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Altitudinal changes in the floral diversity and carbon stock of a tropical montane forest in Cameroon

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Tropical montane forests (TMF) are under threat, as climate change is affecting their species composition and diversity in various ways across altitudinal gradients. This study aimed to assess the floral diversity and carbon biomass stored by the different components of the forests along an altitudinal gradient of the Mount Cameroon National Park. Three hectares of 1ha each were established at three different altitudes of the montane forest. Plot demarcation followed the standard protocol for permanent monitoring plots, where each 1ha was divided into 400, 5 × 5 m², and the names of all plants from a DBH of ≥ 2 cm. There was a total of 1101 individuals, 45 species, and 28 families. The most important species and family were *Syzygium rowlandii* and Fabaceae, respectively. The structure of the forest indicated a reverse J-shape with more individuals in the 5 to 10 cm range. The above-ground, below-ground, and soil organic matter indicated similar patterns of bell-shaped due to the high density of large trees in the sub-montane forest with better environmental conditions for the growth of tree life forms. Total carbon stock for the montane forest was 791.92 ha⁻¹, which sequestered 2906.46 tCO₂ ha⁻¹. Thus, the need to compartmentalize TMF for carbon dynamic research.

Key words: Above ground biomass, biomass, sequestration, stem diameter, structure.

INTRODUCTION

Mountain ecosystems account for approximately one-fifth of the Earth's land surface (Tsering et al., 2010; Price et al., 2011) and tropical mountain forests represent about 11 % of tropical forests over the world (Doumenge et al., 1995). Tropical montane forests (TMF) are ecosystems with high species diversity (Báez et al., 2011) and are often biodiversity hotspots (Price et al., 2011; Admassu et al., 2016); with a heterogeneous floristic composition and

structure (De la Cruz-Amo et al., 2020). TMF are therefore important for the long-term provision of ecosystem goods and services (Werner and Homeier, 2015). These vital ecosystem services are, however, under threat, as climate change is undoubtedly affecting their species composition and metabolic profiles in a myriad of ways. Knowledge of the floristic composition and structure change of a montane forest through its altitudinal gradients is of importance of

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a continuous provision of ecosystem goods and services.

The Mount Cameroon National Park (MCNP) is part of the Cameroon Mountains, which is a chain of volcanic and plutonic isolated mountains covering 40.88 km² (Sainge, 2016). This region ranks high among the biodiversity hotspots in the upper and lower Guinea forest; and is thus considered to be of global conservation importance (Myers et al., 2000; Barthlott et al., 2005; Onana, 2013; Marchese, 2015). The Mount Cameroon massif is the only remaining area in Africa where natural vegetation rises uninterrupted from lowland forest at sea level to subalpine grassland at the summit (Forboseh et al., 2011). There are no strict endemic plants at the upper extent of Mount Cameroon (3500 to 4095 m); however, Cable and Cheek (1998) listed a total of 49 endemics for the massif, of which 20 are montane species. Though studies on the TMF have received much attention globally, this subject remains little studied in the Cameroon Mountains.

Several studies have been carried out on the tropical montane forest zone along the continental part of the Cameroon Volcanic Line (Ayonghe et al., 1999; Marzoli et al., 2000; Sainge et al., 2017), where few studies have assessed the forest structure and composition along elevational gradients using permanent sampling plots (Sunderland et al., 2003; Mbatchou, 2004; Gonmadje et al., 2011; Sainge, 2016). However, most of these studies were based on general plant collection methods (Thomas, 1996, 1997; Cheek et al., 2000) without determining the variation of these collections across altitudinal gradients. Some studies have examined changes in species composition and diversity across environmental and geographic gradients (Gentry, 1988; Imani et al., 2016), but vegetation structure and composition are also influenced strongly by altitude (Richter, 2008; Imani et al., 2016).

Vegetation systems at different altitudes on different substrates in montane ecosystems differ in biomass production, carbon storage and biodiversity conservation value (Pickering and Green, 2009; Chain-Guadarrama et al., 2012), as it regulates several abiotic factors that control the observed vegetation patterns and the ecology of mountain forests. Several authors have indicated that diversity declines with increasing altitude (Richards, 1979; Lieberman et al., 1996; Givnish, 1999). This fits with standard ecological theory on diversity and environmental gradients in that temperature declines with elevation, leading to a lowering of productivity and biotic interaction. However, the pattern is not uniform as the mid-latitudes might have more individuals than the lower altitudes, whose vegetation has been destroyed by anthropogenic activities. This distribution is in accordance with a null model which predicts species diversity to peak at intermediate parts of gradients because of overlapping ranges of species distributions which are bound by the ends of the gradient (Kessler, 2001; Lomolino, 2001; Rahbek, 2005). This has been the case with the Buea cluster of the Mount Cameroon National Park (MCNP)

(Mokake et al., 2025) calling for site-specific investigations on the other clusters of the MCNP to confirm this theory.

Although the relationship between species richness and altitude has been shown to be a function of the vegetation life form studied (Akhtar and Bergmeier, 2015; Zhang et al., 2016), variation of plant species richness in TMF has been studied focusing mainly on trees with a diameter at breast height (DBH) ≥ 10 cm (Imani et al., 2016; Cirimwami et al., 2017; Gonmadje et al., 2017; Sainge et al., 2019) albeit the fact that the floristic richness of tropical forests is highly related to other lifeforms such as shrubs, lianas and herbaceous species (Busmann, 2001; Tchouto et al., 2006). The MCNP is an area of dense forest and shrubs threatened by agricultural land use practices in the area (Tegha and Sendze, 2016). The natural vegetation of this area ranges from evergreen lowland rainforest at sea level, through montane forest, to montane grassland and alpine grassland near its summit, making it have a very diverse lifeform (Ministere des Forets et de la Faune [MINFOP], 2014). Few studies compared the elevational variation in diversity and composition of various plant lifeforms, from herbs to trees in the mountains of tropical Africa (Woldu et al., 1989; Hemp, 2006; Fischer et al., 2011) in general and Cameroon in particular. Knowledge of plant lifeforms in the <10 cm size-class, which ensures the regeneration of the forest ecosystems and constitutes the main life form in the higher altitudes, is key for conservation as well as Reducing Emissions from Deforestation and Forest Degradation+ (REDD+) strategies in a context of climate change (Malhi et al., 2010; Malhi and Marthews, 2013) as several components of REDD+, such as the above ground biomass are influenced by the species richness of studied sites (Gonmadje et al., 2017; Imani et al., 2017).

Tropical forests play a key role in climate change mitigation by sequestering and storing carbon from the atmosphere (Siraj, 2019). African forests constitute 21% of the global total carbon stock of forest biomass and can sequester up to 630 kg C ha⁻¹ year⁻¹, thereby providing a critical shock absorber against global climate change (Food and Agriculture Organization United Nations [FAO], 2010; Abere et al., 2017). However, patterns of spatial variation in carbon stocks remain poorly understood and scarce in the 880,000 km² of TMF located $\geq 1,000$ m above sea level (masl) (Spracklen and Righelato, 2014). Also, Carbon stocks can vary within sites in the soil, litter, above ground, and below-ground. Worldwide soil organic carbon (SOC) in the top 1 m of the soil comprises about 80% of the earth's terrestrial Carbon (Lal, 2008). Carbon stock for aboveground biomass is typically derived by assuming that 50% of the biomass is made up of carbon (Basuki et al., 2009) using allometric equations. Litter stock was reported to be a small fraction of the total carbon stocks, where Heath et al. (2002) reported that only 8% of the total C is in the forest floor fraction. Carbon stocks can thus vary based on the component due to the dynamic structure of the tropical forests. Hence, determination of the carbon

stock in the various components of the forests, within sites across altitudinal gradients, is important to monitor carbon stocks and cycling to calibrate global carbon cycle models and to support frameworks such as the United Nation's REDD+ program (Ngo et al., 2013), especially as there is no specific AGC default value for old-growth Montane Forests (MF) in Africa in the most recent Inter-governmental Panel on Climate Change (IPCC) guidelines.

In Cameroon, very few ecological studies have been carried out to date to estimate biomass and carbon according to altitude gradation (Sainge et al., 2020), with some authors indicating that carbon stock decreased with altitude (Gonmadje et al., 2017; Fogaing et al., 2021). Mokake et al. (2025), however, indicated a higher above-ground biomass in the mid altitudes than in the lower altitudes of the Buea cluster of the MCNP. This controversy of where biomass is highest along an altitude gradient does not give a complete idea of the quantities of biomass available in the different carbon pools at different altitudes of its TMF for a better representation at the national level. Thus, this study hypothesized that there is a spatial variation in the floral diversity and carbon stock along the altitude gradients. The aim of this study was, therefore, to assess the floral diversity and carbon biomass stored by the different components of the forests along an altitude gradient at the West coast cluster of the MCNP. Specifically, it can be determined:

- 1) Floristic composition of the three communities;
- 2) Stand structure of the montane forest;
- 3) Carbon stock of the various components of the West coast cluster of the MCNP which is a biological hotspot.

MATERIALS AND METHODS

Study site

The MCNP lies on the coast, in the Gulf of Guinea, between 3°57' to 4°27' N and 8°58' to 9°24' E. It is a huge volcanic mass, with its long axis (about 45 km long and 30 km wide) running from the SW to the NE; and the main peak is at 4°7'N, 9°10'E, at 4,100 m. Soils on Mount Cameroon are principally of recent origin, mostly on young and older tertiary volcanic rocks, and are relatively fertile but often with poor water retention capacity (Payton, 1993). The Mount Cameroon area has an equatorial climate of four seasons: the dry season runs from December to February, dry to wet season from March to May, wet season from June to August and wet to dry season from September to November. The temperature falls with increasing elevation. For each 100 m ascent, the average temperature drops by about 0.6°C. The temperature on the top of Mount Cameroon is typically a chilly 4°C; while in Limbe at the base, it is 32°C. Payton (1993) pointed out that the humidity remains at 75 to 85% due to the marine influence and the incidence of mist and orographic cloud formation. Mean annual rainfall decreases with altitude to approximately 4,000 mm year⁻¹ at 1000 mm and to less than 3,000 mm year⁻¹, above 2,000 m (Payton, 1993). Despite the abundant precipitation, the Mount Cameroon area is characterized by a low hydrological network, with several rivers, seasonal and permanent streams, springs, lakes and waterfalls (Ako et al., 2012). The MCNP is spatially divided into four

cluster conservation zones which comprise 41 villages. The Buea Cluster in the South and parts of the East consists of 13 villages; the Bomboko Cluster in the Northeast and Northwest areas of the park consists of 12 villages; the Muyuka Cluster, occupying the East consists of 9 villages, and the West coast cluster consists of 7 villages (MINFOF, 2010).

This study was carried out in the West coast cluster (Limbe and Idenau) of the western slope, specifically in the Njonji-Bakingili stretch of the mountain and the Etome-Bakingili forest cover (Figure 1). This is because the western slope of Mount Cameroon is probably the most diverse and richest area of the mountain and appears to be the only area in West and Central Africa where there is an unbroken vegetation gradient from evergreen lowland rainforest at sea-level, through montane forest, to montane grassland and alpine grassland near its summit. At least 2300 species of plants in more than 800 genera and 210 families have been recorded. Out of these, 49 species are strictly endemic and 50 are near-endemic plant species. *Prunus africana*, which occurs in the montane and submontane vegetation type, is the only plant species considered threatened because of overexploitation. The area is currently being threatened by increasing human populations, but it is the most diverse ecosystem in Cameroon and is presented as the 10th most conservable places in the world (International Union for Conservation of Nature [IUCN], 1994).

Data collection

Plot demarcation and plant enumeration

Three plots of 1 ha each (100 m × 100 m) were laid at different altitudes of the MF of the MCNP, giving a total surface area of 30,000 m² (3 ha) surveyed. Plot demarcation followed the standard protocol for permanent monitoring plots described by Condit (1998) where each 1 ha was divided into 25 quadrats of 20 × 20 m² and each 20 × 20 m² was further divided into 16 sub-quadrats of 5 × 5 m², where sampling was carried out. Altitudinal gradient for plot establishment varied between 0 and 800 m asl as tropical lowland forest (TLF) (Plot 1); 800 to 1600 m asl as Sub Montane Forest (SMF) (Plot 2); and 1600 to 2400 m asl as Montane Forest (MF) (Plot 3). All plant species with a DBH ≥ 2 cm were identified by their scientific name, vernacular, and/or commercial names. For each plant species, the DBH was measured at 1.30 m and 0.3 m above the buttresses. The specimens were further identified at the Limbe Botanical Garden Herbarium by comparing and matching specimens with existing herbarium collections and available flora and monographs. Plant classification followed species lists in the Angiosperm Phylogeny Group (APG III, 2009).

Determination of stand characteristics

Determination of the stand composition of the west coast cluster of the MCNP

The absolute density and the species richness were used to determine the stand composition. The absolute density was determined as the number of individuals in each species in the different plots according to Mueller-Dombois and Ellenberg (1974). Species richness (S) was the total number of species per plot present in the population according to Ramade (2003). The absolute density and species richness were used as evidence in assessing the ecological importance of a species and family through the Importance Value Index (IVI), and Family Importance Value (FIV). The Importance Value Index (IVI) was determined according to Curtis and McIntosh (1950) using the formula:

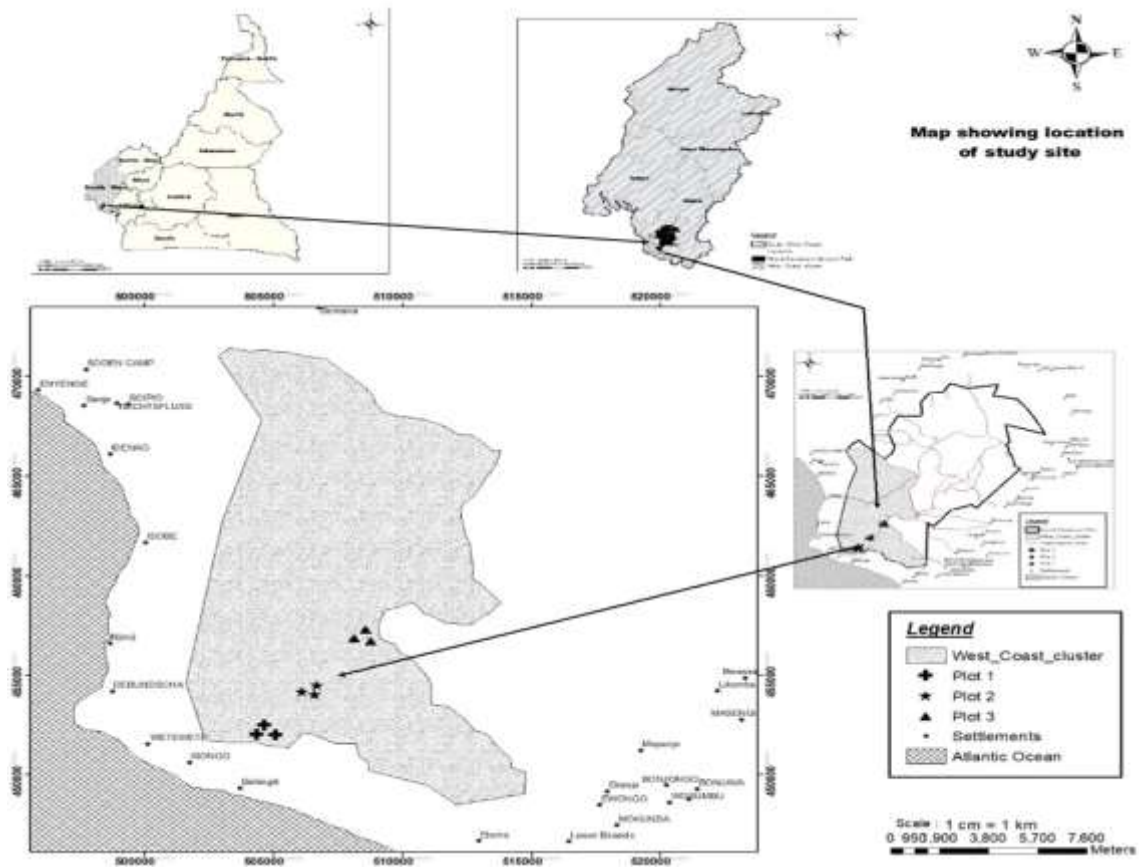


Figure 1. Map of the Mount Cameroon National Park's West Coast Cluster.
Source: MINFOF (2010).

$$IVI = SRDe + SRDo + SRF \quad (1)$$

where SRDe is the species relative density, SRDo is the species relative dominance, and SRF is the species relative frequency.

The family importance value Index (FIV) (Mori et al., 1983) was determined as:

$$FRDe + FRF + FRDo \quad (2)$$

where FRDe is the family relative density, FRDo is the family relative dominance and FRF is the family relative frequency.

In calculating the diversity, only species that were identified to the species level were considered. The species diversity was determined by the Shannon diversity and the Fisher-alpha diversity indices. Shannon diversity was determined as described by Shannon (1949).

$$H = -1 \left(\sum p_i \times \ln p_i \right) \quad (3)$$

where, p_i is the proportion of individuals belonging to the i species in the data set.

Fisher's alpha diversity described by Fisher et al. (1943) was determined as:

$$S = \alpha \times \ln(1 + n/\alpha) \quad (4)$$

where S is number of taxa, n is number of individuals and α is the

Fisher's alpha.

Species evenness which reflects the dominance of species was calculated using the Pielou's evenness index according to Pielou (1969):

$$J' = H/H'_{\max} \quad (5)$$

where H is the observed Shannon diversity and $H'_{\max}$ is the maximum possible Shannon Index.

Sørensen's quantitative index was used to determine floristic similarity within and between the forest stands:

$$S = 2C/A+B \quad (6)$$

where C is the number of species that are common in both plots; while A is the species in A , and B is the number of species in B .

Determination of the stand structure of the west coast cluster of the MCNP

The forest structure was expressed through the relative density, basal area and the number of individuals in each diameter size class. The relative density corresponds to the number of individuals on a given surface area; and this was calculated by dividing the number of trees by the surface area of the sample. The basal area

corresponds to the surface area of all the cross-sections of the trunks, at a height of 1.30 m of the trees present in one hectare of forest (Newton, 2007). It is expressed as:

$$BA = (\pi D^2)/4 \quad (7)$$

where BA = basal area (m²), D = stem diameter at breast height (cm) and π = pi (3.142).

Size-class distribution was determined by the DBH size classes, where stems of a DBH range of 5 cm were grouped together in different diameter size classes. These DBH size classes were: <5 cm; >5 to 10 cm; >10 to 20 cm; >20 to 30 cm; >30 to 40 cm; >40 to 50 cm; >50 to 60 cm; >60 to 70 cm; >70 to 80 cm; and >80 cm.

Determination of carbon stock of the west coast cluster of the MCNP

Estimation of above-ground biomass carbon stock (ABC)

The diameter of all plant trees was used to estimate the above-ground biomass (AGB) of the trees inventoried according to Chave et al. (2005):

$$AGB(kg) = \rho * \exp(-1.239 + 1.980 \ln(D)) + 0.207 (\ln(D))^2 - 0.0281 (\ln(D))^3 \quad (8)$$

where D = diameter at breast height in centimeters, ρ = specific wood density. For species without wood densities, an average for the genus or family was used.

The AGB was used to determine the ABC according to Zapfack et al. (2013):

$$ABC = AGB \times 0.47 \quad (9)$$

Estimation of the below-ground biomass carbon (BBC)

The below-ground biomass (BGB) was determined according to Mokany et al. (2006):

$$Y = 0.235 \times AGB \text{ if } AGBC > 62.5 \text{ t C ha}^{-1}$$

$$Y = 0.205 \times AGB \text{ if } AGBC \leq 62.5 \text{ t C ha}^{-1} \quad (10)$$

The BBC was determined, according to Zapfack et al. (2013):

$$BBC = BGB \times 0.47 \quad (11)$$

Estimation of the litter biomass carbon stock (LBC)

Within each 5 m × 5 m quadrat, sub-quadrats of 1 m × 1 m were randomly established for the collection of litter biomass (dry leaves and twigs), and the litter samples were bulked for each plot. Each collected sample was labeled and transported to the University of Buea's Plant Biology Laboratory. The samples were then weighed (W1) using an electronic scale (HiWEIGH, China) to obtain their masses and oven-dried at 105 °C to constant weight (W2). Litter dry weight was determined as described by Timothy et al. (2007):

$$L = \frac{\text{Total Dry Weight (m.sq)} \times 0.5}{\text{Surface area (m.sq)}} \quad (12)$$

where the total dry weight was obtained from W1 to W2.

Estimation of the soil organic carbon (SOC)

Soil samples were collected randomly from each 5 × 5 cm quadrat at the following soil depths of 0 to 10 cm, 10 to 20 cm and 20 to 30 cm. Samples from each soil depth were bulked together to make one representative sample. A soil auger (Alfairaq, Iraq) was used for each sample collection which was enclosed in a polythene bag and later analyzed in the Life sciences laboratory of the University of Buea. The bulk density was determined by using a soil corer carefully driven into the soil as described by Roshetko et al. (2002). Fifty representative samples were collected for bulk density, and a total of 200 samples were analyzed for SOC. Samples were air-dried for a day in a cool environment to prevent oxidation; sieved using a 2 mm sieve and weighed with an electronic scale to obtain weight (W1). Later, samples were oven-dried at 105°C for 2 days to get the dry weight (W2) and then ashed at 500°C for 5 h to get the percentage of carbon in the samples. The SOC was determined as described by FAO (2019) as follows:

$$SOC = d \times \%C \times BD \quad (13)$$

$$BD = W2 / V \text{ (g.cm}^{-3}\text{)} \quad (14)$$

where d = depth of soil; %C = percentage of carbon; BD = bulk density (kg/ha), and V = volume of core ($\pi r^2 h$); W2= weight of oven-dry sample.

Estimation of the total carbon stock

The total biomass and carbon stock accumulation of the MCNP's Buea Cluster was calculated by summing the biomass and carbon stock of the different pools:

$$C(\text{plot}) = ABC + BBC + LBC + SOC \quad (15)$$

where C(plot) = total carbon content in the plot (tonnes ha⁻¹), ABC = aboveground biomass carbon stock (tonnes ha⁻¹), BBC = belowground biomass carbon stock (tonnes ha⁻¹), LBC= litter biomass carbon stock (tonnes/ha) SOC= soil organic Carbon (tonnes ha⁻¹).

Estimation of the carbon sequestration

Estimation of the carbon sequestration potential of the different carbon pools was calculated according to IPCC (2003) and Pearson et al. (2007):

$$CO_2^e = TCS \times 3.67 \quad (16)$$

where CO_2^e = carbon dioxide equivalent or weight; TSC = total carbon stock and 44/12 (3.67) = ratio of molecular weight of CO_2 to carbon, t CO_2^e t C⁻¹.

Statistical analysis

The collected data were exported to other packages for statistical analysis and graphics. MINITAB was used to produce charts and to run one-way analysis of variance (ANOVA), which was performed after the test of Levene's test of homogeneity of variance to compare the means between plots. The Kolmogorov-Smirnov test was used

Table 1. Tree density and species richness of the west coast of the MCNP.

Plots (ha ⁻¹)	Absolute density (Individuals ha ⁻¹)	Species richness (S ha ⁻¹)	Families (ha ⁻¹)
TLF	555	79	37
SMF	330	67	36
MF	216	14	11
Total per 3 ha	1101	45	28
Mean ha ⁻¹	367	-	-

Figures in bold indicate the highest value in the column. No mean data (dash) is presented for the (S/ha) and Families ha⁻¹ because the same species or family might appear twice.

Table 2. The most important species and families across the altitude gradient in the MCNP.

Plots	Species	IVI (%)	Families	FIV (%)
TLF	<i>Diogoia zenkera</i> (Engl.) Exell and Mendonca	6.79	Meliaceae	37.80
	<i>Rinorea dentata</i> (P. Beauv.) kuntze	6.71	Myristicaceae	33.36
	<i>Trichilia rubescens</i> Oliv.	6.33	Oleaceae	33.11
	<i>Pycnanthus angolensis</i> (L)	5.61	Fabaceae	31.43
SMF	<i>Berlinia bractoesa</i> (Sol.ex Hook.f. and Benth)	15.49	Fabaceae	51.34
	<i>Strombosia grandifolia</i> (Hook.f. ex Benth)	5.78	Olacaceae	36.92
	<i>Rinorea oblongifolia</i> (C.H.Wright) Marquand ex Chipp	5.13	Violaceae	28.31
	<i>Distemonanthus benthamianus</i> Baill.	4.72	Malvaceae	23.50
MF	<i>Syzygium rowlandii</i> Sprague	16.63	Apocynaceae	49.55
	<i>Rauwolfia vomitoria</i> (Afzel)	16.13	Myrtaceae	48.70
	<i>Clausena anisata</i> (Wild) Hook.f. ex Benth.	15.80	Rutaceae	48.66
	<i>Allophylus africanus</i> P. Beauv.	8.88	Sapindaceae	30.26

Figures in bold indicate the highest values.

to test if the data was normally distributed. The Tukey's honest significant difference test was used to separate means of aboveground biomass and carbon stock which differed from one another. Paleontological Statistics (PAST) was used to calculate Fisher's alpha diversity, Shannon's diversity and species evenness, and Sørensen's similarity indices between plots. The Kruskal-Wallis's test, suitable for non-parametric data, was also used to determine the level of significance between soil organic carbon and soil bulk density at different soil depths.

RESULTS

Floristic composition and diversity of the west coast of the MCNP

The three sampled plots had a total of 1101 individuals, 45 species and 28 families. Generally, there was a decrease in the absolute density of individuals with an increase in altitude. The Tropical lowland forest (TLF) had the highest absolute density of 555 individuals ha⁻¹ while the least was found in the MF with 216 individuals ha⁻¹ (Table 1). The

number of families and genera followed the same trend with the highest in TLF and the least in the MF (Table 1).

The most important species in the whole study was *Syzygium rowlandii* in the MF (16.63%). Specifically, the most important species were *Diogoia zenkera* (6.79%) in the TLF, *Berlinia bractoesa* (15.49%) the in SMF and *S. rowlandii* (16.63%) in the MF (Table 2). Generally, the most important family was Fabaceae (51.34). Specifically, the most important families were Meliaceae (37.80 %) in the TLF, Fabaceae (51.34%) in the SMF and Apocynaceae (49.55%) in the MF (Table 2). The five most common species in the whole study were *Rinorea dentata* (64 individuals), *Rauwolfia vomitoria* (52 individuals), *Distemonanthus benthamianus* (51 individuals), *Clausena anisata* (49 individuals), *Diogoia zenkera* (48 individuals). Shannon diversity and the evenness indicated that the SMF was the most diverse (3.6) and even (0.59) plot while the least diverse (2.1) was in MF and evenness (0.40) in the TLF (Table 3). The results also indicated that the SMF and MF were most similar. Table 4 indicates the medicinal and commercial plants that were found in the sampled

Table 3. Floral diversity and evenness across altitude gradient in the MCNP.

Plots	Species richness	Species richness	Species evenness	Sorenson's similarity (%)
TLF	79	79	0.40	--
SMF	67	67	0.59	0.59
MF	14	14	0.58	0.58

Figures in bold indicate the highest values. -- indicates no data for TLF because it has been compared with other data.

plots with the presence of the species *Prunus africana* which is endemic to this site.

Stand structure of the west coast cluster of the MCNP

The DBH size-class distribution showed a reverse J-shape pattern indicated by the fact that there were more individuals in the ≤ 10 cm DBH size-classes across altitudes. However, there was an initial decrease in the number of individuals of the DBH size-class of 0 to 5 cm in the TLF and MF. The DBH size-class with the least number of individuals were in the DBH size-class of 65 to 70 cm in the SMF and MF and in the 60 to 65 DBH size-class in the SMF. However, there were more individuals in the ≥ 70 cm DBH size-class in the SMF. The individuals in the ≤ 10 cm, however, did not make up to half of the mean DBH number of individuals (Figure 2). The mean and total basal area were 17.13 and 51.38 m² ha⁻¹. The basal area was 20.81, 22.03, and 8.54 m² ha⁻¹ in the TLF, SMF and MF, respectively.

The carbon stock across altitude gradients in the MCNP

The aboveground biomass (AGB) and its corresponding carbon stock (ABC) were significantly different across altitudes ($p < 0.05$) with a mean above ground biomass of 638.5 t ha⁻¹. The results of this study indicated a bell-shape pattern where there is initially an increase in AGB with altitude and later a decrease. Thus, the mean AGB was highest in the SMF (936.0 ± 178.0 t ha⁻¹) and least in the TLF (450.6 ± 53.9 t ha⁻¹) (Table 5). Similarly, the mean AGB carbon stock (ABC) was highest in the SMF (468.0 ± 89.0 t ha⁻¹) and least in the LMF (225 ± 26.9 t ha⁻¹) (Table 6).

The below ground biomass (BGB) and its corresponding Carbon stock (BBC) were significantly different across altitudes ($p < 0.05$) with a mean of 150.06 t ha⁻¹. Specifically, the highest BGB was found in the SMF (219.96 t ha⁻¹), and the least was in LMF (105.89 t ha⁻¹) (Table 5). Similarly, its BBC was highest in the SMF (109.98 t ha⁻¹) and least in the LMF (52.95 t ha⁻¹) (Table 6). The mean dry weight of litter was 0.19 kg ha⁻¹, and its carbon stock was 0.09 ± 0.06

t ha⁻¹. The highest dry weight of litter was in TLF (0.22 ± 0.07 t ha⁻¹) while the least was in the MF (0.17 ± 0.03 t ha⁻¹) (Table 5). Similarly, the carbon stock was highest in TLF (0.11 ± 0.04 t ha⁻¹) and least in the MF (0.08 ± 0.15 t ha⁻¹) (Table 6). The SOC was significantly different ($p < 0.05$) across altitudes. The mean SOC was 3.27 t ha⁻¹, with the highest in the SMF (3.91 t ha⁻¹) and least in the TLF (2.91 t ha⁻¹) (Table 6). The total mean carbon stock from the ABC, BBC, LBC and the SOC for the West coast cluster of the MCNP is presented in Table 6. The total Carbon stock was:

$$\begin{aligned} C(\text{plot}) &= C(\text{ABC}) + C(\text{BBC}) + C(\text{LBS}) + C(\text{SOC}) \\ &= 638.5 + 150.06 + 0.09 + 3.27 = 791.92 \text{ t ha}^{-1} \end{aligned}$$

The AGB comprised 80.63%, BBC 18.95%, leaf litter biomass comprised 0.01%, and soil organic matter comprised 0.4% carbon within their biomass. The largest stocks were, therefore, observed in aboveground biomass followed by BBC, soil carbon pool and lastly leaf litter biomass carbon. The mean carbon that can be sequestered in the West coast cluster of the MCNP was 2906.46 CO₂ ha⁻¹ with the highest in the SMF (4257.05 CO₂ ha⁻¹) and the least in the TLF (2408.95 CO₂ ha⁻¹) (Table 7).

DISCUSSION

Stand composition across altitudinal gradients of a MF

The effect of altitude on the vegetation of the west coast cluster of the MCNP influenced the composition, structure and diversity of the forest across an altitudinal range of 0 to 2400 m asl. There were 1,101 individuals, 45 species and 28 families in this study site, a result like that of Jadán et al. (2021) in the montane forest of Ecuador, who had 1,230 stems from trees ≥ 10 cm DBH, belonging to 34 families, 51 genera and 83 species. It is also like the report of Jeyanny et al. (2014) who reported 1,300 trees ha⁻¹ in a Malaysian forest reserve.

Overall, the tropical lowland forest was characterized by a higher number of individuals, while there was a decrease in plant absolute density with increased altitude. Similar

Table 4. Medicinal Plants in the MCNP.

Medicinal plant species	Family	Medicinal uses
<i>Prunus africana</i> (Hook.f.) Kalkman	Rosaceae	Treatment of prostate cancer
<i>Voacanga psilocalyx</i> Pierre ex Stapf.	Apocynaceae	Extract used for the treatment of leukemia
<i>Cola acuminata</i> (P. Beauv.) Schott and Endl.	Malvaceae	Treatment of dysentery, diarrhea and fatigue relief
<i>Rauvolfia vomitoria</i> Afzel.	Apocynaceae	Used for the treatment of diarrhea, jaundice, snake bites, fever, epilepsy and lower blood pressure
<i>Maesa lanceolata</i> Forssk.	Primulaceae	Treatment of pains against bacterial infections
Commercial plant species		Common name
<i>Milicia excelsa</i> (Welw.) C.C. Berg	Moraceae	*Iroko
<i>Diospyros gabonensis</i> (Gürke)	Ebenaceae	Ebene
<i>Entandrophragma angolensis</i> (Welw.) C. DC.	Meliaceae	*Tiama
<i>Distemonanthus benthamianus</i> Baill.	Fabaceae	Ilomba
<i>Piptadeniastrum africanum</i> (Hook.f.) Brenan	Fabaceae	*Dabema

The asterisk (*) indicates the most exploitable timber species according to ITTO (2020).

results were obtained by Sainge et al. (2019) in the Rumpi Hills Forest Reserve (RHFR), which is part of the Cameroon Mountains and associated highland biomes (Burgess et al., 2007; Cronin et al., 2014). As altitudes increase, increased cloudiness and humidity occur where condensation processes are heightened during uplift (Hafkenscheid, 2000). This influences the soil and air temperatures, portraying cooler climates in the MF than in the lowland forests, thus determining the type of plants species that will thrive in that condition. The distributions of plant species along the altitudinal transect thus support the individualistic hypothesis of community organization, which posits that the distribution of each species is determined by its own ability to survive, compete and reproduce successfully in different environments resulting in each species having its own distinctive distribution and in community composition changes continuously along ecological gradients. Also, in the MCNP, grassland vegetation begins at 2000 m

asl (Richards, 1963), as the montane community on Mount Cameroon is poorly developed with a discontinuous low canopy of shrubs (Richards, 1963; Thomas and Achoundong, 1994). The montane forest is much drier and receives lower rainfall than the submontane and lowland forests; and consequently, very prone to damage by fire that occurs both naturally (lightning and volcanic activity) and deliberately (hunters setting fires to flush out game) in the grassland savanna. The number of individuals in the SMF, however, was low when compared to a similar study in the western slopes of Cameroon, where 4,837 individuals were inventoried, belonging to 168 species, 131 genera and 61 families in the submontane altitude (Tiokeng et al., 2025). This could be due to the variation of the agro-ecological zone and human disturbances of the study sites as the western slopes are found in the grassland agroecological zone of Cameroon which is made up of mostly shrubs and small trees. Similarly, the

species richness displayed a monotonic decrease of woody lifeforms with increasing elevation, especially between 810 and 2760 m asl in the MCNP. This is consistent with results obtained in many studies (Richards, 1963; Payton, 1993; Gentry, 1995; Peguy et al., 1999; Forboseh et al., 2011; Chuyong et al., 2011). Specifically, Cirimwami et al. (2019) in the montane forests of the Kahuzi-Biega National Park (KBNP), in the Democratic Republic of the Congo and Sanjeewani et al. (2024) in Sri Lanka indicated that the numbers of species, genera and families decreased linearly with increasing altitude across a wide altitudinal gradient. These decreases indicate that environmental constraints at higher altitudes imposed a limitation on the colonization of tree species like eco-physiological constraints, such as the drop-in temperatures or in CO₂ pressure, which may affect photosynthetic capacity, net primary productivity, and living structure maintenance (Ren et al., 2006; Körner, 2007; Chawla et al., 2008;

Table 5. Mean biomass of the different pools of the west coast of the MCNP.

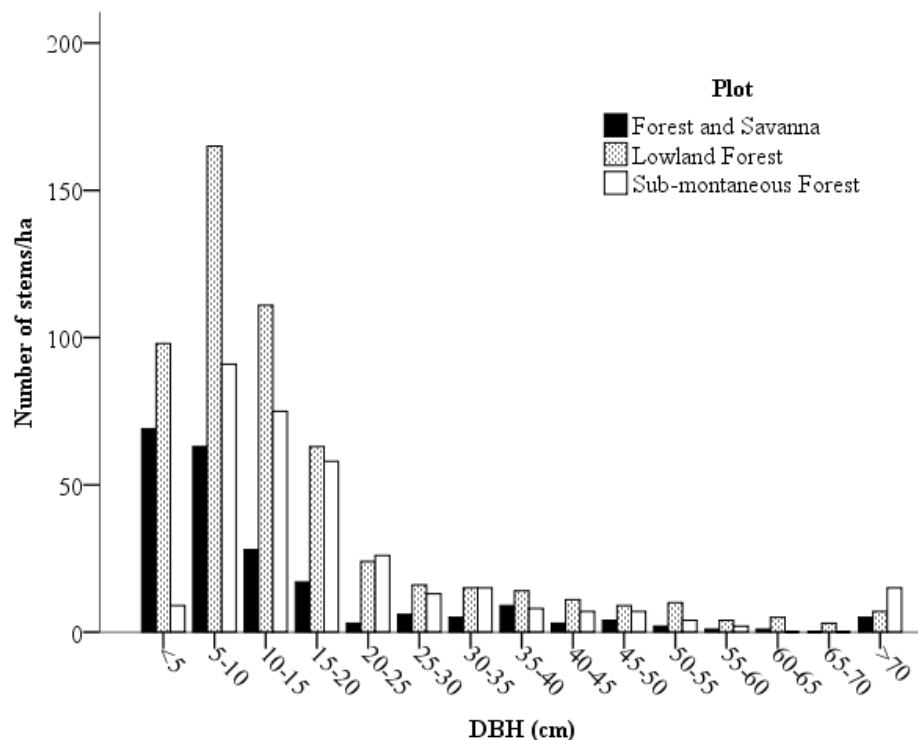
Aspect (t ha ⁻¹)	Vegetation type			
	TLF (tons ha ⁻¹)	SMF (tons ha ⁻¹)	MF (tons ha ⁻¹)	Mean (tons ha ⁻¹)
AGB	450.6 ± 53.9	936.0 ± 178.0	529.0 ± 152.0	638.5 ± 127.9
BGB	105.89 ± 12.7	219.96 ± 41.8	124.32 ± 36.2	150.06 ± 30.1
LB	0.22 ± 0.07^a	0.19 ± 0.04 ^b	0.17 ± 0.03 ^b	0.19 ± 0.05
SOC (%)	3.74	3.70	4.06	3.83

Letters a and b indicate that the means are significantly different. Figures in bold indicate highest values.

Table 6. Mean carbon stock of the west coast of the MCNP

Carbon pools	Carbon stock of the different Carbon Pools			
	TLF (tons ha ⁻¹)	SMF (tons ha ⁻¹)	MF (tons ha ⁻¹)	Mean (tons ha ⁻¹)
ABS	225 ± 26.9	468.0 ± 89.0	264.5 ± 76.0	319.3 ± 63.9
BBS	52.95 ± 6.3	109.98 ± 20.9	62.04 ± 17.9	74.99 ± 15.0
LBC	0.11 ± 0.04	0.09 ± 0.02	0.08 ± 0.15	0.09 ± 0.06
SOC	2.91	3.91	2.99	3.27

Figures in bold indicates the highest values.

**Figure 2.** Diameter size-class distribution across altitude gradient of the MCNP.

Malhi and Matthews, 2013). Grime (1979) indicated that when climbing up, these environmental factors exert more pressure on tree lifeforms than on shrub lifeforms.

The most important species was *S. rowlandii*, belonging to the Myrtaceae family in the montane forest. Sanjeewani et al. (2024) indicated that the Myrtaceae family was the

Table 7. Total Carbon Stock of the different pools of the west coast of the MCNP.

Plot	Pools				Total (t ha ⁻¹)	TMC _{CO₂} ^e (CO ₂ ha ⁻¹)
	Above ground (t ha ⁻¹)	Below ground (t ha ⁻¹)	Litter (t ha ⁻¹)	Soil (t ha ⁻¹)		
TLF	450.6	105.89	0.11	2.91	559.51	2053.40
SMF	936.0	219.96	0.09	3.91	1159.96	4257.05
MF	529.0	124.32	0.08	2.99	656.39	2408.95
Mean	638.5	150.06	0.09	3.27	791.95	2906.46

Figures in bold indicate the highest values.

most dominant family at the 1200–1800 m and was represented by the *Syzygium* spp. across a wide altitudinal gradient in Sri Lanka.

Also, Jeyanny et al. (2014) indicated that *Syzygium* spp. was distributed in a Malaysian forest reserve and indicated that the Myrtaceae family was found at the 1609 to 1644 m asl in the Malaysian tropical forests as one of the common families. *S. rowlandii* is an evergreen shrub or tree growing to a maximum size of 20 m, and it's harvested by the local people for food and medicine (Wrigley and Fagg, 2003), justifying its presence at an altitude of 1600 to 2400 m asl in this study. However, the most important family in this study was the Fabaceae family in the SMF. This is like the results of Sainge et al. (2019) in the RHFR, which is one of the Cameroon mountains in the Gulf of Guinea.

It is also consistent with the report of Cirimwami et al. (2019), who indicated that the Fabaceae family was the first family to be represented in the woody lifeforms.

The Fabaceae family is a widely distributed family that includes trees, shrubs, and herbaceous plants and is the third largest land plant family (Christenhusz and Byng, 2016). Due to its wide variety of forms, it is to be expected that it should have the highest incidence in the SMF, which harbors an environment that is between the lowland and the montane forest. In high altitude areas, the species richness of plants and their diversity of small size (low DBH) in the Fabaceae family dominant with altitude while, large size DBH woody plants decrease with altitude (Wodajo et al., 2020).

The submontane and the montane forests were, however, the most similar in this study as corroborated by Cuello (2002) in Venezuela, who found that the forests at altitudes from 1900 to 2400 m were similar.

Stand structure across altitudinal gradients of a montane tropical forest

The vegetation structure of this study area showed an inverse J-shaped distribution, which indicates great potential for regeneration capacity of young (low DBH) trees, growing faster and having a higher capacity for accumulating large amounts of carbon. However, there

was a higher plant density in the 5 to 10 cm DBH size-class than in the <5cm DBH size-class; especially, in the lowland and submontane forests, a situation that is like the results of Cuello (2002) in Venezuela. This may be due to the fact that at lower altitudes, there are trees which create a canopy preventing the presence of sunlight in the understory, thus preventing the growth of lifeforms in the <5cm DBH size-class. Thus, the highest proportion of individuals was found within the 5 to 10 cm DBH size-class in the <1600 m asl (TLF and SMF). This is contrary to the results of Cuello (2002), who found more individuals between 1960 and 2300 m in Venezuela as 2300 m elevation is already in the montane forest with respect to this study site.

The submontane forests had the highest number of individuals in the >70cm DBH size-class diameter, indicating an increase in plant density for larger tree lifeforms with altitude that later decreases as altitude decreases to the montane forest. This is like the results of Tiokeng et al. (2025) in the western highlands of Cameroon, where there were more individuals in the >70 cm DBH size class at 1600 m asl, represented here as the submontane forests. This result is in line with those obtained in other tropical forests, where it has been shown that in the submontane forests, individuals in this diameter category most often contribute more than 30% to biomass accumulation (Bastin et al., 2015, Gomadje et al., 2017, Loubota et al., 2018). Thus, the density of trees ≥70 cm in diameter would explain the variation in biomass between and within altitudes (Slik et al., 2013). According to some authors, these large trees could be more easily monitored using remote sensing techniques and could then be an interesting predictor of large-scale biomass (Loubota et al., 2018, Meyer et al., 2018). Cuello (2002) indicated that the density increased with altitude up to 2480 m and then decreased to the highest elevation, like our results obtained, where the plant density of large tree forms increased from TLF to SMF and then decreased at MF. This is contrary to the results found by Lovett et al. (2006) in the mountain of Tanzania, where stem density showed a significant increase with altitude. This may be due to the environmental conditions that become colder and cloudier in the montane forest, preventing enough sunlight for growth. Thus, plant growth in the montane forest cannot

be as high as that in the lowland forests and only plants species that can survive in such environmental conditions can thrive in the montane forests.

Similarly, the basal area increased with an increase in altitude with a peak at 800 to 1600 m asl; and later decrease with an increase in altitude. Similar results were indicated by Forboseh et al. (2011) in the Mount Cameroon, Lovett et al. (2006) in Tanzania, and Cuello (2002) in Venezuela, who indicated an increase in basal area with an increase in altitude in the montane forests of Tanzania and Venezuela, respectively, with a peak at the 1000 m due to the presence of a few large individuals. The mean basal area was, however, low when compared to a similar study in the Cameroon mountains as reported by Siange et al. (2019), who indicated a mean basal area of $37.5 \text{ m}^2 \text{ ha}^{-1}$ in lowland evergreen rainforest to $34.4 \text{ m}^2 \text{ ha}^{-1}$ in montane cloud forest. This may be because Sainge et al. (2019) worked on tree forms of $\geq 10\text{cm}$ thereby increasing the basal area.

Also, this study site has had so many anthropogenic activities due to its accessibility and the increase in human population thereby decreasing the basal area as compared to the almost inaccessible RHFR (Sainge et al., 2019). High human densities and continued human immigration into the area have driven this trend and led to the clearance of much of the natural vegetation for both subsistence and commercial agricultural use, as most lowland forests have been cleared for industrial plantations, such as oil palm (*Elaeis guineensis*) (Forboseh et al., 2011; Linder, 2013). Meanwhile, the higher elevations of Mount Cameroon remain largely intact due to their low potential value for exploitation and their relatively inaccessible rugged terrain (Butynski and Koster, 1994; Fotso et al., 2001; Oates et al., 2004). As a result, no major human activities or settlements occur above 2000 m. However, the lowland forest had the highest basal area in this study. This is similar with the results of Sainge et al. (2019) in the RHFR. Deforestation in the lowlands allows sunlight to be available for the growth of trees found in the forest understory and thus increases the number of individuals which in turn increases the basal area. The presence of large herbivores like the elephant (*Loxodonta* spp.) in the higher altitudes can have marked effect on the forest structure by consuming biomass, destroying small stems, dispersing seeds and transporting nutrients (Poulsen et al., 2018). Moreover, due to the recent volcanic eruption in the West coast cluster of the MCNP, accessibility has been reduced; thus, tree species may be adapted to grow slowly but potentially reach great sizes (Lovett, 1996).

Carbon stock across altitudinal gradients of a montane forest

In the present study, all carbon pool results varied with the increasing altitudinal gradient. Altitude had an inverse correlation with all carbon pools except litter biomass. Our

results on the AGB revealed a bell-shaped structure where there's an inverse relationship between the ABC and BBC and altitude. The bell shape indicates that the middle altitude includes the most ABC and BBC, which begins to decrease as altitude increases after a certain altitude.

Based on this, it is possible to say that as altitude decreases biomass carbon increases. The results are similar to previous work carried out in other mountain forests in Cameroon (Gonmadje et al., 2017, Sainge et al., 2020) and in other tropical regions (Leuschner et al., 2013, Girardin et al., 2014), who observed either a decrease in biomass quantities with altitude or a bell-shaped curve (Moser et al., 2007; Sheikh et al., 2012; Imani et al., 2017). According to Brown and Lugo (1982), a more productive stem density of large trees at the middle altitude than in the other altitudes accounts for more carbon proportion. According to these authors, this decrease in biomass with altitude is linked to the supply of nutrients from the soil, which becomes limited as altitude increases in relation to plant demand, thus limiting forest productivity and biomass accumulation. Also, the microclimate and local topographical factors of each site would control the abundance and size of trees in these stands, which would be at the origin of the differences observed in biomass and carbon in each forest.

At the TLF and MF, the density of large trees is low due to anthropogenic activities and environmental conditions, respectively, which in turn reduces their ABC and BBC. Due to the inaccessibility of the submontane and montane forests to human disturbance, there is an increase in the number of large trees, leading to a higher ABC and BBC in the MF than the LMF. As you go higher, the climatic conditions make it impossible for the existence of large trees, and thus, a reduction in the ABC in the MF as compared to the SMF. However, an increase in temperature due to climate change will make the higher altitudes hotter, leading to migration to the sub montane forests and subsequently extinction of certain species. Species extinction may occur alongside migration and geographic displacement of susceptible populations toward areas with a more appropriate climate, which in turn would lead to changes in the carbon cycle and its dynamics in the ecosystem. This, thus, calls for a continuous evaluation of the carbon stock across the altitudinal gradient over time to determine the change in vegetation.

The average ABC, however, in the MCNP forest ($319.3 \text{ t C ha}^{-1}$) was much more than that of previous estimates of $193.64 \text{ t C ha}^{-1}$ for evergreen forests (Salinas et al., 2010), 143 t C ha^{-1} for all types of forest for all Sub-Sahara Africa (Brown, 1997, Gibbs and Brown, 2007); 163 t C/ha in tropical equatorial forests (Gibbs et al., 2007); 73 t C/ha for tropical dry forest (IPCC, 2006); and the IPCC default value of 89.3 t C/ha for Africa (IPCC, 2006).

Results also revealed that the highest Carbon stock was found in AGB as compared to other carbon pools

considered for this study. This is like other studies across an altitudinal gradient, like that of Tadesse and Tamiru (2024) and Yohannes et al. (2015) in Ethiopia. This may be due to the high density of plant stems of large trees which in turn increased the carbon pool, especially in the middle altitude. The study had a mean AGB of 638 t ha^{-1} is similar to the study of Tadesse and Tamiru (2024), who recorded 722.53 t ha^{-1} in a tropical forest in Ethiopia across altitude gradients. The study forest had the potential to sequester $2906.46 \text{ t CO}_2 \text{ ha}^{-1}$, which may help to mitigate climate change.

The SOC followed a bell-shaped pattern of the ABC, where the SOC initially increased with an increase in altitude and later decreased. The presence of large trees in the submontane makes it possible for an increased amount of litter, which decomposes to increase the soil organic matter content, taking into consideration that the air temperature at the submontane is still favorable for plant productivity and decomposition. In the TLF and MF, the tree density of large trees is lower, and thus, may account for low soil organic matter content.

Anthropogenic activities that take place in TLF cause the soil to lose and thus easily lead to soil erosion. It should be noted that this site has registered several landslides and volcanic eruptions that have ended at the level of the sea, thus washing away the SOC, especially at TLF. This may be the reason why the MF had a higher SOC than the TLF. At the summit or the MF, the frequent and persistent fog formation can reduce solar radiation by 10 to 50% (Hafkenscheid, 2000), and this alters the water balance of the atmosphere, keeping the soil constantly wet and impeding decomposition. The value of the SOC was low (3.27 t C ha^{-1}) as compared to 55 t C ha^{-1} for tropical forest soils (Gorte, 2009).

The mean carbon stock in the present study for leaf litter biomass (0.01 t C ha^{-1}) was less than that of 1.58 t C ha^{-1} for evergreen forests (Mohanraj et al., 2011), and 1.4 to 4.8 t C ha^{-1} for tropical and sub-tropical forests (Chang et al., 2010). The lower percentage contribution of litter biomass carbon to the total carbon stock in the study forest might be a result of the high rate of litter decomposition in tropical forests (Salinas et al., 2021). The litter carbon decreased with an increase in altitude; thus, it was highest in the TLF than at any other altitude. This may be due to erosion of litter from the higher altitudes to the lower altitudes of the forests, which facilitates the downward movement of soil, organic debris and water, allowing the accumulation of an ecto-organic layer of organic debris. This indicates the presence of forest floor mass and its prolonged accumulation over time compared to the other sites. According to Sheikh et al. (2009), forest stands with dense canopies and higher inputs of litter can result in maximum storage of carbon stock in the litter pool. However, This can be eroded to the lower altitudes, thereby increasing its Carbon pool, especially from the submontane forests that had a dense canopy due to the

presence of large trees in the TLF.

It should be noted that the West coast of the MCNP harbors the place called Debuncha, which is the wettest place in Cameroon, which encourages erosion and constant landslides in the area. Other authors, however, (Zhu et al., 2011 in China; Yohannes et al., 2015 and Tadesse and Tamiru, 2024 in Ethiopia) indicated that there was no clear pattern between litter carbon stock and altitude in tropical forests as the difference was insignificant. According to these authors, the rate of decomposition of litter, which is altered by temperature and moisture, is also affected by factors like stand age, forest types, disturbance, and climate, which play more important roles in the regulation of litter pool size (De Castilho et al., 2006). Therefore, the present study of low amount of litter fall might be mainly due to decomposition rate and stand properties like disturbance, species type, and canopy cover.

CONCLUSION AND IMPLICATIONS FOR CONSERVATION

The overall trend of total mean carbon stock and sequestration of the forest show similar pattern with ABC and BBC. This might be because total carbon density mostly depended on above ground biomass carbon pool. The carbon stock in the various carbon pools, which had the capacity to slow the rate of enrichment of the CO_2 concentration in the atmosphere could help with efforts to mitigate global climate change.

Therefore, the forest's carbon stock can be increased by using sustainable forest management techniques, such as participatory forest management, to maintain the forest's current carbon stock potential and boost its biomass conservation for the future. There is thus a need for further studies on the role of the study forest in biodiversity conservation for its sustainable management. The changes in the C stock at varying altitudes and different pools in the west coast cluster of the MCNP reconfirms the need to compartmentalize tropical montane forests for C dynamic research.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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