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Allometric equation for the commonest palm in the Central Congo Peatlands, *Raphia laurentii* De Wild.

Yannick Enock Bocko[1*], Grace Jopaul Loubota Panzou[1,2], Greta Christina Dargie[3], Yeto Emmanuel Wenina Mampouya[4], Mackline Mbemba[4], Jean Joël Loumeto[1], Simon L. Lewis[3,5]

[1]Laboratoire de Biodiversité, de Gestion des Ecosystèmes et de l'Environnement, Faculté des Sciences et techniques, Université Marien Ngouabi, République du Congo.

[2]Forest is life, Gembloux Agro-Bio Tech (Liège Université), Gembloux (Belgique).

[3]School of Geography, University of Leeds, Leeds.

[4]Ecole Nationale Supérieure d'Agronomie et de Foresterie, Université Marien Ngouabi, République du Congo.

[5]Department of Geography, University College London.

* Corresponding author

Email: byannickenock@gmail.com (YEB)

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Abstract

The world's largest tropical peatland lies in the central Congo Basin. *Raphia laurentii* De Wild. is a palm which forms dominant to mono-dominant stands across ca. 45 % of the peatland area. However, a lack of allometric equation for this canopy-forming trunkless palm with fronds up to 20 m long, means that this it is currently excluded from aboveground biomass (*AGB*) estimates for these peatland ecosystems. Here we develop an allometric equation for *R. laurentii*, by destructively sampling 90 *R. laurentii* stipes (across six mean petiole diameter size classes of: 2-4 cm, 4-5 cm, 5-6 cm, 6-7 cm, >8 cm) in a peat swamp forest, in the Likouala Department, Republic of the Congo. Prior to destructive sampling, the five parameters were measured for each stipe: diameter at stem base, mean diameter of the palm fronds, total diameter of the palm fronds (TD_{pf}), total height and number of palm fronds. After destructive sampling and before weighing each individual was separated into the stem and the following palm frond categories: sheath, petiole, rachis and leaflets. We fitted a linear model relating *AGB* to each independent predictor variable separately to assess the best variable, finding that palm fronds represented at least 77 % of the total *AGB* in each diameter classes. We found that TD_{pf} was the best single predictor variable for *R. laurentii AGB*. We provide a series of equations, based on sampling *R. laurentii* with fronds ≥2 cm diameter or ≥5 cm diameters. The best allometric equation was: $AGB = Exp(-2.691 + 1.425 \times \ln(TD_{pf}) + 0.695 \times \ln(H) + 0.395 \times \ln(WD)$. A monodominant 1 ha plot near the harvesting site had a palm AGB of 60.8 Mg ha^{-1}, similar to the *AGB* of the trees in the same plot, at 86.2 Mg ha^{-1}. Accounting for the *AGB* of palms is important, and can now be estimated using the allometric equations developed here.

Keywords: *Congo Basin, peat swamp forest, Raphia laurentii, allometric equation, aboveground biomass*

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Introduction

Improved estimates of the carbon stocks and flows in tropical ecosystems is critical to estimating carbon loss from land-use change, and carbon uptake in remaining ecosystems [1]. For example, the implementation of REDD+ (reducing emissions from deforestation and forest degradation) in tropical countries is crucial for climate change mitigation [2]. Each country engaged in the REDD+ process must provide information on their REDD+ strategies and carbon reference levels [3]. However, information on reference levels requires accurate estimates of the biomass, and therefore the carbon stock, of the different forest types and carbon pools: vegetation (dicotyledon and monocotyledon), coarse woody debris, litter and soil.

For the countries of the Congo Basin establishing carbon reference levels is hindered by a scarcity of data. This is particularly true for swamp forest ecosystems. The peatlands of the Cuvette Centrale Congo Basin are estimated to cover 145,500 km^2 and store 30.6 Pg C belowground in the peat [4]. However, *in situ* data on aboveground biomass from these peatland ecosystems is rare [4–6]. Furthermore, these utilise the allometric equations available to estimate the biomass of trees, but these were developed using data from terra firme forests. Additionally, across ca. 45% of these peatlands the palm species *Raphia laurentii* De Wild [4] forms dominant or monodominant stands, but at present there is no obvious allometric equation which can be applied to *R. laurentii*. Hence in past estimates of central Congo peat swamp aboveground biomass palms have been excluded, leading to a systematic bias and underestimation [4–6]. This neglect follows a pattern, as globally, the contribution of palms to forest biomass and productivity is a neglected area of study, and therefore a source of uncertainty in forest carbon stocks and dynamics [7]. This extends to African tropical forests, where *R. laurentii* is likely to be one of the most abundant palm species in the Congo Basin.

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One potential solution to the lack of an allometric equation for *R. laurentii* is to use an allometric equation from a palm from elsewhere in the tropics, as the use of a dicot allometric model for the estimation of the above-ground biomass of a monocot species has been found to be highly inadequate [8,9]. Whilst some allometric equations have been developed for Amazonian [9,10] and Asian [11,12] palm species, these are morphologically dissimilar to the trunkless *R. laurentii*. Generally, in monocot species, using a species-specific allometric model is better than using a multispecies model [9]. Therefore, the development of an allometric equation for what is probably the dominant canopy plant in the world's largest tropical peatland complex, *R. laurentii*, is a fundamental contribution to understanding the carbon cycle in these peatland ecosystems. Without this information to inform sustainable land management policies, the peatlands are at risk from inappropriate development, which could have serious consequences for the region [13].

By linking the aboveground biomass (AGB) of a species to certain physical parameters that can be measured in the field [14], allometric equations permit the AGB of a species to be estimated non-destructively. The physical parameters that can be used to establish an allometric equation are numerous and differ depending on the species. Diameter at breast height (DBH), wood density, height [15] and crown diameter [16] are, in descending order, the most important physical parameters in the estimation of the biomass of a dicotyledonous species. By contrast, for monocots, depending on the architectural type of the stem, number of palm fronds, dry mass fraction, wood density, DBH, diameter at the base of the stem, crown diameter, total height and stem height are often used as physical parameters [8,17,18]. For palms in particular, height and diameter (at the base or at breast height) are the most important physical parameters for estimating above-ground biomass, although it is unclear if this would apply to trunkless palms as well [11,18].

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97 To address the lack of palm allometry for the commonest canopy plant in the central
98 Congo peatlands, the aim of this study is to develop an allometric equation for the monocot
99 species *R. laurentii*, in order to improve the biomass and aboveground carbon stock estimates
100 of the peat swamp forests of the Congo Basin.
101

102 Material and Methods

103 Study area

104 Fieldwork for this study was carried out in February 2019 in the Likouala Department,
105 Republic of the Congo. The study site is located near to the village of Bolembe (1.190288N
106 and 17.84239E; Fig. 1) in a peat swamp forest which occupies an interfluvial basin, extending
107 ~60 km between the black-water Likouala-aux-herbes River and the white-water Ubangui
108 River [19]. The mean annual temperature and precipitation are respectively 25.6 °C and
109 1556.5 mm [20]. The peatland is shallowly domed [19] and the vegetation is composed of two
110 communities; one dominated by dicotyledons such as *Carapa procera* DC., *Symphonia*
111 *globulifera* L. f., *Uapaca mole* Pax, *Grosera macranta* Pax, *Manilkara fouillonna* Aubrev. &
112 Pellegr. and *Drypetes occidentalis* (Mull. Arg.) Hutch., termed hardwood-dominated peat
113 swamp vegetation; the other by monocotyledons such as *Raphia laurentii*, *Aframomum*
114 *angustifolium* (Sonn.) K. Schum. and *Pondanus candelabrum* P. Beauv., termed palm-
115 dominated peat swamp vegetation [4,21,22], with a gradation between these two vegetation
116 types often spanning many kilometres. The fieldwork was conducted in a palm-rich area of
117 swamp forest overlying ~2 m of peat (Fig 1).

118 **Fig 1. Location of the study area**

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Palm selection and sampling

Biomass allometry consists of predicting biomass from easily measurable variables [14]. Botanical characterisation of *R. laurentii* by [23] revealed it to be a cespitose palm (multiple shoots from the same root system) with 4 to 6 stipes (i.e. short trunks) up to 20 cm in diameter. A stipe can have a maximum of 10 palm fronds (each comprising a sheath of c. 1 m in length, a petiole c. 4 m in length and a rachis c. 3 to 4 m in length). Their architecture and their evolution in a compact clump makes it difficult to measure the diameter at the base of the stem or at 1.30 m from the ground. Thus, in order to select palms for destructive harvest across the size-range of the species to construct a robust allometric equation, palm frond diameter data were collected in five subplots (0.04 ha) of a permanently installed plot (1 ha), in a *R. laurentii* dominated forest, called EKG-03, located at (1.191998N, 17.84693E). in February 2019. The diameter of each palm frond was measured using callipers between the sheath and petiole at 1.30 m from the ground where possible or, when it was inaccessible at this point, slightly above 1.30 m. Petiole diameter varied between 2 and 11.5 cm, both between and within *R. laurentii* stipes. Based on the average petiole diameter for each palm stipe, we grouped the palms stipes into six mean petiole diameter classes: [2-4 cm], [4-5 cm], [5-6 cm], [6-7 cm], [7-8 cm] and ≥8 cm. For each mean petiole diameter class we then selected 15 stipes, each with at least three palm fronds, to be destructively samples outside the permanent plot, giving a total of 90 *R. laurentii* stipes.

Prior to felling, for each *R. laurentii* stipe the palm location was recorded with a global positioning system (GPS), the number of live palm fronds was counted [24] and the diameter at the base of the stem was taken approximately 13 cm from the ground [11]. The total height, defined as the length from the base of the stem to the apical meristem [10], was measured

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using a vertex. The diameter of each palm frond was measured on the petiole at 1.30 m from the ground or above 1.30 m at levels as low as possible on the petiole but avoiding the sheath, using a calliper.

Destructive sampling and biomass data

Destructive sampling was carried out using a chainsaw (manufacturer: STIHL; model: MS780). We then measured the length of the felling section at the apical meristem as well as the height of the hinge, before separating each palm frond from the stem via the chainsaw at the base of the sheath. Each stipe of *R. laurentii* was then divided into stem (including the base of the sheath) and palm frond [18,25] components. Each palm frond was further subdivided into four parts: sheath, petiole, rachis and leaflets. The leaflets were detached from the rachis using a machete. The fresh mass (kg) of each palm frond part was weighed in the field using a hand-held balance and the lengths of the sheath, petiole and rachis were measured (Fig 2A). From each *R. laurentii* stipe, three palm fronds were selected and from these fronds five 15 cm samples [12] were collected from the middle of the sheath, the middle of the petiole, at the base of the rachis, the middle of the rachis and the top of the rachis (Fig 2B). A single sample was taken from the leaflets (a minimum of 400 g; Figure 2C), giving a total of 18 samples per *R. laurentii* stipe. For the stem, the length was measured, before we cut it into sections to allow the fresh mass (kg) to be weighed in the field using a hand-held balance with a 300 kg capacity. For each stipe, three discs of 5 cm were collected from the base, the middle and the top of each stem (Fig 2D), weighed with a 1 or 5 kg capacity balance before being sealed in plastic and transported to the laboratory.

In the laboratory, all samples from the stem and palm fronds were weighed in their plastic bags using a suspended 6.2 kg capacity precision balance (Fig 2E). The mass (g) of each plastic bag was then subtracted. The volume (cm^3) of each stem, sheath, petiole and

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rachis sample was measured by hydrostatic weighing (Fig 2F; [26]). All samples were air dried (Fig 2G) before being oven drying at 65 °C (for leaflets) and 101 °C (for the stem, sheath, petiole and rachis; Fig 2H). to constant mass (g) [26].

The wood density (WD) of each sample was calculated as dry mass divided by volume, in units of g cm^{-3} [27]. The mean dry mass/fresh mass ratio of each sample of the stem, sheaths, petioles, rachis and the leaflet was used to convert the fresh mass weighed in the field, to dry mass (kg). The total biomass of each *R. laurentii* stipe was calculated by summing the dry mass (kg) of the stem, sheaths, petioles, rachis and the leaflets.

Fig 2. Illustration of field and laboratory data collection. Measurement of the fresh weight of part of the palm (A), samples taken from a palm (B), samples from leaflets (C), samples taken from the stem (D), measurement of fresh mass precision in the laboratory (E), measurement of green volume (F), sun drying (G) and oven drying (H). b_1 : the middle of the sheath, b_2 : the middle of the petiole, b_3 : the base of the rachis, b_4 : the middle of the rachis, b_5 : the top of the rachis, d_1 : the base of the stem, d_2 : the middle of the stem and d_3 : the top of the stem.

Allometric modelling and evaluating

The power function has been analysed and is often considered as the best functional form model for modelling aboveground biomass prediction in the Congo Basin tropical forest [28], and has been considered the best form for palms in the Amazon [10] and more broadly for tropical forest trees [29]. Therefore, the allometric model of the power function form suggested by Parresol [30] was selected for this study:

$$AGB_{est} = a \times P_1^b \times P_2^c \times P_3^d \quad [1]$$

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194 Where AGB_{est} is the aboveground biomass estimate of the palm stipe, P_1, P_2 and P_3 are the
195 independent predictor variables, a is the allometric coefficient and b, c and d are the
196 allometric exponents. The variables were transformed into a natural logarithm, owing to the
197 data being heteroscedastic [27,31], and the model was then written as follows:

198 $$\ln(AGB_{est}) = \ln(a) + b \times \ln(P_1) + c \times \ln(P_2) + d \times \ln(P_3) \quad [2]$$

199 The systematic biases introduced by the logarithmic transformation were corrected using the
200 correction factor defined below [15]:

201 $$CF = e^{(RSE^2/2)} \quad [3]$$

202 Where CF is the correction factor and RSE ($\sqrt{\frac{1}{n-p}\sum_{i=1}^{n}\varepsilon_i^2}$) is the residual standard error of the
203 linear model. Where n is the sample size, p is the total number of predictor variables in the
204 model and □ is an error term. The independent predictor variables of the AGB were grouped
205 into three types of parameters: coarseness parameter (diameter at stem base (D), mean
206 diameter of the palm fronds (MD_{pf}) and the total diameter of the palm fronds (TD_{pf})), a height
207 parameter (total height (H) of the palm) and the parameters intrinsic to each palm stipe (wood
208 density (WD) and number of palm fronds (N_{pf})). In order to select the best predictor variable,
209 we fitted a linear model relating AGB to each independent predictor variable separately [32].
210 The tested linear model assumed $c = d = 0$ and Equation 2 was written as follows:

211 $$\ln(AGB_{est}) = \ln(a) + b \times \ln(P_1) \quad [4]$$

212 The best predictor variable was selected according the RSE and the Coefficient of
213 Determination (R^2). Afterwards, two types of a linear model were built. The first type
214 assumed $d = 0$ when the best predictor variable (P_1) was combined with one other predictor

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variable belonging to another type parameter (for example: *D with H, D with WD*, MD_{pf} with WD, TD_{pf} with N_{pf}):

$$\ln(AGB_{est}) = \ln(a) + b \times \ln(P_1) + c \times \ln(P_2) \quad [5]$$

The second type of linear model included three predictor variables (the best with two other predictor variables) and assumed *b*, *c* and *d* were different to zero (equation 2).

Data analysis

All statistical analyses were carried out with the R software package (http://www.r-project.org/). The *AIC*, the *RSE*, the R^2_{adj}, the Roots Mean Square Error ($RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(AGB_{est} - AGB_{obs})^2}$) and the Bias prediction ($Bias\% = \frac{1}{n}\sum_{i=1}^{n}[(AGB_{est} - AGB_{observed})/AGB_{observed}]$) were used for the evaluation of established models [26]. Linear models with higher R^2_{adj}, smaller *AIC, RSE, Bias* and *RMSE*, and significant coefficients and *p-value* ($p < 0.05$) were selected as the best-fitted aboveground biomass allometric equations [33].

We also estimated the AGB of two 1 ha plots, the palm-dominated peat swamp forest plot EKG-03, and a hardwood dominated peat swamp forest, EKG-02, to show the impact of including R. *laurentii* in AGB estimates. All tress ≥10 cm diameter using standard protocols (Lewis et al. 2013). For palms the number of living fronds was counted and the diameter at the base of each stipe was measured where possible. To estimate the AGB of the trees, the equation of Chave et al. [29] using *D*, ρ and *E* was used to estimate the aboveground biomass of each tree, with ρ *from* $g.cm^{-3}$ *and D from cm*. For the AGB of *R. laurentii* stipe we used one of the developed models, using palm frond number only. The quantification of the percentage difference in the biomass estimate of the two plots was done between the total biomass (trees

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and palm) and the tree biomass ($\% \, Difference = \frac{(\text{Biomass of Trees+palm}) - (\text{Biomass of trees})}{(\text{Biomasse of trees})} \times 100$).

Results

Aboveground biomass partitioning

The average number of fronds per stipe was 5.7±0.22 (mean±SE), with a range of 3–11 fronds (n=90). The length of these fronds was 13.30±0.41 with a range of 5.13–21.20 m. The diameter at the base of the stipe was 21.67±0.73 with a range of 8.20 – 35.40 cm. The sum (total) of the petiole (frond) diameters was 37.57±2.67 cm, with a range of 7.20–125.40 cm and the average diameter of fronds per stipe was 6.01±0.22 cm with a range of 2.22–12.54 cm. The average of the total height per stipe was 13.30±0.41 m, with a range of 5.13–21.20 m. The minimum, maximum and average values of wood density, dry mass/fresh mass ratio and aboveground biomass of the individual parts of the 90 stipes of *R. laurentii* are presented in Table 1. The tissue density was low compared to trees, ranging from 0.15 to 0.38 g/cm^3, with an average value of 0.24±0.003 g/cm^3 and was approximately constant between the palm stem compartments and the palm fronds compartments (Table 1). The dry mass/fresh mass ratio varied from 0.16 to 0.55, with a mean value of 0.37±0.01 and was significantly different (P-value < 0.001) between the stem and the palm frond compartments.

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Table 1. Physical characteristics (Mean±SE [Min–Max] value) of the 90 stipes of *R. laurentii* felled in the peat swamp forest, Likouala Department, Republic of the Congo.

Variables	Stipe compartments			Palm frond compartments		
	Stem	Palm frond	Sheath	Petiole	Rachis	Leaflet
length (m)	1.43±0.11 [0.37–4.56]	11.65±0.17 [1.46–19.46]	1.12±0.02 [0.20–2.75]	4.11±0.08 [0.07–8.26]	6.58±0.10 [0.43–12.58]	–
Wood density (g/cm^3)	0.21±0.005 [0.15–0.36]	0.25±0.003 [0.15–0.38]	0.26±0.004 [0.17–0.38]	0.21±0.003 [0.15–0.28]	0.28±0.004 [0.21–0.38]	–
Dry mass / fresh mass	0.22±0.004 [0.16–0.35]	0.40±0.005 [0.20–0.55]	0.30±0.004 [0.20–0.40]	0.42±0.004 [0.30–0.55]	0.48±0.003 [0.39–0.55]	0.45±0.004 [0.35–0.56]
AGB (kg)	11.26±2.05 [0.18–106.02]	44.93±5.36 [1.85–280.32]	8.01±1.11 [0.39–51.15]	15.03±1.53 [0.17–68.87]	9.75±1.37 [0.25–75.3]	12.14±1.48 [0.67–89.98]

The average aboveground biomass of the stem compartment (11.26±2.05 kg) was lower than that of the palm fronds (44.93±5.36). The allocation of biomass between each component (i.e., stem, sheath, petiole, rachis and leaflets) was approximately constant between mean petiole diameter classes (Fig 3). Palm frond compartments accounted for more than 77 % of the aboveground biomass in all mean petiole diameter classes (with the stem

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accounting for between 10–23 % of the total biomass). On average the petiole accounted for the largest proportion of biomass (30.17 %) followed by leaflets (25.17 %), rachis (16 %), stem (14.83 %) and sheath (13.83 %). While the proportion of rachis biomass increases with increasing mean stipe diameter classes, the proportion of leaflet biomass decreases (Fig 3).

Fig 3. Aboveground biomass distribution among the stem, sheath, petiole, rachis and leaflet for each mean diameter class of the palm frond for the 90 individual *R. laurentii* sampled.

Palm frond *AGB* was significantly higher than the stem AGB in a stipe of *R. laurentii* (kruskal.test P-value < 0.001; Fig 4a). AGB increased with increasing mean petiole diameter class (Fig 4b).

Fig 4. Variability of aboveground biomass between palm compartments (a) and diameter classes (b).

Allometric equations for AGB estimation

In the analyses where only single predictor variables were used to estimate AGB and petioles ≥2 cm were included in the analysis, TD_{pf} was found to be the best single predictor, followed by MD_{pf}, D, H and N_{pf} respectively, with all five variables showing a strong relationship with AGB (Fig 5a-e).

Fig 5. Allometric relationships between the aboveground biomass of *R. laurentii* stipe and each predictor variable.

Only *WD* showed a very weak relationship with *AGB*. The full list of equations is given in Table 2. Thus, when only one predictor variable was used, model 1 (m1), using $TD_{pf,}$ was the best model (Table 2). Yet, the inclusion of other predictor variables (particularly H)

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295 significantly improved the goodness fit of the models, with the exception of N_{pf} or *WD* (Table
296 2). In fact, the combination of TD_{pf} with *H* increased the R^2_{adj} and significantly decreased the
297 *AIC, RSE, RMSE* and *Bias*, compared to the models which used TD_{pf} in combination with N_{pf}
298 (m5) or *WD* (m6). When three predictor variables were used in the linear model, the fit was
299 slightly improved. The best R^2_{adj}, *AIC* and *RSE* values included the variables TD_{pf}, *H* and *WD*,
300 m11 in Table 2, in the following formula:

301 $$AGB_{est} = e^{-2.691 + 1.425 \times ln(TD_{pf}) + 0.695 \times \ln(H) + 0.395 \times ln\,(WD)} \times 1.01 \quad [6]$$

302 When only individuals with palm frond diameters greater than or equal to 5cm were
303 used for model establishment, the TD_{pf} was the best predictor variable, followed by the N_{pf},
304 MD_{pf}, *D* and *H*. The *WD* was again the single worst predictor variable of the aboveground
305 biomass. Thus, m16 can be used for an estimate of the biomass in the absence of the total
306 diameter of the palm fronds. But when the TD_{pf}, N_{pf}, MD_{pf}, *D*, *H* and *WD* are available, the
307 best model using more than one parameter is m18 (Table 2). However, m11 and m18 tend to
308 underestimate *AGB* for largest *R. laurentii* individuals (Fig 6).

309 **Fig 6. Goodness prediction of aboveground biomass (*AGB*) of model 11 and model 18**.
310 Mean relative error on *AGB* ($\boldsymbol{Error = [(AGB_{est} - AGB_{obs})/AGB_{obs}] \times 100}$) for *AGB*
311 classes.

312 The fastest and most cost-effective field method for estimating the *AGB* of *R. laurentii*
313 stipes is counting palm fronds and using the single parameter equation, N_{pf}, model 5 or model
314 16 in Table 2, for fronds ≥2 cm or ≥5 cm respectively. Therefore, the contribution of the AGB
315 of *R. laurentii* stipes was assessed using model 16, on two 1 ha plots, the hardwood-
316 dominated peat swamp forest EKG-02 and the palm-dominated peat swamp forest EKG-03.
317 The contribution of *R. laurentii* individuals to the total above-ground biomass estimate was
318 8% and 41% for the tree-dominated EKG-02 and *R. laurentii* dominated EKG-03 plots,

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319 respectively. The percentage difference in biomass estimation between total above-ground
320 biomass and above-ground biomass of trees was 9% and 71%, for the tree-dominated and *R.*
321 *laurentii* dominated plot, respectively (Fig. 7).

322 **Fig 7. The contribution of the AGB of Raphia individuals in the total estimation of**
323 **aboveground biomass carbon in the Congo Peatland.**

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344 **Table 2. Allometric equation fitted to estimate aboveground biomass (*AGB*: in kg of dry mass) of *Raphia laurentii* stipe in Congo Basin**

Models		Coefficient and exponent estimate				Performance criteria					Diameter range (n)
N°	Formula	*a*	*b*	*c*	*d*	R^2_{adj}	*RSE*	*AIC*	*RMSE*	*Bias*	
m1	$ln(AGB) = a + b \times ln(TD_{pf})$	-2.496	1.727	NA	NA	0.97	0.21	-19.48	15.44	0.02	
m2	$ln(AGB) = a + b \times ln\,(D)$	-6,308	3,211	NA	NA	0,86	0,44	113,53	39.28	-4.58	
m3	$ln(AGB) = a + b \times ln\,(MD_{pf})$	-1,777	2,993	NA	NA	0,92	0,35	69,6	28.77	-5.59	
m4	$ln(AGB) = a + b \times ln\,(H)$	-5,262	3,404	NA	NA	0,82	0,5	136,13	38.51	-5.55	
m5	$ln(AGB) = a + b \times ln\,(N_{pf})$	-1,837	3,108	NA	NA	0,79	0,55	151,96	37.73	8.61	
m6	$ln(AGB) = a + b \times ln\,(WD)$	7,792	3,206	NA	NA	0,07	1,15	285,26	66.88	8.78	[2-15 cm
m7	$ln(AGB) = a + b \times ln(TD_{pf}) + c \times ln\,(H)$	-3.318	1.431	0.721	NA	0.98	0.18	-46.25	15.37	-1.54	
m8	$ln(AGB) = a + b \times ln(TD_{pf}) + c \times ln\,(N_{pf})$	-2.431	2.087	-0.769	NA	0.97	0.19	-37.86	15.97	-2.01	
m9	$ln(AGB) = a + b \times ln(TD_{pf}) + c \times ln\,(WD)$	-1.751	1.707	0.493	NA	0.97	0.21	-23.09	15.93	0.22	
m10	$ln(AGB) = a + b \times ln(TD_{pf}) + c \times ln(H) + d \times ln\,(N_{pf})$	-3.084	1.683	0.544	-0.383	0.98	0.18	-48.54	15.45	-2.19	
m11	$ln(AGB) = a + b \times ln(TD_{pf}) + c \times ln(H) + d \times ln\,(WD)$	-2.691	1.425	0.695	0.395	0.98	0.18	-49.15	15.71	-1.55	
m12	$ln(AGB) = a + b \times ln(TD_{pf})$	-2.238	1.662	NA	NA	0.94	0.19	-24.05	19.95	-1.67	
m13	$ln(AGB) = a + b \times ln\,(D)$	-5.737	3.048	NA	NA	0.69	0.45	77.3	48.07	-3.76	
m14	$ln(AGB) = a + b \times ln\,(MD_{pf})$	-2.573	3.4	NA	NA	0.77	0.39	59.84	33.89	-5.59	
m15	$ln(AGB) = a + b \times ln\,(H)$	-5.027	3.349	NA	NA	0.64	0.48	86.29	45.59	0.27	
m16	$ln(AGB) = a + b \times ln\,(N_{pf})$	-0.272	2.353	NA	NA	0.8	0.36	50.73	41.86	-2.59	[5-15 cm
m17	$ln(AGB) = a + b \times ln\,(WD)$	6.075	1.497	NA	NA	0.03	0.79	145.41	72.19	-1.24	[(60)
m18	$ln(AGB) = a + b \times ln(TD_{pf}) + c \times ln\,(H)$	-3.37	1.44	0.729	NA	0.96	0.17	-38.32	18.41	-1.25	
m19	$ln(AGB) = a + b \times ln(TD_{pf}) + c \times ln\,(N_{pf})$	-2.478	1.964	-0.491	NA	0.95	0.19	-26.25	18.69	-1.16	
m20	$ln(AGB) = a + b \times ln(TD_{pf}) + c \times ln\,(WD)$	-1.92	1.653	0.209	NA	0.94	0.19	-22.89	19.99	-1.56	
m21	$ln(AGB) = a + b \times ln(TD_{pf}) + c \times ln(H) + d \times ln\,(N_{pf})$	-3.375	1.559	0.678	-0.169	0.95	0.17	-36.87	18.06	-1.43	
m22	$ln(AGB) = a + b \times ln(TD_{pf}) + c \times ln(H) + d \times ln\,(WD)$	-3.232	1.44	0.718	0.08	0.95	0.17	-36	18.44	-1.24	

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Discussion

Aboveground biomass partition

Analysis of the distribution of aboveground biomass (*AGB*) between the different compartments of an individual of *R. laurentii* showed that the palm fronds represented at least 77 % of the total *AGB* in each diameter classes selected for the present study. This distribution of AGB between the stem and the palm fronds of *R. laurentii* was contrary to that observed for *Euterpe precatoria* Mart. (81 % in the stem) in the Amazonian Basin [10] and *Elaeis guineensis* Jacq. (73 % in the stem) in the Congo Basin [34] . This difference in biomass allocation can be linked to the architecture which differs from one type of palm to another [8,10]. Some palm species have a simple architecture, such as *Euterpe precatoria*, *Elaeis guineensis*, *Raphia hookeri* G. Mann and H. Wendl., *Cocos nucifera* L., *Hyphaene guineensis* Schumach. & Thonn., *Areca cotechu* L., which also makes it possible to estimate the stem height and the total palm height. Others, on the other hand, have a more complex architecture, such as *R. laurentii* and *Raphia monbuttorum* Drude [23]. For the latter, the presence of both living and dead fronds around the stem means that often the stem is not visible, impeding the measurement of its height. Practially, this means allometries which include frond measurements are superior to those including height. For *R. laurentii* the practical allometry must include the fronds. The distribution of biomass between sheath, petiole, rachis and leaflets also varies from one palm species to another. In this study, the biomass of the petioles and leaflets were greater than that of the rachis, which is contrary to the findings of [34] for *Elaeis guineensis*, where the biomass of the rachis (13.53%) was greater than that of the petioles (7.95%) and leaflets (6.02%). This difference can be attributed to the length and diameter of the petioles and also the consistency and number of pairs of leaflets which differ between palm species. For *Elaeis guineensis*, Sosef et al. [23] report petiole lengths of only 1–

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1.25 m, with rachis lengths up to 8 m. Our results revealed that the length and diameter of the petioles of *R. laurentii* ranged from 0.07 – 8.26 m to 2.22–12.54 cm, respectively with a rachis length ranging from 0.43–12.58 m (Table 1). Thus the total length of a palm frond, including the petiole and the rachis is up to 19 m. The allows *R. laurentii* to contribute to the canopy in the swamp forests where it dominates, as there are relatively few trees (83 trees ≥10 cm diameter ha^{-1} in EKG-03), which are of modest size (mean diameter 10 cm, maximum 95.5 cm).

Allometric equation for AGB estimation

We found that the best estimates of *R. laurentii AGB* were obtained when TD_{pf}, *H* and *WD* were included as variables in the model (m11; Table 2). However, single variable models, using either TD_{pf}, MD_{pf}, *D, H or* N_{pf} also performed well when estimating *R. laurentii* AGB, with TD_{pf} as the best single variable to predict *AGB* (Table 2). *WD* was the only variable which was not suitable for predicting *R. laurentii AGB* in a single variable model. The finding that TD_{pf} was the best predictor variable of *R. laurentii AGB,* differs from the findings of other palm allometry studies and highlights the need for a *R. laurentii* specific allometric equation. For example both [18] and [11] found palm height was the best predictor variable of *AGB* for nine Amazonian palm species and for *Areca catechu* L. in Papua New Guinea, respectively. Whilst our results showed the inclusion of stem height improved *AGB* estimates, as a single predictor variable it was not the most suitable.

We therefore recommend, that when height data is available, m11, which uses TD_{pf}, *H* and *WD* as variables, is used to estimate *R. laurnentii AGB.* Rather than sampling *WD* in the field, users of our allometric equation could use the *WD* values we provide in Table A1.

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393 However, owing to the tendency of m11 to underestimate the *AGB* of larger *R. laurentii*
394 individuals, we recommend that m18, which includes the same variables but includes only
395 stipes with palm frond diameters ≥ 5cm, is used for larger individuals.

396 The increase in AGB estimates for the two forest plots used in this study, particularly
397 the palm-dominated plot, when estimates of *R. laurentii* biomass were included using m16,
398 highlights the importance of including palms in aboveground biomass estimates. All the
399 models we have developed here, (with exception of the simple linear *WD* model) permit us to
400 estimate the AGB of *R. launrentii*, even when only very simple field measurements, such as
401 the number of palm fronds per individual, are available.

402 If palm-rich peat swamp forest occupies 65,475 km^2 of peatland in the central Congo
403 Basin [4]. using our estimate of 30.4 Mg C ha^{-1} for the palm-dominated plot, we estimate that
404 ~1.99 million tonnes of carbon is stored aboveground in *R. launrentii* across the region.
405 Prolific across the swamp forests of the Congo Basin, the inclusion of accurate estimations of
406 *R. laurentii* palm biomass will be beneficial for Congo Basin countries seeking to benefit
407 from results-based payments for REDD+ activities [35] and will allow a better estimate of
408 forest carbon stocks and emissions across the region [3,36].
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Conclusion

We have developed the first allometric equation for the palm species *Raphia laurentii*, which permits the estimation of its *AGB*. Contrary to the findings of studies of other palm species, we find that the *AGB* of *R. laurentii* is concentrated mainly in the palm fronds (77 %), as it has a largely trunkless morphology. Subsequently, we find that the total diameter of palm fronds was the key variable to estimate *R. laurentii AGB*. This is different to the findings of allometry studies of other palm species, which have shown height to be the key predictor variable of palm *AGB*, highlighting the importance of a species specific allometric equation in the estimation of *R. launrentii AGB*. Whilst the total palm frond diameter single variable model gives good estimates of *AGB*, the model which includes height and wood density as variables gives the best estimates of *R. laurentii AGB*. The use of allometric models developed for the estimation of the biomass of *R. laurentii* stipes will allow a better estimation of the carbon stocks of the Congo Basin peat swamp forest. Future work should focus on other common palms in Africa, to improve biomass estimates and carbons stock estimates of these increasingly valuable ecosystems.

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Supporting information

S1 Fig. Residue graphs of the model 11

S2 Fig. Residue graphs of the model 18

S1 Table. Wood density values of the different compartments of an individual *Raphia laurentii*

Palm compartment	Mean palm diameter range (cm)	Wood density (g/cm³)	
		Mean	SD
Stem	[2 - 4]	0,19	0,03
	[4 - 5]	0,20	0,02
	[5 - 6]	0,21	0,04
	[6 - 7]	0,19	0,03
	[7 - 8]	0,22	0,04
	[+8]	0,27	0,05
Sheath	[2 - 4]	0,27	0,05
	[4 - 5]	0,26	0,03
	[5 - 6]	0,26	0,04
	[6 - 7]	0,27	0,04
	[7 - 8]	0,25	0,04
	[+8]	0,25	0,04
Petiole	[2 - 4]	0,22	0,03
	[4 - 5]	0,21	0,02
	[5 - 6]	0,21	0,03
	[6 - 7]	0,21	0,02
	[7 - 8]	0,20	0,03
	[+8]	0,20	0,02
Rachis	[2 - 4]	0,27	0,04
	[4 - 5]	0,27	0,02
	[5 - 6]	0,29	0,02
	[6 - 7]	0,29	0,04
	[7 - 8]	0,28	0,04
	[+8]	0,29	0,04

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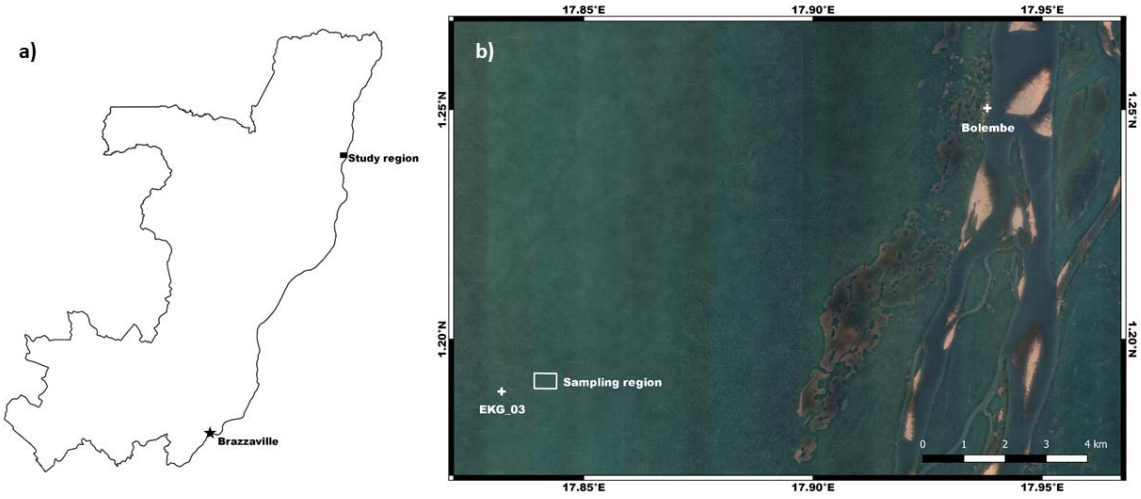


Fig 1. Location of the study area

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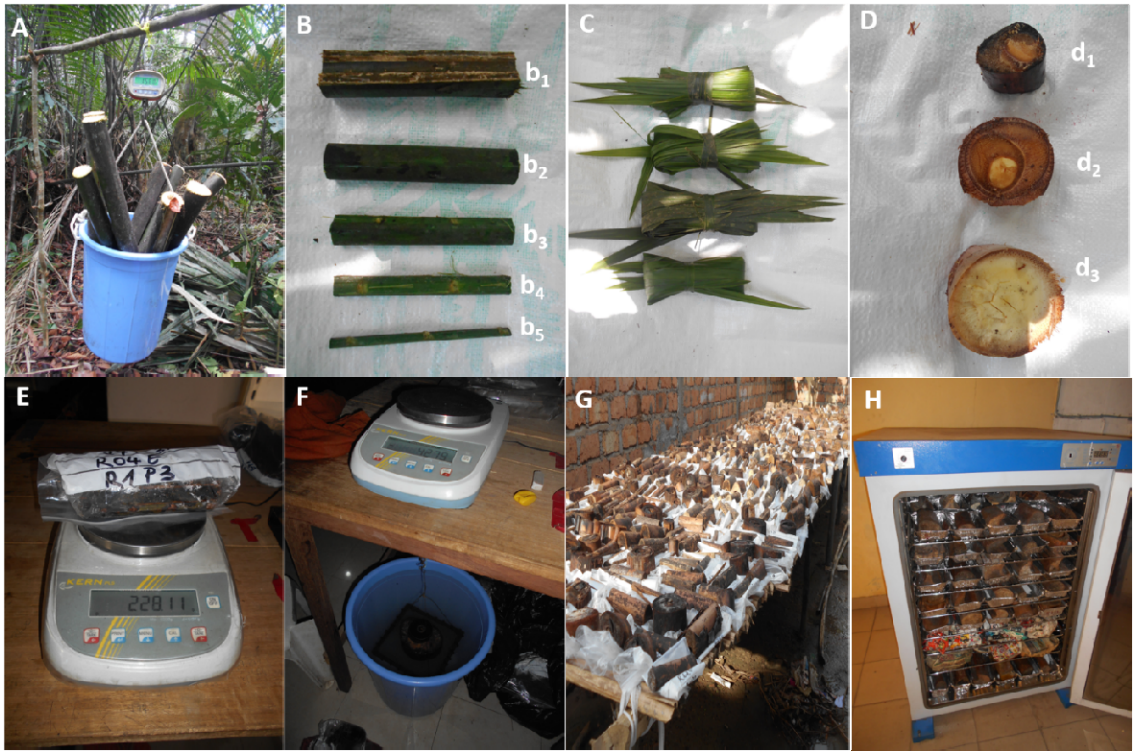


Fig 2. Illustration of field and laboratory data collection. Measurement of the fresh weight of part of the palm (A), samples taken from a palm (B), samples from leaflets (C), samples taken from the stem (D), measurement of fresh mass precision in the laboratory (E), measurement of green volume (F), sun drying (G) and oven drying (H). b_1 : the middle of the sheath, b_2 : the middle of the petiole, b_3 : the base of the rachis, b_4 : the middle of the rachis, b_5 : the top of the rachis, d_1 : the base of the stem, d_2 : the middle of the stem and d_3 : the top of the stem.

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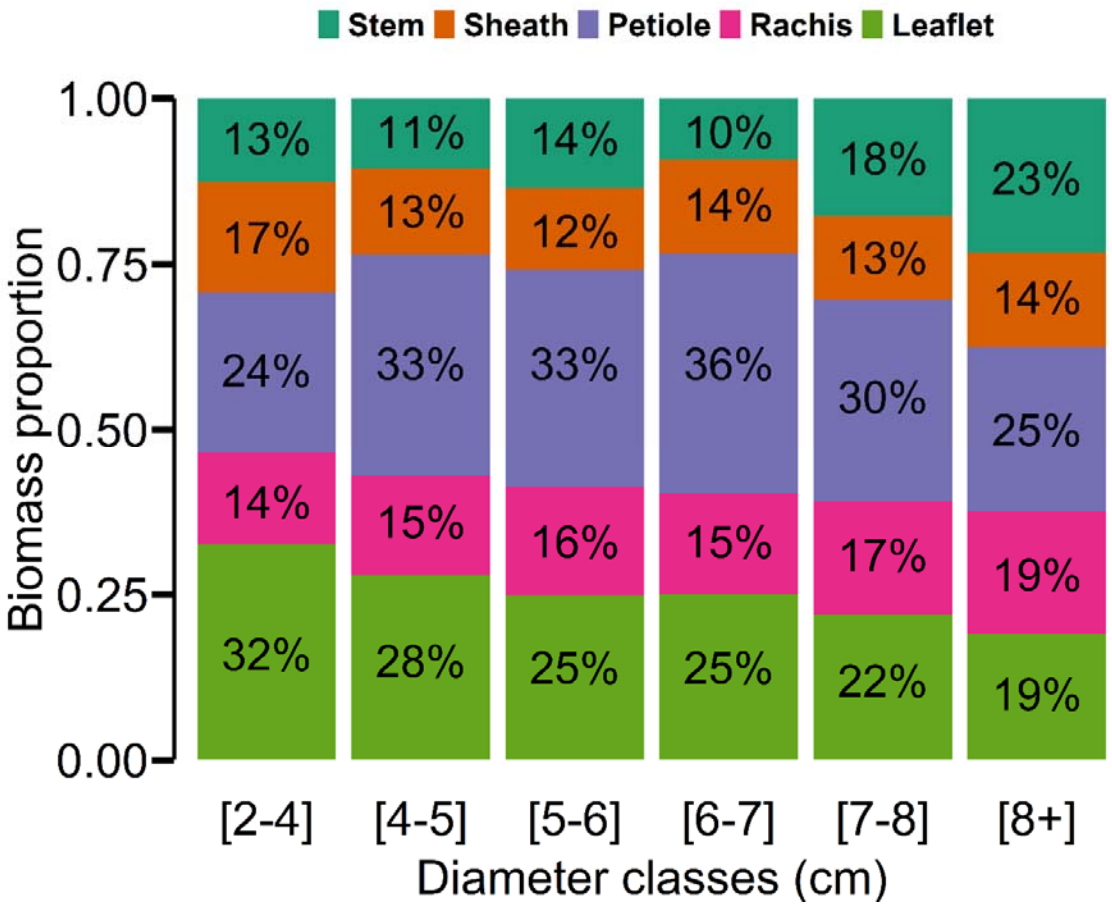


Fig 3. Aboveground biomass distribution among the stem, sheath, petiole, rachis and leaflet for each mean diameter class of the palm frond for the 90 individual *R. laurentii* sampled.

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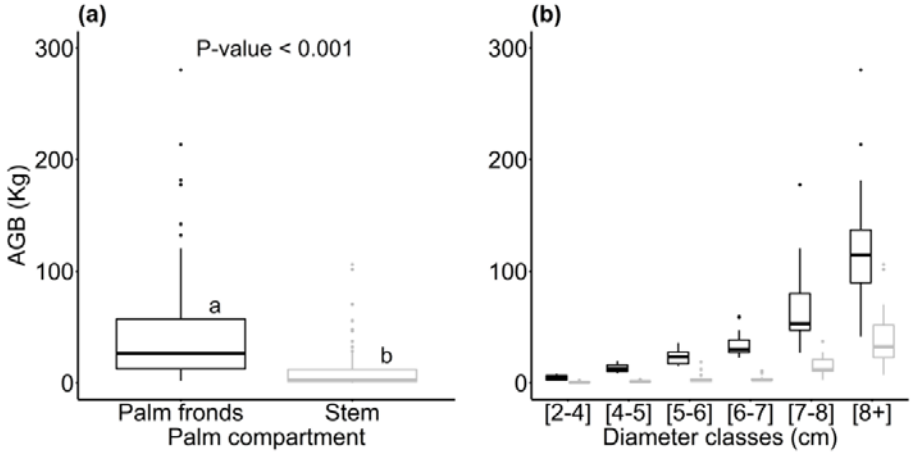


Fig 4. Variability of aboveground biomass between palm compartments (a) and diameter classes (b).

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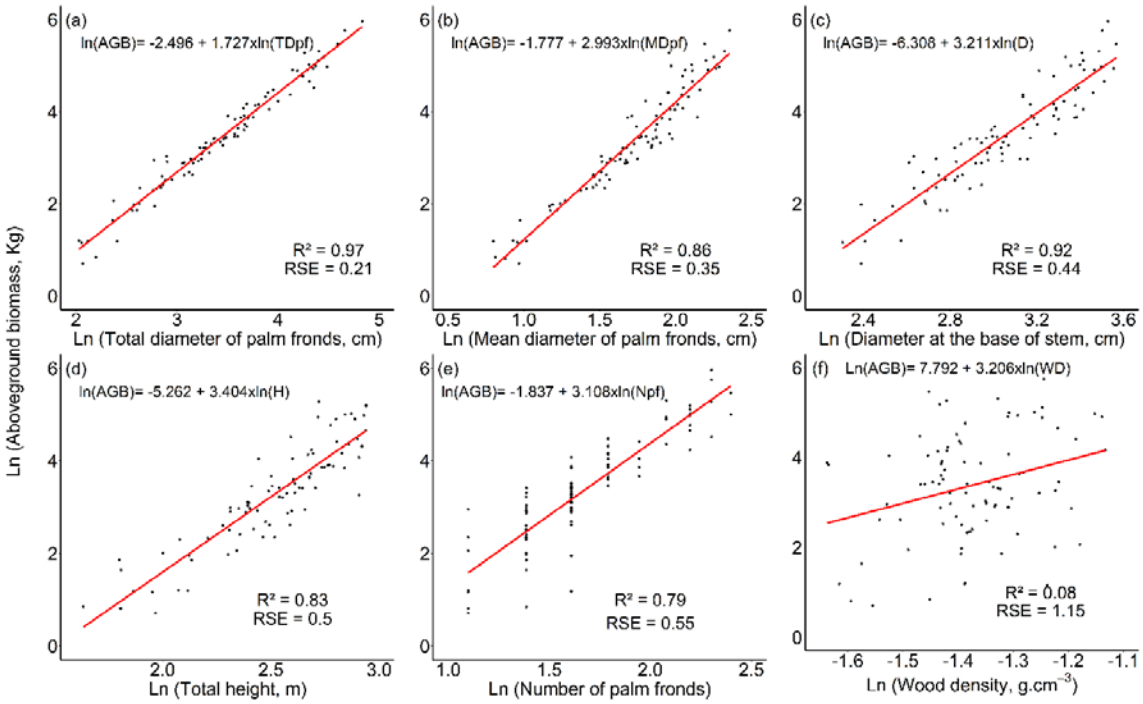


Fig 5. Allometric relationships between the aboveground biomass of *R. laurentii* stipe and each predictor variable.

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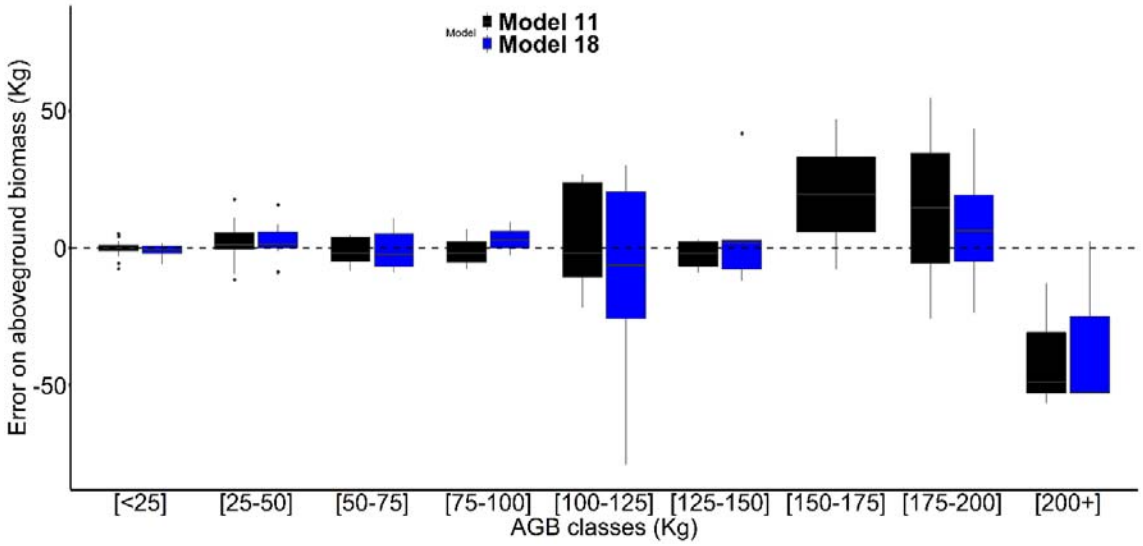


Fig 6. Goodness prediction of aboveground biomass (*AGB*) of model 11 and model 18.

Mean relative error on *AGB* ($\boldsymbol{Error} = [(\boldsymbol{AGB_{est}} - \boldsymbol{AGB_{obs}})/\boldsymbol{AGB_{obs}}] \times \mathbf{100}$) for *AGB* classes.

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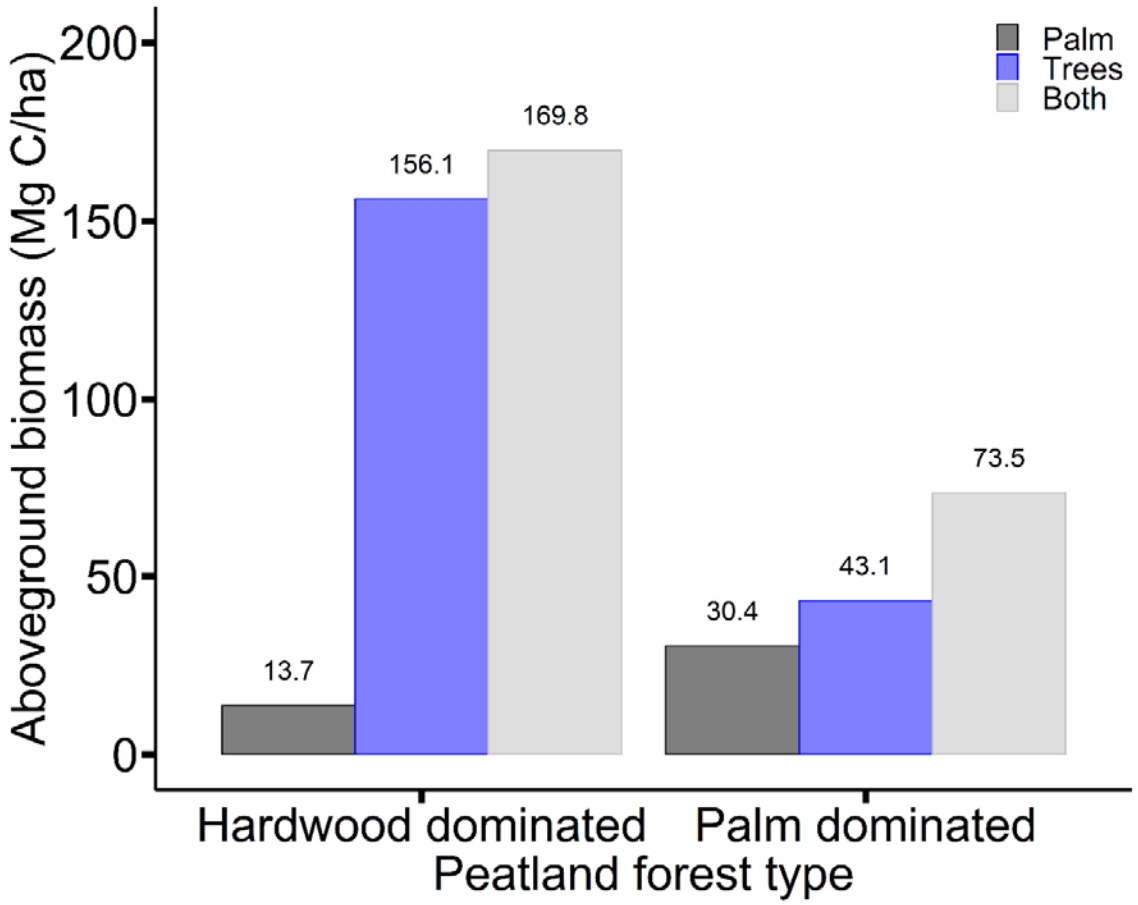


Fig 7. The contribution of the AGB of Raphia individuals in the total estimation of aboveground biomass carbon in the Congo Peatland.