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Variations in Forest Carbon Stocks Along Environmental Gradients in Egdu Forest of Oromia Region, Ethiopia: Implications for Sustainable Forest Management

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Abstract: Forests play a significant role in climate change mitigation by sequestering and storing more carbon from the atmosphere than any other terrestrial ecosystem. Although a number of studies have been done on carbon stock estimations, the influence of environmental factors on forest carbon stocks has not been properly addressed. This study was conducted to estimate the carbon stock and its variation along the altitudinal gradients in Egdu dry afromontane forest found in Oromia Regional State of Ethiopia. The carbon stock in the different carbon pools and analysis of the influence of the environmental variables were studied by collecting data in sixty-nine quadrat plots of 10 x 20 m distributed along transect lines. To estimate carbon in above and below ground biomass; each tree in the study site having diameter at breast height (DBH) of ≥ 5 cm were measured for DBH and height. Above ground biomass was estimated by using allometric model while below ground biomass was determined based on the ratio of below ground biomass to above ground biomass factors. The mean total carbon stock density of Egdu Forest was found to be 614.72 ± 35.79 t ha-1 (ranging from 182.6 to1416 t ha-1), of which 45.24% of carbon was contained in the above ground biomass, 9.05% in below ground biomass, 0.56% in litter carbon and 45.15% was stored in soil organic carbon (0-30 cm depth). The carbon stocks in above ground biomass, below ground biomass, litter biomass and soil organic carbon exhibited distinct patterns along environmental gradients (slope gradient and slope aspect). The analysis of carbon stock variation of different carbon pools on eight different aspects of the forest area showed a significant variation with exception of soil organic carbon stock. The amount of carbon stock in above and below ground biomass, soil organic carbon and the total carbon stock was higher on the northern aspect as compared to other aspects. On the other hand, the carbon density of the forest carbon pool components showed a negative correlation with slope gradient; with increasing % slope, the above and below ground carbon, soil organic carbon and the total carbon stock decreased. This study concluded that the carbon stock value of Egdu Forest is large, and the carbon storage in different carbon pools of the forest area varies with slope aspect and slope aspect.

Keywords: Biomass, Climate Change, Egdu Forest, Environmental Variables, Forest Carbon Stock, Soil Carbon

1. Introduction

Human beings are accelerating the rate for increment of atmospheric greenhouse gases (GHGs) concentration mainly through fossil fuels burning and land-use/cover changes, resulting in global warming and constantly climate change during the recent times [1]. The global GHG emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004 [2]. When the concentration of these GHGs in the atmosphere increases, the temperature of the Earths surface also rises as increasing amounts of solar radiation are trapped inside the GHGs [3]. However, the dramatic increase in global surface temperature is mainly due to the increase in carbon dioxide (CO_2)

concentration in the atmosphere which is largely attributed to human activities [4]. For instance, the average atmospheric CO_2 concentration has increased from pre-industrial concentration of 280 μmol mol^{-1} to 364 μmol mol^{-1} in 1994, and is currently increasing at a rate of about 1.5μmol mol^{-1} year^{-1} [5]. A rise in global mean temperature by 0.74°C has already been recorded, and hence, curbing the global climate change is a widespread and growing concern that has led to extensive international discussions and negotiations [2]. Responses to these concerns have focused on reducing emissions of GHGs, especially CO_2, and on measuring carbon absorbed by and stored in forests, soils, and oceans. One option for slowing the rise of GHGs concentration in the atmosphere, and thus possible climate change, is to increase the amount of carbon removed by and stored in forests [6].

Forests play a critical role in the natural global carbon cycle by capturing carbon from the atmosphere through photosynthesis, converting that photosynthate to forest biomass, and emitting carbon back into the atmosphere during respiration and decomposition. It sequesters and stores more carbon than any terrestrial ecosystem i.e. about 80% of all terrestrial above ground carbon and more than 70% of all soil organic carbon [7]. Forest ecosystems merit consideration in this context of climate change because they can act as sources as well as sinks of CO_2, the most abundant GHGs.

In Ethiopia different factors like deforestation, over-harvesting and permanent conversion to other forms of land use is leading to shrinkage of forest resources. As a result, forest cover has been declining rapidly and only remnant forests are confined to some areas especially in the south and south-western parts of the country, which are less populated [8]. Deforestation is one of the main causes of the prevailing land degradation in Ethiopia. Even though, the available information on the country's forest resource is scarce and inconsistent, the natural forests in Ethiopia are believed to have once covered 35 to 40% of the country's land area. However, the estimates of the Ethiopian forestry program (EFAP) indicate that the closed natural forests have been reduced to 2.7% of the country and these are found mainly in the southwestern highlands [9]. In addition, according to the EFAP report, it is estimated that forests and woody vegetation are disappearing at a rate of 150,000 to 200,000 ha annually.

The reduction of forests in the tropics impairs important atmospheric functions as carbon sinks, and the combustion of forest biomass releases atmospheric CO_2, contributing to the buildup of GHGs and global warming. The climate of Ethiopia has been changing due to global and local effects of vegetation degradation [10]. Today, forest management activities are increasingly taking into consideration the role of forests as carbon sinks and information on factors that determine the forest carbon stock is given concern [11].

The carbon storage in forest can be affected by different environmental factors by affecting the patterns of tree species distribution and this further affects carbon stored in forest ecosystem [11, 12]. For instance, altitude and slope aspect play a key role in determining the temperature regime of any sites by affecting the forest composition. Similarly, different authors [13, 14] stipulated that differences in insolation period may occur according to site aspect, thereby forming a range of microclimates in multifaceted landscapes. Consequently, the microclimate is often linked to soil moisture and distribution of particular plant communities [14] on different slope forms.

With the intense focus on the increasing levels of atmospheric CO_2 and the potential for global climate change, there is an urgent need to assess the feasibility of managing ecosystems to sequester and store more carbon [5]. Unlike in the developed countries, Ethiopia does not have carbon inventories and databank to monitor and enhance carbon sequestration potential of different forests. Only small efforts have been made so far to assess the biomass and soil carbon sequestration potential at small scale level. Furthermore, the studies on the effects of environmental factors on the carbon stocks of forests are still lacking. Under the backdrop of the aforementioned facts, this study was undertaken to estimate the carbon stock of the Egdu Forest and to see the variation caused by slope gradients and slope aspects on the carbon stocks density of different carbon pools (live tree carbon stocks; dead litter and soil organic carbon (SOC).

2. Materials and Methods

2.1. Description of the Study Area

The present study was conducted in Welmera District, Oromia National Regional State, central high lands of Ethiopia in a forest located at about 30 km west of Addis Ababa and 5 km from Menagasha town to the south (Figure 1). Egdu Forest is one of the remnant dry afromontane forests in central Ethiopia and the forest has an altitudinal gradient ranging from 2580 to 2910 m a.s.l. The forest covers a total area of 486 ha and it is home for a variety of flora and fauna. The topography of Egdu Forest which is sometimes called Menagasha Amba Mariam Forest (MAMF) is characterized by dissected island plateau surrounded by cultivated land in all direction. On the top which is plainy, there are two churches at the centre of the plain. These Churches are inhabited by monks. It has some escarpments on the southern part and river valleys in the south-western part.

According to National Meteorological Services Agency of Ethiopia, the average annual rainfall of the study area is 1028 mm ranging from 1236.6 mm maximum in 1990 to minimum of 777.2 mm in 1997 with the rains mainly falling from the end of May to September. The monthly rainfall has a unimodal distribution. Nevertheless, there are rains in any months of the year from small amount of clouds letting additional moisture for the forest. There is high amount of rainfall from June to September. The mean annual temperature of the surrounding area is about 14.3°C with a maximum of 24.5°C recorded from January to May and minimum of 1.6°C which is recorded during December.

The dominant species in the study forest in order of species authorities are *Juniperus procera*, *Olea europaea* subsp. *cuspidata, Olinia rochetiana, Maytenus arbutifolia, Rhamnus staddo, Rhus vulgaris, Eucalyptus globulus, Acacia abyssinica, Myrica salicifolia, Pittosporum viridiflorum, Maytenus obscura* and *Osyris quadripartita*. *Acacia mearnsii, Pinus patula, Erica arborea* and *Cupressus lusitanica* are the dominant planted species at the higher altitudes. During past times the forest was highly exploited by local communities and residents of nearby towns to deteriorate the forest extensively and thus the forest has experienced long and intensive deforestation, exploitation and reforestation. However, the current practice of management system of the forest seems at good position, since its entry in Menagesha Suba State Forest administration and protected by enough number of employed guards.

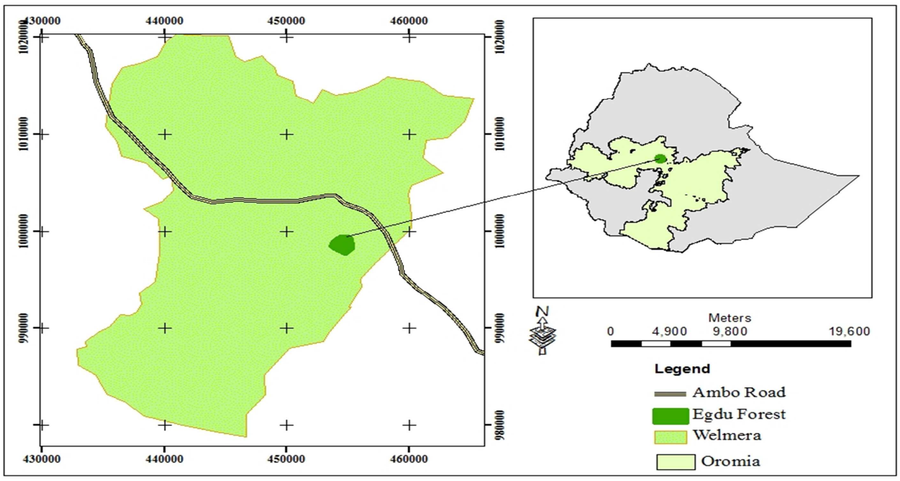

Figure 1. *Location map of the study area.*

2.2. Methodology

Reconnaissance survey was conducted to get an overview of the physical condition of the area such as vegetation cover, land use type, topography of the study area, homogeneity and heterogeneity of the study forest. Stratified sampling based on elevation segments at every 110 m a.s.l. was used in order to stratify the study area using GPS points. After the reconnaissance survey, a systematic transect sampling technique was adopted in this study. Due to the conical nature of the mountain, eight transects were laid at 200 m interval at the peak, 550 m at the middle of the mountain and 1.5 km at the bottom. The transect lines radiate from the top of the mountain to eight directions and each of them contains different number of plots depend on the length of transect. Transects were laid using GPS and compass. A quadrat plot of size 10 x 20 m (200 m^2) was used for vegetation sampling. For each sample plot, altitude was measured and the areas of the forests of each sample plots were determined from recording the UTM coordinates. Similarly, slope angle and slope aspect in each study plots were measured by clinometer and compass, respectively. In each plot, trees with a DBH of ≥ 5 cm were measured for DBH and height. Trees with multiple stems at 1.3 m height were treated as a single individual and DBH of the largest stem was taken. Trees with multiple stems or fork below 1.3 m height were also treated as a single individual [15]. A total of sixty nine plots were laid to sample the vegetation. Plant specimens were collected, dried, and identified and checked at the National Herbarium of the Addis Ababa University using specimens in the Herbarium. Trees with DBH ≥ 5 cm were measured in each plot using diameter tape and each tree was recorded individually, together with its species name and ID to estimate above ground biomass (AGB). AGB was estimated using the equation below [16] since the general criteria described by the author are similar to the study area while below ground biomass (BGB) were obtained as 20% of AGB i.e., though the relationship between above- and belowground biomass varies widely in the tropics and depends on a number of factors including forest age and latitudinal gradient, a general estimate of root-to-shoot ratio value of 1:5 was used [17]. Since the plot areas are part of tropical region, carbon content in the biomass was computed by multiplying 0.5 (50%) of the tree biomass [16].

$$Y = 34.4703 - 8.0617(\mathrm{DBH}) + 0.6589(\mathrm{DBH}^2) \quad (1)$$

Where, Y is above ground biomass, DBH is diameter at breast height.

Litter samples were collected in a 1 x 1 m rectangular sub-plot within the larger plot. A total of five sub-plots (four at corners and one in the center) were collected and weighed. A composite sample of 100g was used for laboratory. The total dry weight was determined in the laboratory using dry ashing method as per [18] and litter carbon t ha^{-1} for each site was determined by multiplying litter dry weight per area with the relative carbon concentration of the samples [19]. Estimation of the amount of biomass in the leaf litter was calculated as:

$$LB = \frac{Wfield}{A}\ \frac{Wsub\_sample(dry)}{Wsub\_sample(fresh)} * \frac{1}{10{,}000} \quad (2)$$

Where: LB = biomass of litter (t ha^{-1}), W_{field} = weight of wet field sample of litter sampled within an area of size 1 m^2 (g); A = size of the area in which litter were collected (ha); W sub-sample, dry = weight of the oven-dry sub-sample of litter taken to the laboratory to determine moisture content (g), and W sub-sample, fresh = weight of the fresh sub-sample of litter taken to the laboratory to determine moisture content (g).

To reduce variability, soil samples were collected from the five sub-plots on the same place used for litter collection using a 30 cm depth core sampler with a diameter of 5 cm. The volume of the soil sample was determined from the height and radius of core sampler. All samples were placed in paper bags with appropriate label. Five equal weights of each sample from each sub-plot were taken and mixed homogenously while a composite sub sample of 100 g from each plot was submitted for laboratory analysis for carbon estimation. Walkley and Black's rapid titration method [5] was used for organic carbon estimation, which is a widely used procedure [19] for organic carbon estimation because it is simple, rapid and has minimal equipment needs. The bulk density, soil organic matter and soil organic carbon were calculated with the help of following formula described [19]:

$$BD = \frac{\text{Wav,dry}}{\text{V}} \quad (3)$$

Where, BD is bulk density of the soil sample per plot, Wav, dry is average air dry weight of soil sample per the quadrant (g cm^{-3}), V is volume of the soil sample in the core sampler in cm3 (Pearson et al., 2005).

Then, the carbon stock in soil was calculated as follows:

$$\text{SOC} = \text{BD} * \text{D} * \%\text{C} \quad (4)$$

Where,

SOC= Soil Organic Carbon stock per unit area (ton/ha^{-1}),

BD = soil bulk density (g cm^{-3}),

D = the total depth at which the sample was taken (30 cm), and

%C = Carbon concentration (%) determined in the laboratory

Finally, above- and below-ground tree carbon, litter carbon and soil organic carbon density' were added to get the total carbon density (t ha^{-1}) of the study forest.

The data obtained from DBH, diameter, height of each species, fresh weight and dry weight of litter and soil were analyzed using SPSS software. Environmental variables were divided in different classes for similar pattern analysis: altitudinal gradients were divided in to three different classes: lower (2580 - 2690 m), middle (2691 - 2800 m) and higher (2800 m - 2910 m) whereas aspect was classified in to eight classes: N (north), NE (northeast), S (south), SE (southeast), E (east), NW (northwest), W (west) and SW (southwest). Slope gradients were grouped in to three different classes: lower = (10 - 30%), middle (30.1 - 60%) and higher = > 60%. One-way ANOVA was used to determine statistically significant differences of carbon stocks along environmental variables for each carbon pools at the 0.05 significant level.

3. Results

3.1. Carbon Stock in the Different Carbon Pools

The carbon stock value of the study site in different carbon pools showed different storage of carbon. About 82.53% (591.66 ± 54.74) t ha^{-1} of the biomass was contained in above ground, while below ground biomass comprised 16.51% (118.33 ± 11.59) t ha^{-1} of the total biomass. It was found that about 0.99% (7.3 ± 0.44) t ha^{-1} of the biomass was contained in the litter. The carbon stock that was stored in the AGB was 45.24% (278.08 ± 25.72) t ha^{-1} whereas 45.15% (277.56 ± 11.56) t ha^{-1} was contained in the soil. The least amount of carbon was stored in litter carbon pool 0.56% (3.47 ± 0.2) t ha^{-1} followed by below ground carbon pool (9.05% (55.62 ± 5.14) t ha^{-1}. The mean carbon density in all carbon pool of the study site was 614.72 ± 35.79 t ha^{-1}.

3.2. Carbon Stock and Slope Aspect

The carbon stock of each carbon pool on various slope aspects in the study forest is showed a variation. Results showing this variation in above- and below-ground tree, litter and soil organic carbon stocks are placed in Table 1. The mean carbon stock density of above- and below ground carbon pool was lowest on SE followed by E aspect and highest on N and NW aspect. The AGB density varied between a mean minimum of 149.23 ± 31.05 t ha^{-1} on SE aspect and mean maximum of 1046.70 ± 87.84 t ha^{-1} on N aspect. Values of BGB density ranged from 29.88 ± 6.15 t ha^{-1} on the S aspect of the study site to 209.4 ± 17.54 t ha^{-1} on N aspect. Statistically, it was recorded a significant difference in above- and below-ground carbon stock among the different slope aspects (*p = 0.000*) (Table 1). Unlike that of the live tree biomass, LC density of the forest site showed statistically significant different on different slope aspects ranging from a minimum of 2.4 ± 0.22 t ha^{-1} on W aspect to maximum of 5.78 ± 0.68 t ha^{-1} on S aspect. With specific to the study site, the litter carbon stock showed a trend as S > SE > E > SW > NE > N > NW > W. SOC varied between 241.00 ± 29.58 t ha^{-1} on SE aspect to 346.38 ± 43.93 t ha^{-1} on N aspect in the study area (Table 1) showing higher on northern aspects as compared with southern aspects. Total carbon density (TCD) was found to be minimum (329.13 t ha^{-1}) on SE aspect and maximum (939.56 t ha^{-1}) on NE aspect of the study forest. Minimum value of total TCD was recorded on SE aspect of the forest (329.13 t $ha^{-1)}$ and followed by the S aspect (433.89 t ha^{-1}).

Table 1. *Variation in mean carbon stocks (t ha^{-1}) on different slope aspects.*

Slope Aspects	AGC	BGC	LC	SOC
S	108.11 ± 26.91	21.67 ± 5.44	5.78 ± 0.68	298.33 ± 34.74
SE	70.25 ± 14.59	14.25 ± 2.88	3.63 ± 0.63	241.00 ± 29.58
E	112.43 ± 27.35	22.57 ± 5.52	3.57 ± 0.75	247.57 ± 30.24
NE	285.13 ± 84.76	56.88 ± 16.98	3.00 ± 0.8	339.88 ± 42.87
N	492 ± 41.30	98.3 ± 8.22	2.88 ± 0.29	346.38 ± 43.93
NW	452.75 ± 84.11	90.38 ± 16.79	2.5 ± 0.38	263.88 ± 37.41
W	293.02 ± 83.22	58.63 ± 16.64	2.4 ± 0.22	241.2 ± 17.23
SW	336.21 ± 34.45	67.31 ± 6.90	3.27 ± 0.27	253.64 ± 15.34
F-value	7.640	7.589	3.891	1.980
p-value	*0.000*	*0.000*	*0.001*	0.065

**Bold values are significant at the p < 0.05 level; ± denotes standard error;

AGC-above ground carbon stock; BGC-below ground carbon stock; LC-Litter carbon stock; SOC-Soil organic carbon; SA-Slope aspect; S-south; SE-south-east; E-east; NE- north-east; N- north; NW- north-west; W-west; SW-south-west.

3.3. Carbon Stock and Slope Gradient

The carbon density of different pools resulted differently in different slope classifications. Above-ground biomass and its carbon stocks were tended to be low in steeply sloped areas of the forest site. Mean AGB and carbon stock were highest and lowest in lower (647.38 ± 103.26 and 304.27 ± 67.33 t ha^{-1}) and higher slope class (537.76 ± 92.04 and 252.75 ± 43.26 t ha^{-1}), respectively (Table 2). Similar trend showed in below ground carbon pool showing a decreasing trend in below ground biomass and its carbon storage with an increase in slope gradient. As shown in Table 2, the higher slope class had the lowest mean below ground biomass and carbon density whereas the lower slope class comprised the highest carbon stock, but the differences were not significant (F= 0.710, p= 0.825) for both above and below carbon stock along the slope gradient. Similarly, the mean SOC stock along slope gradient were ranged from lowest value of 264.19 ± 17.40 t ha^{-1} in higher slope gradient to highest value of 286.33 ± 29.86 t ha^{-1} in lower slope showing a decreasing trend with the increase in slope gradient. The mean soil organic carbon stock in middle slope gradient was 279.72 ± 16.08 (Table 2). However, unlike that of the above- and below-ground biomass carbon, the litter biomass and carbon stock of the study site had showed relatively increasing trend with an increase in slope gradient. Higher slope gradient had the highest mean biomass and carbon stocks followed by middle slope gradient. The lowest mean litter biomass and carbon stock was recorded in the lower slope gradient (5.98 ± 0.9 and 3.00 ± 0.46 t ha^{-1}) (Table 2). The total carbon stock of the study site showed relatively a decrease in carbon stock as slope gradient increased. However, similar to the above and below carbon, the litter carbon stock were not statistically significant along the slope gradient (F = 0.836, p = 0.684) (Table 2). However, the statistical differences of the carbon density in all carbon pools along the slope gradients were not significant ($p > 0.005$).

Table 2. *Variation in mean carbon stocks (t ha^{-1}) on different slope gradients.*

Slope gradient	AGC	BGC	LC	SOC	TCD
Lower	304.27 ± 67.33	60.85 ± 13.47	3.00 ± 0.46	286.33 ± 29.86	654.45 ± 49.66
Middle	278.41 ± 34.61	55.68 ± 6.92	3.47 ± 0.28	279.72 ± 16.08	617.28± 42.23
Higher	252.75 ± 43.26	50.55 ± 8.65	3.91 ± 0.37	264.19 ± 17.40	571.4± 24.16
p-value	0.825	0.825	0.836	0.976	0.966

± denotes standard error; AGC-above-ground carbon stock; BGC-below-ground carbon stock; LC-Litter carbon stock; SOC-Soil organic carbon; TCD-Total carbon density; Slope gradient Class: Lower (10-30%), middle (30.1- 60%) and higher = > 60%.

4. Discussion

The present carbon stock study is the first of its kind for Egdu Forest and covered an estimate of the biomass and carbon density in forest ecosystem components (vegetation, litter and soil) and the variation of carbon stock along environmental gradients in each carbon pool were done. This is helpful for providing relevant information and understanding the patterns of carbon stock along environmental gradients of a representative tropical dry afromontane forests. The mean carbon stock in above- and below-ground biomass of the study forest was twice higher than those reported from Menagasha Suba State Forest (133 and 26.99 t ha^{-1}, respectively) [20] and selected church forests in Addis Ababa (122.85 and 25.97 t ha^{-1}, respectively) [21]. However, this result is comparable to those reported for the global above ground carbon stock in tropical dry and wet forests ranged between 13.5-122.85 t ha^{-1} and 95-527.85 t ha^{-1}, respectively [22]. Tree species in the forest area were dense and has protection due to its reserved status. The higher carbon stock in above ground biomass in the study site could be related to the higher tree density in forest area and presence of protection from human interference. Preventing deforestation from conifer dominated stands would have the largest per unit area impact on reducing carbon emissions from deforestation [5].

On the other hand, the mean carbon stock in litter pool of the present study was less compared to values recorded for selected church forests in Addis Ababa (4.95 t ha^{-1}) [21] but greater than values reported for tropical dry forests (2.1 t ha^{-1}) [22]. The amount of litter fall and its carbon stock of the forest can be influenced by the forest vegetation (species, age and density) and climate [24]. Similarly, the tree stands in the forest area were relatively still young and this could result in low amount of litter fall. In addition, since the study area is located in tropical areas, the rate of decomposition is relatively fast [24]. Thus, the lowest carbon stock in litter pool could probably be due to the high decomposition rate and less amount of litter fall. The mean bulk density of the forest site was low (0.46 g cm^{-3}, ranging between 0.21 to 0.79 g cm^{-3}) which indicates that the study site has high organic matter content in the soil [25]. Thus, the higher mean SOC stock is may be due to the presence of high SOM and fast decomposition of litter which results in maximum storage of carbon stock [26] and hence the study forest in general had large carbon stock and thus sequestered large amount of CO_2 contributing to the mitigation of global climate change.

Aspect is one of environmental factors that can affect the carbon stock of forests in different carbon pools [27] and thus, it can be used as a useful variable to predict the forest carbon stock in different carbon pools. Results of the present study revealed that higher mean values of above- and below-ground biomass and carbon stocks on N and NW aspects compared to the other aspects whereas, the lowest mean values were recorded on the SE and E aspect. Similarly, in the carbon stock study of Apennine Beech Forest [27] it was found that aspect can affect 20% of the variation in AGB and the highest value of above ground biomass appeared in northern aspects of this forest. Overall, the northern aspects of the study area had higher values of above and below ground biomass and carbon stocks as compared to southern aspects. This can be attributed to the occurrence of moister and favorable environment on the northern aspects. This is because the north and south facing slopes receive unequal amount of solar radiation. The south facing slopes receive high solar radiation compared to the north facing which receive less sunlight [5, 27]. Thus, the south facing slopes are warmer and drier whereas the north facing slopes are relatively cooler and forms better growing conditions on the northern aspects than the southern aspects. Furthermore, large number of tree species such as *Cupressus lusitanica*, *Olea europaea* subsp. *Cuspidate* and *Juniperus procera* with maximum DBH value dominates the N aspect of the study forest. Similarly, this seems to be the case for the presence of higher values of the total carbon stock on the northern side of the forest. Besides the south facing aspect of the study forest is very closest to the local community though the forest is protected by forest guards. In this regard, it was indicated that the study forest is under a tremendous effect from grazing and selective cutting of tree species for cultivable land expansion and procuring essential forest products such as constructional materials, energy (fire wood and charcoal production), building and infrastructures networks and to supplement raw materials such as an input for agricultural production and fodder for animals [28]. Forest management activities can improve forest carbon sequestration and increase carbon stocks. Thus the presence of man-made disturbance on the S aspect by the local community could be another reason for the lower carbon stock of the study forest. Therefore, conservation and forest management practice must be given the first priority to have sustainable management of the forest by maintaining the potential of the future generation to meet their own needs.

In addition, the higher values of SOC on the northern aspects have been reported in the present study which may be due to the presence of cooler and moist climate on the northern aspect. This may also be the probable cause for high decomposition rate of a litter which further enhanced large carbon stocks on the northern aspect compared to the other aspects. Similarly, it was revealed that higher amounts of SOC are available on cooler and moister northern aspects, which may also be the probable cause for revealing higher live tree biomass on these aspects [5]. Aspect has significant relationship with biomass in forest areas due to the interaction between soil radiation and soil properties such as soil moisture and soil nutrients [27]. In contrast to the above- and below-ground and soil carbon, the litter biomass and carbon stocks in the present study was recorded statistically higher values on the southern aspects than the northern aspects. This difference might be due to the difference in litter fall amount and its decomposition rate. The forest growing on the southern aspects are generally exposed to various natural disturbances like wind fall [5]. Thus, the presence of high wind fall on the southern aspects could probably be the cause for higher values of litter biomass and carbon on the southern aspects. In addition, the absence of high decomposition rate of a litter on southern aspects may contribute for the presence of high litter biomass and carbon than the northern aspects.

Slope gradient is another environmental variable that can influence the distribution of carbon in different forest carbon pools. The carbon partitioning among forest carbon pools along slope gradients is important in knowing possible change in carbon stock and thus carbon sequestration potential in response to the future climate change in mountain regions [29]. The present result revealed that the forest carbon stock in different carbon pools showed distinct patterns along slope gradient though the variation was not significant in all carbon pools. All the carbon pools (above ground, below ground and soil pool) showed decreasing trend with increasing slope gradient (with exception of litter pool, where litter carbon density increased with an increase in slope gradient). The above and below ground biomass and carbon density showed higher values in lower slope (10-30%) compared to the higher sloped areas of the forest (>60%) which had a lower biomass and carbon density. The vegetation cover varied as a function of slope gradient. Very high slope areas (> 45°) contain little vegetation cover compared to low slope angle (10-20°) [30]. This might be the cause for the decrease in above and below ground biomass carbon with increasing slope gradient. It could also be attributed to soil erosion. On the other hand, litter biomass and its carbon density of the forest area showed an increasing pattern along slope gradient. Slope gradient affects the availability of water and nutrients, which allows more in lower slope or less in higher slope plant growth and litter accumulation [30]. In contrary to this, the higher accumulation of litter carbon on the higher slope might be due to the competitive exclusion of plants by few dominant species at high slope area [13] which is also true in the case of the study forest in which few old individual species dominated at the tip of the mountain where the church is inhabited by monks.

The soil carbon density tended to be low in higher slope and higher in lower slope areas. The SOC and solar radiation is negatively correlated due to the high negative correlation between solar radiation and slope gradient. Flatter areas receive more all year radiation than steeper slopes, which are sheltered for some of the day [31]. Another possibility of high soil carbon density in lower slope area of the forest is that some of the effect comes from erosion, which would remove topsoil and organic matter preferentially from the steeper slopes [32]. A steeper slope is more vulnerable to erosion.

5. Conclusion

The analysis of carbon stock in different carbon pools of the study forest showed different capacity of carbon storage.

The average carbon stocks in the forest area were large and the result is comparable to forests in other tropical countries but higher than most study results of forests in Ethiopia. This indicates the contribution of sustainable forest management for carbon sequestration and hence mitigation of climate changes. Analysis of variation of carbon stock in different carbon pools of the forest area responded differently along different environmental gradients. Overall, the present study result revealed that because of different factors affecting forest carbon stocks, these carbon stocks of different forest ecosystem components showed distinct patterns along environmental gradients and thus these variables can play different roles in carbon sequestration. We recommend that forest carbon related awareness creation for local people and promotion of the local knowledge can be regarded as a possible way for sustainable forest management. This will enhance the capacity of the existing forest for climate change mitigation and other provision from the forest.

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