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Estimation of Biomass and Carbon stock Along an Altitudinal Gradient in the Forests of the Western Highlands Cameroon: Case of Western Slope of the Bamboutos Mountains

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ABSTRACT

Controlling the quantities of biomass and carbon contained in Cameroon's tropical forests is an asset for the successful implementation of climate change mitigation strategies. The aim of this study was to assess the biomass and carbon stored by the forests along the western slopes of the Bamboutos Mountains and to examine whether altitude has an influence on basal area, stem density, wood density and biomass values. Inventory data from 18 plots of 0.5 hectare each, established in mid-altitude and submontane forests were used. Biomasses were obtained using the non-destructive method. Estimates of above-ground biomass using trunk diameter, height and wood density gave a mean value of 155.49±57.54 t. ha^{-1}; 292.28±90.81 t. ha^{-1}, compared with 150.49±42.16 t. ha^{-1}, 165.62±45.74 when height was excluded in mid-altitude and submontane forests respectively. The comparison test showed that there was no significant difference in these biomass values. PCA showed a positive relationship between altitude and these three variables (stem density, basal area and biomass). The large-tree diameter class (≥ 70 cm) contributed 41% to biomass accumulation in the submontane forest compared with 22.9% in the mid-altitude forest. *Napoleonaea egertonii* and *Santiria trimeria* showed the highest biomass values in the mid-altitude and submontane forest respectively, revealing that biomass varies according to species and depends on the size and abundance of the species concerned. This study showed that height made little contribution to biomass accumulation and that the quantities of certain structural parameters increased with altitude. The results of this study highlight the role played by the forests of the Bamboutos Mountains in climate regulation.

Keywords Biomass, Altitudinal gradient, Bamboutos Mountains, REDD+, Allometric.

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INTRODUCTION

The Congo Basin rainforest is one of the largest in the world, estimated at 286 million hectares. These forests constitute an incredible reserve of biodiversity and provide several ecosystem services, including regulation; hence their role in purifying water and absorbing greenhouse gases such as CO_2 (Janicot *et al.* 2015, Spracklen and Righelato 2014). Forest ecosystems make a significant contribution to sequestering the carbon contained in the CO_2 released into the atmosphere each year (EFESE 2019, Janicot *et al.* 2015). Their ability to sequester carbon from the atmosphere and store it makes them an essential means of mitigating climate change (Pilli *et al.* 2016, Galbert *et al.* 2013). Tropical forests store around 55% of the world's forest carbon, acting as carbon sinks thanks to a positive balance between tree growth, recruitment and mortality (Pan *et al.* 2011). Despite their role as carbon reservoirs, tropical forests are increasingly facing degradation and deforestation due to the expansion of agricultural land and local populations' need for wood for a variety of uses. Research has shown that 13% of CO_2 emissions come from agriculture, forestry and other land uses (IPCC 2021). The United Nations Framework Convention on Climate Change therefore encourages developing countries to REDD+ (FAO 2015).

REDD+ aims to progressively halt the loss of carbon from forests in developing countries (WWF 2016). This also involves quantifying the carbon stocks in the various forest ecosystems so that they can be better conserved or improved. Above-ground biomass, dead wood, liter, soil organic matter and roots are the main components of a tropical forest's carbon stock (Gibbs *et al*. 2007). Major efforts are increasingly being made to improve databases on CO_2 stocks and fluxes, by integrating both indirect methods (remote sensing) and direct *in situ* measurements (Zakari *et al.* 2022, Jha *et al.* 2019, Bocko *et al.* 2017, Ekoungoulou *et al.* 20015, Lewis *et al.* 2013, Djuikouo *et al.* 2010). A change in above-ground biomass at the plot scale has been demonstrated in old-growth tropical forests between continents (Slik *et al.* 2013) and across tropical Africa (Lewis *et al.* 2013), and at the local scale in Central Africa (Fayolle *et al.* 2016, Imani *et al.* 2017). Numerous scientific studies have shown that tropical forests vary in structure and species composition along an altitudinal gradient (Girardin *et al.* 2010, 2014, Ashton 2003, Tiokeng *et al*. 2019). The influence of this factor can certainly affect the biomass of these areas and consequently the rate of carbon sequestered by the vegetation in these environments. However, biomass increases exponentially with tree diameter, density of large trees and basal area (Slik *et al.* 2010, Lewis *et al*. 2013, Poorter *et al.* 2015).

Above ground biomass studies carried out along an altitudinal gradient have shown, for some, a decreasing relationship with increasing altitude (Gonmadje *et al*. 2017, Girardin *et al.* 2014, Leuschner *et al.* 2013) and for others, the opposite (Cuni-Sanchez *et al.* 2017). In addition, some research shows that there is no significant relationship between biomass and altitude; thus, the relationship between these two parameters does not seem to be clearly defined. The link between significant change in above-ground biomass at plot level has also been demonstrated in old-growth tropical forests both between continents (Slik *et al.* 2013) and across tropical Africa (Lewis *et al.* 2013) and locally in Central Africa (Doetterl *et al.* 2015, Fayolle *et al.* 2016, Imani *et al*. 2017, Panzou *et al.* 2018). In the mountain forests of northern Kenya, mixed forests were found to store higher quantities of above-ground biomass than other forest types (Cuni-Sanchez *et al.* 2017).

In Cameroon, very few ecological studies have been carried out to date to estimate biomass and carbon according to altitudinal gradation. Examples include the work of Sainge *et al.* (2020) based on above-ground biomass in the Mont Rumpi Forest reserve along an altitudinal gradient and that of Gonmadje *et al.* (2017) in the Ngovayang massifs, which showed high biomass values in low-altitude forests. An assessment of above-ground biomass carried out in the old-growth and secondary forests of Mont Okou and Mont Mbam showed non-significant differences in biomass recorded at different altitudes. However, the highest biomasses were recorded in old-growth forests (Ngute *et al.* 2019). On the other hand, work carried out in the former high-altitude wet savannahs on the eastern slopes of the Bamboutos Mountains shows that carbon stock decreases with altitude (Fogaing *et al.* 2021). Biomass and carbon data based on altitude remain incomplete, as they do not give a more complete idea of the quantities of biomass available in all these zones. Much remains to be done despite the existence of the aforementioned studies. The aim of this study was therefore to assess

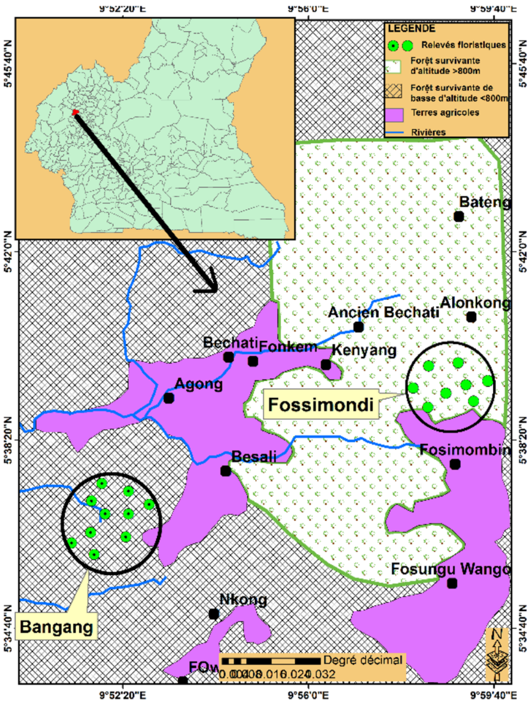

Fig. 1. Representation of floristic surveys in Bangang and Fossimondi forests.

the biomass and carbon stored by the forests along the western slopes of the Bamboutos Mountains and to examine whether altitude has an influence on basal area, stem density, wood density and biomass values.

MATERIALS AND METHODS

Study area

The western slopes of the Monts Bambouto are located in the oceanic part of the Cameroonian ridge (Nzogning 1997). Biafran Atlantic forests are found here (Bergl *et al*. 2007). Bangang mid-altitude forest and Fossimondi submontane forest located along the western slopes of the Mont Bamboutos are the focus of this study. The Bangang mid-altitude forest is located between 200 m and 600 m above sea level. The mean geographical coordinates are 5°36'10.5" north latitude and 9°54'24.5" east longitude. The Fossimondi submontane forest lies between 1000 m and 1900 m above sea level, with mean geographical coordinates of 5°37'54.5" north latitude and 9°57'57.6" east longitude (Fig. 1).

Lebialem has an equatorial climate with two seasons: A long rainy season (March to November) and a short dry season (December to February). Temperatures range from 15.2°C to 18.2°C and 25°C to 27.7°C in Fossimondi and Bangang respectively, with annual averages of 16.8°C and 26.34°C/year (Figs. 2A- 2B). Average rainfall is 2112 mm/year in Fossimondi and 2530 mm/year in Bangang (http://fr.climate-data.org/location/780244/, accessed 01-02-2016). Soil textures vary. Some are ferralitic, acidic lateritic, others are sandy, poorly drained and gravelly (Nembot and Tchanou 1998).

Plant census and identification

Eighteen temporary plots measuring 250 m x 20 m (0.5 ha) were established in two forests on the western slopes of Monts Bamboutos. The coordinates of each plot were taken using a Garmin V GPS. Within each plot, all trees with a diameter at breast height (1.30 m)

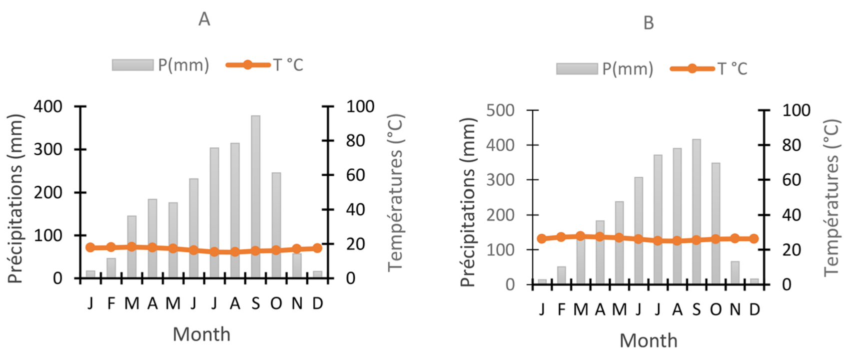

Fig. 2. Umbrothermal diagram for the villages of Fossimondi (A) and Bangang (B). (source: http: //fr.climate-data.org/location/780244/, consulted on 01-02-2016)

≥ 10 cm were counted and their diameter measured using a tape measure. Plants were identified on site with the help of a botanist. Unknown species were taken to the national herbarium for identification by comparison with herbarium samples and using documents dealing with the flora of the tropical zone (Hutchinson and Dalziel 1954-1972, Vivien and Faure 1985).

Estimation of above-ground biomass

Non-destructive method was used to estimate the biomass in order to deduce the carbon stock although the choice of allometric regression model used to convert tree structure data into biomass is one of the most important sources of ambiguity in estimating carbon stocks in tropical forests (Molto *et al.* 2013, Gonmadje *et al.* 2017). Since the study was carried out in dense tropical forests, particularly in the Congo Basin, two regional allometric models developed respectively by Fayolle *et al*. (2018) and Chave *et al.* (2014) were used to calculate the above-ground biomass of each plot. The first equation is based on the diameter and wood density of each tree is that of Fayolle *et al.* (2018).

$$BA=Exp\ (0{,}046+1{,}156\ \log(WSG)+1{,}123\times \log(D)+0{,}436\times(\log(D)^2-0{,}045\times(\log(D)^3)$$

Where, BA is the estimated above-ground biomass (kg), D is the trunk diameter (cm) and WSG is the wood density ($g.cm^{-3}$). The second equation has the particularity of including the height parameter (H) in addition to the diameter and wood density; it is that of Chave *et al.* (2014). It was chosen to see which of the two equations had the highest biomass and carbon values.

$$BA=0{,}0673\times(WSG\times D^2\times H)^{0{,}976}$$

Where, H is the total height of the tree.

Given the difficulty in collecting data on tree height in dense tropical forests, this parameter was calculated on the basis of the equation established by Djomo *et al.* (2016).

$$H= e^{1{,}321+0{,}482\ln D+0{,}027\ln WSG}$$

The wood densities of each species sampled were obtained from wood density databases (Zanne *et al.* 2009, Reyes *et al.*1992). The mean density of African wood (0.65) was used for species with unknown specific density (Lewis *et al.* 2013). For better interpretation and comparison of the results with others, the extrapolation of the plot values to the hectare was done using an expansion factor noted:

$$\text{Expansion factor}=\frac{10000\ m^2}{\text{Plot surface area } m^2}\ \text{(Walker et al. 2011)}$$

Below biomass (SB) was calculated using the equation of Cairns *et al*. (1997), adapted to tropical forests and their tree roots.

$$BS = e^{(-1{,}0587+0{,}8836\times\ln(BA),}$$

To assess the carbon stock of the forests studied, the relationship C stock (tC/ha) = CF*(BA+BS) was used.

With CF = Carbon Fraction, whose default value is 0.47 for all species combined (IPCC 2006).

Mean carbon stock (tC/ha/plot) per plot = Sum of carbon values (tC/ha)/number of plots. Finally, the CO_2 sequestered by the trees was obtained using the relationship CO_2 atm= Stock Cx3.667.

The contribution of the size of the different trees to Biomass values was assessed; thus, three diameter classes were defined according to strata: A lower stratum consisting of small trees (10 dbh < 30 cm), a middle stratum with large trees, most of which reach the canopy (30 cm dbh < 70 cm), and the upper stratum corresponding to the largest trees, which are either in the canopy or emerging, with a dbh greater than or equal to 70 cm (Slik *et al.* 2010, Gonmadje *et al.* 2017).

RESULTS AND DISCUSSION

Variation of different parameters within plots

A total of 4285 individuals comprising 161 species, 127 genera and 48 families were counted in the Bangang mid-altitude forest. In the submontane forest of Fossimondi, a total of 4,837 individuals were inventoried, belonging to 168 species, 131 genera and 61 families. The above ground biomasses recorded over 5 hectares in the mid-altitude forest of Bangang are 1504.99 and 1554.98 tons (mean of 150.49±42.16 and 155.49±57.54 t. ha^{-1} respectively for the equations of Fayolle *et al*. (2018) and Chave *et al.* (2014) whereas in the Fosimondi submontane forest, the above-ground biomasses are 1324.99 and 2338.26 tons over a total sampled area of 4 hectares (i.e. an average of 165.62±45.74 and 292.28±90.81 t. ha^{-1}) for the Fayolle and Chave equations respectively.

Observation of changes in the values of the various variables per plot reveals that the quantities of total biomass, total carbon and total CO^2 vary not only from one plot to another but also with the type of equation used (Table 1). Thus, in the mid-altitude forest of Bangang, the total biomass values per plot vary between 162 and 225.78 t ha^{-1} (mean 201.05 ± 54.55 t ha^{-1}) for the Fayolle equation, whereas for the Chave equation, the variation ranges from 182.3 to 253.67 t. ha^{-1}(mean of 203.5 ± 72.46 t. ha^{-1}). The quantities of carbon stored vary between 80.6 and 160.12 t. ha^{-1} (mean of 100.52± 27.27t. ha^{-1}) with the Fayolle equation, then from 54.04 t. ha^{-1} to 185.18 t. ha^{-1} (mean of 101.74± 36.23 t. ha^{-1}) for the Chave equation. The highest CO_2 values are 402.63 and 678.99 t. ha^{-1} respectively for the Fayolle and Chave equations.

In the Fossimondi submontane forest, biomass values per plot obtained from the equation of Fayolle *et al.* (2018) range from 166.16 to 327.97 t. ha^{-1}(mean of 222.60±59.18 t. ha^{-1} while those of Chave *et al.* (2014) range from 254.42 to 541.99 t. ha^{-1}(mean of 370.50±108.58 t. ha^{-1}). The carbon stock ranges from 83.08 to 163 t. ha^{-1}(with an average of 111.29±29.59 t. ha^{-1}) for the Fayolle *et al*. (2018) equation, whereas in Chave *et al*. (2014), carbon values ranging from 127.21 t. ha^{-1} to 270.99 t. ha^{-1} (with an average of 185.25±54.29t. ha^{-1}) were recorded. The high quantities of CO_2 are 601.23 t. ha^{-1} and 993.64 t. ha^{-1} respectively for the Fayolle and Chave equations.

Table 1. Biomass, carbon and CO_2 recorded per plot in the two forests.

	Forêt de moyenne altitude						
	Alt. (m)	Bt_Fay (t.ha^{-1})	Bt_Ch (t.ha^{-1})	Ct_Fay (t.ha^{-1})	Ct_Ch (t.ha^{-1})	CO_2_Fay (t.ha^{-1})	CO_2_Ch(t.ha^{-1})
BG1	431	162	139,86	81	69,92	297	256,41
BG2	613	201,12	182,3	100,56	91,15	368,7	334,19
BG3	544	320,24	370,38	160,12	185,18	587,06	678,99
BG4	298	216,74	253,67	108,37	126,83	397,329	465,02
BG5	304	182,65	203,1	91,325	101,55	334,85	372,33
BG6	216	112,37	108,08	56,185	54,04	206,01	198,15
BG7	577	208,76	200,93	104,38	100,46	382,71	368,34
BG8	388	225,78	211,69	112,89	105,84	413,9	388,08
BG9	322	161,21	148,3	80,6	74,15	295,55	271,86
BG10	291	219,63	216,69	109,81	108,34	402,63	397,22
	Forêt submontagnarde						
	Alt. (m)	Bt_Fay (t.ha^{-1})	Bt_Ch (t.ha^{-1})	Ct_Fay (t.ha^{-1})	Ct_Ch (t.ha^{-1})	CO_2_Fay (t.ha^{-1})	CO_2_Ch(t.ha^{-1})
FD1	1585	207,29	307,08	103,64	153,53	380	562,98
FD2	1451	259,61	448,73	129,8	224,36	475,93	900,74
FD3	1392	171,63	257,94	85,81	128,97	314,65	472,89
FD4	1431	276,54	488,5	138,26	244,25	506,94	895,58
FD5	1246	171,41	337,98	85,7	168,99	295,57	619,64
FD6	1405	200,21	327,41	100,1	163,7	367,02	600,26
FD7	1345	166,16	254,42	83,08	127,21	304,61	466,44
FD8	1440	327,97	541,99	163,98	270,99	601,23	993,64

BG : Bangang, FD : Fonsimondi, Alt. : Altitude, Bt_Fay : Biomasse total Fayolle, Bt_Ch : Biomasse total Chave, Ct_Fay Carbone total Fayolle, Ct_Fay: Carbone total Chave, CO_2_Fay: Dioxide de Carbone fayolle, CO_2_Ch : Dioxide de Carbone Chave.

Post-hoc Bonferroni test carried out on the biomass, carbon and carbon dioxide values of the two forests according to the Fayolle and Chave equations at a significance level of 5% (Fig. 3) shows no significant difference in the biomass values originated from the two equations, not only within the Fossimondi submontane and Bangang mid-altitude forests but also between the two forests. Thesame remarks were made for the quantities of carbon stored by these plants and amounts of CO_2.

In this study, two allometric equations developed from trees in the tropical zone were used. The difference between these equations was in the predictors (diameter and height), one of which consider diameter and the other, the two predictors in order to better understand the biomass and carbon values from the stands studied. The mean values of above-ground biomass obtained in the mid-altitude forest of Bangang (150 and 155 t. ha^{-1} respectively for the equations of Fayolle *et al*. (2018) and Chave *et al.* (2014) and those of the submontane forest of Fosimondi (165 and 292 t. ha^{-1} respectively for the equations of Fayolle *et al*. (2018) and Chave *et al.* (2014) showed no significant difference despite dissimilarities in the specific composition and structure of these forests. Depending on the equation used, we would have expected the above-ground biomasses from the Chave *et al*. (2014) equations to be higher because it incorporates both tree diameter and height. Indeed, the work of Chave *et al.* (2005) revealed that biomass equations incorporating height are the most likely to be accurate. In the case of this study, it can be assumed that height had very little influence on above ground biomass quantities. The results obtained in the mid-altitude forest are lower than the average estimates of above-ground biomass observed in African tropical forests at the same altitude, that is 282 and 252 t. ha^{-1} respectively (Imani *et al.* 2017, Sainge *et al.* 2020). The biomasses obtained in the submontane forest of Fosimondi are lower than those of Imani *et al.* (2017), which are 365 t. ha^{-1}, but close to the 258 t. ha^{-1} observed by Sainge *et al*. (2020) in the same type of forest in Central Africa. All these contrasts in mean above ground biomass are linked to the size of the sample and also to the allometric equation models chosen.

Influence of altitude on biomass and structural parameters

The biomass obtained from the Fayolle equation was

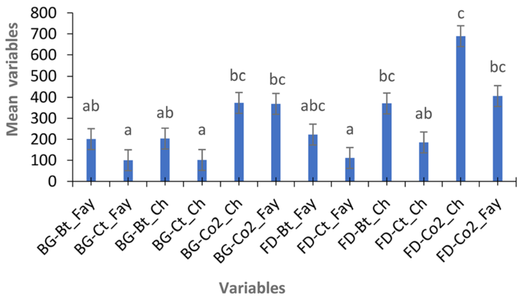

Fig. 3. Comparison of biomass, carbon and CO_2 according to the type of equation and forest. BG: Bangang, FD: Fonsimondi, Alt. : Altitude, Bt_Fay : Total biomass Fayolle, Bt_Ch : Total biomass Chave, Ct_Fay: Total carbon Fayolle, Ct_Fay: Total carbon Chave,- CO_2_Fay: Carbon dioxide Fayolle,CO_2_Ch: Carbon dioxide Chave.

* Bars with the same letter are not significantly different from each other according to the analysis of variance (Bonferroni correction, p=0.05).

* Bars with a different letter show a significant difference between them according to the analysis of variance (Bonferroni correction, P<0.01).

* Bars with more than one letter did not differ significantly from bars with one, two or more letters in the analysis of variance (Bonferroni correction, p<0.01).

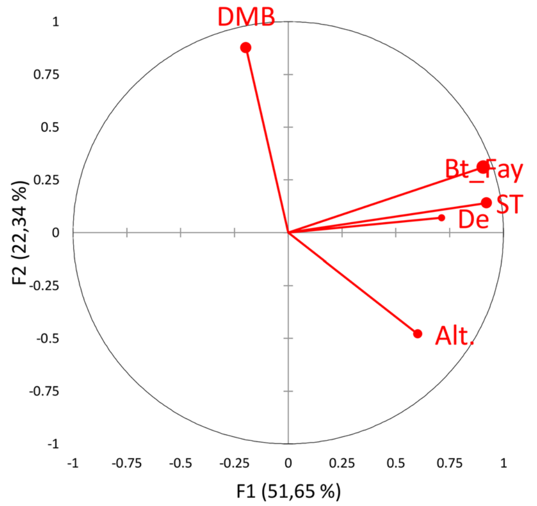

Fig. 4. Correlation circle of the principal component analysis (PCA; first two axes) of the variables characterizing the study plots established in the submontane forest of Fosimondi and the mid-altitude forest of Bangang. The variables are altitude (Alt), total biomass (Bt_Fay), average specific wood density (DMB), stem density (De) and basal area (ST).

used for the principal component analysis (PCA) because it is an equation developed on the basis of diameter; this parameter is easily measurable in the field and is therefore very powerful in predicting biomass. The PCA carried out on the basis of biomass, altitude and stand structural parameters revealed two main axes explaining 74% of the total variance (Fig. 4). Axis 1 (51.65% inertia) shows a strong positive correlation not only between basal area and biomass (Pearson; R = 0.98) but also between individual density and biomass (Pearson; R =0.51). There is also a positive relationship between altitude and these three variables (individual density, basal area and biomass), although it is weak. Axis 2 (22.34% inertia) shows a weak negative correlation between mean wood density and altitude (Pearson; R =-0.26).

Analysis of the linear relationship between the various variables and altitude shows an increase in structural parameters (basal area, density) and total biomass with altitude. However, the coefficients of determination values are very low (Figs. 5A, B-C), with R^2 = 0.132, 0.181 and 0.085 for basal area, density and total biomass respectively. This shows that increasing altitude contributes to an increase of 13.2%, 18.1% and 8.5% respectively in each value of basal area, individual density and total stand biomass.

On the other hand, a decrease in the average density of the wood was noted with increasing altitude (R^2= -0.068, Fig. 5D), i.e. a decrease of 6.8% in the value of the average density of the wood with increasing altitude. In general, all these parameters

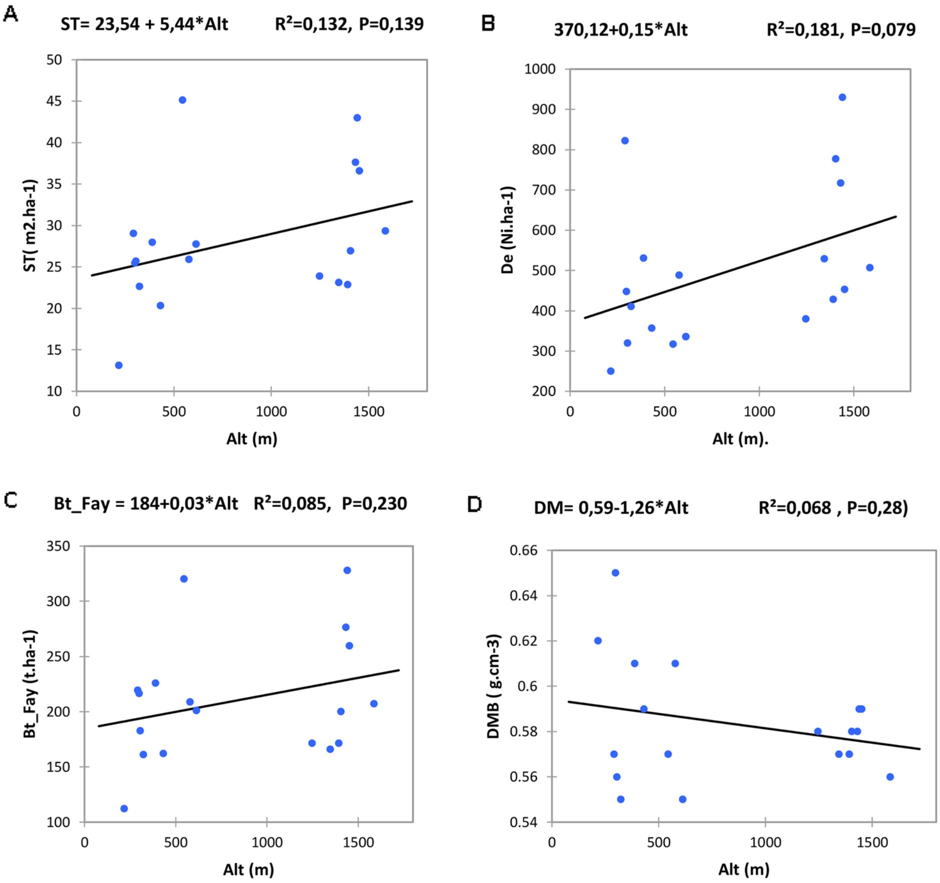

Fig. 5. Linear regressions showing the effect of altitude on basal area (A), individual density (B), total biomass (C) and mean wood density (D) on the study plots.

varied very little with increasing altitude.

Overall biomass increased with altitude in the forests studied. The increase in biomass observed with increasing altitude in this study is similar to the results obtained by some researchers in tropical forests (Alves *et al.* 2010, Marshall *et al.* 2012). However, the results are contrary to previous work carried out in other mountain forests in Cameroon (Gomadje *et al.* 2017, Sainge *et al.* 2020) and in other regions (Leuschner *et al*. 2013, Girardin *et al.* 2014), which observed either a decrease in biomass quantities with altitude or a bell-shaped curve (Imani *et al.* 2017). 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. Moreover, some studies have shown that there is no significant relationship between biomass and altitude (Dossa *et al.* 2013). In general, 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.

Biomasses and carbon stock total obtained in the mid-altitude and submontane forest according to the two equations used showed no significant difference. These results are similar to those of Sainge *et al.* (2020) carried out along an altitudinal gradient in the tropical forests of Cameroon, that is 252.6 $t.ha^{-1}$ and 126.3 $t.ha^{-1}$ respectively for biomass and carbon at mid-altitude, then 258 $t.ha^{-1}$ and 129 $t.ha^{-1}$ respectively for biomass and carbon in submontane forests. Imani *et al.* (2017) found biomass values of 282.2 t. ha^{-1}, 267.1 t. ha^{-1} and 127.7 t. ha^{-1} in mid-altitude, submontane and montane forests respectively. For these two types of stands studied, we can assume that, unlike the montane forest, species growth may not yet be limited by the drop in temperature, poor soil quality and exposure (Moser *et al.* 2011, Marshall *et al.* 2012); in addition, photosynthesis is not yet inhibited by low air temperatures.

Table 2. Species with the highest biomass, carbon and carbon dioxide values in the two forests.

	Bangang					
	Bt_Fay ($t.ha^{-1}$)	Ct_Fay ($t.ha^{-1}$)	CO_2_Fay ($t.ha^{-1}$)	Bt_Ch ($t .ha^{-1}$)	Ct_Ch ($t .ha^{-1}$)	CO_2_Ch ($t.ha^{-1}$)
Napoleonaea egertonii	122,31	61,15	224,22	96,05	48,02	176,08
Lophira alata	111,94	55,96	205,21	217,2	108,6	398,16
Irvingia gabonensis	99,03	49,51	181,51	124,45	62,22	228,14
Strombosia pustulata	84,19	42,09	154,34	70,13	35,06	128,57
Pycnanthus angolensis	79,23	39,61	145,26	85,36	42,68	156,49
Pentadesma grandifolia	75,34	37,62	138,12	107,75	53,37	195,68
Chrysophyllum perpulchrum	69,92	34,96	128,2	97,11	48,55	178,02
Piptadeniastrum africanum	65,26	32,62	119,64	101,29	50,64	185,67
Canarium sp.	59,52	29,76	109,11	67,63	33,81	124
Trichilia rubescens	51,75	25,87	94,86	/	/	/
Syzygium guineense	/	/	/	51,53	25,76	94,46
	Fosimondi					
	Bt_Fay ($t.ha^{-1}$)	Ct_Fay ($t.ha^{-1}$)	CO_2_Fay ($t.ha^{-1}$)	Bt_Ch ($t .ha^{-1}$)	Ct_Ch ($t .ha^{-1}$)	CO_2_Ch ($t.ha^{-1}$)
Santiria trimeria	212,34	106,17	389,26	354,3	177,15	649,53
Cola anomala	106,05	53,02	194,42	177,47	88,73	325,36
Uvariodendron connivens	91,8	45,89	168,3	169,76	84,88	311,23
Leptaulus daphnoides	83,27	41,65	152,74	109,48	54,74	200,7
Cola verticillata	79,95	39,97	146,58	170,77	85,36	313,07
Tabernamontana sp.	63,34	31,66	116,13	97,08	48,54	177,97
Drypetes molunduana	41,29	20,64	75,7	/	/	/
Syzygium guineense	38,85	19,42	71,22	66,12	33,06	121,22
Placodiscus angustifolius	38,24	19,12	70,12	57,4	28,69	105,23
Hypodaphnis zenkeri	37,89	18,94	69,47	116,77	58,38	214,09
Maesobotrya barteri	/	/	/	67,94	33,97	124,56

BG : Bangang, FD : Fonsimondi, Bt_Fay : Biomasse total Fayolle, Bt_Ch : Biomasse total Chave, Ct_Fay: Carbone total Fayolle, Ct_Fay: Carbone total Chave, CO_2_Fay: Dioxide de Carbone Fayolle, CO_2_Ch : Dioxide de Carbone Chave.

Biomass, carbon and CO_2 values by species in the two forests

In accordance with the allometric equations, the formulae of Fayolle *et al.* (2018) and Chave *et al.* (2014) were used to obtain quantities of Biomass, Carbon and CO_2 that varied from one species to another, but above all according to each forest (Table 2). In the mid-altitude forest of Bangang, the highest values were observed in *Lophira alata* using the Chave equation (i.e. 217.20 t.ha^{-1}, 108.6 t.ha^{-1} and 398.16 t.ha^{-1} respectively for biomass, carbon and CO_2) whereas the Fayolle equation gave *Napoleonaea egertonii* (122.31, 61.15 and 224.22 t.ha^{-1} respectively for biomass, carbon and CO_2). In the Fosimondi sumontane forest, *Santiria trimeria* showed the highest values for both equations, but the most notable values were obtained from the Chave equation (354.30, 177.15 and 649.53 t. ha^{-1} respectively for biomass, carbon and CO_2). This species is followed by *Cola anomala,* which again recorded the highest values using the Chave equation (including 177.47, 88.73 and 325.36 t. ha^{-1} respectively for biomass, carbon and CO_2).

In this study, the species with the highest quantities of biomass and carbon in the mid-altitude forest were different from those in the submontane forest. This spatial variability in biomass and carbon observed at the specific level can be explained by the physico-chemical nature of the soil (Gourlet-Fleury *et al*. 2011, Bocko *et al*. 2017), rainfall and the ecological niche of each species. Indeed, several authors have revealed that soil fertility not only controls species composition, but also explains the differences between biotopes through natural selection linked to species adaptation (Laurence *et al.* 1999, Jaffré and Veillon 1990). In addition, this floristic composition, through wood density, is an important explanatory variable for biomass variation (Gourlet-Fleury *et al.* 2011, Loubota *et al.* 2018).

Distribution of biomass by diameter class

The biomasses from all the individuals were classified by stratum according to the size of each diameter. Analysis of the Chi^2 test carried out to see whether diameter classes have an influence on biomass quantities shows that biomass values are related to the different diameter classes, regardless of the type of allometric equation chosen (Chi^2 =12.59, $p< 0.0001$, α =0.05). For example, in the Fosimondi submontane forest, the large tree diameter class (≥ 70 cm) contributed 41% to biomass accumulation according to the Chave equation, whereas in the Bangang mid-altitude forest, it contributed 22.9% according to the same equation (Table 3).

Table 3. Proportion (%) of biomass by diameter class.

	[10-30]	[30-70]	≥ 70	Total
FD-Bt_Ch	27,1	29,3	41,0	33,9
FD-Bt_Fay	27,6	17,2	16,9	19,9
BG-Bt_Ch	18,9	27,8	22,9	23,2
BG-Bt_Fay	26,3	25,7	19,2	23,0
Total	100	100	100	100

BG: Bangang, FD: Fonsimondi, Bt_Fay: Total biomass Fayolle, Bt_Ch: Total biomass Chave.

The contributions of the other diameter classes are almost similar in the two forests: 27.1% and 29.3% respectively for the (10-30 cm and 30-70 cm) classes in the submontane forest. In the Bangang mid-altitude forest, the (10-30 cm and 30-70 cm) classes accounted for 18.9% and 27.8% respectively. In contrast, the Fayolle equation showed biomass proportions that varied very little within the diameter classes but decreased from the lower to the upper strata. The fluctuations in biomass per stratum can be seen in Fig. 6.

The distribution of biomass by diameter class showed a large contribution from diameter classes ≥70 cm. This result is in line with those obtained

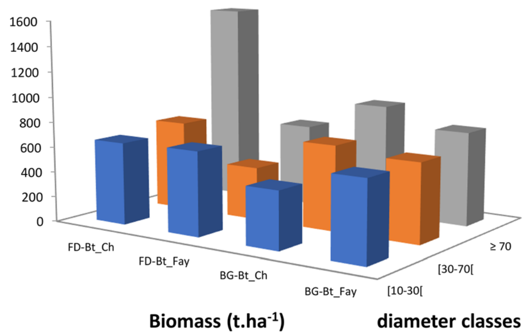

Fig. 6. Change in biomass by diameter class.

in other tropical forests, which have shown that in these 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 over 70 cm in diameter would explain the variation in biomass between and within continents (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).

CONCLUSION

This work has enabled us to understand the evolution of biomass and carbon stored by tropical forests along the western slopes of the Monts Bamboutos in Cameroon. Although the increase in biomass and certain structural parameters with altitude was not very significant, a decrease in the average density of wood with increasing altitude was observed. Depending on the type of equation used, there were no significant differences in biomass or carbon values. The upper stratum represented by the large trees made a major contribution to biomass formation. This study highlights the role of tropical forests in purifying the biosphere through the quantities of carbon dioxide they store. The dense forest of the Bamboutos Mountains is a carbon sink and should be taken into consideration in the program to implement REDD+ mechanisms.

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