Hindawi
International Journal of Forestry Research
Volume 2022, Article ID 3691638, 14 pages
https://doi.org/10.1155/2022/3691638

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

Academic Editor: Ahmad A. Omar

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 m^2 were laid to record trees and shrubs with a diameter at breast height (DBH) $\geq$ 5 cm. The soil data were collected from 1 m^2 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 $\geq$ 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 $t{\cdot}ha^{-1}$ (aboveground carbon stock) and 40.76 ± 2.47 $t{\cdot}ha^{-1}$ (belowground carbon stock). The highest proportion of aboveground carbon ($t{\cdot}ha^{-1}$) (42.34%) was contributed by a few tree individuals with DBH > 70 cm. The soil organic carbon stock (SOCS) ($t{\cdot}ha^{-1}$) 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 (CO_2) has increased significantly due to human activities since the start of the industrial era [1]. The prominent sources of increase in CO_2 concentration are fossil fuel use [2–4] and global land-use change [5, 6]. The prominent sources of methane (CH_4) and nitrous oxide (N_2O), which have a significant effect on atmospheric concentration, are agricultural activities [7–9]. A study indicated the cumulative anthropogenic emission of 2,040 Pg CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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% CO_2 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

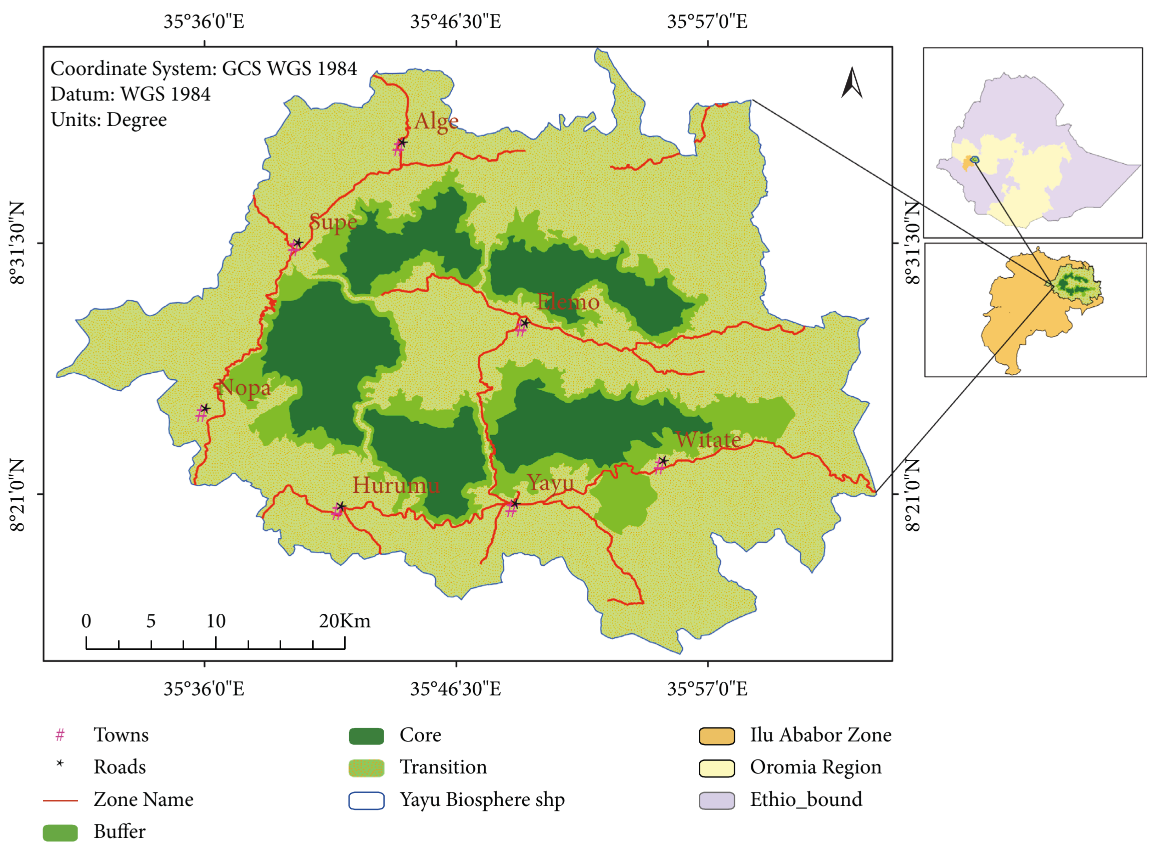

Figure 1: Map of the study area.

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^{-1} 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 m^2. The soil samples were collected from subplots of 1 m^2 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 m^2 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 m^2) at the four corners and the middle of the main plot for the determination of soil organic carbon (SOC). Sampling from a single soil depth mostly generates a bias in soil carbon stock estimation [70]. Two soil samples were collected from a single pit of 0–15 cm and 15–30 cm in depth near the center of all subplots. This sampling approach was used to best represent forest types in terms of slope, aspect, vegetation, density, and cover [71]**.** A total of 200 composite soil samples (2 depth ×100 plots) were collected from the study area. A total of 200 bulk soil samples (2 depths × 100 plots) were also collected on the center of the main plots using a core sampler of 250 cm^3 to determine bulk density. The samples from each of the two depths were composited separately, labeled, placed in plastic bags, and transported to the laboratory analysis.

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].

$$AGB\,(kg) = 0.0559 \times \left(\rho D^2 H\right), \tag{1}$$

where AGB = predicted aboveground total biomass (kg), D = diameter at breast height (cm), H = total height (m), and ρ = 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.

$$BGB\,(kg) = AGB \times 0.2, \tag{2}$$

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

The aboveground carbon for each plot was calculated by summing up the aboveground carbon for all tree and shrub species. The carbon was determined considering 47% carbon content in biomass of tropical region [69]. The conversion factor of 3.67 (44/12) was used to estimate CO_2 equivalent [75].

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

$$SOCS = BD \times d \times \%SOC, \tag{3}$$

where SOCS = soil carbon stock per unit area ($t{\cdot}ha^{-1}$), BD = bulk density ($g{\cdot}cm^{-3}$), 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:

$$BD = \frac{M_{av,\mathrm{dry}}}{V}, \tag{4}$$

where BD = bulk density of soil sample ($g{\cdot}cm^{-3}$), $M_{av,\ dry-}$ = average air-dry weight of soil sample per plot (g), and V = volume of soil sample in the core sampler (cm_3) [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 m^2) that was occupied by a given plot using expansion factors [75].

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

$$C_{\mathrm{density}} = C_{AGB} + C_{BGB} + SOC, \tag{5}$$

where C_{density} = carbon stock density for all major pools ($t{\cdot}C\,ha^{-1}$); C_{AGB} = carbon in aboveground tree biomass ($t{\cdot}C\,ha^{-1}$); C_{BGB} = carbon in belowground biomass ($t{\cdot}C\,ha^{-1}$); and SOC = soil organic carbon ($t{\cdot}C\,ha^{-1}$).

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 Afromontane forest. Seven dominant tree species including *Sapium ellipticum, Cordia africana, Morus mesozygia, Albizia grandibracteata, Ficus lutea, Trichilia dregeana, and Maytenus undata* contributed 51.11% t ha^{-1} of AGCS. The ten dominant tree species *Ficus vasta, Ehretia cymosa, and Celtis africana* including the seven species mentioned above have contributed about 64.37% t ha^{-1} of AGCS. A total of 22 tree species with 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 4.49 ± 0.149 for topsoil depth of 0–15 cm and 1.14–7.78 and 3.50 ± 0.149 for subsoil depth of 15–30. 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 (15–30cm) 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 h^{-1} was recorded between the higher elevation class and other classes (at $P < 0.05$) (Table 2).

Table 1: Descriptive summary of AGCS, BGCS, and carbon dioxide equivalent of the study forest.

Measured variables	Minimum	Maximum	Mean	
			Statistics	Std. error
DBH (cm)	5	189	19.37	0.40
H (m)	2	44	16.58	0.24
AGCS (t ha^{-1})	11.14	775.40	203.80	12.38
AG CO_2 equivalent (t ha^{-1})	40.87	2845.72	747.95	45.42
BGCS (t ha^{-1})	2.227	155.08	40.76	2.47
BG CO_2 equivalent (t ha^{-1})	8.17	569.14	149.59	9.08
Total carbon stock (t ha^{-1})	13.36	930.48	244.56	14.85
Total CO_2e (t ha^{-1})	49.04	3414.87	897.54	54.51

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 ($R^2 = 0.0437$, $P > 0.05$). 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 ($R^2 = 0.0128$, $P > 0.05$).

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) ($R^2 = 0.0057$, $P > 0.05$). SOC (%) was negatively correlated with mean canopy cover percent (CC%) ($R^2 = 0.0005$, $P > 0.05$) and number of individuals per plots ($R^2 = 0.0143$, $P > 0.05$). 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.

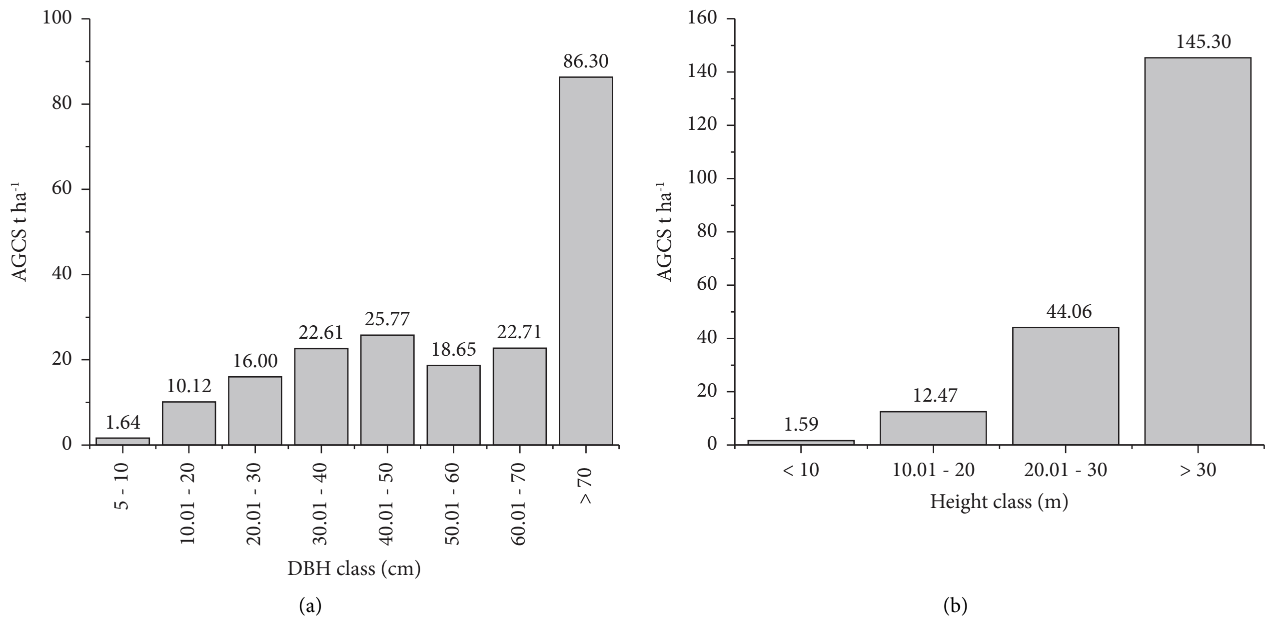

Figure 2: Variation of AGCS across DBH class (a) and height classes (b).

Table 2: Comparative analysis of mean carbon stock between elevation, slope, and aspect classes.

Topographic factors	SOCS ($t{\cdot}ha^{-1}$)	AGCS ($t{\cdot}ha^{-1}$)
Slope (%)		
Steep (> 20) (N = 34)	117.96 ± 6.88	211.71 ± 18.98^{b}
Intermediate (10–20) (N = 42)	118.75 ± 5.06	219.79 ± 22.99^{b}
Flat (<10) (N = 24)	118.68 ± 8.34	167.92 ± 16.67^{a}
Elevation (m)		
Higher (1483–1615) (N = 19)	114.48 ± 8.68	161.18 ± 17.96^{a}
Middle (1406–1480) (N = 52)	115.42 ± 4.47	210.81 ± 20.5^{b}
Lower (1242–1392) (N = 29)	128.69 ± 8.41	221.29 ± 20.56^{b}
Aspect		
N (N = 33)	113.46 ± 5.49	212.01 ± 16.95
NE (N = 10)	132.86 ± 11.99	213.01 ± 51.32
NW (N = 7)	146.89 ± 15.17	249.76 ± 43.64
S (N = 25)	118.12 ± 7.07	185.23 ± 22.60
SE (N = 6)	89.84 ± 4.94	195.23 ± 52.90
SW (N = 18)	117.23 ± 6.23	192.66 ± 39.43
W (N = 1)	112.86 ± 0.00	202.94 ± 0.00

N is the number of plots. N: north, NE: northeast, NW: northwest, S: south, SE: southeast, SW: southwest, W: west. Different letters in vertical refer to significant difference at $P < 0.05$.

3.5. Comparison of Carbon Stock between Undisturbed and Disturbed Forests

3.5.1. Difference in Soil Organic and Aboveground Carbon Stock of Forest Types. The mean SOCS ($t{\cdot}ha^{-1}$) between UF and DF does not show statistically a significant difference (at p > 0.05). The soil bulk density ($g{\cdot}cm^{-3}$), 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 $t{\cdot}ha^{-1}$ to 775.40 $t{\cdot}ha^{-1}$, with an estimated mean value of 203.80 ± 12.38 $t{\cdot}ha^{-1}$. 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 $Mg{\cdot}ha^{-1}$) [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

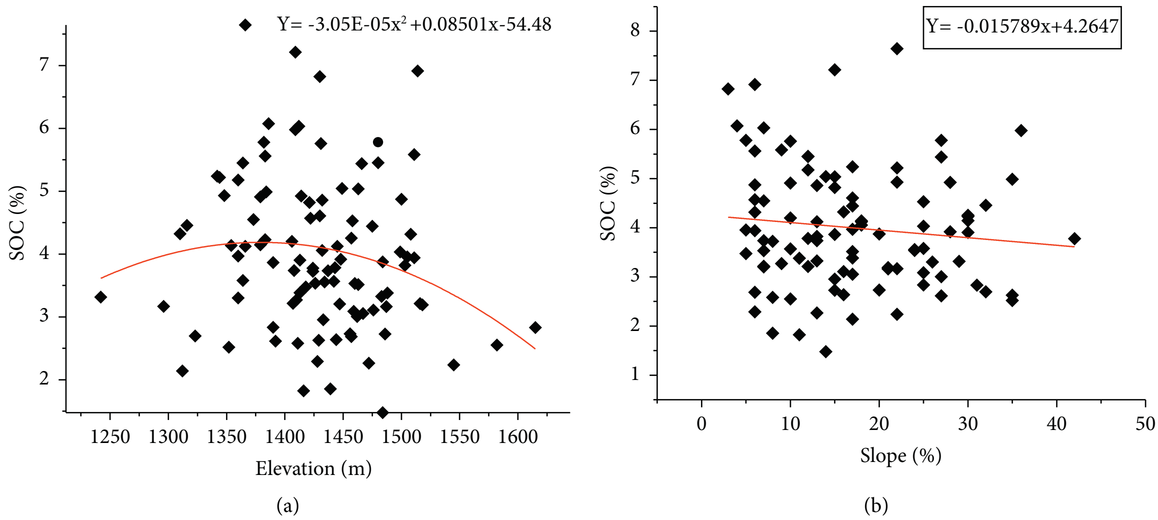

Figure 3: Response of mean SOC (%) against elevation and slope; x = the independent variable on the x-axis; y = the response variable on the y-axis; the dot and lines represent observed and fitted values of plots, respectively.

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 (t ha^{-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 Afromontane 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 Afromontane 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 Afromontane forest of 128 t·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 Afromontane 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 Afromontane 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

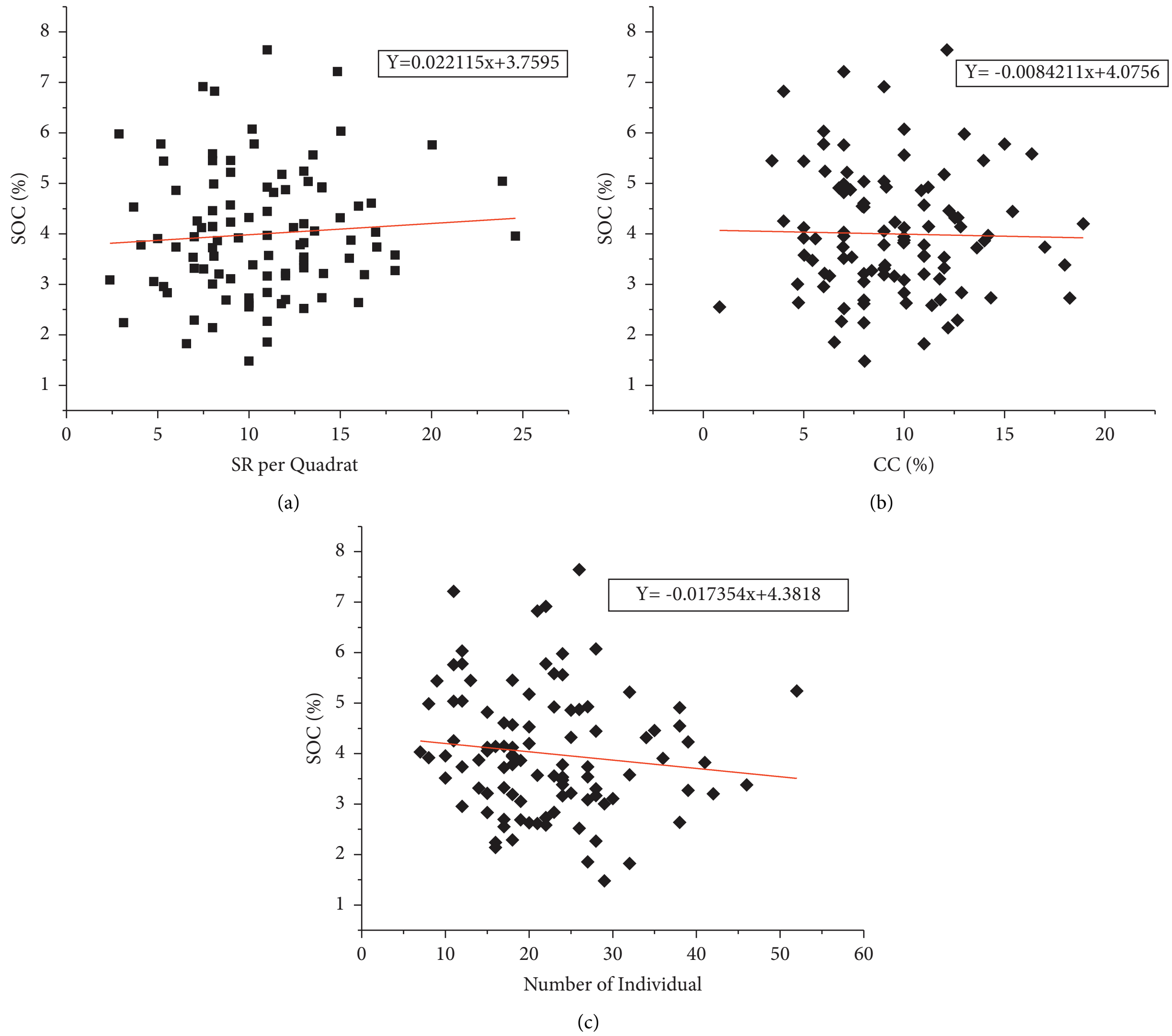

Figure 4: Response of mean SOC (%) against stand structural attributes (CC% = canopy cover percent, number of individuals per plot, SR = plot species richness, x = the independent variable on x-axis, y = the response variable on the y-axis); the dot and line represent observed and fitted values of plots, respectively.

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.

Variables	Soil depth (cm)	Undisturbed forest		Disturbed forest	
		Min-Max	Mean ± SE	Min-Max	Mean ± SE
BD (g·cm^{-3})	0–15	0.62–1.38	0.95 ± 0.021^{a}	0.67–1.22	0.91 ± 0.018^{a}
	15–30	0.61–1.39	1.131 ± 0.026^{b}	0.73–1.442	1.02 ± 0.022^{b}
SOC (%)	0–15	1.79–7.51	4.139 ± 0.184^{a}	1.82–9.09	4.88 ± 0.229^{a}
	15–30	1.14–7.78	3.355 ± 0.195^{b}	1.166–7.678	3.66 ± 0.227^{b}
SOCS (t·ha^{-1})	0–15	28.3–98.51	57.96 ± 2.49	32.89–120.84	65.34 ± 2.86^{a}
	15–30	22.01–140.73	56.75 ± 3.64	20.79–122.59	54.52 ± 3.14^{b}
DBH (cm)		5–189	17.84 ± 0.48^{a}	5–153	21.65 ± 0.69^{b}
H (m)		2.7–48	16.78 ± 0.30	2–45	16.54 ± 0.38
AGCS (t·ha^{-1})		11.14–775.40	215.92 ± 17.83	23.53–617.73	190.67 ± 17.07
AGCO$_2$e (t·ha^{-1})		40.87–2845.72	792.44 ± 65.44	86.36–2267.07	699.75 ± 62.66

Table 4: Comparison of aboveground carbon stock between large diameter tree species in UF and DF.

Scientific name	Forest types	Density (stem ha^{-1})	DBH (cm)	Height (m)	Mean AGCS (t ha^{-1})	AGCS (t ha^{-1})	$AGCO_2e$ (ton ha^{-1})
Cordia africana	UF	14.36	44.08 ± 5.62	26.57 ± 2.02	2.899 ± 0.69	87.42	308.57
	DF	18.75	36.74 ± 4.09	24.80 ± 1.53	1.764 ± 0.42	61.75	226.64
Morus mesozygia	UF	28.71	23.68 ± 2.46	25.28 ± 1.88	1.429 ± 0.36	81.50	299.09
	DF	15.1	27.78 ± 5.13	21.46 ± 2.56	2.269 ± 0.82	63.54	233.19
Ficus vasta	UF	1.49	130.67 ± 37.75	38.00 ± 6.43	21.18 ± 11.2[a]	63.55	233.24
	DF	3.65	61.60 ± 13.27	22.20 ± 3.15	4.135 ± 5.09[b]	20.67	75.87
Celtis africana	UF	43.07	17.35 ± 1.69	17.24 ± 1.09	0.654 ± 0.13	56.21	206.3
	DF	43.75	16.17 ± 1.43	15.94 ± 1.61	0.313 ± 0.48	12.84	47.11
Ficus lutea	UF	21.78	25.75 ± 4.41	16.75 ± 1.82	1.331 ± 0.45	55.91	205.18
	DF	13.02	40.95 ± 8.21	20.21 ± 2.09	2.459 ± 0.95	56.57	207.6
Elaeodendron buchananii	UF	43.56	16.75 ± 1.28	22.40 ± 1.37	0.722 ± 0.17	51.81	190.14
Mimusops kummel	DF	18.75	26.40 ± 2.49	23.26 ± 1.73	1.37 ± 0.33	50.77	186.32
Diospyros abyssinica	UF	51.49	15.58 ± 1.28	20.31 ± 2.13	0.458 ± 0.10	46.75	171.58
	DF	7.32	16.18 ± 2.81	16.12 ± 2.45	0.515 ± 0.20	13.40	49.18
Sapium ellipticum	UF	10.89	39.10 ± 5.03	25.24 ± 2.09	2.196 ± 0.75	46.12	169.26
	DF	17.71	51.17 ± 4.36	26.12 ± 1.85	3.508 ± 0.69	115.78	424.9
Maytenus undata	UF	30.2	20.20 ± 1.84	19.25 ± 1.39	0.743 ± 0.15	43.86	160.98
	DF	19.27	24.71 ± 3.78	19.21 ± 1.98	1.560 ± 0.54	54.60	200.4
Albizia grandibracteata	UF	19.8	27.14 ± 2.88	25.25 ± 1.84	1.035 ± 0.24	40.35	148.09
	DF	53.13	24.18 ± 1.51	21.84 ± 0.98	0.717 ± 0.11	72.42	265.78
Trilepisium madagascariense	UF	16.34	27.42 ± 3.04	26.78 ± 2.29	1.155 ± 0.28	36.96	135.66
	DF	7.29	30.29 ± 6.52	25.75 ± 4.38	1.577 ± 0.72	20.51	75.42
Ficus carica	UF	10.89	30.86 ± 3.96	24.00 ± 1.97	1.727 ± 0.66	36.27	133.12
	DF	5.73	27.04 ± 3.74	19.3 ± 2.65	0.901 ± 0.32	9.01	33.06
Trichilia dregeana	UF	27.23	19.55 ± 2.48	19.54 ± 1.34	0.655 ± 0.23	35.36	129.77
	DF	14.06	39.17 ± 5.54	29.02 ± 3.01	2.712 ± 0.72	70.51	258.76
Olea welwitschii	UF	18.32	15.01 ± 3.60	16.00 ± 09	0.918 ± 0.79	33.04	121.25
	DF	4.17	27.3 ± 0.14	18.84 ± 4.36	1.847 ± 0.24	12.93	47.45
Ficus sur	UF	8.42	31.38 ± 6.11	24.19 ± 3.48	1.459 ± 0.63	23.34	85.66
	DF	3.65	38.92 ± 13.27	18.33 ± 3.15	1.623 ± 1.15	9.74	35.73
Millettia ferruginea	UF	26.73	17.35 ± 1.47	16.81 ± 1.13	0.439 ± 0.11	23.28	85.42
	DF	17.71	14.72 ± 1.96	15.58 ± 1.23	0.376 ± 0.15	12.39	45.49
Antiaris toxicaria	UF	15.35	19.93 ± 2.94	20.25 ± 2.25	0.637 ± 0.25	19.12	70.18
	DF	9.38	23.17 ± 3.38	22.15 ± 2.21	0.591 ± 21	9.45	34.69
Ehretia cymosa	UF	43.23	20.44 ± 8.56	9.58 ± 0.41	0.098 ± 0.01	68.19	256.29
	DF	42.71	20.44 ± 0.62	9.59 ± 0.41	0.059 ± 0.01	68.2	250.29
Albizia gummifera	UF	3.13	43.6 ± 17.28	20.8 ± 4.79	3.138 ± 3.14	15.69	57.59
	DF	11.98	21.82 ± 3.30	18.59 ± 1.69	0.673 ± 0.27	14.8	54.33
Cassipourea malosana	UF	13.54	11.8 ± 1.47	16.52 ± 2.14	0.211 ± 0.08	5.07	18.61
	DF	4.69	23.98 ± 9.42	23.63 ± 6.09	1.894 ± 1.47	15.15	55.62
Ekebergia capensis	UF	6.25	18.55 ± 6.21	16.34 ± 3.49	0.842 ± 0.58	9.26	33.99
	DF	2.08	41.38 ± 13.79	29.75 ± 8.74	3.317 ± 1.87	12.55	46.05

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

[1] IPCC, *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team*, R. K. Pachauri and L. A. Meyer, Eds., p. 151, IPCC, Geneva, Switzerland, 2014.

[2] R. Heede, "Tracing anthropogenic carbon dioxide and methane emissions to fossil fuel and cement producers, 1854–2010," *Climatic Change*, vol. 122, no. 1-2, pp. 229–241, 2013.

[3] F. Perera, "Pollution from fossil-fuel combustion is the leading environmental threat to global pediatric health and equity: solutions exist," *International Journal of Environmental Research and Public Health*, vol. 15, no. 1, p. 16, 2017.

[4] R. Quadrelli and S. Peterson, "The energy–climate challenge: recent trends in CO2 emissions from fuel combustion," *Energy Policy*, vol. 35, no. 11, pp. 5938–5952, 2007.

[5] D. deB Richter and R. Houghton, "Gross CO2 fluxes from land-use change: implications for reducing global emissions and increasing sinks," *Carbon Management*, vol. 2, no. 1, pp. 41–47, 2011.

[6] T. Eglin, P. Ciais, S. L. Piao et al., "Historical and future perspectives of global soil carbon response to climate and land-use changes," *Tellus B: Chemical and Physical Meteorology*, vol. 62, no. 5, pp. 700–718, 2017.

[7] F. A. Dijkstra, S. A. Prior, G. B. Runion et al., "Effects of elevated carbon dioxide and increased temperature on methane and nitrous oxide fluxes: evidence from field

experiments," *Frontiers in Ecology and the Environment*, vol. 10, no. 10, pp. 520–527, 2012.
[8] IPCC, "Summary for policymakers," in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning et al., Eds., Cambridge University Press, Cambridge, NY, USA, 2007.
[9] K. R. Sistani, M. Jn-Baptiste, N. Lovanh, and K. L. Cook, "Atmospheric emissions of nitrous oxide, methane, and carbon dioxide from different nitrogen fertilizers," *Journal of Environmental Quality*, vol. 40, no. 6, pp. 1797–1805, 2011.
[10] E. A. Ainsworth, P. Lemonnier, and J. M. Wedow, "The influence of rising tropospheric carbon dioxide and ozone on plant productivity," *Plant Biology*, vol. 22, no. S1, pp. 5–11, 2020.
[11] T. Bhowmick, S. Nag, and S. B. Majumder, *Carbon Dioxide Sensing Characteristics of LaFe0. 8Co0. 2O3–ZnO Thin Films: The Role of Homo and Heterojunctions*, IOP Publishing, 2019.
[12] K. Hashimoto, *Global Temperature and Atmospheric Carbon Dioxide Concentration Global Carbon Dioxide Recycling*, pp. 5–17, Springer, Berlin, Germany, 2019.
[13] H. Tian, C. Lu, P. Ciais et al., "The terrestrial biosphere as a net source of greenhouse gases to the atmosphere," *Nature*, vol. 531, no. 7593, pp. 225–228, 2016.
[14] Y. Pan, R. A. Birdsey, J. Fang et al., "A large and persistent carbon sink in the world's forests," *Science*, vol. 333, no. 6045, pp. 988–993, 2011.
[15] R. Prăvălie, "Major perturbations in the Earth's forest ecosystems. Possible implications for global warming," *Earth-Science Reviews*, vol. 185, pp. 544–571, 2018.
[16] R. Mant, E. Perry, M. Heath et al., *Addressing Climate Change—Why Biodiversity Matters*, UNEP-WCMC, Cambridge, UK, 2014.
[17] FRA, *Global Forest Resources Assessment 2010 Main Report*, Food and Agriculture Organization of the United Nations, Rome, 2010.
[18] J. Balesdent, I. Basile-Doelsch, J. Chadoeuf et al., "Atmosphere-soil carbon transfer as a function of soil depth," *Nature*, vol. 559, no. 7715, pp. 599–602, 2018.
[19] J. A. Foley, G. P. Asner, M. H. Costa, M. T. Coe, R. DeFries, and H. K. Gibbs, "Amazonia revealed: forest degradation and loss of ecosystem goods and services in the amazon basin," *Frontiers in Ecology and the Environment*, vol. 5, 2007.
[20] R. C. Goodman and M. Herold, *Why Maintaining Tropical Forests Is Essential And Urgent For A Stable Climate Why Maintaining Tropical Forests Is Essential And Urgent For A Stable Climate*, Center for Global Development, Washington, DC, USA, 2014.
[21] R. D. Lasco and F. B. Pulhin, "Carbon budgets of forest ecosystems in the Philippines," *Journal of Environmental Science and Management*, vol. 12, no. 1, pp. 1–13, 2009.
[22] K. M. Ngo, B. L. Turner, H. C. Muller-Landau et al., "Carbon stocks in primary and secondary tropical forests in Singapore," *Forest Ecology and Management*, vol. 296, pp. 81–89, 2013.
[23] T. Riutta, Y. Malhi, L. K. Kho et al., "Logging disturbance shifts net primary productivity and its allocation in Bornean tropical forests," *Global Change Biology*, vol. 24, no. 7, pp. 2913–2928, 2018.
[24] A. R. Townsend, C. C. Cleveland, B. Z. Houlton, C. B. Alden, and J. W. C. White, "Multi-element regulation of the tropical forest carbon cycle," *Frontiers in Ecology and the Environment*, vol. 9, no. 1, pp. 9–17, 2011.
[25] Y. Malhi, C. E. Doughty, G. R. Goldsmith et al., "The linkages between photosynthesis, productivity, growth and biomass in lowland Amazonian forests," *Global Change Biology*, vol. 21, no. 6, pp. 2283–2295, 2015.
[26] Y. Malhi and J. Grace, "Tropical forests and atmospheric carbon dioxide," *Trends in Ecology & Evolution*, vol. 15, no. 8, pp. 332–337, 2000.
[27] S. Moore, S. Adu-Bredu, A. Duah-Gyamfi et al., "Forest biomass, productivity and carbon cycling along a rainfall gradient in West Africa," *Global Change Biology*, vol. 24, no. 2, pp. 496–510, 2018.
[28] R. A. Houghton, "Carbon emissions and the drivers of deforestation and forest degradation in the tropics," *Current Opinion in Environmental Sustainability*, vol. 4, no. 6, pp. 597–603, 2012.
[29] H. M. Jayathilake, G. W. Prescott, L. R. Carrasco, M. Rao, and W. S. Symes, "Drivers of deforestation and degradation for 28 tropical conservation landscapes," *Ambio*, vol. 50, no. 1, pp. 215–228, 2021.
[30] T. Molina and E. Abadal, "The evolution of communicating the uncertainty of climate change to policymakers: a study of IPCC synthesis reports," *Sustainability*, vol. 13, no. 5, p. 2466, 2021.
[31] A. Baccini, S. J. Goetz, W. S. Walker et al., "Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps," *Nature Climate Change*, vol. 2, no. 3, pp. 182–185, 2012.
[32] G. R. van der Werf, D. C. Morton, R. S. DeFries et al., "CO2 emissions from forest loss," *Nature Geoscience*, vol. 2, no. 11, pp. 737-738, 2009.
[33] H. K. Gibbs, S. Brown, J. O. Niles, and J. A. Foley, "Monitoring and estimating tropical forest carbon stocks: making REDD a reality," *Environmental Research Letters*, vol. 2, no. 4, Article ID 045023, 2007.
[34] B. A. Beymer-Farris and T. J. Bassett, "The REDD menace: resurgent protectionism in Tanzania's mangrove forests," *Global Environmental Change*, vol. 22, no. 2, pp. 332–341, 2012.
[35] E. Corbera and H. Schroeder, "Governing and implementing REDD+," *Environmental Science & Policy*, vol. 14, no. 2, pp. 89–99, 2011.
[36] F. Danielsen, M. Skutsch, N. D. Burgess et al., "At the heart of REDD+: a role for local people in monitoring forests?" *Conservation Letters*, vol. 4, no. 2, pp. 158–167, 2011.
[37] C. J. Paul and E. Weinthal, "The development of Ethiopia's Climate Resilient Green Economy 2011–2014: implications for rural adaptation," *Climate & Development*, vol. 11, no. 3, pp. 193–202, 2019.
[38] E. Ethiopian, "Ethiopia's climate-resilient green Economy (CRGE)," p. 188, Federal Democratic Republic of Ethiopia, Addis Ababa, Ethiopia, 2011.
[39] S. Brown, A. Grais, S. Ambagis, and T. Pearson, *Baseline GHG Emissions from the Agricultural Sector and Mitigation Potential in Countries of East and West Africa*, CGIAR Research Program On Climate Change, Agriculture And Food Security (CCAFS), Copenhagen, Denmark, 2012.
[40] IUCN, *Review of the Protected Areas System in the Afrotropical Realm*, IUCN, Gland, Switzerland, 1986.
[41] A. H. Kirk-Spriggs and B. R. Stuckenberg, *Chapter Six. Afrotropical Diptera—Rich Savannas, Poor Rainforests Diptera Diversity: Status, Challenges and Tools*, pp. 155–196, Brill, Ledien, Netherlands, 2010.

[42] R. W. Bussmann, “Vegetation zonation and nomenclature of African Mountains - an overview,” *Lyonia, a journal of Ecology and application*, vol. 11, no. 1, pp. 11–66, 2006.
[43] R. Persson, *Forest Resources of Africa—An Approach to International Forest Resource Appraisals. Part II: Regional Analyses*, Rapporter och Uppsatser, Institutionen for Skogstaxering, Stockholm, Sweden, 1977.
[44] I. Friis, S. Demissew, and P. van Breugel, *Atlas Of the Potential Vegetation Of Ethiopia: The Royal Danish Academy of Sciences and Letters’, Denmark*, 2010.
[45] IBC, *National Biodiversity Strategy and Action Plan*, Addis Ababa University, Addis Ababa, Ethiopia, 2005.
[46] IBC, *Convention on biological diversity (CBD) Ethiopia’s 4th country report*, Addis Ababa University, Addis Ababa, Ethiopia, 2009.
[47] IBC, *The State of the World’s Forest Genetic Resource. Country Report Submitted to FAO on the State of Forest Genetic Resources of Ethiopia*, Addis Ababa University, Addis Ababa, Ethiopia, 2012.
[48] J. A. Oldekop, G. Holmes, W. E. Harris, and K. L. Evans, “A global assessment of the social and conservation outcomes of protected areas,” *Conservation Biology*, vol. 30, no. 1, pp. 133–141, 2016.
[49] R. A. Rasolofoson, P. J. Ferraro, C. N. Jenkins, and J. P. G. Jones, “Effectiveness of community forest management at reducing deforestation in Madagascar,” *Biological Conservation*, vol. 184, pp. 271–277, 2015.
[50] D. B. Lindenmayer, J. F. Franklin, A. Lõhmus et al., “A major shift to the retention approach for forestry can help resolve some global forest sustainability issues,” *Conservation Letters*, vol. 5, no. 6, pp. 421–431, 2012.
[51] R. Pool-Stanvliet, S. Stoll-Kleemann, and J. H. Giliomee, “Criteria for selection and evaluation of biosphere reserves in support of the UNESCO MAB programme in South Africa,” *Land Use Policy*, vol. 76, pp. 654–663, 2018.
[52] T. Schaaf and D. Clamote Rodrigues, *Managing MIDAS: harmonising the management of Multi-Internationally Designated Areas*, IUCN, Gland, Switzerland, 2016.
[53] T. Gole, F. Senbeta, K. Tesfaye, and F. Getaneh, *UNESCO - Man and the Biosphere (MAB) Programme – Yayu Coffee Forest Biosphere Reserve Nomination Form*, 2009.
[54] R. A. Mittermeier, P. R. Gil, M. Hoffman et al., *Hotspots Revisited*, CEMEX. Sierra, Garcia, Mexico City, 2004.
[55] D. E. Daba and T. Soromessa, “The accuracy of species-specific allometric equations for estimating aboveground biomass in tropical moist montane forests: case study of Albizia grandibracteata and Trichilia dregeana,” *Carbon Balance and Management*, vol. 14, no. 1, pp. 18–13, 2019.
[56] T. W. Gole, T. Borsch, M. Denich, and D. Teketay, “Floristic composition and environmental factors characterizing coffee forests in southwest Ethiopia,” *Forest Ecology and Management*, vol. 255, no. 7, pp. 2138–2150, 2008.
[57] A. Asrat, M. Demissie, and A. Mogessie, “Geoheritage conservation in Ethiopia:the case of the simien mountains,” *Quaestiones Geographicae*, vol. 31, no. 1, pp. 7–23, 2012.
[58] M. Fazzini, C. Bisci, and P. Billi, “The climate of Ethiopia,” *Landscapes and Landforms of Ethiopia*, Springer, Berlin, Germany, 2015.
[59] M. Kent and P. Coker, *Vegetation Analysis and Description: A Practical Approach*, John Wiley & Sons, Hoboken, NJ, USA, 1992.
[60] D. Mueller- Dombois and H. Ellenberge, *Aims and Methods of Vegetation Ecology*, John Wiley & Sons, Hoboken, NJ, USA, 1974.
[61] K. Hairiah, S. M. Sitompul, M. Noordwijk, and C. Palm, “Methods for sampling carbon stocks above and below ground,” pp. 10–15, Southeast Asian Regional Research Programme, Bogor, Indonesia, 2001.
[62] S. Edwards, S. Demissew, and I. Hedberg, *Flora of Ethiopia: Hydrocharitaceae to Arecaceae*, p. 586, Addis Ababa and Uppsala University, Addis Ababa, Ethiopia, 1997.
[63] S. Edwards, M. Tadesse, S. Demissew, and I. Hedberg, *Flora of Ethiopia and Eritrea Magnoliaceae to Flacourtiaceae*, p. 532, Addis Ababa University and Uppsala University, Addis Ababa, Ethiopia, 2000.
[64] S. Edwards, M. Tadesse, and I. Hedberg, *Flora of Ethiopia and Eritrea: Canellaceae to Euphorbiaceae*, p. 456, Addis Ababa University and Uppsala University, Addis Ababa, Ethiopia, 1995.
[65] I. Hedberg and S. Edwards, *Flora of Ethiopia: Pittosporaceae to Araliaceae*, p. 659, Addis Ababa University and Uppsala University, Addis Ababa, Ethiopia, 1989.
[66] I. Hedberg, S. Edwards, and S. Nemomissa, *Flora of Ethiopia and Eritrea: Apiaceae to Dipsaceae*, p. 352, Addis Ababa University and Uppsala University, Addis Ababa, Ethiopia, 2003.
[67] A. Zanne, G. Lopez-Gonzalez, D. Coomes et al., *Global Wood Density Database*, 2009.
[68] K. G. A. MacDicken, “Guide to monitoring carbon storage in forestry and agro-forestry projects,” in *Forest Carbon Monitoring Program*p. 87, Winrock International Institute for Agricultural Development Arlington, Arlington, VA, USA, 1997.
[69] IPCC, *IPCC 2006 Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*, H. S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe, Eds., IGES, Japan, 2006.
[70] J. Lee, J. W. Hopmans, D. E. Rolston, S. G. Baer, and J. Six, “Determining soil carbon stock changes: simple bulk density corrections fail,” *Agriculture, Ecosystems & Environment*, vol. 134, no. 3-4, pp. 251–256, 2009.
[71] B. P. Subedi, S. S. Pandey, A. Pandey, E. B. Rana, S. Bhattarai, and T. R. Banskota, *Forest Carbon Stock Measurement: Guidelines for Measuring Carbon Stocks in Community-Managed Forests*, ANSAB, FECOFUN, ICIMOD, NORAD, 2010.
[72] A. Walkley and I. A. Black, “An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method,” *Soil Science*, vol. 37, no. 1, pp. 29–38, 1934.
[73] S. Allen, A. Grimshaw, and S. Rowland, “Chemical analysis,” *Methods in plant ecology*, Scientific Publications, 1986.
[74] J. Chave, M. Rejou-Mechain, A. Burquez et al., “Improved allometric models to estimate the aboveground biomass of tropical trees,” *Global Change Biology*, vol. 20, no. 10, pp. 3177–3190, 2014.
[75] T. Pearson, S. Walker, and S. Brown, *Sourcebook for Land-Use, Land-Use Change and Forestry Projects*, pp. 19–35, Winrock International and the Bio-carbon fund of the World Bank, Arlington, VA, USA, 2005.
[76] A. Cuni-Sanchez, M. J. P. Sullivan, P. J. Platts et al., “High aboveground carbon stock of African tropical montane forests,” *Nature*, vol. 596, no. 7873, pp. 536–542, 2021.
[77] M. De Beenhouwer, L. Geeraert, J. Mertens et al., “Biodiversity and carbon storage co-benefits of coffee agroforestry across a gradient of increasing management intensity in the SW Ethiopian highlands,” *Agriculture, Ecosystems & Environment*, vol. 222, pp. 193–199, 2016.

[78] A. Dibaba, T. Soromessa, and B. Workineh, “Carbon stock of the various carbon pools in Gerba-Dima moist Afromontane forest, South-western Ethiopia,” *Carbon Balance and Management*, vol. 14, no. 1, pp. 1–10, 2019.

[79] S. Mensah, R. Veldtman, A. E. Assogbadjo, R. Glele Kakai, and T. Seifert, “Tree species diversity promotes aboveground carbon storage through functional diversity and functional dominance,” *Ecology and Evolution*, vol. 6, no. 20, pp. 7546–7557, 2016.

[80] A. Thokchom and P. Yadava, “Biomass and carbon stock along an altitudinal gradient in the forest of Manipur,” *Northeast India*, vol. 58, no. 2, pp. 389–396, 2017.

[81] J. F. Bastin, E. Rutishauser, J. R. Kellner et al., “Pan-tropical prediction of forest structure from the largest trees,” *Global Ecology and Biogeography*, vol. 27, no. 11, pp. 1366–1383, 2018.

[82] J. A. Lutz, T. J. Furniss, D. J. Johnson et al., “Global importance of large-diameter trees,” *Global Ecology and Biogeography*, vol. 27, no. 7, pp. 849–864, 2018.

[83] P. Sist, L. Mazzei, L. Blanc, and E. Rutishauser, “Large trees as key elements of carbon storage and dynamics after selective logging in the Eastern Amazon,” *Forest Ecology and Management*, vol. 318, pp. 103–109, 2014.

[84] Y. Xu, S. B. Franklin, Q. Wang et al., “Topographic and biotic factors determine forest biomass spatial distribution in a subtropical mountain moist forest,” *Forest Ecology and Management*, vol. 357, pp. 95–103, 2015.

[85] M. T. Wondimu, Z. A. Nigussie, and M. M. Yusuf, “Tree species diversity predicts aboveground carbon storage through functional diversity and functional dominance in the dry evergreen Afromontane forest of Hararghe highland, Southeast Ethiopia,” *Ecological Processes*, vol. 10, no. 1, p. 47, 2021.

[86] S. K. Behera, N. Sahu, A. K. Mishra, S. S. Bargali, M. D. Behera, and R. Tuli, “Aboveground biomass and carbon stock assessment in Indian tropical deciduous forest and relationship with stand structural attributes,” *Ecological Engineering*, vol. 99, pp. 513–524, 2017.

[87] K. C. Cavanaugh, J. S. Gosnell, S. L. Davis et al., “Carbon storage in tropical forests correlates with taxonomic diversity and functional dominance on a global scale,” *Global Ecology and Biogeography*, vol. 23, no. 5, pp. 563–573, 2014.

[88] S. Tashi, B. Singh, C. Keitel, and M. Adams, “Soil carbon and nitrogen stocks in forests along an altitudinal gradient in the eastern Himalayas and a meta-analysis of global data,” *Global Change Biology*, vol. 22, no. 6, pp. 2255–2268, 2016.

[89] L. Wu, L. Li, Y. Yao et al., “Spatial distribution of soil organic carbon and its influencing factors at different soil depths in a semiarid region of China,” *Environmental Earth Sciences*, vol. 76, no. 19, pp. 654–713, 2017.

[90] H. Yu, T. Zha, X. Zhang, and L. Ma, “Vertical distribution and influencing factors of soil organic carbon in the Loess Plateau, China,” *Science of the Total Environment*, vol. 693, Article ID 133632, 2019.

[91] S. A. Bangroo, G. R. Najar, and A. Rasool, “Effect of altitude and aspect on soil organic carbon and nitrogen stocks in the Himalayan Mawer Forest Range,” *Catena*, vol. 158, pp. 63–68, 2017.

[92] S. Ouyang, W. Xiang, M. Gou et al., “Variations in soil carbon, nitrogen, phosphorus and stoichiometry along forest succession in southern China,” *Journal Biogeosciences*, 2017.

[93] M. A. Tesfaye, F. Bravo, R. Ruiz-Peinado, V. Pando, and A. Bravo-Oviedo, “Impact of changes in land use, species and elevation on soil organic carbon and total nitrogen in Ethiopian Central Highlands,” *Geoderma*, vol. 261, pp. 70–79, 2016.

[94] A. Addi, S. Demisse, T. Soromessa, and Z. Asfaw, “Carbon stock of the moist Afromontane forest in gesha and sayilem districts in kaffa zone: an implication for climate change mitigation,” *Journal of Ecosystem & Ecography*, vol. 9, p. 259, 2019.

[95] W. I. J. Dieleman, M. Venter, A. Ramachandra, A. K. Krockenberger, and M. I. Bird, “Soil carbon stocks vary predictably with altitude in tropical forests: implications for soil carbon storage,” *Geoderma*, vol. 204-205, pp. 59–67, 2013.

[96] V. Meyer, S. Saatchi, D. B. Clark et al., “Canopy area of large trees explains aboveground biomass variations across neotropical forest landscapes,” *Biogeosciences*, vol. 15, no. 11, pp. 3377–3390, 2018.

[97] N. Solomon, O. Pabi, T. Annang, I. K. Asante, and E. Birhane, “The effects of land cover change on carbon stock dynamics in a dry Afromontane forest in northern Ethiopia,” *Carbon Balance and Management*, vol. 13, no. 1, p. 14, 2018.

[98] N. Rahman, A. de Neergaard, J. Magid, G. W. J. van de Ven, K. E. Giller, and T. B. Bruun, “Changes in soil organic carbon stocks after conversion from forest to oil palm plantations in Malaysian Borneo,” *Environmental Research Letters*, vol. 13, no. 10, Article ID 105001, 2018.

[99] C. A. J. Girardin, Y. Malhi, L. E. O. C. AragÃO et al., “Net primary productivity allocation and cycling of carbon along a tropical forest elevational transect in the Peruvian Andes,” *Global Change Biology*, vol. 16, no. 12, pp. 3176–3192, 2010.

[100] C. Gonmadje, N. Picard, S. Gourlet-Fleury et al., “Altitudinal filtering of large-tree species explains above-ground biomass variation in an Atlantic Central African rain forest,” *Journal of Tropical Ecology*, vol. 33, no. 2, pp. 143–154, 2017.

[101] T. Yelemfrhat Simegn and S. Teshome, “Carbon stock variations along altitudinal and slope gradient in the forest belt of simen mountains national park, Ethiopia,” *American Journal of Environmental Protection*, vol. 4, no. 4, p. 199, 2015.

[102] L. F. Alves, S. A. Vieira, M. A. Scaranello et al., “Forest structure and live aboveground biomass variation along an elevational gradient of tropical Atlantic moist forest (Brazil),” *Forest Ecology and Management*, vol. 260, no. 5, pp. 679–691, 2010.

[103] A. Ensslin, G. Rutten, U. Pommer, R. Zimmermann, A. Hemp, and M. Fischer, “Effects of elevation and land use on the biomass of trees, shrubs and herbs at Mount Kilimanjaro,” *Ecosphere*, vol. 6, no. 3, p. 45, 2015.

[104] A. Don, J. Schumacher, and A. Freibauer, “Impact of tropical land-use change on soil organic carbon stocks - a meta-analysis,” *Global Change Biology*, vol. 17, no. 4, pp. 1658–1670, 2011.

[105] Z.-Q. Yuan, C. Fang, R. Zhang, F.-M. Li, M. M. Javaid, and I. A. Janssens, “Topographic influences on soil properties and aboveground biomass in lucerne-rich vegetation in a semi-arid environment,” *Geoderma*, vol. 344, pp. 137–143, 2019.

[106] H. Yohannes and T. Soromessa, “Carbon stock analysis along slope and slope aspect gradient in gedo forest: implications for climate change mitigation,” *Journal of Earth Science & Climatic Change*, vol. 06, no. 09, 2015.

[107] G. Gebeyehu, T. Soromessa, T. Bekele, and D. Teketay, “Carbon stocks and factors affecting their storage in dry Afromontane forests of Awi Zone, northwestern Ethiopia,” *Journal of Ecology and Environment*, vol. 43, no. 1, p. 7, 2019.

[108] K. Vanderhaegen, B. Verbist, K. Hundera, and B. Muys, "REALU vs. REDD+: carbon and biodiversity in the Afromontane landscapes of SW Ethiopia," *Forest Ecology and Management*, vol. 343, pp. 22–33, 2015.
[109] C. P. Chen, K. W. Juang, C. H. Cheng, and C. W. Pai, "Effects of adjacent land-use types on the distribution of soil organic carbon stocks in the montane area of central Taiwan," *Botanische Studien*, vol. 57, no. 1, p. 32, 2016.
[110] M. Mayer, C. E. Prescott, W. E. A. Abaker et al., "Tamm Review: influence of forest management activities on soil organic carbon stocks: a knowledge synthesis," *Forest Ecology and Management*, vol. 466, Article ID 118127, 2020.
[111] C. A. Sierra, J. I. del Valle, S. A. Orrego et al., "Total carbon stocks in a tropical forest landscape of the Porce region, Colombia," *Forest Ecology and Management*, vol. 243, no. 2-3, pp. 299–309, 2007.
[112] M. Rial, A. Martinez Cortizas, and L. Rodriguez-Lado, "Understanding the spatial distribution of factors controlling topsoil organic carbon content in European soils," *Science of the Total Environment*, vol. 609, pp. 1411–1422, 2017.
[113] E. Badalamenti, G. Battipaglia, L. Gristina et al., "Carbon stock increases up to old growth forest along a secondary succession in Mediterranean island ecosystems," *PLoS One*, vol. 14, no. 7, Article ID e0220194, 2019.
[114] R. B. de Andrade, J. K. Balch, A. L. Parsons, D. Armenteras, R. M. Roman-Cuesta, and J. Bulkan, "Scenarios in tropical forest degradation: carbon stock trajectories for REDD+," *Carbon Balance and Management*, vol. 12, no. 1, pp. 6-7, 2017.
[115] C. M. Sharma, N. P. Baduni, S. Gairola, S. K. Ghildiyal, and S. Suyal, "Tree diversity and carbon stocks of some major forest types of Garhwal Himalaya, India," *Forest Ecology and Management*, vol. 260, no. 12, pp. 2170–2179, 2010.
[116] F. d'Albertas, K. Costa, I. Romitelli, J. M. Barbosa, S. A. Vieira, and J. P. Metzger, "Lack of evidence of edge age and additive edge effects on carbon stocks in a tropical forest," *Forest Ecology and Management*, vol. 407, pp. 57–65, 2018.