Article

Carbon stock variation along environmental gradient of Wacho Forest, South-Western Ethiopia

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Abstract
The carbon stock of forest is disturbed by environmental variables. Therefore, the study was undertaken to examine the variation of carbon sock along environmental gradient of wacho forest, South-Western Ethiopia. A systematic random sampling technique was employed to collect the data from 20 m × 20 m of 73 sample quadrants. Trees and shrubs having ≥5 cm diameter at breast height were collected from 20 m × 20 m, whereas litter and soil samples were collected from each of the five 1 m × 1 m subplots situated at the four corners and one at the midpoint of the main plot. The carbon stock of trees, shrubs, litter, and soil was determined by using different equations. One-way analysis of variance was used to analyze the variation of carbon stock along environmental gradient of wacho forest, while descriptive statistics were used to estimate the maximum, minimum, mean and standard deviations of carbon stock in the study forest. An altitudinal gradient had a statistically significant effect on dead tree and dead wood carbon, litter carbon, and soil organic carbon. The carbon pools of above-ground carbon, below-ground carbon, dead tree and dead wood carbon, and soil organic carbon were statistically varied with slope gradient. Aspect had a statistically significant effect on the above-ground and below-ground carbon stocks, dead tree and dead wood carbon, litter, and soil organic carbon stock.

Keywords Wacho forest; Ethiopia; environmental gradient; carbon stock.

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1 Introduction

The carbon stock of the forest is impaired by deforestation and forest degradation, which result in the release of carbon dioxide into the atmosphere (IPCC, 2000). This increases the concentration of greenhouse gases (HGs) in the atmosphere, which is documented as the leading cause of human-induced global climate change (IPCC, 2007). Carbon dioxide is the major greenhouse gas, which accounts for about 60% of the global warming that is projected to increase the world temperature (Grace, 2004). Carbon dioxide and other greenhouse gas emissions have increased, causing man-made and dramatic global warming (IPCC, 2006). The intensive cropping regime leads to a diminution in the vegetation yield and penury of the soil in Africa, and this degradation is often associated with a lessening in organic carbon stocks (Touré et al., 2013). In Africa, deforestation accounts for nearly 70% of the total greenhouse gas emissions (FAO, 2005). The clearing of tropical forests destroys globally important carbon sinks that are currently sequestering carbon dioxide from the atmosphere and which are critical for future climate stabilization (Stephens et al., 2007). Climate change and anthropogenic stress factors are accelerating the rate of tropical forest degradation and increasing carbon dioxide emissions (Gibbs et al., 2007). The trees and forests of Ethiopia are under tremendous pressure because of the radical decline in mature forest cover and the continual pressures of population increase, inappropriate farming techniques, land use competition, land tenure, forest modification, and forest conversion (Yetebitu et al., 2010). The ecosystem services that can be generated from the dry Afro-Montane forests of Ethiopia are threatened mainly by anthropogenic pressures, including extensive forest resource utilization and land use changes (Tesfaye et al., 2014). Thus, the government of Ethiopia has developed a climate resilient green economy since 2012 aimed at keeping greenhouse gas emissions constant and making the country carbon neutral by 2025 by applying abatement measures in different sectors of the country like forestry, agriculture, and industries (Karki et al., 2016).

The content of carbon stock (above ground tree carbon, below ground tree carbon, dead tree and dead wood carbon, litter carbon, and soil organic carbon) is radically influenced by various environmental factors such as climate, topography, parent materials, and vegetation type, as well as human activities (management strategies and land uses) (deOliveira et al., 2015). Among carbon pools, soil is the prime carbon reservoir of the terrestrial carbon series, which holds double and three times more carbon than the atmosphere and the world's vegetation, respectively. About 30 cm of soil holds about 1500 Pentagram of carbon (Batjes, 1996). Soils contain 3.5 percent of the earth's carbon reserve as compared to the carbon reserves of the atmosphere (1.7 percent), fossil fuel (8.9 percent), biota (1.0 percent) and the ocean (84.9 percent) (Lal, 1995). Elevation, slope, and aspect are the principal environmental factors that affect the spatial inconsistency of carbon stock (Chen et al., 2016). Slope and aspect can shape the solar radiation, leading to an affected carbon stock in the forest (McCune and Keon, 2002). Slope position affects the pattern of carbon stock along the toposequences of the environment (Lozano-García and Parras-Alcántara, 2014). Moreover, slope position affects the status of trees and soil organic carbon stock in the course of soil attrition and putrefaction in the regions experiencing a higher frequency of extreme precipitation events and disturbed soils (Ma et al., 2016).

Previous researchers such as Feyissa et al. (2013), Melese et al. (2014), Gedefaw et al. (2014), Nega et al. (2015), Chinasho et al. (2015), and Abere et al. (2017) have studied the carbon stock variation along the altitudinal gradient of Edgu forest, woody plants of Arba Minch ground water forest, Tara Gedam forest, Danaba community forest, Humbo forest, and Banja forest, respectively. But no study has been conducted on Wacho forest, and any of the above researchers didn't investigate the carbon stock variation of dead trees and dead wood carbon along the environmental gradient of the aforesaid study areas. Furthermore, Sheikh et al. (2009) investigated the variation of soil organic carbon stock along an altitudinal gradient of coniferous subtropical and broadleaf temperate forests in the Garhwal Himalaya; Hugelius and Kuhry (2009) investigated the effects of landscape partitioning and environmental gradients on soil organic carbon in a permafrost environment; and Zhu et al. (2019) investigated the effects of topography on soil organic carbon stocks in the semia. Yet, the aforesaid authors did not study the variation of carbon stock along environmental gradients, particularly slope and aspect. Therefore, the present study investigates the variation of carbon stock along the environmental gradient (altitude, slope, and aspect) of wacho forest (above ground carbon, below ground carbon, litter carbon, dead tree and dead wood carbon, and soil organic carbon). Hence, this study fills the gap left by the aforementioned authors and the lack of quantitative data regarding the effect of environmental gradients on the carbon stock of the wacho forest. This study is planned to address the following research questions:

(1) What is the effect of the altitudinal gradient on the carbon stock of wacho forest?
(2) What is the effect of slope gradient on the carbon stock of wacho forest?
(3) What is the effect of aspect on the carbon stock of wacho forest?

2 Materials and Methods

2.1 Description of the study area

Wacho forest is located in the Hawa Galan district, in the south-western Ethiopia. It is located about 630 km south-west of Addis Ababa, which is the capital city of Ethiopia and about 22 km far from the town of Dambi Dollo. Geographically, it is found between 8°42'32"N - 8°42'34"N and 40°52'49"E - 40°53'55"E (Fig. 1). The total area of Wacho forest is estimated to be 720 hectares of land.

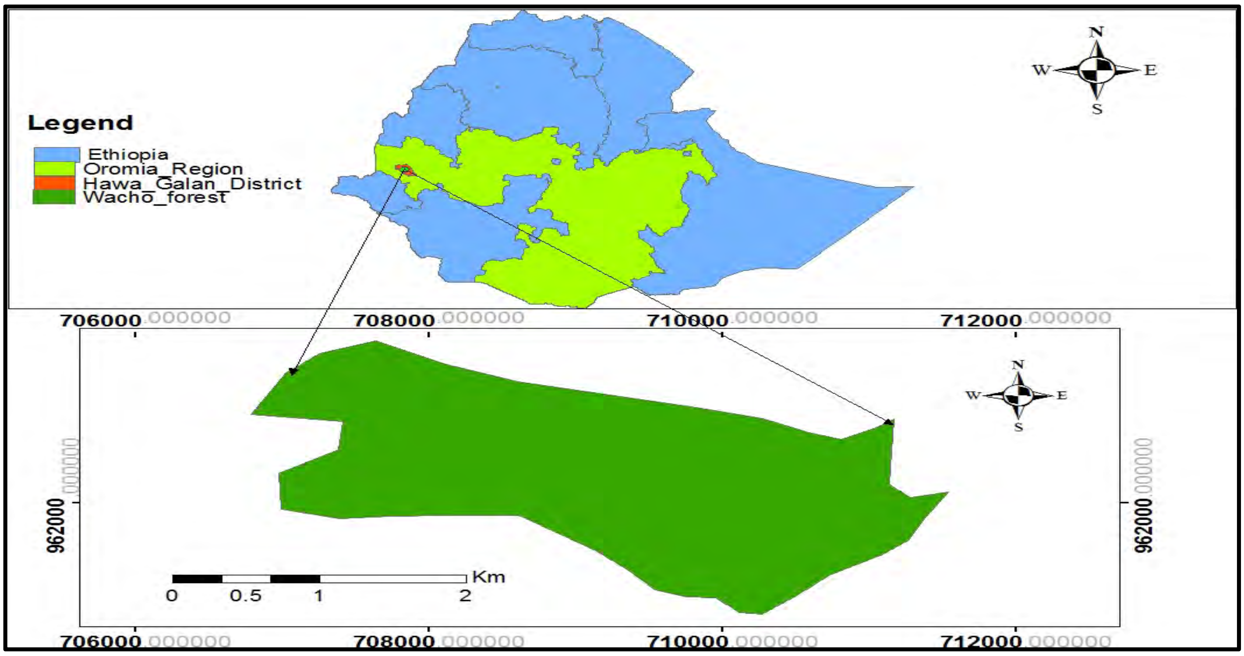

Fig. 1 Location map of the study area.

The elevation range of the study area ranges from 1435 m to 1704 m above mean sea level. The study area's mean maximum and minimum temperatures were 30.84°C and 16.38°C, respectively. The mean annual rainfall of the study area was 1,645 mm (Fig. 2).

2.2 Procedures of data collection

2.2.1 Delineation of the study area

The borders of the study area were delineated by taking geographic coordinates of the forest land using the instrument of the geographic positioning system.

2.2.2 Selection of sampling design

A systematic random sampling technique was selected for the sampling of trees, shrubs, grass, and soil. The samples were collected from 400 m^2 of sample plots at every 200 meter interval between each sample plot and

300 meter intervals between each transect line. Finally, a total of 73 sample plots were plotted, starting from the lower altitudinal class to the upper altitudinal class of the study area, and the sample plots were lined up using an instrument called geographical positioning system (Fig. 3).

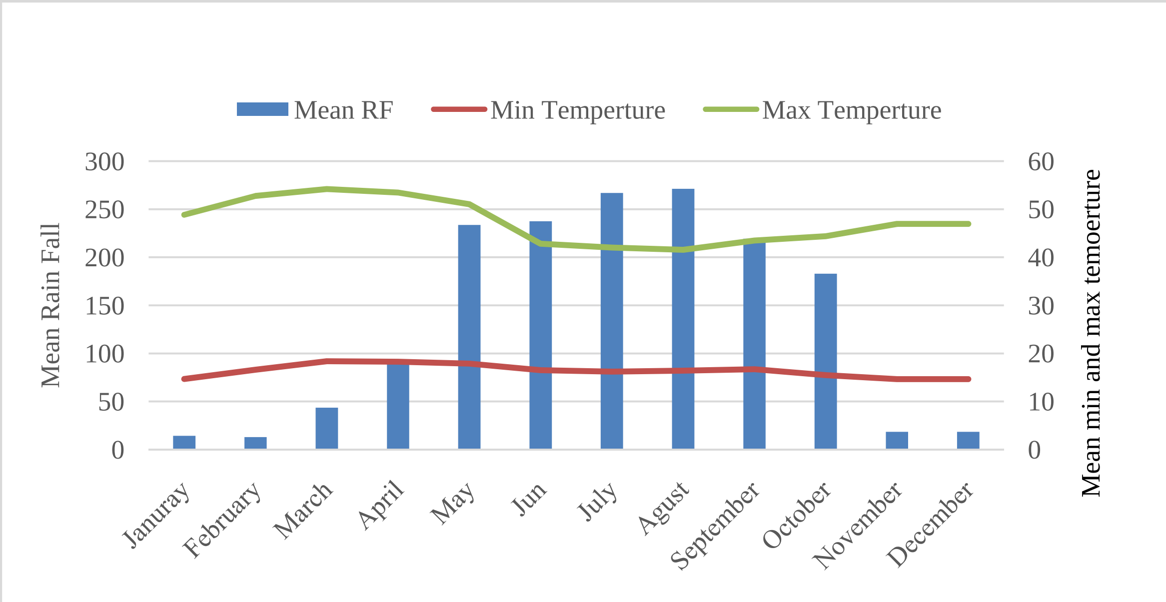

Fig. 2 The mean maximum temperature, mean minimum temperature, and mean rainfall of the study area.

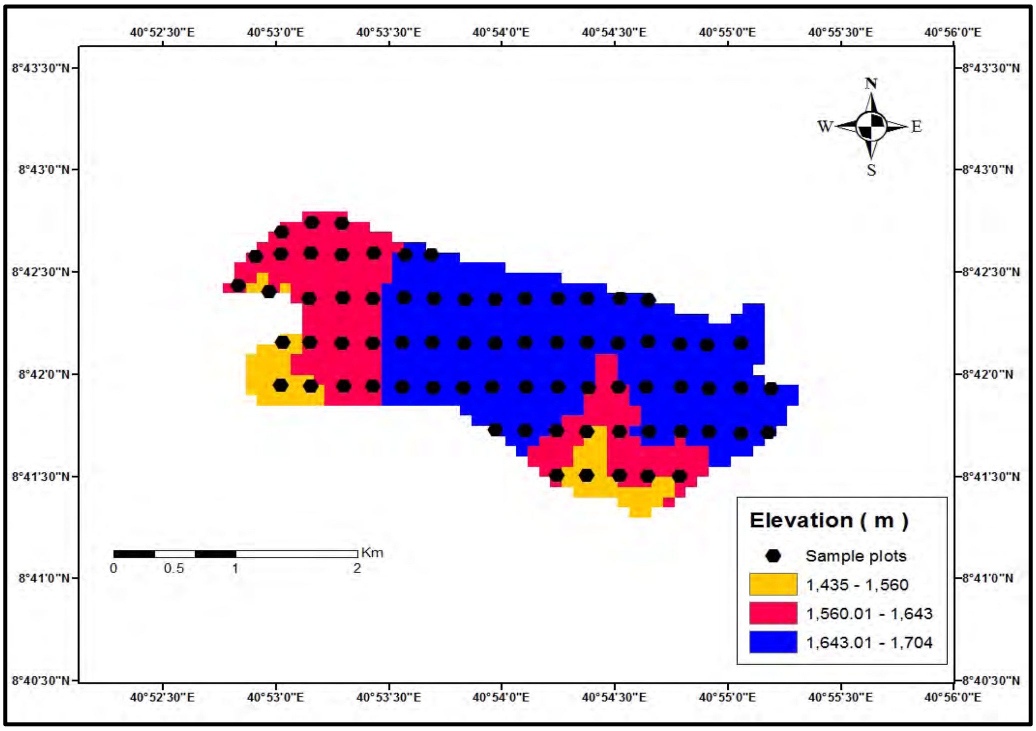

Fig. 3 Distribution of sample plots in the study area.

2.2.3 Data collection

2.2.3.1 Sampling of trees and shrubs

The entire trees and shrubs having ≥ 5 centimeter diameter at breast height (DBH) or diameter at shrub height (DSH) were sampled from 20 meter ×20 meter of sample plots using diameter tape (Pearson et al., 2005). The height of those trees and shrubs was measured by an instrument called a hypsometer. Woody plants with several stems were considered and counted as a single tree at breast height, and the largest stem was taken. The botanical names and local names of all trees and shrubs were identified using Bekele's (1993) published volumes of Flora of Ethiopia and Eritrea.

2.2.3.2 Sampling of dead trees and dead wood

The samples of the dead tree and deadwood were collected by following the principles of Pearson et al. (2005) and Goslee et al. (2015). According to Pearson et al. (2005), dead trees have four classes as follows:

Class 1: Trees with branches and twigs but that resemble living trees (except for leaves).

Class 2: Tree without twig, but with persistent small and enormous branches.

Class 3: Trees with large branches only.

Class 4: Bole (trunk) only, no branches.

Standing dead trees in class 1, which have ≥ 5 cm DBH, were measured from 400 m^2 of sample plots using a caliper, and the height of these trees was measured by a hypsometer (Pearson et al., 2005). The diameter of dead trees and dead wood in class 2, 3, and 4 was measured at the bottom of the dead tree using a caliper, and the height of these dead standing trees was measured by a hypsometer within 400 m^2 of sample plots (Goslee et al., 2015). The fallen (lying) dead woods, having ≥10 cm, diameter were divided into sections of roughly 1 m, and the exact length and diameter at the center of each section were recorded. The diameter and height of these lying dead woods were measured by caliper and meter, respectively. The dead woods below 10 cm in diameter were sampled with litter (Bhishman et al., 2010).

2.2.3.3 Sampling of litter biomass (LB)

Firstly, the litter biomass was sampled from 1 m x 1 m of subplots situated at the four corners and one at the midpoint of the main plot. Secondly, by combining the litter samples from the five subplots of the main plot, 100 grams of composite samples were taken. Thirdly, the composite samples were put in a plastic bag and labeled with the sample plot to which they belonged. Fourthly, 73 labeled composite litter samples were forwarded to Debrezeit Horticoop Agricultural Research Center for laboratory testing.

2.2.3.4 Sampling of soil for estimation of soil organic carbon fraction

Disturbed soil samples were collected from 1 m × 1 m of the five sub-plot profile pits using augers within depth of 30 cm. About 100 grams of 73 composite soil samples were taken by mixing soil samples obtained from each of the five sub-plots of the main plot. Then the soil samples were placed into a plastic bag and numbered according to where they belonged in the sample plot. Then all the composite soil samples were forwarded to Addis Ababa Agricultural Research Center for laboratory analysis of soil organic carbon fraction.

2.2.3.5 Sampling of soil for estimation of bulk density

In order to estimate the bulk density of soil samples found in wacho forest, undisturbed soil samples were collected by a core sampler from each of the five sub-plots of the main plot, situated at the four corners and one at the center of the main plot. The soil samples were collected at a depth of 30 cm. Then the sub samples of bulk density were forwarded to Addis Ababa Agricultural Research Center for laboratory analysis.

2.3 Estimation of biomass and carbon stocks

2.3.1 Estimation of above-ground tree/shrub biomass and its above-ground carbon stock

The above-ground biomass of trees and shrubs in the wacho forest was examined and calculated using an allometric model developed by Chave et al. (2014) as shown below:

$$AGB=0.0673\times(\rho DBH^2H)^{0.976} \quad (1)$$

where AGB denotes above-ground tree biomass (kg), DBH denotes diameter of trees at breast height (cm), H denotes tree height (m), and ρ denotes wood density = (0.6 ton/m^3), which is the average value of tree wood density in Africa (Henry et al., 2010). The above-ground carbon stock and above-ground biomass carbon dioxide equivalent of trees and shrubs within the study forest were examined and calculated by following the methodology used by Pearson et al. (2005) and (2007) as revealed below:

Above-ground carbon stock (AGC) =above-ground biomass × 50% (2)

where The above-ground biomass CO_2 equivalent (AGBCO_2 eq) =AGC × 3.67, which is the molecular mass ratio of carbon dioxide to carbon (44/12)

2.3.2 Estimation of below-ground tree/shrub biomass and below-ground carbon stock

The below-ground biomass of trees and shrubs within the wacho forest was determined by using the root-shoot proportion of trees and shrubs' biomass, in which below-ground biomass of trees is 20% of the above-ground biomass of trees (Mac Dicken, 1997). The study forest's below-ground carbon stock (BGC) was calculated by multiplying below-ground biomass by 50% (Mac Dicken, 1997; Pearson et al., 2005). The below-ground biomass CO_2 equivalent (BGB CO_2 eq) found in the study forest was calculated by multiplying BGC with the molecular mass ratio of carbon dioxide to carbon (44/12) (Pearson et al., 2007).

2.3.3 Estimation of dead trees and dead wood biomass and its carbon stock

The biomass of standing dead trees in class 1 was calculated using the equations of Chave et al. (2014) as biomass estimation techniques of live trees, but about 6% of the biomass of leaves was subtracted (Pearson et al., 2005).

$$SDWB = 0.0673\times(\rho DBH^2H)^{0.976} - 6\% \quad (3)$$

where SDWB = standing dead tree biomass (kg), DBH = diameter at breast height/shrub height (cm), H = dead tree height (m), ρ= wood density (0.5 g/cm^3) (Hairiah et al., 2001). The carbon stock of standing dead trees was calculated by multiplying the standing dead tree biomass by 0.47 (IPCC, 2006). The biomass of standing dead trees in class 2, 3, and 4 was calculated using the volume of the cone (Goslee et al., 2015):

$$VOL\ cone\ (cm^3) = \frac{1}{3}\pi h\ (d1)^2 \quad (4)$$

$$DB = V\times\rho\times 0.001 \quad (5)$$

where VOL cone=volume of cone (cm^3), h=height (cm), d1=diameter at the base of the tree (cm), DB = dry biomass (kg), ρ=density of wood (0.5 g/cm^3) (Hairiah et al., 2001). The carbon stock of those dead trees was calculated by multiplying the dry biomass of the dead tree by 0.47 (IPCC, 2006). The biomass of lying dead wood was calculated using the volume and density of wood (Pearson et al., 2005):

$$BLDW = V\times\rho \quad (6)$$

$$V=\pi^2\,[d1+d2+d3+\ldots..dn]/8L \quad (7)$$

where BLDW = biomass of lying dead wood, V = volume of lying dead wood (m^3/ha), ρ = density of the wood (0.5 g/cm^3) (Hairiah et al., 2001). d1, d2, d3+…dn = diameter of intersecting pieces of dead wood (cm), L = length of the dead lying wood (m). The carbon stock of those dead lying woods was calculated by multiplying the dry biomass of each dead tree with 0.47 (IPCC, 2006). The total carbon stock of dead trees and dead wood was calculated by summing up all the carbon stocks of dead trees and dead wood as follows:

$$TDWC = SDTC1 + SDTC2 + DLWC \quad (8)$$

where TDWC denotes the total carbon stock in dead tree and dead wood, SDTC1 denotes the carbon stock of standing dead tree in class 1, SDTC2 denotes the carbon stock of standing dead tree in class 2, and DLWC denotes the carbon stock of dead lying wood.

2.3.4 Estimation of litter biomass and litter carbon stock

The collected litter samples were oven-dried to a constant weight at 105°C for 12 hours, and the carbon fraction of the litter samples was analyzed in the laboratory using the Walkley-Black Method, 1934**.** Then the biomass and carbon stock of litter samples within the study forest were estimated by the formula of Pearson et al. (2005) as shown below**.**

$$LB=\frac{Wfield}{A}*\frac{Wsubsample(dry)}{Wsubsample(fresh)}*\frac{1}{10{,}000} \quad (9)$$

where LB = litter biomass (t/ha), W field = weight of a wet field sample of litter in gram from a 1 m^2 area, A = size of the area in which litter samples were collected, W sub-sample (dry) = weight of the oven dry sub sample of litter taken to the laboratory to determine moisture content (g), W sub-sample (fresh) = weight of the fresh sub sample of litter taken to the laboratory to determine moisture content (g).

$$CL = LBM \times \%\,C \quad (10)$$

where CL is the total carbon stock in the litter biomass (t/ha), LBM is the oven-dry biomass of litter, and %C is the carbon fraction of litter samples dogged in the laboratory.

2.3.5 Estimation of soil organic carbon fraction

The collected soil samples were dried to a constant weight in an oven at 105°C for 12 hours, and the percentage of organic carbon was determined in the laboratory using the Walkley-Black chromic acid wet oxidation method. The oxidisable soil organic matter is oxidized by a common chemical reagent of one nitrogen potassium dichromate (1 N $K_2Cr_2O_7$) solution. The chemical reaction process of soil was assisted by the heat produced when two volumes of H_2SO_4 are mixed with one volume of Cr_2O_7.

2.3.6 Estimation of soil bulk density

The bulk density of soil samples was estimated by the formula as shown below.

$$BD = \frac{\text{Wav,dry}}{V} \quad (11)$$

where BD is the bulk density of the soil (g/cm^3), Wav is the average oven dry weight of the soil sample per sample plot, and V is the volume of the soil sample in a core sampler (cm^3). The soil samples were oven dried to a constant weight in an oven at 105°C for 24 hours to estimate the oven dry weight of soil samples that existed in the study area. The volume of the soil core sampler (cm^3) was estimated by multiplying the height of the core sampler (cm) by π (3.14), and the radius of the core sampler (r).

2.3.7 Estimation of soil organic carbon stock

The organic carbon stock of wacho forest soil was estimated using the formula as shown below.

$$SOCS = BD * d * \%\,C \quad (12)$$

where “SOCS” represents soil organic carbon stock per unit area (t/ha), “BD” represents the bulk density of soil (g/cm^3), “d” represents the total depth at which the soil samples were taken (30 cm) and “%C” represents the carbon fraction of soil samples obtained from the laboratory**.**

2.4 Statistical analysis

First of all, the normality of the data was tested using the Kolmogorov–Smirnov tests. Then the effect of independent variables such as altitude, slope, and aspect on the dependent variable (carbon stock) was analyzed by one-way analysis of variance (ANOVA) at a 95% confidence interval. Descriptive statistics were used to calculate the maximum, minimum, mean, and standard deviations of the carbon stock of wacho forest. The mean comparisons of carbon stock along the environmental gradient of the study forest were processed using Gabriel post-hoc significant testing. The statistical analysis was carried out with the help of the Statistical Package for Social Science (SPSS) software version 26.

3 Results

3.1 Variation of carbon stock along altitudinal gradient of Wacho forest

The mean carbon stock of each carbon pool was varied along the altitudinal class of the study area. The largest mean above-ground carbon stock (280.1±31.69) and the mean below-ground carbon stock (56.02±6.34) were found in the second altitudinal class (1560.01-1643), while the least mean above-ground carbon stock (274.52±50.13) and below-ground carbon stock (54.9±10.03) were found in the third altitudinal class of the study area (1435-1560 m) (Table 1). Even though both the mean AGC and BGC were not evenly distributed along the altitudinal class of the study area, their variations were not statistically significant at α=0.05 (Table 1).

The mean carbon stock of dead trees and dead wood was slightly varied in each altitudinal class of the study area. The largest (3.3±1.3) and the least (3.02±0.27) mean dead tree and dead wood carbon stock was existed in the first and the second altitudinal class of the study area, respectively. But the variation of the mean dead tree and dead wood carbon stock distribution was not statistically significant along the altitudinal class of the study area at α=0.05 (Table1).

The mean largest (2.13±0.62) and the mean lowest (1.70±0.4) LC stocks were found in the first altitudinal class and the third altitudinal class of the study area, respectively (Table 1). The variation of the mean LC stock distribution was statistically significant between the first altitudinal class and the second altitudinal class, as well as between the first and the third altitudinal class of the study area at α=0.05 (Table 1).

The mean organic carbon stock reserved in the altitudinal gradient of wacho forest soil was nearly identical. The mean largest (109.92±14.5) and the mean lowest (107.79±16.57) SOC were found in the third altitudinal class and the first altitudinal class of the study area, respectively (Table 1). But the variation of the mean SOC stock distribution was not statistically significant along the altitudinal class of the study area at α=0.05 (Table 1).

Table 1 Variation of carbon stock along altitudinal gradient of the study forest.

Altitudinal gradient (m)	Carbon stock(t/ha)				
	AGC	BGC	DTDWC	LC	SOC
1435-1560	278.95a±7.25	55.79a±1.45	3.3a±1.3	2.13a±0.62	107.79a±16.57
1560.01-1643	280.1a±31.69	56.02a±6.34	3.02a±0.27	1.80b±0.31	109.60a±14.56
1643.01-1704	274.52a±50.13	54.9a±10.03	3.07a±0.34	1.70b±0.4	109.92a±14.5

3.2 Variation of carbon stock along slope gradient of Wacho forest

The mean largest stock of above-ground carbon (289±17.5) and the mean largest stock of below-ground carbon (57.8±3.5) were reserved in the first (5-10%) slope class of the study area (Table 2). The variation of the above-ground and below-ground carbon stock was statistically significant between the first slope class and the second slope class, as well as between the first and the third slope class of the study area (Table 2). The largest and the lowest stocks of dead tree and dead wood carbon were stocked in the first and the third slope class of the study area, respectively (Table 2). The variation of the dead tree and dead wood carbon stock was statistically significant between the first and the second slope class and between the first and the third slope class of the study area (Table 2). The stock of litter carbon in the slope class of the study area was nearly identical. The variation of carbon stock was not statistically significant among the slope classes of the study area (Table 2). The mean largest and the mean lowest concentrations of soil organic carbon were stocked in the first and second slope classes of the study area, respectively. The effect of slope class was statistically significant between slope class 1 (5-10%) and slope class 2 (10.1-15%) as well as between slope class 1 (5-10%) and slope class 3 (15.1-20%) (Table 2). This statistically significant variation could be due to the differences in nutrient availability and deposition of sediments within the slope classes.

Table 2 Variation of carbon stock along slope gradient of the study forest.

Slope gradient (%)	Carbon stock (t/ha)				
	AGC	BGC	DTDWC	LC	SOC
5-10	289a±17.5	57.8a±3.5	4a±1.2	1.90a±0.25	130a±14
10.1-15	274.27b±12	54.85b±2.4	2.9b±0.9	1.92a±0.2	102b±10.6
15.1- 20	270.29b±18	54.06b±3.6	2.5b±0.88	1.83a±0.22	94.58b ±9.6

Table 3 Variation of carbon stock in aspects of the study forest.

Aspect	Carbon stock(t/ha)				
	AGC	**BGC**	**DTDWC**	**LC**	**SOC**
North	286a±28.5	57.2±5.7	3.06a±0.93	2.02a±0.45	94.9b±12
North east	290a±20	58±4	3.05a±0.85	1.72a±0.36	120a±16
North west	276b±30	55.2±6	3.3a±1.1	1.8a±0.92	99b±11
South	273b±24.2	54.6±4.84	3.3a±1.3	2.1a±0.55	98b±9
South east	284a±14	56.8±2.8	3.2a±0.98	2a±0.78	126a±16
South west	268b±28	53.6±5.6	2.89a±1.22	1.7a±0.85	109b±20
East	294.5a±15.5	58.9±3.1	2.9a±.75	2.04a±0.69	140a±16.5
West	255c±18	51±3.6	3.2a±.96	1.85a±0.77	92c±14

3.3 Variation of carbon stock in aspects of wacho forest

The above-ground and below ground carbon stocks towards the aspects of wacho forest were different. The largest and the lowest above-ground and below-ground carbon stocks of wacho forest were recorded in the east and west directions, respectively (Table 3). The variation of above-ground and below-ground carbon stock of wacho forest was statistically significant between north and north west, north and south, north and south west, north and west, north east and north west, north east and south, north east and south west, and north east and west (Table 3).

The stocks of dead tree and dead wood carbon and litter carbon were nearly similar in all aspects of the study forest. The variation of carbon stock in dead trees, dead wood, and litter was not statistically significant at α=0.05 (Table 3). The mean largest organic carbon stock of wacho forest soil was reserved in east direction, followed by the south east and north east directions, respectively (Table 3). This could be due to sunlight, which affects rainfall, temperature, soil moisture and aeration. The concentration of soil organic carbon was statistically significant between north and north east, north and south east, north and east, north and west, north east and north west, north east and south, north east and south west, north east and west etc (Table 3).

4 Discussions

4.1 Carbon stock variation along altitudinal gradient of wacho forest

Temperature, precipitation, atmospheric pressure, solar radiation, and wind velocity are some examples of environmental elements that change with altitude. As a result, altitudinal gradients are one of the most important natural variables influencing forest carbon stocks (Korner, 2007). The variation of AGC and BGC stocks along the altitudinal gradient of the study area could be due to the difference in DBH and the height of the tree. The non-statistically significant difference of AGC and BGC stock among the altitudinal classes of the study area could be due to the similarity of soil nutrient accessibility, climate, geography, and disturbance regime of the study area as indicated by Houghton (2005). The study area's narrow range of altitudinal differences could also be a factor in the non-statistically significant AGC and BGC stocks of wacho forest. The mean AGC and BGC stock of wacho forest was in line with the mean AGC and BGC stock of Banja forest (Abre et al., 2017), in which the largest mean AGC and BGC stock of Banja forest was reserved in the middle altitudinal class of the study area without a statistically significant mean difference in carbon stock at α=0.05. The nearly similar dead tree and dead wood carbon stock along the altitudinal gradient of wacho forest could be due to the similarity of the disturbance regime of the forest. The variation of litter carbon stock along the altitudinal class of the study area could be due to the existence of an open canopy of trees, which favors the growth of understory vegetation, annual herbs, and grasses (Ewunetie et al., 2021). The mean LC stock distribution of wacho forest was in line with the mean LC stock distribution of Tara Gedam forest (Gedefaw et al., 2014). The largest mean LC stock of Tara Gedam forest was existed in the first altitudinal class of the study area, with statistically significant mean differences in LC stock at α=0.05. Soil is the most effective sequestration reservoir for carbon in many ecosystems (Lal, 2004). Soil organic carbon stock increased with precipitation and clay content but decreased with temperature (Jobbagy and Jackson, 2000). The variation of soil organic carbon stock among altitudinal classes of the study area could be due to the status of soil erosion and sedimentation within the study area. Other factors influencing soil organic carbon stock variation include vegetation cover, tree species, and the degree of disturbance regime. The organic carbon stock of wacho forest soil was similar to that of Sekele Mariam forest soil (Ewunetie et al., 2021), because in both study areas, soil organic carbon was not statistically significant at α=0.05.

4.2 Variation of carbon stock along slope gradient of Wacho forest

The statistically significant variation of AGC and BGC stock between the first slope class and the second slope class, as well as between the first slope class and the third slope class of the study area, could be due to the difference in DBH of trees, height of trees, density of trees, and disturbance regime. The statistically significant variation of DTDWC stock between the first slope class and the second slope class and between the first slope class and the third slope could be due to the difference in the disturbance regime of the slope class. The effect of slope had no statistically significant effect on the litter carbon stock of the study area, which could be due to the relatively uniform distribution of litter within slope classes. SOC is important in regulating the dynamics of greenhouse gases (GHG) because its pools and transformations in terrestrial ecosystems can influence carbon dioxide and other greenhouse gas concentrations in the atmosphere (Błońska and Lasota, 2017).

SOC reduces when slope area and water flow velocity increase, resulting in more runoff. SOC content is prima rily governed by slope gradient, although other factors such as land use/cover, slope aspect, management practi ces, soil type, depth, and elevation have a substantial impact on its values (Jakšić et al., 2021). In the present study, the statistically significant variation of SOC stock among slope class could be due to the rate of soil erosion and sedimentation.

4.3 Variation of Carbon Stock towards aspect of Wacho forest

Aspects and climatic variables such as precipitation, temperature, and radiation influence forest diversity and composition, which in turn determine the above-ground and below-ground carbon stock of a forest ecosystem (Lenka et al., 2013). The statistically significant variations of AGC and BGC stock in different aspects of the study area could be due to the variations in temperature, precipitation, solar radiation, and moisture, which determine the DBH, height, density, and cover of trees. The drying of woody and leafy components on the forest floor is aided by high temperatures (Sharma and Rikhari, 1997). The variation of dead tree and dad wood carbon in wacho forest might be due to the degree of disturbance regime.

The intensity of solar radiation, temperature, and moisture can vary with aspects, which determine the growth and cover of litter, herbs, and grasses and, litter carbon stock. Thus, the above-mentioned variables and microclimatic conditions can determine the carbon stock of litter in the study area. Mountainous regions have a wide range of SOC stocks due to their diverse environment, soil type, vegetation, and land use (Hoffmann et al., 2014). The combined effect of aspect, climatic conditions, vegetation types, and soil microbiology can determine soil organic carbon decomposition and buildup rates (Matus et al., 2014). The variation in temperature and soil moisture, which vary with aspect, maintains the soil organic carbon stock (Garcia et al., 2016). Soil texture, particularly clay soil and land use management techniques and practices, influences the stock of soil organic carbon (D'Angelo et al., 2009). The rate of evaporation on a sunny aspect is larger than the rate of evaporation on a shady aspect, which determines the stock of soil organic carbon stock. Temperature and precipitation have a significant impact on soil organic carbon stock (Jobbagy and Jackson, 2000). As a result, these factors create microclimate differences, which may give better conditions for soil organic matter decomposition and soil organic carbon stock (Sidari et al., 2008). In the present study, the statistical variation of soil organic carbon stock in different aspects of the study area could be due to the variation of vegetation cover, sedimentation, and decomposition of soil organic matter with the corresponding aspect.

5 Conclusion

Environmental factors such as altitudinal gradient, slope gradient, and aspect affect the carbon stock of wacho forest. An altitudinal gradient had a statistically significant effect on dead tree and dead wood carbon, litter carbon, and soil organic carbon. Except for litter carbon stock, slope gradient had a statistically significant effect on all carbon pools of the study area. Aspect had a statistically significant effect on the above-ground and below-ground carbon stocks, dead tree and dead wood carbon stocks, litter carbon stock, and soil organic carbon stock of the study forest.

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