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Diversity, structure and biomass (above and below) in a semi-deciduous moist forest of East Region of Cameroon

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Abstract

Tropical forests contribute effectively to the mitigation of climate change despite human action which alters their structure and the local climate. Their consideration in climate change mitigation policies requires the estimation of their potential carbon stocks which can be estimated by reliable allometric equations available. The Region of East Cameroon where this study was carried out is an area of intense logging activity. The objective of this study was to make an analysis of the forest structure and to estimate the biomass using site-specific equations and to compare the effects of other equations frequently used. Trees with $dbh \geq 1$ cm were used in 7 plots of $250m \times 20m$ to characterize the forest using diversity index, density per hectare and basal area. The biomasses of tree compartments were estimated using site-specific allometric equations and the equations most used in African forests were used to test the effect of these equations on the estimation of the aboveground biomass. The biomass was stratified into diameter classes and in root, trunk and crown compartments and their contribution estimated. Shannon index (2.47-3.88), showed a rich diversity. The biomass of trunk ($220 t \cdot ha^{-1}$), crown ($146 t \cdot ha^{-1}$) and roots ($55 t \cdot ha^{-1}$) represented respectively 52%, 35% and 13% of the total biomass. Aboveground biomass estimate with site-specific equation was $358 t \cdot ha^{-1}$. Depending of the equation used, the biomass varied between 261 and $437 t \cdot ha^{-1}$. This study contributes to a better understanding of the contribution of tree compartments to forest biomass and the implications of using existing equations.

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Introduction

Climate change has become a reality of our time. This phenomenon has been accentuated by anthropogenic activities in recent decades (IPCC, 2007). In forest ecosystems, these human activities cause changes in forest structure, floristic composition, species density, regeneration capacity of the forest, carbon storage potential, etc. (Nguenang *et al.*, 2010; Djomo, 2015a). For Saatchi *et al.* (2011), these activities are responsible for about 12-20 % of greenhouse gas emissions over the past 20 years. It is in order to mitigate climate change that the potential of the forests has been recognized on the international scale; Reducing Emissions from Deforestation and Forest Degradation and carbon stock enhancement (REDD+) has been introduced as a strategy to reach this goal (Djomo *et al.*, 2017). In fact, through photosynthesis process, forests absorb the atmospheric gas (CO₂) and store it in their tissues as biomass (Brown and Pearson, 2005).

Tropical forests which represent nearly 33% of World's forested area, contain nearly 42% of the total forest carbon (FAO, 2011) in its aboveground, dead wood, litter and soil (Rusu, 2013). In the Congo Basin tropical forests, the carbon stored varies from 100 to more than 300 tC.ha⁻¹ (Djuikou *et al.*, 2010; Lewis *et al.*, 2013; Zapfack *et al.*, 2013; Noiha *et al.*, 2015; Tabue *et al.*, 2016). The trunk biomass is higher than the other compartments of the trees (Vahedi *et al.*, 2014). According to Ploton *et al.* (2016) the mean crown biomass alone represents 36% of the aboveground biomass compared to 64% for the trunk biomass. The belowground biomass which are most often neglected in biomass estimation studies due to difficulties in field sampling, represent about one-quarter of total forest biomass (Mokany *et al.*, 2006). Measuring destructive trees is the most accurate method for the forest biomass estimation, but it requires high financial inputs and may also contribute to forest ecosystem degradation (Basuki *et al.*, 2009). Its advantage is that, the data obtained by this destructive method are used for example for the establishment of allometric equations which will later

be used for the biomass estimation by indirect methods (e.g. Brown *et al.*, 1989; Chave *et al.*, 2014). These allometric equations thus allow the estimation of the forest biomass from the direct measurable dendrometric parameters of the tree such as diameter at breast height (dbh), the height, the diameter of the crown (Zapfack *et al.*, 2013; Ploton *et al.*, 2016) and/or data from the literature such as species wood density (Zanne *et al.*, 2009) and environmental index depending of climatic condition of specific area (Chave *et al.*, 2014).

Errors in biomass estimation are greatly reduced when species or groups of species specific equations from the same study site are used (Basuki *et al.*, 2009). These equations are therefore recommended for their reliability in the estimates. Since it is difficult to have site-specific equations, some authors have established pantropical equations depending of biomass data collected in several regions, countries and continents of the tropics (Chave *et al.*, 2014; Djomo *et al.*, 2016). These equations are generally used when site-specific equations are missing for local biomass estimation. According to Henry *et al.* (2011) about 22% of allometric equations available give unsatisfactory results. This study used site-specific equation developed from a moist tropical forest of East Cameroon (Djomo and Chimi, 2017) to estimate biomass and compare the results obtained with other equations applicable in that area. The objectives of this study were (1) to characterize the structure of the forest; (2) estimate the contribution of tree compartments to forest biomass and (3) compare the biomass estimated from the site-specific, local and pantropical equations.

Material and methods

Study site

This study was carried out in a forest management unit (FMU) located in Belabo Sub-Division, Lom and Djerem Division in the East Region of Cameroon. This FMU initially administrated by SOFIBEL ("Société Forestière et Industrielle de Belabo") is now by decree N° 2014/0057/PM of the 05th February 2014 administrated by "La Cotière Forestière" company.

Its relief is relatively flat and does not exceed 700 m of altitude. Soils are essentially lateritic (Moby *et al.*, 1979). The climate is equatorial Guinean with two dry seasons (a major dry season from December to February and a minor dry season from July to August) and two rainy seasons (a major rainy season from September to November, a minor rainy season from March to June). Hydrography is irrigated by the Sanaga and its tributaries such as Lom, Sessé, Yasso. The annual rainfall is about 1,500 mm and the average annual temperature varies between 22-25 °C (Anonymous, 2012). The vegetation of this area belongs to the semi-deciduous dense forests marked by Sterculiaceae and Ulmaceae (Letouzey, 1985). However, the most representative commercial species of the flora are *Triplochiton scleroxylon*, *Pterocarpus sayauxii*, *Terminalia superba*, *Mansonia altissima*, *Entandophrama cylindricum*, etc.

Data collection

Inventoried data of all trees of dbh ≥ 1 cm was collected in 7 plots of 250m \times 20m. In each of these plots, 2 sub-plots of 10 \times 10 m and 10 \times 20 m were installed respectively for the individuals of diameter < 5 cm and between $5 \leq \text{dbh} < 10$ cm and the trees with dbh ≥ 10 cm were inventoried in the entire plot. The scientific, vernacular and/or commercial names of each tree were recorded and tree samples (leaves, barks, fruits) collected to confirm the identification of these species at the Yaoundé National Herbarium.

The dendrometric parameters such as diameter at breast height (dbh) and the height were measured for each tree. The dbh was measured at 1.30 m aboveground and at 30 cm above buttresses for trees having buttresses or defects above 1.30 m. The height of the trees were obtained by direct measurements for small trees and indirect measurements for big trees by the trigonometric method using the Bitterlich Relascope. Wood density was obtained from samples of trees species collected in the study area (Ngoukwa, 2016). However, for species whose wood density data was determined, their values were obtained from the "Global Wood Density Data Base" (Zanne *et al.*, 2009).

Allometric equations were used to convert the dendrometric variables of the tree collected into biomass.

Data analysis

Calculation of floristic diversity indices

The flora was stratified into three classes of diameter (< 5 cm, [5-10 [and ≥ 10 cm). For each class, the flora was characterized by the diversity indices using "Biodiversity" package of R software version 3.3.2. The diversity indices considered in this study were:

(1) the Shannon index is expressed by the formula $ISH = -\sum \frac{N_i}{N} \times \log \frac{N_i}{N}$ where N_i is the number of species i and N the total number of species in the sample. It is the most widely used index because in addition to giving more importance to rare species, it is independent of the size of the population studied.

(2) Evenness is expressed by the formula $EQ = \frac{ISH}{\log(N)}$. This index, which varies from 0 to 1, gives an idea of the distribution within the species. An EQ close to 0 reflects an unequal distribution between species and EQ close to 1 represents an even dominance of some species.

(3) Simpson's index is expressed by the formula $S = \frac{n_i(n_i-1)}{N(N-1)}$ where n_i is the frequency of species i in the sample and N is the sum of the frequencies of all species in the sample; it reports the abundance of one or a few species and expresses the probability that two individuals drawn at random from an infinite population belong to the same species.

Characterization of forest structure

The forest structure was characterized with the following parameters: mean and dominant dbh (dbh > 60 cm), mean and dominant height (dbh > 60 cm), mean and dominant basal area ($\text{m}^2 \cdot \text{ha}^{-1}$), diameter class distribution and number of stems $\cdot \text{ha}^{-1}$. The amplitude of 10 cm was used for the distribution of the diameter classes of all inventoried trees (dbh ≥ 10 cm). The basal area (SA) was calculated using the formula $SA = \frac{\pi \times D^2}{4}$ where D is the diameter (cm) and $\pi = 3.14$ and the results obtained converted per hectare using the factor $FE = \frac{10000}{Se}$ where Se is the sample area in m^2 (Brown and Pearson, 2005).

Estimation of forest biomass

The biomass of the different compartments of the tree (root, trunk and crown) was estimated using site-specific allometric equations (Djomo and Chimi, 2017). The biomass estimates was stratified according to the following diameter classes: 1 < dbh < 10, 10 ≤ dbh < 30, 30 ≤ dbh < 60, 60 ≤ dbh < 90 and dbh ≥ 90 cm. The best site-specific equations which take into account diameter, height and wood density were used to estimate trunk, crown and root biomass (Djomo and Chimi, 2017). These equations are:

$M = \exp^{(-2.931+0.896 \times \ln(D^2 \times H))}$ for the biomass of the trunk;

$M = \exp^{(-2.988+2.474 \times \ln(D)+1.652 \times \ln(\rho))}$ for the crown biomass;

$M = \exp^{(-2.217+1.042 \times \ln(D^2 \times \rho))}$ for root biomass;

The total biomass was obtained through the sum of root biomass and the aboveground biomass (trunk + crown).

Two specific equations were used for aboveground biomass estimation.

$M = \exp^{(-2.448+2.578 \times \ln(D))}$ and $M = \exp^{(-1.836+2.619 \times \ln(D)+1.268 \times \ln(\rho))}$. For these equations, M is the aboveground biomass (kg); D the diameter at breast height (cm), ρ the wood density and H the height of the tree (m).

These equations were derived from the data collected on 237 trees with dbh spanning 1-121 cm (Djomo and Chimi, 2017). The mean value of these two equations was considered as the aboveground biomass of the study area. The result obtained was compared with those of the existing local equations (Fayolle *et al.*, 2013; Ngonmanda *et al.*, 2014) and pantropical equations (Chave *et al.*, 2005; Djomo *et al.*, 2010; Chave *et al.*, 2014; Djomo *et al.*, 2016). For Djomo *et al.* (2016), two equations were considered; the first (1) for tropical rain forests in Africa and the second (2) for all forest types in tropical Africa (Table 1). The ANOVA and Turkey tests were used to compare aboveground biomass from these equations.

Results and discussion

Floristic diversity

30 species were recorded in the class of trees with dbh < 5 cm. The most abundant families in this diameter class are Fabaceae, Euphorbiaceae, Meliaceae with at least 3 species each. For class 5 ≤ dbh < 10 cm, 24 species were identified and the most abundant families are Meliaceae (4 species) and Euphorbiaceae, Anonaceae, Moraceae, Malvaceae with 3 species each. For the class of dbh ≥ 10 cm, 127 species were inventoried and the most abundant families are Meliaceae, Rubiaceae, Moraceae, Malvaceae, Euphorbiaceae.

Table 1. Allometric equations used to assess the aboveground biomass of study area. N = number of trees; Y= aboveground biomass; D= diameter of the tree (cm); H= height (cm); ρ= wood density.

Allometrics equations	Types	N	Authors
$Y = \exp^{(-2.378+0.289 \times (\ln(D))^2 - 0.037 \times (\ln(D))^3 + 0.742 \times \ln(D^2 \times H) + 0.284 \times \ln(\rho))}$	pantropical	274	Djomo <i>et al.</i> (2010)
$Y = \exp^{(-2.359+1.325 \times \ln(D)+0.469 \times \ln(D^2 \times H)+0.802 \times \ln(\rho))}$ (1)	Pantropical (moist forest)	570	Djomo <i>et al.</i> (2016)
$Y = \exp^{(-1.656+2.541 \times \ln(D)+1.112 \times \ln(\rho))}$ (2)	Pantropical (all forest type)	844	Djomo <i>et al.</i> (2016)
$Y = \rho \times \exp^{(-1.183+1.940 \times \ln(D)-0.239 \times (\ln(D))^2 - 0.029 \times (\ln(D))^3)}$	Cameroon	133	Fayolle <i>et al.</i> (2013)
$Y = \exp^{(-2.568+0.952 \times \ln(D^2 \times H)+1.189 \times \ln(\rho))}$	Gabon	101	Ngomanda <i>et al.</i> (2014)
$Y = \rho \times \exp^{(-1.499+2.148 \times \ln(D)+0.207 \times (\ln(D))^2 - 0.028 \times (\ln(D))^3)}$	pantropical	2410	Chave <i>et al.</i> (2005)
$Y = 0.0673 \times (D^2 \times H \times \rho)^{0.976}$	pantropical	4004	Chave <i>et al.</i> (2014)

The Shannon index, which varies from 2.47 for trees with dbh<5 cm to 3.88 for trees of dbh> 10 cm, shows a rich floristic diversity in the study area.

The values of the Simpson and Evenness indices are greater than 0.70 for any given diameter class (Table 2).

Table 2. Species richness, Shannon, Evenness and Simpson index.

Diameter class (cm)	Species richness	Shannon	Evenness	Simpson
< 5	30	2.47	0.73	0.85
[5-10]	24	2.83	0.88	0.90
≥ 10	127	3.88	0.80	0.96

Unlike many inventory studies carried out in forest areas in Cameroon, this study took into account the diversity of the trees with dbh<10 cm (1-10 cm). Thus, a total of 30 species of dbh<5 cm, 24 species for the class 5 ≤ dbh<10 and 127 species of dbh ≥ 10 cm was identified. This result (dbh ≥ 10 cm) is similar to the study of Djomo *et al.* (2011) who found 145 species in the tropical rainforests of South-west region of

Cameroon and those of Djomo (2015a), who obtained 105 species in the Yokadouma district in eastern region Cameroon. However, it remains lower than the 207 and 205 species inventoried respectively by Djuikouo *et al.* (2010) in *terra firme* forests of the peripheries of the Dja Wildlife Reserve and by Tabue *et al.* (2016) in the eastern part of the same reserve.

Table 3. Characterization of the forest structure.

Diameter class (cm)	Stems.ha ⁻¹	Basal area (m ² .ha ⁻¹)	Number of stems (%)	Basal area (%)
< 5	4633	2.79	80.68	6.71
[5-10[700	2.06	12.19	4.95
≥ 10	409	36.75	7.12	88.34
Total	5742	41.60	100	100

As this study was carried out in the same ecological conditions, the differences observed could be due to the methodologies used. Djuikouo *et al.* (2010) used square plots of 1 ha whereas the present study used

the rectangular plots of 250 m × 20 m. Similarly, Tabue *et al.* (2016), although using transects of 2500 m × 20 m, had a total sample area of 50 ha compared to 3.5 ha for the present study.

Table 4. Estimation of tree biomass (t.ha⁻¹)(root, trunk, crown and total).

Diameter class (cm)	Stems.ha ⁻¹	Root (t.ha ⁻¹)	Trunk (t.ha ⁻¹)	Crown (t.ha ⁻¹)	Total biomass (t.ha ⁻¹)
1<dbh< 10	5333	5	11	7	23
10 ≤ dbh< 30	273	7	33	18	58
30 ≤ dbh< 60	103	15	71	42	128
60 ≤ dbh< 90	25	15	63	44	122
dbh ≥ 90	8	13	42	35	90
Total	5742	55	220	146	421

The most abundant families Meliaceae, Malvaceae and Euphorbiaceae found in this study area corroborates those obtained by Sonké (2004) and Tabue *et al.* (2016) in the Dja reserve (Cameroon).

A better characterization of a plant population is based on the interpretation of the diversity indices (Sonké, 2004). The indices considered in this study were the specific richness, Shannon index, Evenness and Simpson index.

The high Shannon index (3.88) of this study for the diameter class ≥ 10 cm indicates a rich floristic diversity (Djuikouo *et al.*, 2010). However, Evenness and Simpson index justify the representativeness of the flora by some species according to their abundance (Sonké 2004). McElhinny *et al.* (2005) showed that diversity indices such as Shannon, Simpson and Evenness are only elements of

measurement and characterization of biodiversity, but cannot provide information's on the structure of the forest. For this reason, mean and dominant diameter, mean and dominant basal area, mean and dominance height, diameter classes distribution of the stems were used as suggested by Day *et al.* (2013), Lewis *et al.* (2013) and Djomo (2015a, 2015b), to analyze the structure of the forest.

Table 5. Biomass estimate ($t \cdot ha^{-1}$) using site-specific and other existing equations.

Diameter class (cm)	Djomoand Chimi (2017)	Chaveet al. (2005)	Chave et al. (2014)	Djomo et al. (2010)	Fayolle et al. (2013)	Ngomanda et al. (2014)	Djomo et al. (2016) moist forest	Djomo et al. (2016) all forest type
1<dbh<10	11	14	12	13	15	11	13	14
10 ≤ dbh< 30	38	49	44	54	48	35	44	42
30 ≤ dbh< 60	100	127	108	142	123	83	109	106
60 ≤ dbh< 90	112	132	106	136	129	78	114	115
dbh ≥ 90	97	101	75	92	101	54	88	96
Total	358	423	345	437	416	261	368	373

Forest structure characterization

In this study area, 5742 stems per hectare of dbh ≥ 1 cm was recorded; the abundance of these stems decreased with increasing diameter classes showing the J shape inverse (Fig. 1). The diameter class <5 cm had a high abundance of stems per hectare ($4633 N \cdot ha^{-1}$) representing 81% of all trees per hectare recorded. Despite its high abundance, this class has the lowest basal area ($2.79 m^2 \cdot ha^{-1}$) representing 6.71% of the total basal area. On the other hand, trees

of $dbh \geq 10$ cm with a low abundance ($409 N \cdot ha^{-1}$) representing 7.12% had an important basal area of $36.75 m^2 \cdot ha^{-1}$ representing 88% of the total basal area. The basal area in the entire study sample, trees with $dbh \geq 1$ cm was $41.60 m^2 \cdot ha^{-1}$ (Table 3). The mean diameter of the forest (tree with $dbh \geq 1$ cm) was 25.17 cm and the dominant diameter ($dbh > 60$ cm) 78.53 cm; this corresponds to the average height of 17.43 m, dominant height of 32.48 m and basal area of the dominant diameter of $16.95 m^2 \cdot ha^{-1}$.

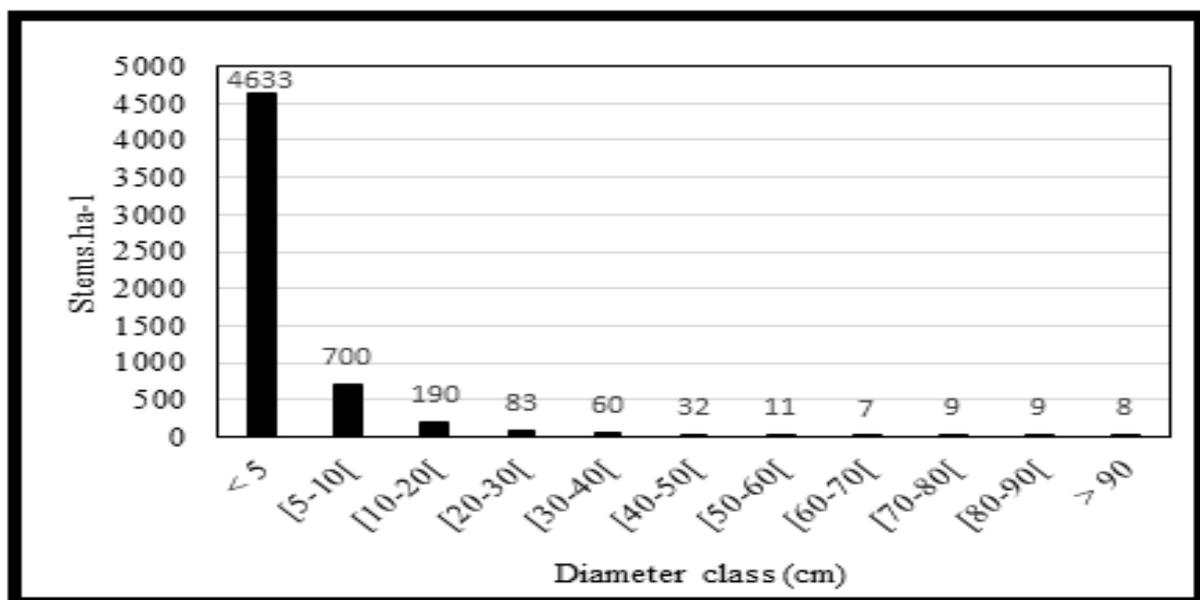


Fig. 1. Diameter distribution of the number of stems per hectare in the study area.

The forest unit in which this study was carried out has been subjected to logging activities for a long time in the past. In natural environments, after anthropogenic disturbances, the ecosystem could be reconstituted because the clearing created promotes natural regeneration through the development of the seed bank contained in the lower forest stratum or understory (Nguenang *et al.*, 2010; Jiagho *et al.*, 2016). This would explain the abundance of stems.ha⁻¹ of the diameter class <5 cm, thus favoring an important decrease in the number of stems per

hectare with increasing diameter classes. Similar results have been obtained by different authors in forest ecosystems (Djomo *et al.*, 2011; Day *et al.*, 2013; Djomo, 2015a; Tabue *et al.*, 2016). In fact, when the ecosystem is more disturbed, the number of stems per hectare in the lower classes increases (Djomo *et al.*, 2011). The density of 409 stems.ha⁻¹ for trees ≥10 cm diameter is in accordance with 426 and 460 stems.ha⁻¹ found by Lewis *et al.* (2013) and Djuikouo *et al.* (2010) in undisturbed African tropical forests and in the Dja Wildlife Reserve.

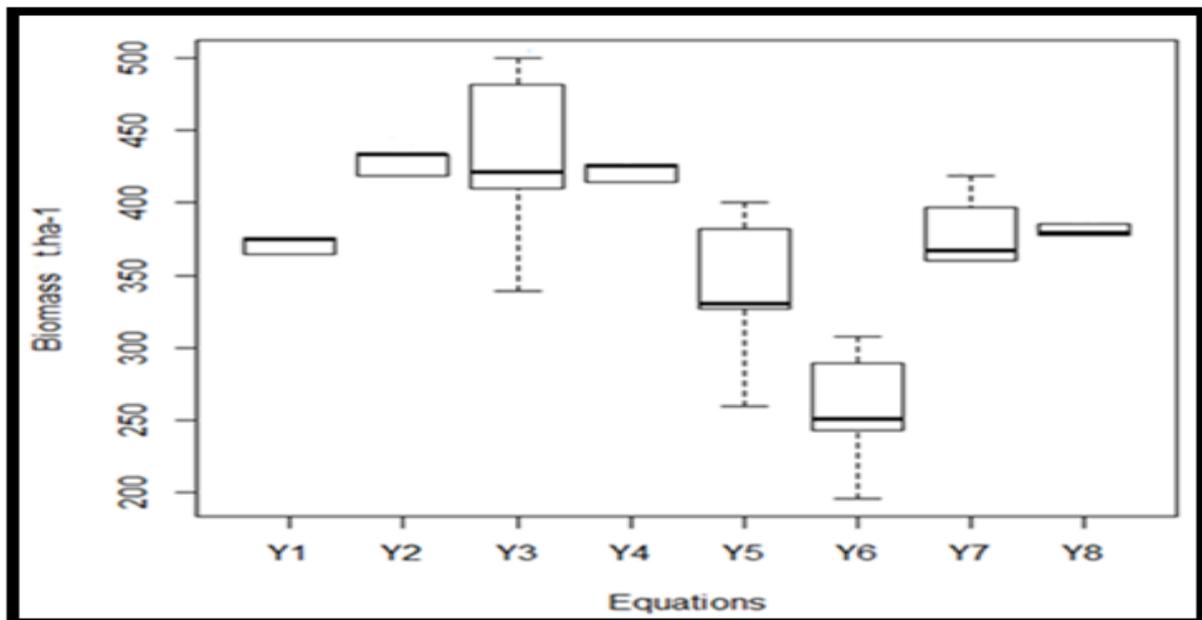


Fig. 2. Comparison of estimated biomass in relation to the 8 equations considered. Y1= Djomo and Chimi (2017); Y2= Chave *et al.* (2005); Y3=Djomo *et al.* (2010); Y4= Fayolle *et al.* (2013) ; Y5=Chave *et al.* (2014); Y6= Ngomanda *et al.* (2014); Y7= Djomo *et al.* (2016, Moist) ; Y8=Djomo *et al.* (2016, all forest type).

The basal area of the present study was 41.6 m².ha⁻¹ (dbh ≥ 1 cm and 36.75 m².ha⁻¹ (dbh ≥10 cm). This value is consistent with the 37.5 and 30.5 m².ha⁻¹ found by Djuikouo *et al.* (2010) respectively in forests dominated by *Gilbertiodendron dewevrei* and in the mainland forests of the Dja reserve, and with 35.3, 35.8 and 30.3 m².ha⁻¹ found in the communal forests of Yokadouma, Campo-Ma’an National Park and some tropical African forests respectively by Djomo (2015a), Day *et al.* (2013) and Lewis *et al.* (2013). However, this study confirms that the basal area increases with tree diameter because for small diameter classes, despite the abundance of the number of stems.ha⁻¹, the basal area is low and inversely for high diameter classes that

have a low number of stems.ha⁻¹ this value increases (Djomo, 2015a).

Biomass in tree compartments

With 220 t.ha⁻¹, the trunk biomass was the largest tree compartment (52% of total above and below), followed directly by the crown biomass 146 t.ha⁻¹(35%) and the root biomass 55 t.ha⁻¹(13%).

Based on the five diameter classes (Table 4), the biomass of the root system in the diameter classes 30 ≤ dhp < 60 and 60 ≤ dhp < 90 cm (15 t.ha⁻¹ each) was higher than in the other classes where it varied between 5 to 13 t.ha⁻¹.

The proportion of trunk biomass was similar between the class $1 \leq \text{dbh} < 10$ cm (48%) and the upper class $\text{dbh} \geq 90$ (47%); however it decreased successively for the other classes: $10 \leq \text{dbh} < 30$ (57%), $30 \leq \text{dbh} < 60$ (55%) and $60 \leq \text{dbh} < 90$ (52%). The trunk biomass is larger in the $30 \leq \text{dbh} < 60$ cm class ($71 \text{ t}\cdot\text{ha}^{-1}$).

In correlation with the trunk biomass, the proportion of crown biomass varied slightly from the lower to upper classes, ie 30%, 31%, 33%, 36%, 39% respectively in $1 \leq \text{dbh} < 10$ cm, $10 \leq \text{dbh} < 30$, $30 \leq \text{dbh} < 60$, $60 \leq \text{dbh} < 90$ and $\text{dbh} \geq 90$ cm classes. The diameter of the lowest class $1 \leq \text{dbh} < 10$ cm which represented 93% of the total number of the stems had the lowest total biomass ($23 \text{ t}\cdot\text{ha}^{-1}$); the highest total biomass was obtained in the diameter class $30 \leq \text{dbh} < 60$ cm ($128 \text{ t}\cdot\text{ha}^{-1}$). The biomass distribution of the dominant diameter class ($\text{dbh} > 60$ cm) with 33 stems. ha^{-1} was 51% (root), 48% (trunk) and 54% (crown) (Table 4).

The biomass estimated with the site-specific equations developed in the study area (Djomo and Chimi, 2017) was $358 \text{ t}\cdot\text{ha}^{-1}$. However, using this equation in tree compartments resulted to $220 \text{ t}\cdot\text{ha}^{-1}$ for the trunk biomass and $146 \text{ t}\cdot\text{ha}^{-1}$ for the crown biomass with a total above-ground of $366 \text{ t}\cdot\text{ha}^{-1}$. This difference shows that using allometric equation to estimate tree assortment may result to a sur-estimation of the total which in this case represented 2.2% of the total.

Vahedi *et al.* (2014) showed that trunk biomass has the higher contribution to the total biomass, which was consistent with the results of this study which represented 60% of the total aboveground biomass and 52% of the total (below and aboveground) biomass. Our result is also close to the value of 54% reported by Araújo *et al.* (1999) for a tropical rainforest of Brazil. This shows that logging activity removes only about 50% of the total biomass and the rest remains in the forest and will later decompose to favor carbon emission or tree growth.

The contribution of the crown estimated at 36% by Ploton *et al.* (2016) for moist tropical forests is close to 40% obtained by this study. Depending on the diameter classes, Ploton *et al.* (2016) showed that the proportion of the crown varied from 3% for small trees ($\text{dbh} < 10$ cm) to 88% for large trees ($\text{dbh} \geq 10$ cm). This study showed that this contribution of the crown to the total aboveground biomass varied from 35% for the diameter class of $10 \leq \text{dbh} < 30$ cm to 45% for the diameter class $\text{dbh} \geq 90$ cm.

Roots of trees, in addition to playing an important role in the dynamics of forest ecosystems store a quantity of carbon (Mokany *et al.*, 2006). According to Green *et al.* (2005) and Mokany *et al.* (2006), root biomass represents about a quarter of forest biomass in tropical areas. This study showed that root biomass contributes about 13% of the total biomass and the ratio of root biomass/aboveground biomass found was 0.15.

Comparing aboveground estimate with site-specific allometric equations and other existing allometric equations

Aboveground biomass varied from 261 to $437 \text{ t}\cdot\text{ha}^{-1}$ depending on the allometric equations used (Table 5); the lowest biomass estimate was obtained from Ngomanda *et al.* (2014) ($261 \text{ t}\cdot\text{ha}^{-1}$) and the highest from the equation of Djomo *et al.* (2010) ($437 \text{ t}\cdot\text{ha}^{-1}$). The biomass estimated with the site-specific equations developed in the study area (Djomo and Chimi, 2017) was $358 \text{ t}\cdot\text{ha}^{-1}$.

For diameter class $1 \leq \text{dbh} < 10$ cm, the biomass varied little according to the equations used (from 11 to $15 \text{ t}\cdot\text{ha}^{-1}$). Although having the highest abundance of stems ($5333 \text{ stems}\cdot\text{ha}^{-1}$), it is the diameter class that contributes the least to aboveground biomass (3-4%). Trees with $\text{dbh} \geq 10$ cm ($409 \text{ stems}\cdot\text{ha}^{-1}$) had a biomass representing 96-97% of the aboveground biomass depending of the equation used.

The proportion of biomass with Djomo and Chimi (2017) equation increased successively by 3%, 11%,

28% and 31% respectively for the classes of $1 \leq \text{dbh} < 10$ cm, $10 \leq \text{dbh} < 30$, $30 \leq \text{dbh} < 60$, $60 \leq \text{dbh} < 90$ cm; then decreased to 24% for the class $\text{dbh} \geq 90$ cm. The same tendency was observed with the equations of Chave *et al.* (2005), Chave *et al.* (2014), Fayolle *et al.* (2013), (1) Djomo *et al.* (2016, for tropical rainforests in Africa) and (2) Djomo *et al.* (2016, for all types of forests in tropical Africa). However, with Djomo *et al.* (2010) equation, the aboveground biomass increased for the first three diameter classes (3%, 12% and 32% corresponding to $1 \leq \text{dbh} < 10$ cm, $10 \leq \text{dbh} < 30$, $30 \leq \text{dbh} < 60$ cm classes), then decreased from 31% to 21% for classes $60 \leq \text{dbh} < 90$ cm and $\text{dbh} \geq 90$ cm. The same tendency was obtained with Ngomanda *et al.* (2014) equation where it increased from 4%, 13% to 32% for classes $1 \leq \text{dbh} < 10$ cm, $10 \leq \text{dbh} < 30$, $30 \leq \text{dbh} < 60$ cm and decreased from 30% to 21% for the classes of $60 \leq \text{dbh} < 90$ and $\text{dbh} \geq 90$ cm.

The ANOVA test showed that the aboveground biomass was significantly different depending on the equations used ($p=0.001$). Considering the samples ($\text{dbh} \geq 10\text{cm}$) as being dependent and comparing two by two the equations of the study area, we found a significant difference between Djomo *et al.* (2010) ($P=0.021$) and Ngomanda *et al.* (2014) ($p=0.000$) equations. Similarly, considering the samples ($\text{dbh} \geq 10\text{cm}$) as being dependent, we found a significant difference ($p=0.000$) between the equation of Chave *et al.* (2005), Djomo *et al.* (2010), Fayolle *et al.* (2013) and Ngomanda *et al.* (2014). There was no significant difference between the equations of this study area (Djomo and Chimi, 2017) and the equations of Chave *et al.* (2014) and Djomo *et al.* (2016) (Y7 and Y8)(Fig. 2).

According to Djomo *et al.* (2010) and Basuki *et al.* (2009), site-specific or/and species-specific allometric equations are recommended for local forest biomass estimation. However, to reduce the cost of operations and minimize the impact on environment, existing equation or pan-tropical equations are often used.

Comparing site-specific equations with other existing equations changed from no significant to significant variation (ANOVA, $p < 0.001$) depending of the equations used (Djomo *et al.*, 2011).

There was no significant difference of aboveground biomass estimate with site-specific equations and the two equations of Djomo *et al.* (2016 (Y7) and (Y8)) tested and also with the equation of Chave *et al.* (2014). This difference represented 2.8% (Djomo *et al.*, 2016 (Y7)), 4.2% (Djomo *et al.*, 2016 (Y8)) and -3.6% (Chave *et al.*, 2014) of aboveground biomass, However, there was no significant difference of aboveground estimate between site-specific equations and the equations of (Chave *et al.*, 2005), (Djomo *et al.*, 2010), (Fayolle *et al.*, 2013) and (Ngomanda *et al.*, 2014). The difference represented 18.2% (Chave *et al.*, 2005), 22.1% (Djomo *et al.*, 2010), 16.2% (Fayolle *et al.*, 2013) and -27.1% (Ngomanda *et al.*, 2014) of aboveground biomass.

In the Central Africa ecosystems, the pantropical equations of Chave *et al.* (2005) have been used to estimate aboveground biomass (e.g. Lewis *et al.*, 2009; Djuikouo *et al.*, 2010; Day *et al.*, 2013; Noiha *et al.*, 2015). The aboveground biomass estimate with this equation (Chave *et al.*, 2005) was $423 \text{ t}\cdot\text{ha}^{-1}$ which is similar to the value of $429 \text{ t}\cdot\text{ha}^{-1}$ and $401 \text{ t}\cdot\text{ha}^{-1}$ found by Lewis *et al.* (2013) in some forests of Central Africa and by Djuikouo *et al.* (2010) in the forests of the Dja Wildlife Reserve which were estimated with the same equation (Chave *et al.*, 2005).

These authors considered the trees of $\text{dbh} \geq 10$ cm whereas this present study considered all the trees of $\text{dbh} \geq 1$ cm; the contribution of dbh trees < 10 cm was $14 \text{ t}\cdot\text{ha}^{-1}$. Also, it is important to notice that aboveground biomass estimate with site-specific allometric equation was $358 \text{ t}\cdot\text{ha}^{-1}$ which is lower than $423 \text{ t}\cdot\text{ha}^{-1}$ obtained with Chave *et al.* (2005). This suggests that there might be an overestimation of biomass using this equation of Chave *et al.* (2005) which should be corrected using the site-specific

equation or Djomo *et al.* (2016) (Y7) for moist forest which gave the same precision with the equation developed for this site.

Conclusion

Human intervention on the forest cover for decades altered its structure; however, this forest remains an important ecological area due to the rich floristic biodiversity that it contains. In addition, the abundance of dbh < 5 cm trees which represents up to 81% of the number of stems.ha⁻¹ confirms the fact that this area was subsequently subjected to logging. The root biomass that is most often not included in the forest carbon estimation due to the difficulties associated with its collection represented in average 13% of the total forest biomass. The dominant diameter class (dbh > 60 cm), despite their low abundance (33 stems.ha⁻¹) represented 52% of the forest biomass. The choice of the equation used for biomass estimation is essential for the reliability of the results.

The aboveground biomass obtained from 8 equations considered varied from 261 t.ha⁻¹ to 437 t.ha⁻¹. The site-specific equation is the most recommended when it is well-developed. This study recommends in the absence of reliable local equations to use the allometric equation Y7 or to make the arithmetic mean of the equation Y7, which has a difference of + 2.8% and the equation Y2 which has a difference of - 3.6% to improve the accuracy.

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