Research Article

Effect of Forest Management on Carbon Stock of Tropical Moist Afromontane Forest

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Received 5 February 2022; Revised 16 June 2022; Accepted 18 August 2022; Published 30 September 2022

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Moist tropical forests have a significant role in provisioning and regulating ecosystem services. However, these forests are under threat of deforestation and forest degradation. In Ethiopia, the moist evergreen Afromontane forests have the potential for carbon storage and support a high diversity of plant species. However, it is under severe threat of deforestation and degradation. This investigation was conducted to obtain adequate information on the carbon stock potential of the moist Afromontane forest of southwestern Ethiopia. A comparison of carbon stock was conducted between disturbed and undisturbed forests. A systematic sampling design was applied for recording woody species and soil data. A total of 100 main plots of 400 m2 were laid to record trees and shrubs with a diameter at breast height (DBH) ≥ 5 cm. The soil data were collected from 1 m2 subplots established at the four corners and the center of each main plot. The DBH and height were measured to calculate the aboveground carbon of trees and shrubs with DBH ≥ 5 cm. A total of 68 tree and shrub species belonging to 59 genera and 33 families were recorded. The mean carbon stock density was 203.80 ± 12.38 t·ha⁻¹ (aboveground carbon stock) and 40.76 ± 2.47 t·ha⁻¹ (belowground carbon stock). The highest proportion of aboveground carbon (t·ha⁻¹) (42.34%) was contributed by a few tree individuals with DBH > 70 cm. The soil organic carbon stock (SOCs) (t·ha⁻¹) for the depth of 0–30 cm is ranging from 58.97 to 198.33 across plots; the mean is 117.16 ± 3.15. The carbon stored in the moist Afromontane forest indicates its huge potential for climate change mitigation. Therefore, for the enhancement of forest biodiversity and carbon sequestration effective conservation measure and sound management approach is essential.

1. Introduction

The global atmospheric concentration of carbon dioxide (CO₂) has increased significantly due to human activities since the start of the industrial era [1]. The prominent sources of increase in CO₂ concentration are fossil fuel use [2–4] and global land-use change [5, 6]. The prominent sources of methane (CH₄) and nitrous oxide (N₂O), which have a significant effect on atmospheric concentration, are agricultural activities [7–9]. A study indicated the cumulative anthropogenic emission of 2,040 Pg CO₂ between 1750 and 2011, predominantly from fossil fuel and land-use change [10]. Different investigations describe an extreme threat to our planet after 1970 associated with carbon dioxide emission [1], and it has been accumulating at an increasing rate and is estimated to exceed 400 ppm [11, 12].

The terrestrial biosphere can release and/or absorb GHGs such as CO₂ and has considerable importance in regulating the atmospheric composition and climate change [13]. Compared with other terrestrial parts, a huge portion of the carbon is stored in forest ecosystems [14, 15]. The terrestrial vegetation alone is estimated to store approximately 450–650 gigatons of carbon [16]; the global forest ecosystem total carbon is also estimated at 638 gigatons [17], which is more than the amount of carbon content in the entire atmosphere [18]. Currently, an investigation on the storage
and emission of CO₂ in a forest ecosystem is a topic of considerable importance. Predominantly, the tropical forest ecosystem is known for the highest carbon pool in its biomass compared with other biomes of the world [19–24]. Generally, the tropical biome is the most productive and accounts for over 60% of global terrestrial photosynthesis and one-third of global net primary productivity [25–27].

Currently, associated with deforestation and forest degradation the increase in atmospheric CO₂ is the prominent environmental challenge. The conversion of forest land to agriculture, infrastructure development, and settlements are the major drivers aggravating the situations linked to human population growth [28, 29]. However, a great discrepancy was observed among study reports concerning the quantity of CO₂ sink and emission from global forests. Currently, a report from Intergovernmental Panel on Climate Change is one of very high confidence in science [30]. Forests produce around 17 percent of global emissions [1, 31], which is the largest source of greenhouse emissions [32]. Therefore, the conservation and management of forest resources to solve this problem necessitate accurate and continuously updated data. In addition, understanding the current situation of the forest resource helps resource managers to give attention and optimize resource allocation either on the driver side through prevention or on the impact side through mitigation.

In Africa, about 70% of GHG emission is caused by deforestation [33]. Conversely, global forests play a dynamic role in response to the increasing concentration of carbon dioxide. REDD+ was devised under the United Nations Framework Convention on Climate Change (UNFCCC) to combat CO₂ emissions [28, 34]. It is the central issue in the global climate negotiation and is very important for participating countries to benefit from the carbon credit. The forestry-based mitigation strategy reducing emission from deforestation and forest degradation, forest conservation, sustainable forest management, and enhancement (REDD+) requires a precise and verifiable estimate of carbon stock that helps to evaluate whether forestry-based policies to mitigate the emission of CO₂ have achieved the target [35, 36]. Ethiopia’s Climate Resilient Green Economy (CRGE) strategy underpinned the importance of adaptation and mitigation [37]. More than 87% of CO₂ emission in Ethiopia is from the agricultural and forestry sectors, while the total contribution of the other sectors is less than 15% [38]. The forestry sector alone accounts for the total emission of about 37% CO₂ in Ethiopia [39].

The Afromontane regions are subregions of Afrotropical realms that constitute plant species found in mountains of Africa and the southern Arabian Peninsula [40, 41]. The Afromontane regions of Africa are discontinuous, separated from each other by low-lying areas, and this region mostly follow the East African Rift from the Red Sea to Zimbabwe [42, 43]. The moist Afromontane vegetation is characterized by one or more closed strata of evergreen trees, which may reach a height of 30 to 40 m [44]. These forests occur in the southwestern part of Ethiopia Highlands between 1500 and 2600 elevation range [45] and on the southeastern plateau, on the southern portion of the Bale Mountains at an altitudinal range of between 1,450 and 2,700 masl [44, 46]. However, this vegetation is under threat of deforestation and degradation in Ethiopia, regardless of its great significance for biodiversity conservation and the source of multiple ecosystem services [47].

Previous conservation approaches rely on strict protection of resources, and human utilization has not been considered [48, 49]. However, the current biosphere reserve approach of natural resource management is preferable to the pristine concept of resource protection previously mentioned. The biosphere reserve approach was intended to encourage the sustainable development and conservation of biodiversity [50–52]. Yayu Forest-Coffee Biosphere Reserve was established to ensure its sustainability and for the improvement of local community livelihood [53]. Vegetation of the biosphere reserve was designated as Afromontane rainforest, which is home to the endemic Coffea arabica L. population. This vegetation is a component of the Eastern Afromontane Biodiversity Hotspot, which has global significance [54].

The vegetation of the core zone (undisturbed forest) in the biosphere reserve is strictly protected for the conservation of biological diversity, investigation, and monitoring of ecological processes. The buffer zone (disturbed forest) is identified area surrounding the undisturbed forest (UF), used for activities compatible with sound ecological practices [53]. The transitional zone of the biosphere contains settlement areas, farms, and other human activities. A comparative analysis of carbon stock potential in major pools of UF and disturbed forest (DF) was not yet conducted in the biosphere reserve. Therefore, this study was conducted to (i) determine aboveground and soil carbon stocks, (ii) understand the relationship between carbon stocks with topographic factors and stand structures, and (iii) obtain sufficient information about the carbon stock potential of undisturbed and disturbed forests in Yayu Forest-Coffee Biosphere Reserve.

2. Materials and Methods

2.1. Location of Study Site. The study was conducted in Yayu Forest-Coffee Biosphere Reserve located in Illubabor Zone, southwestern Ethiopia. The biosphere reserve covers latitude ranging from 8°15′0″ to 8°35′0″ N and longitude ranging from 35°30′0″ to 36°0′0″ E of zone 36 (Figure 1). The total area covered by the undisturbed forests (UFs) is 27,733 hectares and disturbed forests (DFs) is 21,552 hectares, and the transitional zone is 117,730 hectares of the total 167,021 hectares of the biosphere reserve [53]. The UF is located at the lower elevation areas near river banks. However, the DF is found on the higher elevation of the biosphere in proximity to human settlements.

2.2. Description of the Study Area. The topography of Yayu Forest-Coffee Biosphere Reserve is characterized by undulating terrain, and detailed information on topography and soil type can be found in [55, 56]. The geological formation of the moist Afromontane forest areas consists of intensively
folded and faulted Precambrian bedrock, overlain by mesozoic marine and tertiary basalt types [57, 58]. The mean annual temperature is about 20.4°C, ranging from a mean maximum of 27.2°C to a mean minimum of 13.7°C. The mean annual rainfall is 1803 mm/year with high variation from year to year (1257 to 2514 mm·year⁻¹). The moist Afromontane forest is characterized by multiple strata of evergreen trees that reach a height of 30 to 40 m. Characteristic species in the canopy include *Olea capensis* subsp. *welwitschii* and subsp. *hochstetteri*, *Albizia schimperiana*, *Millettia ferruginea*, and *Celtis africana*. Sub-canopy species include *Croton macrostachyus*, *Cordia africana*, *Dracena steudneri*, and *Sapium ellipticum* [44, 46].

A systematic sampling design was adopted to collect the environmental and vegetation data within 52 plots of UF and 48 plots of DF. A total of 16 parallel transect lines that are 500 m apart were laid across the undisturbed and disturbed forests considering mainly elevation gradients. Along the transect lines, plots were established at every 300 m. A total of 100 plots of 20 m × 20 m were established for documentation of tree and shrub species [59, 60] with DBH ≥ 5 cm. Within the main plots, four subplots of 1 m × 1 m were laid at the corner and one in the middle for soil sampling [61].

2.2.1. Field Measurements. Trees and shrubs with a diameter at breast height (DBH) ≥ 5 cm were recorded within the main plots of 400 m². The soil samples were collected from subplots of 1 m² within main plots. The DBH at 1.3 m was measured using caliper for small- and medium-sized trees/shrubs, and diameter tape was used for large diameter trees. The tree height was measured using a clinometer and visual estimation. The geographical coordinates of plots and altitudes were measured using Garmin eTrex 10 GPS receiver. The aspect was measured using compass, and clinometer was used to measure the slope. The voucher specimens for woody species encountered were collected and brought to the National Herbarium, Addis Ababa University, for taxonomic identification. The identification was done using the Flora of Ethiopia and Eritrea and by comparing the specimens with the authentic specimens in the National Herbarium [62–66].

**Measurement of Aboveground Biomass (AGB).** The diameter (DBH) and total height of individual trees and shrubs with DBH ≥ 5 cm were measured in every 400 m² plot. The wood density values were taken from global wood density database [67]. Trees on the border with > 50% of their basal area falling within the plot were included and excluded when < 50% of their basal area falls outside the plot [68]. Trees overhanging into plots were excluded, but those with trunks inside the plot and branches outside were included [61].

**Measurement of Belowground Biomass (BGB).** The measurement of belowground biomass is more difficult and time-consuming than AGB measurement. Therefore, the standard method for estimation of BGB is 20% of AGB, which is determined as the root-to-shoot ratio value of 1:5 [68].
Soil Data Collection. Soil samples were collected from the top 30 cm depth as prescribed by [69] guideline for forest soil. The composite soil samples were collected from subplots (1 m²) at the four corners and the middle of the main soil. He composite soil samples were collected from sub-top 30 cm depth as prescribed by [69] guideline for forest soil. The soil samples were analyzed in the laboratory analysis. He samples from each of the two depths were composited separately, labeled, placed in plastic bags, and transported to the soil fertility laboratory of the Water Works Design and Supervision Enterprise (WWDSE) in Addis Ababa, Ethiopia.

2.3. Laboratory Analysis. The soil samples were analyzed in the soil fertility laboratory of the Water Works Design and Supervision Enterprise (WWDSE) in Addis Ababa, Ethiopia. About 100 g of the collected soil samples from each depth was used for the determination of soil organic carbon (SOC). They were air-dried and passed through a 2 mm sieve for SOC analysis. SOC concentrations were determined based on the method/procedure developed by [72]. Each bulk soil sample was oven-dried at a temperature of 105°C for 24 hours to achieve a constant weight. The soil sample was analyzed for organic matter following the standard procedure outlined in [73].

2.4. Estimation of Carbon Stock. Computation of tree biomass was the primary step for the estimation of carbon stock, which was employed using the standard conversion factors. The carbon stock of major pools AGCS, BGCS, and SOCS was computed as follows in the subheadings.

2.4.1. Estimation of Aboveground Carbon (AGC). The aboveground carbon stock of trees and shrubs was estimated using an appropriate biomass equation developed by [74]. The global wood density database was used as a source of the wood density values for the species [67].

\[ AGB(kg) = 0.0559 \times \left( \rho D^2 H \right), \]

where \( AGB = \) predicted aboveground total biomass (kg), \( D = \) diameter at breast height (cm), \( H = \) total height (m), and \( \rho = \) wood density (g cm⁻³) from global wood density database.

2.4.2. Estimation of Belowground Carbon (BGC). The equation developed by [68] was used.

\[ BGB(kg) = AGB \times 0.2, \]

where \( BGB = \) belowground biomass, \( AGB = \) aboveground total biomass, and 0.2 = conversion factor (or 20% of AGB).

2.4.3. Estimation of Soil Organic Carbon. The quantity of soil carbon per hectare was computed as recommended by [69, 75].

\[ SOCS = BD \times d \times \%SOC, \]

where \( SOCS = \) soil carbon stock per unit area (t ha⁻¹), \( BD = \) bulk density (g cm⁻³), \( d = \) total depth at which soil sample was taken (30 cm), and \( \%SOC = \) soil organic carbon concentration.

Bulk density was computed using the following equation:

\[ BD = \frac{M_{av,dry}}{V}, \]

where \( BD = \) bulk density of soil sample (g cm⁻³), \( M_{av,dry} = \) average air-dry weight of soil sample per plot (g), and \( V = \) volume of soil sample in the core sampler (cm³) [75].

2.4.4. Total Carbon Stock Density. The total carbon stock density was calculated by summing the carbon stock densities of major carbon pools. The carbon stock estimate was produced by extrapolating data at plot level to a full area of hectare. Extrapolation was occurred by calculating the proportion of a hectare (10,000 m²) that was occupied by a given plot using expansion factors [75].

The total carbon stock density of a study area is calculated as follows:

\[ C_{density} = C_{AGB} + C_{BGB} + SOC, \]

where \( C_{density} = \) carbon stock density for all major pools (t Cha⁻¹); \( C_{AGB} = \) carbon in aboveground tree biomass (t Cha⁻¹); \( C_{BGB} = \) carbon in belowground biomass (t Cha⁻¹); and \( SOC = \) soil organic carbon (t Cha⁻¹).

2.5. Data Analysis. The collected data were summarized in the excel spreadsheet. Statistical packages in R software version 3.6.1 were used for carbon data analysis. The normality of the data was checked using the Shapiro–Wilk normality test before conducting statistical analysis; log transformation was employed when data distribution was found not normal. The Shapiro–Wilk test statistic W is small for non-normal samples. The test rejects the hypothesis of normality when the P value is less than 0.05.

3. Results

3.1. Carbon Stock Estimation of Major Pools

3.1.1. Aboveground and Belowground Carbon Stocks. The result revealed that mean belowground carbon stock (BGCS)
was estimated at 40.76 ± 2.47 t·ha⁻¹, whereas the aboveground carbon stock (AGCS) was 203.80 ± 12.38 t·ha⁻¹ (Table 1).

3.1.2. Variation of Aboveground Carbon Stock across Tree Size Classes. The result showed that the proportion of AGCS (t·ha⁻¹) increased across successive DBH and height classes. Particularly, individuals with stem diameter in the higher DBH class (DBH >70 cm) contributed the highest proportion of AGCS (t·ha⁻¹) (42.34%). On the other hand, upper story trees within height class >30 m contributed the highest proportion AGCS (t·ha⁻¹) (71.43%). Individuals with height >20 m have contributed 93.09% AGCS (t·ha⁻¹) of the forest. The result verifies that an enormous amount of AGCS (t·ha⁻¹) was stored in large trees (Figure 2).

3.1.3. Aboveground Carbon Stock Difference among Tree Species. A total of 68 trees and shrub species with DBH≥ 5 cm were recorded at the study site. The result revealed that only a few tree species of large size (DBH and H) contributed a significant amount of AGCS to moist Afrotomante forest. Seven dominant tree species including Sapium ellipticum, Cordia africana, Morus mesozygia, Albizia grandibracteata, Ficus lutea, Trichilia dregeana, and Maytenus undata contributed about 64.37% t·ha⁻¹ of AGCS. A total of 22 tree species with the higher DBH sizes contributed 93.20% t·ha⁻¹ to the total AGCS of the forest. However, the smallest proportion of AGCS was contributed by the majority of less dominant species. Tree populations with the higher density (stem·ha⁻¹) and higher mean value of DBH and H were found to contribute a significant amount of carbon stock storage.

3.2. Distribution of Soil Organic Carbon. Analysis for the 100 plots described that value of the bulk density for topsoil (0–15 cm) is 0.62–1.38 g·cm⁻³ and for subsoil (15–30 cm) is 0.61–1.44 g·cm⁻³. The range and mean value of soil organic carbon concentration (SOC (%)) are 1.79–9.09 and 3.50 ± 0.61 g·cm⁻³ for topsoil depth of 0–15 cm and 1.14–7.78 and 2.47 ± 0.98 g·cm⁻³ for subsoil depth of 15–30 cm. A comparison of the SOC (%) means value between the topsoil and subsoil revealed significant differences (at F = 22.21, P = 0.001). The result also showed that, the soil organic carbon stock (SOCs) of topsoil (range = 8.3–120.84, mean = 61.50 ± 1.91 t·ha⁻¹); and for the subsoil (15–30 cm) the SOCS (range = 20.79–140.73, 55.68 ± 2.41 t·ha⁻¹). The higher mean SOCS (t·ha⁻¹) was recorded for the topsoil; however, the mean difference does not show a statistical significance (at F = 3.58, P = 0.06). On the other hand, the SOCS (t·ha⁻¹) for the depth of 0–30 cm ranged from 58.97 to 198.33, with a mean of 117.16 ± 3.15 across the plots in the studied forest.

3.3. Variation of Aboveground and Soil Organic Carbon Stock with Topographic Factors. The mean of SOCS (t·ha⁻¹) did not show significant variation within different elevation, aspect, and slope classes. However, a significant difference in mean AGCS (t·ha⁻¹) was observed only between lower slopes and intermediate and lower and steep slope classes. Similarly, the significant variation of AGCS t·ha⁻¹ was recorded between the higher elevation class and other classes (at P < 0.05) (Table 2).

3.4. Variation of Soil Organic Carbon Concentration with Topographic Factors. The mean SOC (%) of 30 cm depth was plotted against topographic gradients (Figure 3). The variation of SOC (%) against elevation gradient exhibited quadratic pattern (R² = 0.0437, P > 0.05). The SOC (%) showed optimum quantity in the middle elevation ranges and decreased for higher elevations. The SOC (%) has a direct relationship with aboveground biomass productivity, which is potentially influenced by elevation. Therefore, decreasing SOC (%) with increasing elevation is possibly related to the effect of elevation on biomass productivity. In addition, biomass productivity is directly related to soil organic matter, which is a potential source of soil organic carbon. On the other hand, SOC (%) was found to be negatively correlated against the slope gradient, however statistically not significant (R² = 0.0128, P > 0.05).

3.4.1. Variation of Soil Organic Carbon Concentration in Response to Stand Structure. The result showed that SOC (%) was correlated with stand structural attributes (plot species richness, mean canopy cover, and the number of stems per plot). However, the responses of SOC (%) against these stand structural parameters do not show statistical significance (Figure 4). The soil organic carbon concentration was positively correlated with plot species richness (SR) (R² = 0.0057, P > 0.05). SOC (%) was negatively correlated with mean canopy cover percent (CC%) (R² = 0.0005, P > 0.05) and number of individuals per plots (R² = 0.0143, P > 0.05). However, either of the relationships with stand structure did not show statistical significance. The observed values along the regression lines show great dispersion, which is an indication of variability of data.
3.5.1. Difference in Soil Organic and Aboveground Carbon Stock of Forest Types. The mean SOCS (t·ha⁻¹) between UF and DF does not show a significant difference (at \( p > 0.05 \)). The soil bulk density (g·cm⁻³), SOC (%), and SOCS (t·ha⁻¹) comparative analysis between the soil depths (0–15 cm and 15–30 cm) and between forest types are presented in Table 3. The difference in mean AGCS (t·ha⁻¹) between UF and DF does not show significance (\( P > 0.05 \)). The higher mean DBH value of the DF is related to the predominance of only higher DBH individuals in this forest (Table 3).

3.5.2. Comparison Aboveground Carbon Stock of the Large Diameter and Height Tree Species in UF and DF. The large diameter and height tree species contribute a significant amount of AGCS (t·ha⁻¹) to both undisturbed and disturbed forests. However, the comparison of AGCS (t·ha⁻¹) for similar tree species across the forest types showed higher value for many tree species of the undisturbed forest as presented in Table 4.

4. Discussion

4.1. Carbon Stock of Afromontane Rainforest

4.1.1. Aboveground Carbon Stock. The aboveground carbon stock (AGCS) of the Afromontane rainforest showed high variation across the plots. The amount of AGCS ranged from 11.14 t·ha⁻¹ to 775.40 t·ha⁻¹, with an estimated mean value of 203.80 ± 12.38 t·ha⁻¹. The mean AGCS (t·ha⁻¹) from our study is higher than the mean from different Afromontane forests [76]. However, the mean AGCS (t·ha⁻¹) reported in our study is lower than that from other moist evergreen Afromontane forests [77, 78]. However, the AGCS value of our study report is within the range when compared with reports from some tropical rainforests (49.1–476.1 Mg·ha⁻¹) [79]. On the other hand, the AGCS value from our study is higher when compared with (60.09 to 121.43 t·ha⁻¹) [80]. The highest proportion of AGCS was contributed by a few tree species and individuals, which are dominant in the higher DBH classes (42.34%) and emergent canopy layers (71.43%). Studies have also confirmed the storage of a significant amount of AGCS in the large-size classes (DBH and H) of tropical rainforests [81–83]. However, a study described the unimodal pattern of aboveground carbon stock across increasing diameter classes [84]. Overall, upper canopy individuals of tropical forests have a significant contribution to aboveground carbon storage. Previous
researches also confirmed the effect of functional dominance on carbon storage of a forest stand; the functional traits (wood density, specific leaf area, and maximum plant height) have a noticeable effect on optimum carbon storage [79, 85]. A few tree species contributed a significant amount of AGCS to a forest stand. In our study, 51.11%, 64.37%, and 93.20% of AGCS (tha⁻¹) were contributed by a population of 7, 10, and 22 tree species, respectively. The structural attributes and functional dominance of tree species are important in biomass productivity and carbon storage. The stocking of tree population, DBH, and height are the important parameters that determine biomass productivity and carbon storage of a species [86, 87].

4.1.2. Soil Organic Carbon Stock. The soil bulk density (SBD) and soil organic carbon concentration (SOC (%)) between the topsoil and subsoil of the studied moist Afrotomontane forest have shown a significant difference. SBD was found to increase with increasing soil depth, while SOC (%) decreases with increasing soil depth [88–90]. In addition, several studies have confirmed the inverse relationship between SBD and SOC (%) along with soil depth in moist Afrotomontane forests [78] and tropical rainforests [91, 92]. The mean SOCS is 117.16 ± 3.15 t·ha⁻¹ for the depth of 0–30 cm, which is higher than the study report with 105 ± 18.73 t·ha⁻¹ [93]. The mean SOCS value of our study is lower than moist Afrotomontane forest of 128t·ha⁻¹ [94] with 162.62 ± 3.20 t·ha⁻¹ [78]. Studies verified the effect of tree species, altitude, and land-use difference in variation SOCS across tropical forests [93, 95].

4.1.3. Variation of Carbon Stocks with Site Factors. The canopy cover percent has shown a positive linear relationship with the aboveground carbon storage of the moist Afrotomontane forest. Large tree crown correlates with the basal area of large DBH trees. A study verified the great significance of large tree crown areas in explaining the aboveground biomass, which is directly related to the carbon storage [96]. In addition, plot species richness (PSR) has shown a positive linear relationship with aboveground carbon storage in our study. Species richness is the simplest measure of species diversity; a study has also verified the significant effect of species diversity on aboveground carbon storage through functional diversity and functional dominance of species [79]. A positive relationship was demonstrated between AGCS and SOCS, which is consistent with the previous study’s report [80, 97].

In addition, AGCS was found negatively correlated with elevation gradients, whereas the slope was positively correlated. In the studied moist Afrotomontane forest, the higher elevation areas were exposed to selective removal associated with Coffea arabica L. management in the understory. A study verified a significant effect of disturbance on stand structural attributes and on reduction in AGCS in primary forest conversion [98]. There is a great discrepancy among studies concerning relationships between AGCS and topographic factors (elevation and slope); a decreasing trend was observed for AGCS along with increasing elevation gradients [99–101]. However, studies in tropical forests have shown a positive relationship of AGCS with slope and elevation gradients [102]. On the other hand, a unimodal pattern was exhibited for the relationship between AGCS and elevation gradients in natural habitats [103].

The SOC (%) of our study exhibited a unimodal pattern of distribution along increasing elevation gradients. The optimum value of SOC (%) was observed in the middle elevation ranges, possibly related to the effect of elevation on biomass productivity and plant community composition [93, 95]. The SOC (%) in the higher elevation gradients was highly exposed to human disturbance due to Coffea arabica L. production under natural forest. The adverse effect of anthropogenic disturbance on soil carbon stock of a tropical forest was described [104]. Inconsistent results were reported concerning the relationship between SOC (%) and elevation gradients in different studies. The SOC was found
Table 3: Variation of SOCS between AGCS in undisturbed and disturbed forests (key: SOCS = soil organic carbon stock; AGCS = aboveground carbon stock; AGCO₂e = aboveground carbon dioxide equivalent; BD = bulk density, SOC (%) = soil organic carbon concentration; DBH = diameter at breast height, H = total height). Different letters in the column of variables show a significant difference at a 5% significance level.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Soil depth (cm)</th>
<th>Undisturbed forest</th>
<th>Disturbed forest</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min-Max</td>
<td>Mean ± SE</td>
<td>Min-Max</td>
</tr>
<tr>
<td>BD (g cm⁻³)</td>
<td>0–15</td>
<td>0.62–1.38 ± 0.021ᵃ</td>
<td>0.67–1.22 ± 0.018ᵃ</td>
</tr>
<tr>
<td></td>
<td>15–30</td>
<td>1.13–1.39 ± 0.026ᵇ</td>
<td>1.02–1.22 ± 0.022ᵇ</td>
</tr>
<tr>
<td>SOC (%)</td>
<td>0–15</td>
<td>1.79–7.51 ± 0.184ᵃ</td>
<td>1.82–9.09 ± 0.229ᵃ</td>
</tr>
<tr>
<td></td>
<td>15–30</td>
<td>3.35–7.78 ± 0.195ᵇ</td>
<td>3.66–7.67 ± 0.227ᵇ</td>
</tr>
<tr>
<td>SOCS (t ha⁻¹)</td>
<td>0–15</td>
<td>28.3–98.51 ± 2.49</td>
<td>32.89–120.84 ± 2.86ᵃ</td>
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<tr>
<td></td>
<td>15–30</td>
<td>57.96 ± 2.49</td>
<td>65.34 ± 2.86ᵇ</td>
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<tr>
<td>DBH (cm)</td>
<td>5–189</td>
<td>17.84 ± 0.48ᵃ</td>
<td>21.65 ± 0.69ᵇ</td>
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<tr>
<td>H (m)</td>
<td>2.7–48</td>
<td>16.78 ± 0.30</td>
<td>16.54 ± 0.38</td>
</tr>
<tr>
<td>AGCS (t ha⁻¹)</td>
<td>11.14–775.40</td>
<td>215.9 ± 17.83</td>
<td>23.53–617.73 ± 17.07</td>
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<tr>
<td>AGCO₂e (t ha⁻¹)</td>
<td>40.87–2845.72</td>
<td>792.4 ± 65.44</td>
<td>86.36–2267.07 ± 62.66</td>
</tr>
</tbody>
</table>
to decrease with increasing elevation gradients in a tropical forest [91]; a positive correlation was exhibited between SOC and elevation gradient [88, 105]. On contrary, the indirect influence of plant community composition on SOC (%) was also predicted [79]. A linear relationship was observed between SOC (%) and slope gradients; SOC (%) has shown a decreasing pattern along increasing slope gradients for our study. The soil on a steep slope is highly exposed to nutrient losses, leading to lower SOC (%). Studies in tropical forests have also confirmed a negative correlation between SOC (%) and slope gradients [101, 106].

The SOC (%) has revealed a weak positive correlation with plot species richness, a weak negative correlation with mean CC%, and a weak negative correlation with stem abundance. The observed values of SOC (%) have shown great variance in either of the relationships. The relationship between SOC (%) and stand structural attributes is indirect. Multiple environmental variables influence the biomass productivity of a forest stand that directly affects soil organic matter accumulation. Investigation on tropical forests has revealed the increase in carbon storage with increasing taxonomic diversity and functional dominance [79, 87].
Studies verified the significant effect of stand structural attributes on SOC (%) in Afromontane forests [107, 108].

4.2. Comparison of Carbon Stocks between Undisturbed and Disturbed Forests. Comparing the mean of SOCS (t ha$^{-1}$) for topsoil (0–15 cm) was found different between the UF and DF of moist Afromontane forests; the mean was found higher for DF. The comparative result of our study was found consistent with the finding in [22], which reports the accumulation of higher SOCS in secondary forests. The mean difference in SOCS (t ha$^{-1}$) is significant between topsoil and subsoil of DF, but insignificant between depth classes of UF. A study revealed the significant effect of forest disturbance on the emission of CO$_2$ from forest soil [104]. Less SOCS was reported in DF due to the higher mineralization rate of carbon in soil [98, 109, 110]. Contrary, to our finding, a study in tropical forests reports an accumulation of higher SOCS in the primary forest compared with the secondary forest [111], suggesting the role of forest protection in conserving soil organic carbon. Studies report the decline of SOCS along with the soil depth; however, the trend is not consistent [22, 112].

The higher mean of AGCS was recorded for UF (215.92 ± 17.83 t ha$^{-1}$) compared with the DF (190.67 ± 17.07 t ha$^{-1}$) of moist Afromontane forests. The DBH and height of trees and shrubs are the best explanatory variables for the estimation of aboveground carbon storage. The mean difference in DBH is significantly higher for individuals of DF, compared with UF. However, lower AGCS was reported for DF, associated with selective removal of large DBH and emergent canopy individuals to promote coffee production. Studies have also described the influence of human disturbance on the AGCS storage of forests [113, 114]. Compared with DF, the quantity of AGCS (t ha$^{-1}$) stored in dominant and codominant tree species is higher for UF. Sorting in descending order, the dominant species contributing significant AGCS (t ha$^{-1}$) are different between the forest categories. The variation of carbon stock storage among dominant species is influenced by DBH and height growth and the abundance of individual species [96, 102, 115]. Previous studies have also confirmed the role of functional dominance (maximum DBH, height, specific leaf area) of species in affecting the aboveground carbon storage of a forest [79, 87]. A study has also verified the influence of stem density on the carbon stock of tropical forests [116].

5. Conclusions

A considerable amount of carbon stock was found in aboveground biomass, belowground biomass, and soil pools of the studied moist Afromontane forest. The highest amount of AGCS was stored in tree species with higher stocking, large DBH, and higher height. However, a few tree species contributed a substantial amount of AGCS to the studied forest. The distribution of the SOCS showed variation vertically and horizontally in the forest site. The relationship was revealed between AGCS and SOCS with topographic factors. The forest structural attributes have explained the variation of AGCS and SOCS. The difference in AGCS between UF and DF is not significant. The amount of AGCS and SOCS depends on the intensity of anthropogenic disturbance. The AGCS was positively correlated with species richness or diversity of the forest stand. It verifies the role of species richness or diversity in promoting carbon storage through functional diversity and dominance. To enhance the carbon sequestration potential of DF, conservation efforts should focus on balancing the structural attributes of the forest and coffee plant population.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

The authors express their deep gratitude to Oromia Forest and Wildlife Enterprise (OFWE) for their unlimited assistance during the field data collection and to Yayu District Administration offices for their cooperation in providing them necessary information about the study site. The financial support for this work was obtained from the Center for Environmental Science of Addis Ababa University from Thematic Research Project.

References


