | 0.467 | −0.212 | 1.725 |
| TCS | N | 329.166[a] | 44.455 | 236.972 | 421.359 |
| | NE | 231.495[a] | 52.912 | 121.763 | 341.227 |
| | NW | 366.473[a] | 39.490 | 284.576 | 448.370 |
| | S | 177.628[a] | 56.749 | 59.937 | 295.319 |
| | SE | 286.823[a] | 66.269 | 149.389 | 424.257 |
| | SW | 353.125[a] | 45.673 | 258.405 | 447.845 |
| | E | 300.115[a] | 125.737 | 39.352 | 560.877 |
| | W | 534.786[a] | 48.017 | 435.206 | 634.366 |

[a]Based on modified population marginal mean.

the northeastern (NE) followed by the southern (S) aspects. On the other hand, the lowest DWC was revealed in the eastern (E) aspect, followed by the western (W) aspect (Table 14). AGBC, BGBC, and TCS revealed statistically significant variation between the means at $P < 0.05$, whereas the mean carbon stock results of SCS ($P = 0.407$), DWC ($P = 0.278$), USBC ($P = 0.052$), and LC ($P = 0.128$) were statistically not significant (Table 7). On the other hand, the maximum total carbon stock (TCS) was recorded at west aspect, whereas the south aspect (S) had the lowest value (Table 14).

In Ziba forest, the mean AGBC, BGBC, and SCS stocks were highest in the west (W) aspect, whereas the highest mean values of USBC, DWC, and LC were revealed in the northeast (NE), flat (F), and north (N) aspects, respectively. Then again, the lowest mean values of AGBC, BGBC, and LC were exhibited in the flat (F) aspect, whereas the least USBC value was observed at NW aspect. On the N aspect, the lowest SCS was recorded. Strangely, the lowest mean carbon stock values of DWC were observed in the two different geographical faces, in the east and north aspects (Table 14). In addition to this, AGBC, BGBC, and TCS were statistically significant between different aspects, $P < 0.05$. However, the differences between the means of SCS, USBC, DWC, and LC pools were statistically not significant in different aspects, $P > 0.05$ (Table 10). On the other hand, the maximum total carbon stock was recorded in the western (W) aspect, while the flat (F) aspect had the lowest value (Table 14).

## 4. Discussion

### *4.1. Carbon Stock Potential of the Ecosystem*

*4.1.1. Carbon Stock in the Aboveground and Belowground Biomass.* The forests in the study sites potentially mitigate climate change by sinking huge amount of carbon stock in the aboveground and belowground biomass. In comparison to the unprotected mixed forest (Ziba), the protected forest (Anshirava) had greater aboveground and belowground carbon stocks (Table 4 and Figure 5). Human intervention for charcoal production, firewood collection, fencing, building, and animal grazing might all be factors contributing to decreased carbon stores in the Ziba forest. Grazing, as is well known, aggravates soil and vegetation degradation, which in turn has a detrimental impact on vegetation and the buildup of aboveground and belowground biomass [90]. Furthermore, variations in AGBC and BGBC between the two forests may be explained by differences in management techniques, basal area, species richness, the number of individuals per ha, species diversity, and species composition. According to Jati [91] and Atsbha et al. [92], basal area is an essential characteristic that influences the carbon content of the species. Negasi et al. [93] also said that the greater the basal area and diameter, the greater the biomass and hence the greater the carbon storage. Furthermore, the timber and charcoal production activity in the Ziba forest may contribute to this discrepancy. Because timber harvesting targets high-value species and eliminates large DBH and high-biomass trees from a forest stand [94].

The mean aboveground biomass carbon stocks revealed in this study were lower than those found in earlier Ethiopian investigations done in afromontane forest ecosystems [49, 75, 95–97], but greater than that found in [93], they reported $40.99 \pm 0.40\,t\cdot ha^{-1}$ aboveground carbon stock in Tigray dry forests under community management (Table 15). The discrepancies might be attributable to changes in the allometric model employed, the age of the stand, and forest management [98]. Environmental differences, topography and altitude, spp. differences, and the size of the trees sampled might all have a role. According to Brown and Lugo [8], a few large individual trees can account for a significant proportion of the plots aboveground and belowground biomass carbon stock. The aboveground carbon stock amounts in our study, on the other hand, were more equivalent to Tulu and Zewdu [99] and Mesfin [100] estimates of $129.85 \pm 154.11\,t\cdot ha^{-1}$ and $133\,t\cdot ha^{-1}$, respectively. In tropical dry forests, Murphy and Lugo [101] reported global aboveground carbon stocks ranging from 13.5 to $122.85\,t\cdot ha^{-1}$, which is comparable to the Ziba forest result. Naveenkumar et al. [102] reported 99–216 $t\cdot ha^{-1}$ as well. As a result, the current result in both forests falls in the middle of this range. The results of this study's mean belowground biomass carbon stock were higher than those discovered in earlier Ethiopian research by Negasi et al. [93], Tulu and Zewdu [99], and Mesfin [100], as shown in Table 15. On the other hand, Muluken et al. [49], Abel et al. [95], and Abyot [96] investigations are equivalent to the present Ziba result. A value obtained in Anshirava, on the other hand, is more comparable to a result observed in Banja forest [75].

*4.1.2. Dead Wood Biomass Carbon Stock.* The results indicated that the mean dead wood biomass carbon (DWC) stock comprised in Ziba is greater than Anshirava forest (Table 4 and Figure 5). There was significantly more fallen and standing woody debris in Ziba forest than in Anshirava forest. Anthropogenic disturbance in Ziba forest may result in somewhat greater dead wood carbon than in Anshirava forest. According to Mishra et al. [108], both anthropogenic and natural disturbances can affect the amount of coarse woody debris in the forest stand. Similarly, Feldpausch et al. [109] thought that logging events also increase the production of coarse woody debris, from which carbon is released when the decomposition process occurs. Furthermore, Anshirava forest may have less deadwood carbon as a result of improved management and protection. In support of this, Berta et al. [110] thought that deadwood dynamics are significantly linked to forest management. Furthermore, Abbott and Crossley [111] and Bani et al. [112] claimed that the warm and humid climate promotes the breakdown of dead wood.

Since the elevation of the Anshirava forest is lower than that of the Ziba forest, the rate of decomposition and conversion of dead wood into soil is relatively fast. As a result, carbon availability in dead wood may be lower in Anshirava. In support of this, Gale et al. [113] also suggested that variation in dead wood carbon stock might be influenced by topography, which influences tree

Table 14: Estimated marginal means of aspect in Ziba forest.

| Dependent variable | Aspect | Mean | Std. error | 95% confidence interval | |
|---|---|---|---|---|---|
| | | | | Lower bound | Upper bound |
| DWC | N | 4.441E-15[a] | 2.276 | −4.734 | 4.734 |
| | NE | 2.183[a] | 1.394 | −0.716 | 5.081 |
| | NW | 1.423[a] | 0.767 | −0.172 | 3.017 |
| | S | 3.796[a] | 1.039 | 1.635 | 5.957 |
| | SE | 4.161[a] | 0.813 | 2.471 | 5.852 |
| | F | 8.200[a] | 2.276 | 3.466 | 12.934 |
| | E | −2.220E-16[a] | 1.610 | −3.347 | 3.347 |
| | W | 0.947[a] | 0.867 | −0.856 | 2.750 |
| USBC | N | 6.350[a] | 2.753 | 0.625 | 12.075 |
| | NE | 9.128[a] | 1.686 | 5.622 | 12.633 |
| | NW | 3.394[a] | 1.048 | 1.214 | 5.574 |
| | S | 3.674[a] | 1.256 | 1.061 | 6.287 |
| | SE | 5.928[a] | 0.983 | 3.883 | 7.972 |
| | F | 5.530[a] | 2.753 | −0.195 | 11.255 |
| | E | 5.110[a] | 1.947 | 1.062 | 9.158 |
| | W | 5.533[a] | 0.927 | 3.605 | 7.461 |
| LC | N | 8.680[a] | 1.810 | 4.915 | 12.445 |
| | NE | 6.785[a] | 1.109 | 4.479 | 9.091 |
| | NW | 3.688[a] | 0.610 | 2.420 | 4.956 |
| | S | 3.579[a] | 0.826 | 1.861 | 5.298 |
| | SE | 5.319[a] | 0.647 | 3.974 | 6.664 |
| | F | 3.170[a] | 1.810 | −0.595 | 6.935 |
| | E | 3.475[a] | 1.280 | 0.813 | 6.137 |
| | W | 5.824[a] | 0.689 | 4.390 | 7.258 |
| AGBC | N | 82.796[a] | 42.101 | −4.757 | 170.349 |
| | NE | 86.632[a] | 25.781 | 33.017 | 140.247 |
| | NW | 87.041[a] | 14.179 | 57.555 | 116.528 |
| | S | 91.657[a] | 19.216 | 51.694 | 131.619 |
| | SE | 99.893[a] | 15.036 | 68.624 | 131.162 |
| | F | 18.149[a] | 42.101 | −69.404 | 105.702 |
| | E | 95.699[a] | 29.770 | 33.789 | 157.608 |
| | W | 172.665[a] | 16.031 | 139.326 | 206.005 |
| BGBC | N | 16.559[a] | 8.420 | -0.951 | 34.070 |
| | NE | 17.326[a] | 5.156 | 6.603 | 28.049 |
| | NW | 17.408[a] | 2.836 | 11.511 | 23.306 |
| | S | 18.331[a] | 3.843 | 10.339 | 26.324 |
| | SE | 19.979[a] | 3.007 | 13.725 | 26.232 |
| | F | 3.630[a] | 8.420 | −13.881 | 21.140 |
| | E | 19.140[a] | 5.954 | 6.758 | 31.522 |
| | W | 34.533[a] | 3.206 | 27.865 | 41.201 |
| SCS | N | 77.627[a] | 15.587 | 45.212 | 110.042 |
| | NE | 84.273[a] | 9.545 | 64.423 | 104.123 |
| | NW | 95.141[a] | 5.249 | 84.224 | 106.058 |
| | S | 83.912[a] | 7.114 | 69.117 | 98.707 |
| | SE | 97.456[a] | 5.567 | 85.879 | 109.032 |
| | F | 94.923[a] | 15.587 | 62.508 | 127.338 |
| | E | 90.901[a] | 11.022 | 67.980 | 113.821 |
| | W | 101.920[a] | 5.935 | 89.577 | 114.263 |
| TCS | N | 192.012[a] | 44.995 | 98.440 | 285.583 |
| | NE | 206.326[a] | 27.553 | 149.025 | 263.627 |
| | NW | 210.235[a] | 15.154 | 178.721 | 241.748 |
| | S | 204.949[a] | 20.537 | 162.240 | 247.659 |
| | SE | 232.735[a] | 16.070 | 199.317 | 266.154 |
| | F | 133.601[a] | 44.995 | 40.030 | 227.173 |
| | E | 214.324[a] | 31.816 | 148.159 | 280.489 |
| | W | 319.283[a] | 17.133 | 283.653 | 354.914 |

[a]Based on modified population marginal mean.

Table 15: Comparison of carbon stock with previous studies.

| Source | Carbon stock in different pools ($t{\cdot}ha^{-1}$) | | | | | | | Study area |
|---|---|---|---|---|---|---|---|---|
| | AGBC | BGBC | DWC | USBC | LC | Soil | TCS | |
| Adugna et al. [73] | 278.08 | 55.62 | | — | 3.47 | 277.56 | 614.72 | Egdu forest, Ethiopia |
| Hamere et al. [103] | 281 | 56.1 | 2.37 | — | 0.41 | 183.69 | 523.64 | Gedo forest, Ethiopia |
| Tamene [104] | 466.08 & 169.02 | 93.22 & 33.80 | | | 2.51 & 1.15 | 155.75 & 149.63 | 717.56 & 353.6 | Gergeda and Anbessa forest, respectively, in Ethiopia |
| Abyot [96] | 243.85 | 45.97 | 4.64 | 0.01 | 0.03 | 292.13 | 586.73 | Gerba Dima forest, Southwestern Ethiopia |
| Negasi et al. [93] | 40.99 | 11.62 | | 3.72 | | — | 58.11 | Community managed forest in Tigray |
| Naveenkumar et al. [102] | 99-216 | | | 3.6-9.3 | | | | Tropical dry forest |
| Tibebu and Teshome [105] | 270.89 | 54.18 | 0.725 | | 0.019 | 242.5 | 568.314 | |
| Abere et al. [106] | 338.72 | 67.74 | | | 2.58 | 230.82 | 639.86 | Banja forest, Ethiopia |
| Alemu [97] | 291.78 | — | | | | — | — | Guangua forest, Ethiopia |
| Abel et al. [95] | 237.20 | 47.60 | | | | 57.62 | 348.91 | Mount Zequalla Monastery |
| Muluken et al. [49] | 277.78 | 41.65 | | | 1.06 | 186.40 | 506.89 | Danaba community forest |
| Tulu and Zewdu [99] | 129.86 | 25.97 | | | 4.95 | 135.94 | | Ethiopian church forests |
| Mesfin [100] | 133 | 26.99 | 6.34 | 4.3 | 6.5 | 121.28 | 293.12 | Menagesha Suba state forest |
| Ngo et al. [107] | | | 31.2 & 8.3 | | | | | Primary and secondary forests of Singapore, respectively |
| Current study Ziba forest | 106.71 | 45.41 | 2.00 | 5.41 | 4.82 | 100.07 | 240.36 | Choke Mountain ecosystem |
| Current study Anshirava forest | 180.18 | 77.51 | 1.36 | 6.09 | 2.69 | 111.43 | 338.18 | |

mortality. This variation can also be attributed to forest type and age [114], mortality rate [115], the chemical composition of the debris and therefore the forest's tree species composition [116], and the land use history and management of an area.

The result in this study is considerably lower than the findings of [96]conducted in Gerba Dima Forest, Southwestern Ethiopia ($4.64\,t{\cdot}ha^{-1}$), [100] $6.34 \pm 38\,t{\cdot}ha^{-1}$, and a research done in Singapore's primary and secondary tropical forests found $31.2\,t{\cdot}ha^{-1}$ and $8.3\,t{\cdot}ha^{-1}$ dead wood carbon, respectively [107] (Table 15). The smaller DWC may be due to the smaller number of dead standing and fallen trees in the current study.

*4.1.3. Litter Carbon Stock.* In Anshirava, the mean carbon stock and its $CO_2$ equivalent in the dead litter were $2.69\,t{\cdot}ha^{-1}$ and $9.87\,t{\cdot}ha^{-1}$, respectively, while in Ziba, they were $4.82\,t{\cdot}ha^{-1}$ and $17.68\,t{\cdot}ha^{-1}$ (Table 4 and Figure 5). The present result at Ziba site is consistent with Tulu and Zewdu [99] results, which revealed an average of $4.95\,t{\cdot}ha^{-1}$ (Table 15). However, it is roughly twice as much as Anshirava site litter carbon. On the other hand, the amount of litter carbon observed in Anshirava was consistent with the findings in dry tropical forests [8], which ranges from 2.52 to $3.69\,t{\cdot}ha^{-1}$. It is also comparable to the figure obtained in tropical dry forests [17], which is around $2.1\,t{\cdot}ha^{-1}$. It is also more comparable to the $2.58\,t{\cdot}ha^{-1}$ found in Banja forest [106].

On the other hand, Mesfin [100] found a $6.5\,t{\cdot}ha^{-1}$ average carbon stock in the dead litter of Menagesha forest. This is a higher figure than the current one. According to Joshi and Ghose [117] and Reddy et al. [118], the lower values in the current study could be attributable to forest successional stages, varying tree density, species composition, and heterogeneity. In contrary to the other carbon pools, Ziba has more dead litter carbon than Anshirava forest. This could be attributable to the fact that the Ziba site has a higher level of human encroachment. Similar to this finding, following forest encroachment, carbon stocks in surface litter in Texas increased linearly over time, according to Boutton et al. [119]. Furthermore, according to Feldpausch et al. [109] and Houghton [120], logging activities might hasten the accumulation of coarse woody debris, from which carbon is liberated and potentially added to the litter carbon pool. Similarly, both anthropogenic and natural disturbances can alter the quantity and quality of yearly litterfall and litter depth [108]. Furthermore, plant species composition, litter quality, soil quality, Ziba's colder climate, and higher elevation may all play a greater role. According to [121], the amount of litter produced is strongly connected to the atmospheric temperature and the amount of rain that falls during the year. According to Parsons et al. [122] and Becker et al. [123], the amount of litter produced by ecosystems varies based on elevation, latitude, soil fertility, stand structure, climate, and tree species composition. Since different forest ecosystems are made up of a diverse range of tree species, each spp. contributes to annual litter input in a different quantity and quality, which in turn has a significant impact on overall litter production and litter pool [124]. Again, soil characteristics and leaf litter quality are two of the most important factors that influence litter decomposition rates [125].

Furthermore, the composition of decomposer communities has also a significant impact on the physical breakdown of litter, the conversion of organic matter to nutrients, and the release of carbon dioxide into the atmosphere [126].

*4.1.4. Understory Biomass Carbon Stock.* In Anshirava and Ziba forests, the mean USB carbon stock was 6.09 t·ha$^{-1}$ and 5.62 t·ha$^{-1}$, respectively (Table 4 and Figure 5). The mean USB carbon stock observed in this study is not much different from that of other studies conducted in dry tropical forests, 4.3 t·ha$^{-1}$ [100], 3.72 t·ha$^{-1}$ [93], and 3.6–9.3 t·ha$^{-1}$ [102] (Table 15). However, Abyot [96] found very smaller carbon stock (0.01 t·ha$^{-1}$) than the current study.

In the present study, the understory biomass of Anshirava was higher as compared to the Ziba forest. This could be attributed to the presence of dense and tall grass in Anshirava. The reason for the relatively higher herb biomass carbon stock in Anshirava forest could be due to the presence of higher species density and less human and livestock interference than in Ziba forest. This might be due to the fact that continuous human and livestock encroachment and livestock grazing inhibit the growth of herbaceous layers and decrease herbaceous biomass through direct removal, leading to the depletion of the herb carbon stock. Livestock, alone or in combination with other disturbances, has a significant impact on stand structure and other features such as litter depth, basal area, and understory density [124, 127]. Similarly, González et al. [124] stated that, through grazing and trampling, livestock could have more detrimental impact on forest regeneration, understory structure, and herbaceous layer. In addition to this, the continuous harvesting of trees for charcoal production could damage the understory vegetation in the Ziba forest. According to Wiebe [128], frequent log removal for firewood and snag cutting will lead to lower structural complexity. In addition to this, opening roads for timber extraction and logging operations will also contribute to the destruction and alteration of the understory vegetation [108, 129]. Site characteristics and subsequently soil characteristics are also the main influential factors that determine ground flora composition [130] and productivity, which invariably affect the biomass of the understory.

The mean soil carbon stock at 45 cm depth showed 111.43 t·ha$^{-1}$ and 100.07 t·ha$^{-1}$ in Anshirava and Ziba forests, respectively (Table 4 and Figure 5). The mean $CO_2$ was 408.96 t·ha$^{-1}$ in Anshirava and 367.27 t·ha$^{-1}$ in Ziba. According to Watson et al. [81], the global carbon stock in the soil carbon pool to a depth of 1 m was 216 t·ha$^{-1}$. This is almost two-fold the result obtained in this study. Correspondingly, the authors of [131] reported that dry forests can store around 20–150 t·ha$^{-1}$, and the present findings fall within this range. Also, it is more comparable to the findings of Tulu and Zewdu [99], which is 135.94 + 21.26 t·ha$^{-1}$. The SOC density of different forest types of Kolli Hills in India ranges from 63.37 to 273 t·ha$^{-1}$, and the average SOC density was 96.05 t·ha$^{-1}$ [132]. This is in close agreement with the present study. However, it is smaller than the findings of Muluken et al. [49], Fentahun [75], and Abyot [96]. Those are 230.82 t·ha$^{-1}$, 186.40 t·ha$^{-1}$, and 292.13 t·ha$^{-1}$, respectively, whereas the present result is much greater than the finding of Abel et al. [95], which is 57.62 t·ha$^{-1}$.

Anshirava forest had higher soil carbon stocks than Ziba forest at the depth of 0–45 cm. The greater soil carbon stock in Anshirava may be due to the bulk density, vegetation characteristics, particularly the dominance of grasses in the understory, terrain features etc. as compared to Ziba forest. This could also be due to the adventitious root binding and leaching of surface carbon by grasses. Soils in grasslands are rich in organic carbon and hold an extensive fibrous root system that forms a favorable environment for soil microbial activity, leading to the accumulation of more soil carbon [133]. The low SCS in Ziba forest could also be due to the existence of low soil organic matter and different factors such as slope, higher altitude, and low temperature of the area. The greater carbon stock in Anshirava might also be due to the presence of high DBH-sized trees in the site as compared to the Ziba forest. According to Bekele et al. [134], trees have the potential to produce larger quantities of aboveground and belowground biomass compared to shrubs or herbs. More biomass results in increased production of aboveground litter and belowground root activity, and this makes trees an important factor for SOC sequestration. Besides, among various other factors, the stage of conservation of the forest can considerably influence this stock [135]. The same reasoning applies to the current study's lower value when compared to prior studies with a higher carbon stock. The management practice through area closure has contributed to increased soil organic carbon. Soil organic carbon has grown as a result of the management approach of area closure. Proper forest management can eliminate livestock and human encroachment and allow for the restoration of native vegetation, resulting in an increase in SOC in the top soil [136].

*4.1.5. Total Carbon Stock.* By adding the carbon stocks found in each carbon pool, the total mean carbon stock of the forests was calculated. As a result, the average TCS in Anshirava was estimated to be 338.18 t·ha$^{-1}$, with a mean $CO_2$ equivalent of 1241.14 t·ha$^{-1}$. In Ziba, however, the total mean carbon stock was 240.369.88 t·ha$^{-1}$, with a mean $CO_2$ equivalent of 882.12 + 36.24 t·ha$^{-1}$ (Table 4 and Figure 6).

According to the reports of Brown [26], Eggleston et al. [69], DeFries et al. [137], and Gibbs et al. [138] on national level forest biomass carbon stock estimates, Ethiopia's average carbon stock is 183 t ha$^{-1}$, 153 t ha$^{-1}$, 553 t ha$^{-1}$, and 168 t·ha$^{-1}$, respectively. As a result, the current study's estimations were lower than the IPCC estimates but higher than all of the other national assessments mentioned above. According to Murphy and Lugo [101], global patterns of aboveground biomass in tropical dry and wet forests vary from 30 to 275 ton/ha and 213–1173 ton/ha, respectively. The findings of this study show that the average carbon storage of Anshirava forest is larger than the global average of tropical dry forests, but the carbon stock of Ziba forest is within the range. Furthermore, the current findings are significantly lower than those reported by Muluken et al. [48], Fentahun [72], and Abyot [93]. In contrast, Negasi et al. [93] discovered a substantially lower total carbon stock than the current study. However, the Ziba forest estimate is more comparable to the earlier study in Menagesha Suba state forest [100]. Also, the carbon estimate in Anshirava forest is more comparable with the estimates of Abel et al. [95] (see Table 15). The observed variations may be explained by differences in tree age and species, forest management, the allometric model used [98], regional variability in soil, topography, height, and DBH range of trees [8]. The author stated that a few huge individuals can account for a substantial amount of the plots' aboveground and belowground biomass carbon. Environmental and anthropogenic factors, as well as regional variations, also have a prominent role.

Ziba forest had a lower total carbon stock (TCS) and $CO_2$ sequestration than Anshirava forest. Except for DWC and LC, Anshirava forest had a larger carbon quantity in all of the other carbon pools than Ziba forest (Figure 5 and Table 4). In addition to this, the differences are statistically significant except for DWC and USBC. This variation is attributed to the presence of higher species richness, diversity, DBH, and herb biomass in Anshirava as compared to Ziba, which makes Anshirava forest higher in total carbon stock. In addition, this may be due to the less management and human interventions in Ziba forest. Adjacent to the forest, there are a large number of agricultural communities whose livelihoods depend on the forest product. They are constantly removing fallen litter, dead wood, and twigs to use as firewood. Legal logging for the production of charcoal is carried out by state-organized youth groups. The nearby settlements are also illegally logging for construction, fencing, and fuel wood purpose. Cattle grazing in the forest and agricultural growth surrounding the Ziba forest are also problems. The state-organized youth groups are allowed to cut and use old aged *Acacia abyssinica* spp. for charcoal production. Though the government does not allow it, they additionally sometimes use *Cupressus lusitanica* for charcoal production. To replace what the youth groups cut, the government usually plant *Cupressus lusitanica* and *Albizia gummifera*. Therefore, there are ample *Cupressus lusitanica* and *Albizia gummifera* seedlings within the forest. There is also new planted *Eucalyptus globulus* plantation in the forest. However, most of the planted trees are found in the sapling and seedling stages. Therefore, newly planted seedlings and saplings, unlike large trees, may not store a significant amount of carbon in their biomass. All of these factors could have an effect on the forest carbon stock balance. This suggests that forest management and protection from human and cattle encroachment can increase stand structure and carbon sequestration potential because carbon losses from various land use systems are linked to loss of vegetation cover and soil erosion [90].

*4.1.6. Percent Share of Carbon Pools.* The carbon stock distribution and percent share of each carbon pool were investigated, and the greatest carbon stock was recorded in the AGB in both forests, which is 180.18 $t{\cdot}ha^{-1}$ (53%) in Anshirava forest and 106.71 $t{\cdot}ha^{-1}$ (44%) in Ziba forest. The next largest carbon share is stored in soil, which is 33% in Anshirava and 42% in Ziba (Figures 7 and 8). In the same way, Pan et al. [139] reported that tropical forests store 56% of carbon in their biomass and 32% in soil. In Ziba forest, the proportion of SOC was within the range commonly recorded for tropical forests. According to Don et al. [140], the proportion of carbon stored in the soil carbon pool in tropical forests ranges from 36 to 60%. Again, in support of the current finding, the biomass had contained twice as much carbon (64%) as the soil (36%) of Malaysia's tropical lowland forest [141]. A wet tropical forest in Africa also contained more than three times the carbon in its aboveground biomass than it had in its soil [142].

In contrast to this study, Subashree and Sundarapandian [143] reported the highest percentage of carbon stored in the soil, which is around 47–55%. Again García-Oliva et al. [144] reported that 51% of the total carbon stock of tropical forest in Mexico was found in the soil. It may be due to its ecosystem difference from the current study. Becouse [15] affirmed that tropical evergreen forests are likely the biomes with the highest SOC storage in the world.

On the other hand, the minimum carbon stock was observed in the dead wood biomass (1%), followed by litter and understory biomass in both forests (Figures 7 and 8). At both research sites, the mean carbon stock contained in the AGB pool was higher than in other pools. The larger carbon stock in the aboveground biomass may be attributed to the higher tree density in both forests and the absence of human intervention in Anshirava forest. Furthermore, the low carbon content in litter and dead wood pools is most likely owing to the rapid rate of decomposition. Since the study areas are located in tropical area, the rate of decomposition is relatively fast [145]. The findings were similar to [49, 103, 104, 146, 147], which identified AGB as the largest reservoir of carbon stock and soil as the second carbon pool. Another study conducted in Ethiopia's Banja forest discovered a similar trend in the percent share of various carbon pools. They discovered the greatest carbon reservoir in trees, accounting for 64% (53% of AGC and 11% of BGC), while the soil was the second largest carbon reservoir, accounting for 36%, with the litter herbs and grass pool (LHGs) containing the least carbon stock [106]. Similar to our study, Tulu and Zewdu [99] found the lowest carbon stock in the dead litter pool, while they found greater carbon in the soil. The proportion of carbon pools was found to be AGC > SOC > BGC > USBC > LC > DWC in decreasing order in this study, which is consistent to the findings of [92, 95, 148].

*4.1.7. Correlation between Different Carbon Pools.* Statistically significant positive correlation between AGBC and BGBC is obvious since BGB was calculated from AGB. The significant positive correlation of USBC with SOC and LC might be explained by the fact that herbs are usually annual plants that live for short periods of time before being forced to die and are periodically mixed with soil to enrich the litter and SOC pool. The current Ziba result is consistent with the findings of Getaneh et al. [96]. Like Anshirava, Gebeyehu et al. [149] discovered a positive strong correlation between AGBC stock and SOC stock. The negative correlation of DWC with AGBC and BGBC and other carbon pools could be due to human activities and livestock encroachment, which could generate dead wood biomass carbon to accelerate naturally low rates of deadwood carbon production while also having a negative impact on aboveground biomass carbon by reducing the number of live trees. In addition to this, the residual logging damage as well as the trampling effect could reduce the other carbon pools opposite to DWC. In line with this study, Pfeifer et al. [94] discovered that the carbon storage of live trees declined exponentially as forest degradation increased due to anthropogenic activities, whereas deadwood accounted for more than double the amount commonly assumed in the literature.

#### *4.1.8. Carbon Stocks in response to Topographical Factors*

*(1) Carbon Stocks in response to Altitude*. One of the most important environmental gradients affecting biomass, stem size, and stand density, as well as the quantity of soil organic carbon, is altitude. This indicates that there would be substantial variation in carbon storage as a result of a significant effect on climatic parameters such as temperature and precipitation [150]. In this research, carbon stock in Anshirava forest exhibited significant variation throughout the altitudinal gradient in aboveground, belowground, understory biomass, dead wood biomass, litter biomass, and soil at $P \leq 0.05$ (Table 7), whereas in Ziba forest, only SCS and LC did not present significant variation along altitude (Table 8). Similar to the current finding, the amount of carbon stock in different pools varied significantly over an altitudinal gradient, according to [76, 151, 152]. With rising altitude, all carbon pools in the Anshirava forest exhibited an increasing tendency. Similarly, in Ziba forest, USBC, DWC, and SCS all showed an increasing tendency as altitude increased. The current study revealed an increasing tendency of different carbon pools with altitude, which may be attributed to lower temperature and increased precipitation as elevation increases. Elevation has a complicated and presumably indirect influence. In general, as altitude increases, temperature decreases and precipitation increases. Then, climate variations along altitudinal gradients alter the composition and productivity of vegetation and hence the quantity and turnover of SOM [153]. According to Leifeld et al. [154], the combination of a decline in temperature and an increase in elevation may lower SOC and DWC turnover rates, resulting in higher SOC and DWC levels. Generally, higher rates of plant growth, and therefore higher rates of organic carbon input and SOC accumulation, are typically related to higher rates of precipitation. Mohammed et al. [76] also stated that climatic variables can have an impact on the forest carbon stock along an elevation gradient. Lower temperatures, according to [149], reduce rates of organic matter decomposition because breakdown of organic matter activities by microorganisms is slower at cooler temperatures, allowing for the formation of thicker litter layers and greater soil organic matter. These circumstances result in reduced $CO_2$ emissions from the soil, which helps in the storage of greater SOC stock. The increase in soil nutrients, the presence of large tree species, and the decreased amount of grazing and human disturbance as altitude increases could all be factors in this pattern.

In accordance with the findings from the Anshirava site, an increasing trend in AGBC and BGBC with increasing altitude was observed in [95]. The findings are consistent with Abyot [155], who discovered a statistically significant positive correlation between altitude and carbon pools such as USBC, DWC, and SCS. The authors of [149] observed a positive relationship between altitude and AGB and soil carbon stock pools. The authors of [156] also found that carbon stocks and altitude had positive linear correlations. Hoffmann et al. [157] found a positive relationship between SCS and altitude as well. This result, however, contradicts earlier studies, which stated that the greatest AGBC was found at lower altitudes [105, 158].

In Ziba forest, however, AGBC and BGBC showed a declining tendency with increasing altitude. This is owing to a natural decrease in large DBH trees at higher altitudinal ranges of the forest site and an increase in large DBH trees at lower altitudinal ranges. This result is in line with [105, 158]. Similarly, Asaminew et al. [159] found significant differences in aboveground, belowground, litter biomass, and soil organic carbon across environmental gradients. They discovered that, as altitude increased, AGBC and BGBC decreased, but soil organic carbon and liter carbon increased. Some investigations in other regions of the world have discovered a trend comparable to the Ziba forest. For example, Leuschner et al. [160], Luo et al. [161], and Moser et al. [162, 163] reported that aboveground and belowground tree biomass decreases as altitude increases. Furthermore, the insignificant variation of SCS and LC along altitude in Ziba forest may be attributable to the study area's narrow altitudinal range. In general, total carbon stock accumulation in Anshirava forest increased with altitude, but it did not display a distinct pattern in Ziba, despite the fact that other carbon pools varied along this gradient. Similar to Ziba's finding, the total carbon stock did not exhibit a clear trend with altitude in [95].

*(2) Carbon Stocks in response to Slope*. The slope gradient was also a factor that influenced the carbon stocks of different pools in the forests that were investigated. In both forests, all of the biomass and soil carbon stocks varied in response to slope. In both forests, the differences in means of all carbon pools along the slope gradient were statistically significant ($P < 0.05$) with the exception of DWC and LC in Ziba (Table 10).

Similar to this finding, the authors of [159] observed significant variation in aboveground and belowground carbon stocks, but not in liter carbon stock, along a slope gradient. Getaneh et al. [149] found that AGBC and SCS varied significantly across the slope gradient. In agreement with this outcome, because of the connection between solar radiation and soil parameters such as soil moisture content and nutrient availability, Bayat [89] also indicated that the slope has a significant relationship with biomass in forest areas.

As the slope increased, the mean AGBC, BGBC, SCS, USBC, and LC all decreased. DWC, on the other hand, showed a significant increasing trend at both locations. The higher dead wood carbon at the steep slope may be attributed to less human invasion, such as dead standing and fallen wood collecting, because its geographical nature is difficult to reach in comparison to flat and intermediate slopes. On the other hand, because it is easier and more accessible for the populations living surrounding the forest, continual removal of fallen and standing dead wood for the purpose of fuelwood may occur on the lower slopes. The lower carbon stock in the remaining pools on steep slopes may be attributed to the influence of soil erosion, which can cause soil to lose nutrients, diminish the litter layer and vegetation cover, and therefore influence the soil and biomass carbon of the study area. Furthermore, the lower vegetation cover as well as the kind of plant spp. may have an impact on carbon reservoirs. Because most steep slopes are covered by lower plants such as grasses, herbs, and shrubs [105], which contain lesser biomass and carbon relative to other plants. These scholars also reported an increasing trend in DWC and a declining trend in AGBC, BGBC, LC, and USBC stock with increasing slope, which is consistent with our study. Asaminew et al. [159] discovered a decreasing tendency of AGB, BGBC, LC, and SCS with increasing slope, which is also compatible with our findings. According to Adugna and Teshome [146], the aboveground and belowground carbon, soil organic carbon, and total carbon stock of the forest all exhibited a negative association with slope gradient. In contrast to this work, Getaneh et al. [149] discovered a statistically significant positive connection between slope and AGB and soil carbon stock. He discovered that flat regions had the lowest AGBC stock, while steep slopes had the highest.

*(3) Carbon Stocks in response to Aspect.* Aspect is one of the environmental variables that might affect the forest carbon stock in different carbon pools [89], and thus, it can be utilized as a helpful factor to evaluate the forest carbon stock in different carbon pools. In the current study, eight distinct geographical aspects were identified in both locations, and the examination of carbon stock variation of AGBC, BGBC, and TCS pools in all parts of the forest regions revealed significant variation, whereas SCS, USBC, DWC, and LC pools exhibited insignificant variation across different aspects.

The west (W) aspect of both forests revealed the highest mean carbon stock values of AGBC, BGBC, SCS, and TCS pools (Tables 13 and 14). This can be attributed to the western aspect's greater availability of moisture and soil fertility than the other aspects. Furthermore, a large number of tree species with high DBH and height dominate the western aspects of the studied forests. This study agrees with Mohammed et al. [76]; they reported the highest AGBC, BGBC, and TCS stocks in the western aspect of the investigated forest. Wolde et al. [38] also observed a higher soil carbon stock in the western aspects of Arba Minch forests.

On the other hand, the flat (F) aspect in Ziba forest had the lowest mean values of AGBC, BGBC, LC, and TCS (Table 13). As indicated above, there is a significant level of human intervention in Ziba forest, including legal and illegal logging, replanting, and cattle encroachment. Also, because flat aspects are more easily accessible to people, these activities are more likely to take place there. Thus, all of this might result in a decreased amount of carbon stock on the flat aspects of the forest site. Based on this finding, we may conclude that forest exclosure can promote forest carbon sequestration and increase carbon stocks in both flat aspects and the forest as a whole.

In Anshirava forest, on the other hand, the south aspect (S) exhibited the lowest values of AGBC, BGBC, SCS, and TCS (Table 14). In contrast to the current study, Getaneh et al. [149] reported the highest values of AGBC and BGBC in the southern and lowest values in the northern aspects, whereas the SCS and DWC of Ziba forest were found to be the lowest in the N aspect. The absence of high-biomass trees, a smaller quantity of litter fall, a lower quantity of fallen and standing dead wood, and a slower rate of decomposition may also be contributing factors to the finding of reduced soil and dead wood carbon in the N aspect.

The highest mean values of USBC stock were observed in the northeast (NE) and east (E) aspects of Ziba and Anshirava forests, respectively. Because it faces the rising sun, there is enough solar radiation and warm temperatures on the site for the fallen wood, stumps, and woody debris to decompose faster, increasing organic matter in the soil and creating a favorable environment for the growth of grasses and herbs. Furthermore, in this study's forests, there is lower tree density and greater canopy openness in the northern and eastern aspects of Ziba and Anshirava forests, respectively, which can promote the growth of herbaceous plants.

In addition to this, LC was higher in the north (N) and south (S) aspects in Ziba and Anshirava, respectively. There is an incidence of higher natural disturbances such as windfalls on the southern aspect [164]. This could lead to higher bark, branch, and litter fall in the forest ground and enhance the litter biomass stock on the southern aspect. The greater litter carbon stocks in the northern aspect of the Ziba forest may be attributed to the quality and amount of litter fall and lower decomposition rate. North-facing slopes get less solar radiation than south-facing slopes. As a result, the north-facing slopes are considerably colder [89, 164]. This causes a slower rate of decomposition and a larger accumulation of carbon in the litter pool. However, Adugna and Teshome [146] found significant litter biomass and carbon in the southern aspects.

Furthermore, Ziba forest in the flat aspect and Anshirava forest in the south aspect had the highest mean DWC values. The cause might be human and cattle encroachment in the Ziba forest as well as natural disturbances in the Anshirava forest. Many studies have found that human encroachment is more prevalent in the flat aspects of the forest. For example, Kinnaird et al. [165] reported that there is a higher encroachment on the flat parts of the forest than in the other parts surrounded by settlements. Furthermore, several studies have shown that natural disturbances such as windfall [164] and high radiation [89, 164] are more common in the southern aspects of a forest than the other slope sides, resulting in damaged trees as well as hot and dry forest soil [166]. As a result, large trees may fall to the ground or dry and die while standing. Similarly, the occurrence of lower AGBC, BGBC, SCS, and TCS stock levels in the southern side of the forest might be due to this. Moreover, the south-facing part of the study forest is near to the communities, despite the fact that the forest is still controlled by forest guards. In general, the total carbon stocks in the various pools were ordered as follows: W > NW > SE > SW > E > N > NE > S in Anshirava forest and W > SE > NW > S > E > NE > N > F in Ziba forest. Similarly, Mohammed et al. [76] reported a higher total carbon stock value in the west aspect. Despite the fact that the highest carbon stock value contradicts this study, Adugna and Teshome [146] discovered the lowest value in the south aspect, which is similar to the Anshirava site.

## 5. Conclusions and Recommendations

According to the findings of this study, forests have a significant potential for carbon storage in plant biomass and soil. By adding the carbon stocked in plant biomass and forest soil, the carbon content of the Choke Mountain ecosystem ranges from 240.36 t·ha$^{-1}$ to 338.18 t·ha$^{-1}$. Furthermore, it can be inferred that it helps to mitigate global warming by stocking 882.12 t·ha$^{-1}$–1241.14 t·ha$^{-1}$ $CO_2$. Besides, it is also evident that these dry evergreen montane forests can store substantial biomass carbon equivalent to global averages.

This first assessment of carbon stocks in Anshirava and Ziba forests indicated a considerable difference between the two sites. Total carbon stocks were higher in Anshirava forest than Ziba forest, with the majority of carbon stored in the AGB (44–53%) and the second larger portion is stored in soil (33–42%) followed by BGB. USB, litter, and DW, on the other hand, had the least carbon and $CO_2$.

The percent share of carbon in distinct carbon pools in these two forests is similar to literature values and in close agreement with other national and tropical forests. The management effect, such as area closure, which has been implemented in Anshirava forest, has led to enhanced species richness, diversity, higher biomass, and soil organic carbon compared to Ziba forest, making Anshirava forest higher in total carbon stock. The findings also show that well-protected forests can sequester significantly more biomass and soil carbon than heavily manipulated forests.

According to the ANOVA result, AGBC, BGBC, and DWC in Ziba forest and AGBC, BGBC, USBC, SCS, and LC in Anshirava forest exhibited variations in response to altitude. Except AGB and BGB carbon stock pools in Ziba forest, all the carbon pools in both sites exhibited an increasing trend with increasing altitude. Aside from that, all of the carbon pools in Anshirava showed slope-dependent variations. Also, with the exception of DWC and LC, all carbon pools in Ziba forest showed statistical variation along the slope gradient. Furthermore, with the exception of DWC, all carbon pools showed a declining tendency with increasing slope.

Only the AGBC, BGBC, and TCS pools, on the other hand, differed significantly in different aspects of both forests. The total carbon stocks in the different pools were ordered as follows: W > NW > SE > SW > E > N > NE > S in Anshirava forest and W > SE > E > NW > S > NE > N > F in Ziba forest.

Based on the findings, it is possible to conclude that the dry evergreen montane forests of the Choke Mountain ecosystem have the capacity to sequester a significant quantity of $CO_2$, with a significant variance along altitude, slope, and aspect gradients. This also demonstrated that the carbon pool components of forest ecosystems may respond differentially to climatic variables and play an essential role in climate change mitigation. As a result, suitable community-based forest management alternatives should be developed to ensure its long-term viability. Society, government, and concerned stakeholders should engage in various participatory forest management activities such as enrichment planting, conservation, and rehabilitation of these forests in order to increase their carbon stock potential, to contribute to the reduction of atmospheric $CO_2$, to mitigate the challenge of global climate change, and to benefit from them.

On the other hand, the findings of this study confirmed that the presence of man-made disturbances in Ziba forest, such as the removal of large trees for the purpose of charcoal and timber production, would significantly contribute to the escalation of the greenhouse effect, through the release of both forest biomass and soil carbon. Therefore, tree harvesting in Ziba forest as well as other community forests for the purpose of charcoal making and timber production and to get other benefits should be done under the oversight of responsible organizations and should be monitored by forest specialists. Besides, for the forest to continue to exist, conservation and forest management practices must take precedence.

## Data Availability

The data used to support the findings of this study are accessible upon request to the corresponding author.

## Conflicts of Interest

The authors declare that there are no conflicts of interest. David Russel Smart was a Professor Emeritus in the College of Agricultural and Environmental Sciences at the University of California Davis, California. Sadly, he passed away in April of 2020.

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