CARBON STOCK VARIATION OF WOODY SPECIES ALONG ALTITUDINAL GRADIENTS OF MUHABURA VOLCANO, NORTHERN RWANDA

Uwimbabazi Agnes[1,2*], Sintayehu Workeneh Dejene[2], Nduwamungu Jean[3], Petros Chavula[2]

[1]Department of Nature Conservation, Rwanda Polytechnic-College of Kitabi, PO.Box 33O Huye, Rwanda.
[2]African Center of Excellence for Climate Smart Agriculture and Biodiversity Conservation, Haramaya University, P O. Box 138, Dire Dawa, Ethiopia.
[3]College of Agriculture, Environment and Veterinary Medicine, School of Forestry and Biodiversity Conservation, University of Rwanda, P O. Box 4285, Kigali, Rwanda.

ABSTRACT: The study estimated the woody plant species' carbon stock along the Muhabura volcano's altitudinal gradient. Three strata namely low, middle, and high altitudes were created within the study site depending on vegetation appearance and elevation gradients. A total of 60 plots of 20 x 20 m with four transect lines and 100 m apart from one another, were established along the transect to collect data on the carbon in above-ground, below-ground biomass, dead litter, and soil. Height, and Diameter at Breast Height (DBH) of each woody species that had a DBH bigger than 5 cm were measured. The allometric equations were used to estimate the above-ground biomass and below-ground biomass. The result showed 326 individual species belonging to 21 woody plant species and 16 families in the study area. No woody plant species with DBH ≥ 5 cm were found at high altitudes. The estimated total carbon stock in low, middle, and high altitudes were 162.029±9.094 tC ha^{-1},142.767±0.398 tC ha^{-1}, and 132.923±18.806 tC ha^{-1}, respectively, and they showed a significant difference ($P < 0.05$). Likewise, the organic carbon in soil differed significantly ($P < 0.05$) across different depths (0-30 cm, 30-60 cm) in altitudinal gradients. The largest carbon pool in all the three altitudinal gradients was the soil organic carbon pool, sinking the highest carbon amount of 397.551±77.307 tons ha^{-1}. The results showed that Muhabura Volcano can be important for carbon stocks, and effectively conserving this mountain has a considerable contribution to climate change mitigation and biodiversity conservation.

Keywords: Carbon Sequestration, Climate Change, Volcanoes National Park

INTRODUCTION

Global climate change is a pressing environmental issue resulting in extreme weather patterns, global warming, natural disasters, biodiversity loss, and rising sea levels (Siraj, 2019). The primary cause of this is greenhouse gases including nitrous oxide, methane, and carbon dioxide generated from anthropogenic

*Corresponding author: agnesmbabazi1@gmail.com

activities such as deforestation, and the burning of fossil fuels (Liu et al., 2018). According to the Intergovernmental Panel on Climate Change, per decade, a 0.3°C increase in global mean temperature is expected during the next century, and this increase is anticipated to grow by 1.4 to 5.8 °C by 2100 (IPPC, 1990). Carbone dioxide has been seen to be the most important greenhouse gas. The two main causes of the carbon cycle distortion are changes in land cover, land use, and the use of fossil fuels. Practically, the burning of fossil fuels for transportation, building heating and cooling, and the production of cement and other commodities accounts for roughly 75% of the world's CO_2 emissions (Fischer et al., 2019). The significance of soil and forests in reducing greenhouse gas emissions (methane, carbon dioxide, and other gases) was acknowledged by the Kyoto Protocol. As possible sinks for increased carbon dioxide emissions, forests and soils are taken into account for determining the permissible offset (Mulugo et al., 2020). The extension of wooded areas and sustainable forest development is an economical, safe, and ecologically friendly method of storing, and capturing significant volumes of carbon from the atmosphere and financial incentives are provided for taking carbon storage into account when making decisions about forest management by the parallel creation of marketable carbon credits (Fischer et al., 2019). According to the latest estimates, the earth has 3952 million hectares of forest where 16% are found in Africa (Nel, 2018). Tropical natural vegetation is regarded as a significant storage of carbon globally (Gizachew et al., 2018) and has the potential to balance the amount of CO_2 in the atmosphere. This is due to having higher Carbon (C) content per unit area compared to any other terrestrial ecosystem. While climate change in Africa is complex, the Rwandan situation is even more complex (Ototo and Vlosky, 2018; Kazoora et al., 2019; Mawa et al., 2022). Historically, deforestation in Rwanda has been reported in most of the country's regions attributed to extensive anthropogenic activities such as grazing, agricultural expansion as well as residential land expansion, and fuelwoods related to increasing population demands, all coupled with climate change (RoR, 2016; Namanji et al., 2019; Mwawa et al., 2022). To restrict further forest degradation, most of the natural forests are protected either as national parks or as forest reserves. Protected areas cover around 10.8

% of the country and the total forest cover is about 30.4% of the dry country land (RoR, 2015; Chapman et al., 2018; RoR, 2018). The increment of forest cover has affected more the carbon sink where between 2001 and 2022, the forests in Rwanda removed 4.61 MtCO_2e/year, and in the same period, an average of 1.29Mt/year was released into the atmosphere as a result of tree cover loss in Rwanda. This represents a net carbon sink of 3.32 MtCO_2e/year (MoE, 2019). Hence, mitigating the emission of greenhouse gases as a source of climate change leading to ecosystem degradation is crucial. This can be achieved through sustainable management of existing natural vegetation that can attract potential financial, and technical incentives from industrialized nations to developing nations like Rwanda through climate finance funds such as REDD+ (Tumushabe et al., 2023). However, there are limited studies on quantifying carbon stocks sequestered by natural forests in Rwanda (Nsabimana, 2009; Nsengumuremyi et al., 2022; Mugabowindekwe et al., 2023). In this context, consistent and accurate data that meet international standards with a favourable environmental policy are the most critical requirements to derive the benefits from climate funds. For achieving international standards, it is important to bridge the gap in characterizing biomass, and carbon stock of the Rwandan natural vegetation such as the one found at Muhabura volcano, using standardized carbon stock accounting methods. Therefore, this study aimed to estimate the potential of carbon sequestration of woody species and its variation along altitudinal gradients at Muhabura volcano in the North of Rwanda.

MATERIALS AND METHODS

Description of the study area

Muhabura Volcano lies partly in the Volcanoes National Park (VNP) situated in the Albertine Rift of the Great African Rift Valley, in northwestern Rwanda and borders Virunga National Park in the Democratic Republic of Congo and Mgahinga Gorilla National Park in Uganda. Muhabura is an extinct volcano in the Virunga massif (1°21'-1°35'S, 29°22'-29°44'E) with an altitude ranging from 2300 m to 4,500 m above sea level on the border between Rwanda and Uganda (Derhe et al., 2020; Zajadacz and Uwamahoro, 2021)

(Figure 1). Muhabura Volcano receives a steady stream of rain and mist. Combined with the high altitude, this means that the climate is wet and cold with wind speed variation with altitude (Akayezu et al., 2019). Temperatures of 16°C during the day do not change much throughout the year and at night, it cools off to about 6°C. The range of altitudes means a range of climatic conditions. The temperature drops by about 6.5°C for every 1,000 m climbed. According to Dondeyne et al. (2017), the soils at Muhabuara Volcano are fertile and of volcanic type and there is a variation in composition from one area to another. They are in the category of andosols and andic soils with a black colour. Fine alluvial peat formation in the wetland occurs. In addition, soils are generally characterized by high moisture, rich organic matter content, high pH levels, and high permeability. Furthermore, in the Eastern part of Muhabura volcanoes the soil is dry and rocky soil with silt or silty-clay textile in most cases. The bulk densities in all horizons are very low mostly between 0.2 and 0.7 gcm^{-3} for oven-dry samples (Uwitonze et al., 2016; Turamyenyirijuru et al., 2019). Muhabura volcano harbors 245 plant species; 17 of which are threatened and 13 species of orchids (REMA, 2009; IUCN, 2019). Vegetation varies with altitudinal gradients and the forest is characterized by an open canopy and frequent wind like in the savanna (Ngiramahoro et al., 2018). In general, the VNP has been constantly under direct or indirect threat due to pressure from the farming population in search of fertile volcanic soils in its immediate vicinity. Currently, it covers 160 km^2 (Owiunji et al., 2005). Particularly, a large part of Muhabura was highly disturbed by a fire outbreak in 2009 due to beekeeping along the edge, in addition to the agriculture of a dense population bordering on its bottom (Ngiramahoro et al., 2018).

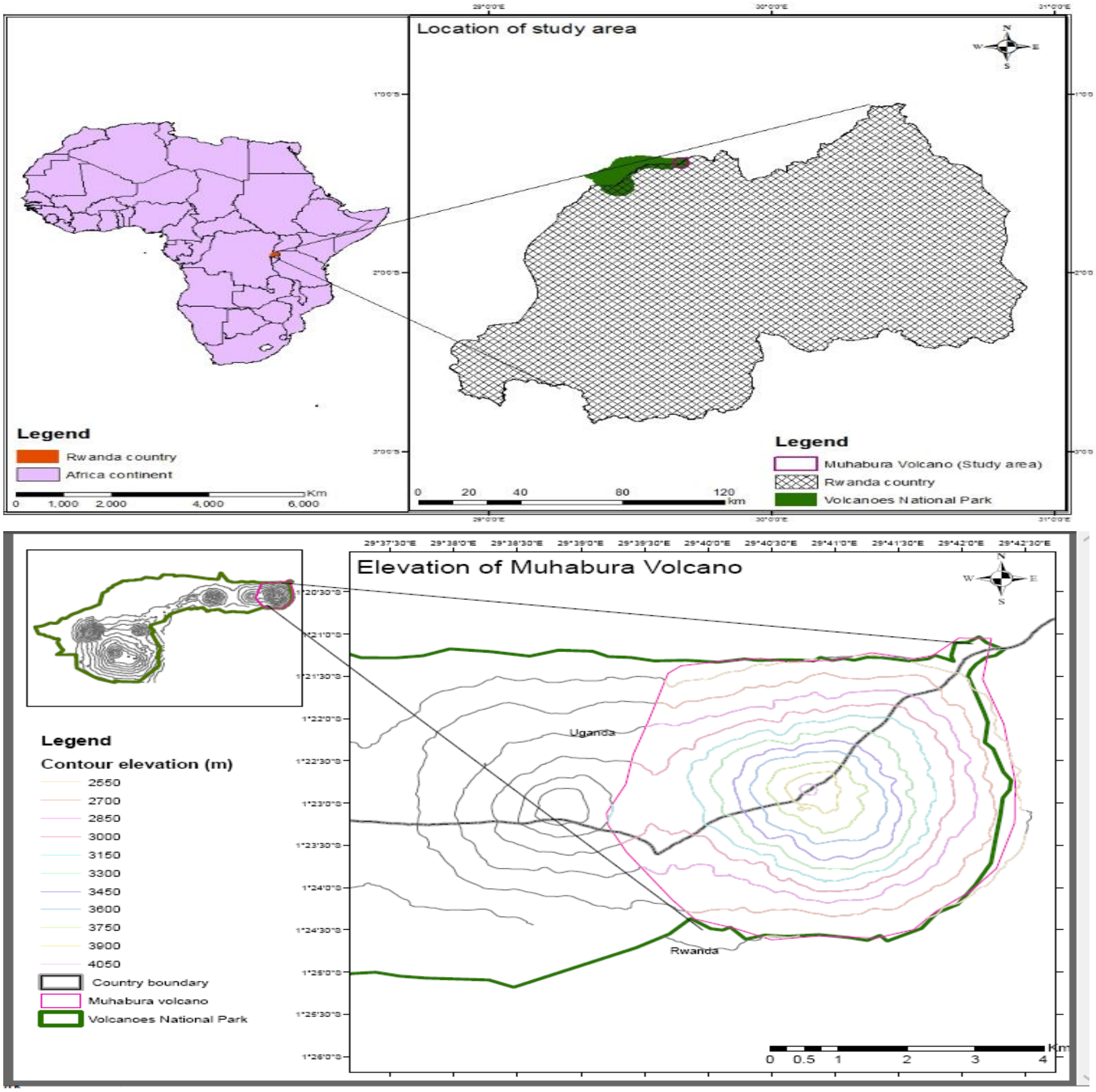

Fig 1. Map of the study area.

Data Collection

To form relatively homogenous units and obtain accurate data from the fieldwork, stratified sampling by elevation segments was used since the area under the study presents an altitudinal variation (Mlotha, 2018). That helped to determine the elevation variations as predictor variables to relate with forest carbon stocks. The study area was classified into three altitudinal gradients based on the physical appearance of vegetation using GPS: lower altitude between 2502-2882 m a.s.l. (stratum 1), middle altitude between 2883-3109 m a.s.l. (stratum 2), and upper altitude between 3110-4127 m a.s.l. (stratum 3), based on a reconnaissance survey. In each stratum, a total of four transect lines, 100 m apart from each other, were established systematically, along with five plots of 20 m x 20 m plots and subplots of 1 m x 1 m (4 at the corner 1 at the center of each plot) for litter and soil samples within the main plots. The plots were laid out at 100 m intervals along the transect for woody species records and carbon stock potential (Matakala et al., 2023).

A total of 60 plots were established in the study area. All woody species individuals encountered in the area were recorded. The diameter at breast height was measured at 1.3 m above the ground using a diameter tape (Abere et al., 2017; Aabeyir et al., 2020). In the case of multi-stemmed woody species above 1.3 m in height, the tree was treated as a single individual. In the case where the tree forks below 1.3 m, measurement of each stem was done (Snowdon et al., 2002; Bilous et al., 2024). Diameter data for all tree species individuals with a DBH ≥ 5cm were collected. This is due to the fact that the study area was a degraded montane forest with small trees and secondary forest in some zones where woody species with small DBH were present. The heights of all trees were also measured using Suunto and Haga hypsometers. Trees on the border of the plot were included if more than 50% of their basal area fell within the plot or excluded if more than 50% of their basal area fell out of the plot (Bhishma, 2010). Trees with their trunks inside the plot but their branches hanging outside were included but those overhanging in the plot were excluded.

All litter samples in the sub-plots of 1 m × 1 m were collected manually in each main plot at each corner and center. A 100 g composite sample was prepared for field wet weight and taken for laboratory analysis at a later stage. The litter samples were oven-dried at 105^{0}C for 48 hrs using the dry ashing method (Allen et al., 1986). Oven-dried samples were taken in pre-weighed crucibles. Then the samples were ignited at 550^{0}C for one hour in a muffle furnace. After cooling, the crucibles with ash were weighed and the percentage of organic carbon was calculated. Finally, carbon in litter (t ha^{-1}) was determined for each sample.

Soil samples of 100 g each from two depths of 0-30 cm and 30-60 cm were collected from five pits in the main plot (one at the center, and four at the corners of each plot) and mixed properly in their respective layers and a composite sample was prepared. Two depths were considered in this study (BSSS, 2023; Freeze, 2024; Raffeld et al., 2024) due to severe fire disturbance of the topsoil (30 cm) in the study site, which showed a high variation of soil organic components and other soil properties (Lu et al., 2017; Agbeshie et al., 2022). Soil samples were placed in plastic bags labeled separately and taken to INES Ruhengeri laboratory for analysis using the Walkley and Black method (Walkley and Black, 1934). These samples were air-dried and passed through a 2 mm sieve at the soil laboratory to remove the soil moisture and finally, the bulk density and soil organic carbon percentage were calculated (Pearson et al., 2005).

Data analysis

Carbon stock analysis

Above-ground woody species biomass (AGB): this study applied equations developed via dimensional analysis, as the only reasonable method to estimate tree biomass without destructive sampling (Yilma and Derero, 2020). The equation by Chave (2014) was used to estimate the above-ground biomass. The allometric equation considers DBH, height, and density of trees; and then, the above-ground biomass (AGB) was computed as follows:

$$\text{AGB} = 0.0673\text{x } (PxD^2xH)^{0.076}$$ (Chave, 2014)... Equation 1

Where AGB= above-ground biomass in kg, D= diameter at breast height in cm, H= height in m, P = density in g cm^{-3}. The wood density of each tree species was obtained from the global woody density database.

Results were then converted into tonnes per hectare (Tuffour et al., 2014). Finally, the carbon content in the biomass was estimated by multiplying by 0.47 a conversion factor according to REDD and IPCC defaults, while multiplication factor 3.67 was used to estimate CO_2 equivalent (IPCC, 2006).

In the case of multi-stemmed trees prone to multi-stem below 1.3 m diameter, the measurement of the diameter was calculated by the diameter equivalent (de) as follows:

$\mathrm{de} = \sqrt{\sum_{i=1}^{n} \mathrm{di2}}$ (Snowdon et al., 2002; Bilous et al., 2024).. Equation 2

where, de = diameter equivalent, di = diameter of the i^{th} stem at 30 cm height. The results were recorded in a prepared data sheet.

Below-ground woody species biomass (BGB)

The equation developed by MacDicken (1997) to estimate below-ground carbon was used.

$\mathrm{BGC} = AGC\ x\ 0.2$ (Yilma and Derero, 2020)... Equation 3

where BGC is below ground Carbon, AGC is above-ground carbon, and 0.2 is the conversion factor (or 20% of AGC).

Estimation of carbon stock in litter biomass (LB)

The equation by Pearson et al (2005) adopted by Toru and Kibret (2019), estimates the amount of biomass in the litter as used.

$\mathrm{LB} = \frac{\mathrm{Wfield}}{\mathrm{A}} \times \frac{\mathrm{Wsub\ sample\ (dry)}}{\mathrm{Wsub\ sample\ (fresh)}} \times 0.0001$ .... Equation 4

Where, LB = Litter biomass (ha^{-1}), Wfield = 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 was collected (ha^{-1}), Wsub-sample (dry) = weight of the oven-dry sub-sample of litter taken to the laboratory to determine moisture content (g) and Wsub-sample, (fresh) = weight of the fresh sub-sample of litter taken to the laboratory to determine moisture content (g). The litter samples were oven-dried at 105^0C for 48 hrs using the dry ashing method (Allen et al., 1986). Oven-dried samples were taken in pre-weighed crucibles. Then the samples were ignited at 550 ^{0}C for one hour in a muffle furnace. After cooling, the crucibles with ash were weighed and the percentage of organic carbon was calculated. Therefore, carbon stored in litter was calculated as:

$\mathrm{LC} = LB\ x\ \%CC$ .... Equation 5

Where Where, LC = Litter carbon, LB = Litter biomass (ha^{-1}), CC= carbon concentration

Estimation of carbon stock in the dead wood biomass

For the standing stump of dead wood, the amount of biomass was estimated using the allometric equation from REDD (2009) adopted by Dondo et al. (2019)

$$BSDW = \frac{1}{3} \times \pi \times \left(\frac{D}{200}\right) 2 \times H \times S \text{ .... Equation 6}$$

Where, BSDW= Biomass of Standing Dead Wood (kg), H = Height of Standing Dead Wood (m), D = Basal Diameter of Standing Dead Wood (cm), and S = Mean Wood Density of Dead Wood (gcm^{-3}). The specific density is estimated at 0.5 gcm^{-3} as a default value, but 0.8 can be used for dense hardwoods and 0.3 for very scattered species in tropical regions. In this study, the total carbon stock in dead wood was computed by multiplying the total biomass of the dead wood by 0.5 (Pearson et al., 2005; Sakai et al., 2008).

Soil organic carbon estimation

Collected composite soil samples were examined for soil organic carbon estimation for all three strata using the Walkley-Black method (Dondo et al., 2019). The soils were sieved through a 2 mm sieve mesh and mixed to a uniform consistency, and then a sub-sample of soil was taken and carbon analysis was done. SOC was calculated as follows:

$$\text{Soil organic carbon} = \text{bulk density x depth } x \text{ \% } Carbon \text{ .... Equation 7}$$

where: Bulk density (gcm^{-3}) = oven-dry mass (g)/volume (cm^3), % Carbon = carbon concentration (%). Soil bulk density was determined after oven drying of the soil samples as recommended by Solomon et al. (2018).

Bulk density (ρ_b)

Soil bulk density was determined after oven drying from the soil samples that were taken with a core sampler as recommended by Pearson et al. (2005) and adopted by Toru and Kibret (2019).

$V = h \text{ x } \pi r^2$ Where: V = volume of the soil in the core sampler in cm^3, h = height of the core sampler in cm, π= 3.14, r = the radius of the core sampler in cm. Then, the bulk density of a soil sample was calculated as follows:

$$\rho b = \frac{Wav,dry}{v} \text{ .... Equation 8}$$

Where ρ_b is the bulk density of the soil sample per plot (gcm^{-3}), Wav, dry is the average dry weight of soil sample per plot, V is the volume of the soil sample in the core sampler auger in cm^3 (Pearson et al., 2007).

Total carbon stocks estimation

The total carbon stock was estimated by summing the carbon stock densities of the individual carbon pools of the stratum using the Pearson (2005) formula.

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

$$CT = AGC \text{ x } BGC + LC + SOC \qquad \text{Equation 9}$$

Where, CT = total carbon stock for all pools (t /ha^{-1}), AGC = above ground carbon stock (t /ha^{-1}), BGC = below ground carbon stock (t /ha^{-1}), LC = litter carbon stock (ton/ha) and SOC= soil organic carbon (t /ha^{-1}). The total carbon stock was then converted to tons of CO_2 equivalent by multiplying it by 44/12, or 3.67 as indicated by Pearson et al. (2007).

Analysis of Variance

R software version 4.0.1 was used to analyze data and analysis of variance was used to compute the mean of soil organic carbon across the soil depths and altitudinal ranges, and also to analyze the mean of change in carbon stocks with change in strata. The least significant difference was also used to separate the means at a significant level of $p < 0.05$.

RESULTS

Woody species identified at Muhabura Volcano

The families, genus, and species names, the number of individuals in each species (NoS), their corresponding percentage, and the number of plots (NP) these individual species were found at Muhabura Volcano is presented in Table 1. A total of 21 woody species distributed in 16 families were identified in which all 16 families were identified in low altitude and 4 families in middle altitude. No woody species with DBH ≥ 5 were identified in high altitudes. The high number of individuals' woody species were 30, 24, and 15 for *Hagenia abyssinica*, *Faurea saligna*, *and Neoboutonia macrocalyx* respectively in low altitude. *Erica arborea* had a high number of individuals (155) compared to other species in the middle altitude. Low number of individuals (1) was recorded for *Anthocleista grandiflora*, *Carapa grandiflora*, *Yushania alpina* and *Prunus Africana* in low altitude while 2 individuals were recorded as low number for *H. abyssinica* in middle altitude (Table 1).

Table 1. Families with their corresponding species at Muhabura Volcano.

AG	Family Name	Genus Name	Species Name	NoS	%S	NP
Lower	Asteraceae	*Solanecio*	*Solanecio mannii* (Hook.f.)	3	2.38	3
Lower	Betulaceae	*Alnus*	*Alnus acuminata* Kunth	3	2.38	2
Lower	Celastraceae	*Catha* Forssk	*Catha edulis* (Vahl) Forssk. *ex*	3	2.38	2
Lower	Ericaceae	*Erica L.*	*Erica arborea L.*	5	3.96	4
Lower	Ericaceae	*Agauria*	*Agauria salicifolia (*Comm. *ex*	2	1.58	1
Lower	Euphorbiaceae	*Neoboutonia*	*Neoboutonia macrocalyx* Pax	15	11.9	6
Lower	Euphorbiaceae	*Macaranga*	*Macaranga kilimandscharica* Pax	2	1.58	1
Lower	Gentiaceae	*Anthocleista*	*Anthocleista grandiflora* Gilg	1	0.79	1
Lower	Meliaceae	*Carapa*	*Carapa grandiflora* Sprague	1	0.79	1
Lower	Hypercaceae	*Hypercum*	*Hypercum revolutum* Vahl.	4	3.17	3
Lower	Meliaceae	*Lepidotrichilia*	*Lepidotrichilia volkensii* (Gürke)	10	7.93	4
Lower	Moraceae	*Ficus* Tourn. ex	*Ficus thonningii* Blume	2	1.58	1
Lower	Myrtaceae	*Syzygium* Gaertn.	*Syzygium guineense* (Willd.) DC.	3	2.38	2
Lower	Myrtaceae	*Eucalyptus*	*Eucalyptus maidenii* F.Muell.	2	1.58	1
Lower	Pentaphylacacea	*Balthasaria*	*Balthasaria schliebenii (*Melch.)	3	2.38	2
Lower	Poaceae	*Yushania*	*Yushania alpina*	1	0.79	1
Lower	Podocarpaceae	*Podocarpus*	*Podocarpus latifolius* Wall.	3	2.38	2
Lower	Proteaceae	*Faurea* Harv.	*Faurea saligna* Harv.	24	19.04	11
Lower	Rosaceae	*Hagenia*	*Hagenia abyssinica* (Bruce) J. F.	30	23.81	12
Lower	Rosaceae	*Prunus* L.	*Prunus Africana* (Hook. f.)	1	0.79	1
Lower	Sterculiaceae	*Dombea* Cav.	*Dombea torrida* (J.F.Gmel.)	8	6.34	6
Middle	Ericaceae	*Erica* L.	*Erica arborea L.*	155	77.5	20
Middle	Ericaceae	*Agauria*	*Agauria salicifolia (Comm. ex*	12	6	7
Middle	Hypercaceae	*Hypercum*	*Hypercum revolutum* Vahl.	17	8.5	9
Middle	Proteaceae	*Faurea* Harv.	*Faurea saligna* Harv.	14	7	7
Middle	Rosaceae	*Hagenia*	*Hagenia abyssinica (*Bruce) J. F.	2	1	2

AG=Altitudinal Gradients, NoS=Number of individuals of a species, %S=Percentage of species, NP=Number of plots where species presented.

Variation in carbon pool

The AGC for all altitudinal levels were 0.0015±0.0001138 and 0.0013±0.000033 for low altitude, and middle altitude respectively and no woody species were recorded in high altitude, the reason for AGC absence. The BGC for all altitudinal gradients did not show any significant difference at $p < 0.05$ and the estimated mean of BGC stocks were as follows, 0.0003±0.0000234 and 0.0003±0.0000069 tC/ha for low, and middle altitude respectively while no BGC for high altitude. Deadwood carbon stocks along altitudinal levels did not show any significant difference, (p=0.08; Table 2). The mean DWC stocks for lower and middle altitudes were 0.0008±0.00262 and 0.0003±0.006 t C/ha respectively. Mean SOC were 135.6636±0.1797, 128.966±0.2870 and 132.9230±18.8068 for low, middle and high altitudes respectively with a significant difference at $p > 0.05$. Carbon stock in litter for low and middle altitudes showed a significant difference at $p < 0.05$. The mean carbon stock in litter biomass in low and middle altitudes were 26.36±8.91 t/ha and 13.80±10.54 t/ha respectively (Table 2).

Table 2. The variation of carbon pools to altitudinal gradients at Muhabura volcano.

Carbon pools	Altitudinal gradients			p-value
	Low	Middle	High	
AGC	0.0015±0.0001138^{Ba}	0.0013 ±0.000033^{Ba}	-	0.000
BGC	0.0003±0.0000234^{Ba}	0.0003 ±0.0000069^{Ba}	-	0.000
DWC	0.0008 ±0.00262^{Ba}	0.0003±0.0060 ^{Ba}	-	0.085
SOC	135.6636±0.1797^{Aa}	128.966±0.2870^{Aa}	132.9230±18.8068^{Aa}	0.577
LC	26.36100 ±8.9120^{Ba}	13.80 ±0.10547^{Bb}	-	0.000
Total	162.0299±9.0944	142.7676±0.3984	132.9230±18.8068	

AGC = above ground carbon, BGC = Below ground carbon, DWC = dead wood carbon, SOC = soil organic carbon, LC = litter carbon. The values are in mean and standard deviation. The small letter compares the mean in a row and the capital letters compare the means in the column. Different letters show significant between means at $p < 0.05$.

Soil organic carbon

The results showed that the mean soil organic carbon stocks for low middle and high altitude were 135.6636±0.1797, 128.966±0.287 and 132.923±18.8068 t ha^{-1}, respectively and they did not show any significant difference at $p < 5$ (p=0.577, Table 3). The results showed that the soil carbon stock at 0-30 cm and 30-60 cm depth of three altitudinal levels were not significantly different in each group. However, SOC at the 0-30 cm depth showed a significant difference with SOC at 30-60 cm in all altitudinal gradients.

Table 3. Distribution of SOC content with depth at altitudinal gradients of Muhabura volcano.

	Soil depth		
Altitudinal gradients	**0-30 cm**	**30-60 cm**	**Mean**
Low	170.227 ±34.012^{Aa}	101.100 ±10.479^{Ab}	135.663±22.245
Middle	154.060 ± 51.009^{Aa}	103.871 ± 12.896^{Ab}	128.965±31.952
High	164.482 ±38.253^{Aa}	101.364 ±7.984^{Ab}	132.923±23.110
Total			397.551±77.307

Note: Means showed by similar superscripts (letters) within a column or within a row is not significantly different at a 5% level of significance. The values in the Table are means of triplicate samples.

Analysis of correlation among different carbon pools

The results of this study showed that there was a strong and positive correlation (0.99) between BGC and AGC. This means that BGC depends on BGC and any destruction of above-ground woody species can affect directly the below-ground carbon (Table 4). A positive correlation of 0.744 and 0.741 was found between LC with AGC and BGC respectively. However, there was a weak correlation between DWC and AGB, BGC, and LC, meaning that each carbon pool affected the other (Table 4).

Table 4. Pearson correlation analysis results of carbon pools at Muhabura volcano

	AGC	**BGC**	**DWC**	**SOC**	**LC**
AGC	1.00				
BGC	0.999**	1.00			
DWC	0.131	0.129	1.00		
SOC	-0.020	-0.017	-0.127	1.00	
LC	0.744**	0.741**	0.142	-0.071	1.00

AGC = above ground carbon, BGC = Below ground carbon, DWC = dead wood carbon, SOC = soil organic carbon, LC = litter carbon. **Correlation is significant at α=0.01; *Correlation is significant at α =0.05

DISCUSSION

Carbon stock in above and below ground biomass

Low and middle altitudes of Muhabura volcano did not show any significant difference in AGC and BGC and the study showed low AGC in the same altitudinal gradient. Biodiversity is linked to carbon stock in the way that a low number of woody plant species often linked to reduced biodiversity which in return negatively affects the ecosystem's stability to hold carbon (Ntukey et al., 2022). According to Youan et al. (2018) tree species attributes such as stand structure, woody density, and height play a significant role in the storage of carbon. In a disturbed forest ecosystem, the loss of tree species with a high potential to sequester carbon can considerably reduce AGC. The number of individuals and species of woody plants is reduced by different disturbances such as logging and deforestation, resulting in low AGC (Ntukey et al., 2022). This is in line with the current study where the number of woody species individuals recorded was the result of disturbance by human activities in the previous years before the current enforced protection in addition to low regeneration of woody species after fire outbreak (Ngiramahoro et al., 2018). This is supported by a study which revealed that fire characteristics and environmental conditions shape vegetation communities via regeneration strategy along altitudinal gradients where selective species can be more affected (Day et al., 2020). According to Bunker (2005), tropical forest biodiversity, functional diversity, and relative abundance influence both the magnitude and variability of aboveground biomass. Furthermore, aboveground biomass substantially determines an ecosystem potentiality for above-ground carbon storage, which plays an important role in regulating atmospheric CO_2 and global climate change (Tebeje, 2020). Biodiversity, however, is changing rapidly in response to a variety of anthropogenic drivers (Isbell, 2010; Sintayehu, 2018). The potential for terrestrial above-ground carbon sequestration could be altered sharply by ensuing changes in species composition (Daba et al., 2022; Ngute et al., 2020).

The findings in low BGC stocks of the lower and middle altitudes have contradicted the results of Binyam (2012) revealing that trees have much more potential to produce a larger quantity of BGC. This is due to a positive relation between AGC and BGC in the way that above-ground forest structure and composition influence the variability of below-ground carbon fluxes and content in tropical forests. Hence, a low AGC content in vegetation results in low BGC content (D’Andrea et al., 2020). A low number of individual woody species in addition to the Muhabura volcano's sharp slope and climatic factors might explain the low AGC and BGC found (Owiunji et al., 2005; Derhe et al., 2020).

Carbon stock in standing stamp of dead wood biomass

All strata showed a very low amount of carbon in standing stump of dead wood which might be due to woody species that are not closely and evenly distributed in a disturbed area (Ngiramahoro et al., 2018) and thus, therefore, a low contribution to the dead wood carbon pool. The results of this study are supported by the study of Paletto and Tosi (2010) showing that dead wood is an important component for conserving carbon stock and maintaining species diversity in forests. In natural forests, deadwood results from tree mortality caused by senescence processes or by tree competition, while in semi-natural and managed forests deadwood may be due to natural disturbances or human interventions (Lu et al., 2017; Woodall et al., 2019). Therefore, the presence or absence, variation in quantity structure, and function of deadwood in forest ecosystems change over time depending on natural disturbances (e.g., windstorms, forest fires, landslides, avalanches) and human interventions (e.g., thinning, selective cutting, clear cutting) applied under the priorities of forest management planning. These may determine the number of lags in the forest ecosystem leading to a given DWC content (Woodall et al., 2019).

Carbon stock in litter biomass

The findings on carbon stock in litter for both low and middle altitudes were recorded lower than the value cited in IPCC (2006) of about 49 t ha^{-1} for tropical forests. This might be attributed to young woody species, disturbance by fire or human activities, soil and climate in the study area, which caused little litter drop and made some deviation to the currently estimated result from a similar study conducted on other tropical forests (Ngiramahoro et al., 2018; Gebrewahid and Meressa, 2020). Leff et al. (2012) stated that the aboveground litter biomass in forests is likely to change due to changes in atmospheric carbon dioxide (CO_2) concentrations, temperatures, and rainfall patterns. Litterfall accumulation can be controlled by age and density of woody species, soil nutrient levels, species composition, quantity and quality of annual litter accumulation in combination with decomposition rate (Taylor et al., 2007; Sayer et al., 2011), human disturbances, and management history (Zhang and Wang, 2010). As litter fall represents a major flux of carbon from vegetation to soil, changes in litter inputs have direct consequences for soil carbon dynamics. According to Leff et al. (2012), the increase in aboveground litter production as a result of global climate change has the potential to cause considerable losses of soil carbon to the atmosphere in tropical forests. Physical characteristics of the atmosphere, sloppy tropical montane forest, and tropical storms are unlikely to decrease litterfall production, and canopy disturbance has large and lasting effects on carbon and nutrient cycling (Sayer et al., 2011). The physical and climatic condition of Muhabura volcano might be linked to low carbon stock in litter biomass.

Soil organic carbon

The findings of this study revealed a decrease in SOC with increased soil depths in all strata. Higher organic carbon content was observed at soil depth 0-30 cm compared to 30-60 cm. The higher organ carbon content in the top layer could be attributed to the rapid decomposition of forest litter in a favorable environment. This is supported by recent studies that have reported high SOC content in topsoil 0-20 cm (Dibaba et al., 2019), 0-25cm (Parras –Alcantara et al., 2015), 0-30cm (Shedayi et al., 2016). The results showed as well that SOC content decreased from low to middle altitude and then increased at high altitude. The higher SOC stock found in low altitudes might be due to the type of woody species and vegetation found in this altitudinal range and the frequent addition of litterfall (Chimdessa et al., 2023). Soil organic matter can also increase or decrease depending on numerous factors, including climate (Von Fromm et al., 2021), altitudinal and topographic variation (Chinasho et al., 2015), vegetation types (Gachhadar et al., 2022), nutrient availability, and soil types (Bukombe et al., 2022), disturbance, and management practice (Mayer et al., 2020; Nave et al., 2022). Though no woody species (DBH >5) in high altitudes were recorded, it had higher mean SOC content than at middle altitudes. This might be due to silt or silty clay, the carbon-rich soils resulting from a fire outbreak that burned almost all vegetation mainly the high altitude in the eastern part of Muhabura volcano slopes (Ngiramahoro et al., 2018). Decreasing SOC along high altitudes (±3000 m a.s.l) can be attributed to a considerable decrease in temperature and low decomposition rate (Shedayi et al., 2016). This is the same altitudinal range of middle altitude (2863-3112) of Muhabura volcano.

This study revealed a strong correlation between DWC and AGB, BGC, and LC. These correlations highlight how change in one carbon pool can impact others. Meng et al. (2021), revealed a critical linear relationship between above-ground biomass and below-ground biomass, signifying that the increase in above-ground biomass results definitely in an increase in below-ground biomass in the forest ecosystem. The process of deadwood decomposition enhances the release of nutrients into the soil, thereby encouraging the development of aboveground biomass (Yuan et al., 2018). Fallen small branches and leaves (litter) are decomposed to make soil organic carbon. From this process, soil fertility is maintained which plays a significant role in plant growth, affecting in return above-ground and below-ground biomass. The interaction between SOC and LC is a key component of the carbon cycle in tropical rainforest ecosystems (Salunkhe et al., 2018). However, the disturbance of the ecosystem by anthropogenic activities such as logging, land use, and deforestation can lead to a reduction in carbon stock capacity (Lu et al., 2017). The regime of disturbances such as bushfires and landslides can also impact the correlation between other carbon pools and soil organic carbon by changing the balance between the inputs and outputs of carbon (Dibaba et al., 2019). This is in line with a negative weak correlation estimated between SOC and LC, DWC, AGC, and BGC can be linked as well to the high disturbance of the study area by bushfires, human activities, and climatic conditions (Ngiramahoro et al., 2018).

Total carbon stocks

In the three altitudinal levels studied, low altitude showed high total carbon stock and the lowest total carbon stock was found in the high altitude. Numerous factors can be attributed to such findings such as climate and temperature. The lower altitude zones of the mountain present a warmer temperature which enhances the growth of vegetation and the continuous production of biomass. This results in sequestration of the large amounts of carbon in above and below-ground biomass (Cuni-Sanchez, 2021). Soils in lower elevations are more fertile attributed to the runoff from the higher altitude, leading to continuous accumulation of nutrients. This serves as a support for the robust growth of plants and enormous carbon accumulation in the soil (Solomon et al., 2024). Low elevations tend to hold more dense and diverse vegetation in forest ecosystems explained by the fact that the variability of plant species plays an important role in storing high amounts of carbon in their biomass (Tura et al., 2013; Solomon et al., 2024). Ahmed and Lemessa (2024) revealed that lower altitude areas of the Afromontane zone present often water availability that promotes the production of plant growth and biomass production which in return contributes to higher carbon storage. Moreover, in the protected areas, due to conservation interventions, lower altitudes areas can present large amounts of carbon storage attributed to effective conservation (Ahmed and Lemessa, 2024).

The results showed that the largest total carbon pool in all three strata was the total SOC pool contributing to sequestering the highest amount of carbon (Tsozue et al., 2019). According to Sheikh et al. (2009), about 40% of the total SOC stock of the global soils resides in forest ecosystems and is considered as the largest pool of terrestrial organic carbon, soils interact strongly with atmospheric composition, climate, and land cover change. In this study, despite recording zero number of woody species in the high altitude, it also presented a mean SOC due to grasses, herbs, and mosses, and typical volcanic soil rich in organic matter after the fire outbreak (Owiunji et al., 2005; Shedayi et al, 2016). This may also be attributed to longer vegetative growing periods at high altitudes without human interference than at low altitudes (Ngiramahoro et al., 2018; Tsozue et al., 2019; Derhe et al., 2020).

CONCLUSION AND RECOMMENDATION

The study revealed the variation of carbon stocks of woody species along the altitudinal gradient of Muhabura volcano. However, in altitudinal gradients, some estimated carbon pools were low compared to standards, attributed to the low number of individual woody species recorded resulting in reduced biomass and the overall Muhabura Volcano's carbon sequestration potential. Therefore, the protection of Muhabura volcano by supporting its carbon stock through assisting woody species regeneration has to be the center of attention in integrating the maintenance of the mountain to meet the objectives of both conservation and climate change mitigation. The results also provided information for future researchers, managers, and policymakers for developing and implementing management policies and plans for Muhabura volcano ecosystem. Policies should be implemented to take advantage of its carbon sequestration for probable carbon marketing to boost the overall management of Muhabura Volcano and Volcanoes National Park in general. This aligns with Rwanda's vision for 2015-2030 in its 2020 updated Nationally Determined Contribution (NDC) target of mitigation by sequestering a large amount of CO_2 through proper natural forest conservation and management. The reduction of emissions from deforestation and forest degradation by properly managing and sustainably utilizing the existing flora at Muhabura Volcano and Volcanoes National Park in general, may continue to bring financial and technical incentives from industrialized nations to Rwanda through REDD+ and other climate funds. Moreover, further studies with accurate and consistent data that meet international standards, are highly needed to obtain data for deriving benefits from climate funds and drawing national environmental policies related to climate change mitigation and adaptation.

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