

RESEARCH ARTICLE

Allometric equations for estimating tree volume and aboveground biomass of *Acacia mangium* Willd. in the Batéké Plateau, Republic of Congo

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ABSTRACT

Acacia mangium Willd. is one of the most widely planted fast-growing tropical species, yet it remains poorly documented in Central Africa, particularly in terms of biomass accumulation. This knowledge gap, combined with the lack of robust allometric equations, limits the development of reliable Measurement, Reporting, and Verification (MRV) protocols for plantations. Since accurate estimates of tree volume and aboveground biomass (AGB) are essential for carbon stock assessment and for implementing climate change mitigation strategies such as REDD+, this study developed allometric equations for tree volume and AGB in *A. mangium* plantations on the Batéké Plateau, Republic of Congo, using destructive sampling of 54 trees (4–24 cm DBH; 25, 42, and 66 months old). Trees were measured, felled, and partitioned into trunks and large branches (>4 cm), small branches (1–4 cm), foliage, and stumps. Samples of each compartment were oven-dried and weighed. Results showed that AGB allocation to trunks and large branches increased with age, while allocation to small branches declined. A power-law model ($Y = a(D^2H)^b$) provided the best fits for both volume ($Y = 0.401(D^2H)^{0.984}$) and AGB ($Y = 0.259(D^2H)^{0.900}$). When applied to inventory data from permanent sample plots in plantations in the Batéké Plateau, estimates rose from 38.3 m³ ha⁻¹ and 29.4 Mg ha⁻¹ at 28 months to 157.6 m³ ha⁻¹ and 105.5 Mg ha⁻¹ at 64 months. These equations provide a robust reference for *A. mangium* in the Batéké Plateau and will strengthen the accuracy of biomass and carbon monitoring for effective forest-based climate mitigation initiatives.

Keywords: allometric equations, tree volume, aboveground biomass, Batéké Plateau, diameter, height, power-law model

INTRODUCTION

Estimating aboveground tree biomass to assess carbon stocks is essential for quantifying the carbon balance in tropical forests. Such estimation has become a global priority, particularly for the implementation of initiatives such as Reducing Emissions from Deforestation and Forest Degradation (REDD+) and Afforestation, Reforestation and Revegetation (ARR) [1,2]. The successful implementation of such initiatives in tropical countries plays a key role in global climate change mitigation, and participating countries must provide detailed strategies and carbon reference levels [3]. However, establishing these reference levels requires accurate estimates of biomass and carbon stocks.

Traditionally, allometric relationships have been used to estimate stem volume or tree biomass [4]. Allometry describes the relationship between a tree's measurable characteristics, such as diameter and/or height, and another variable that is more challenging to measure directly, such as biomass or volume [5,6]. A major limitation of allometric models is that their initial development requires the destructive sampling of trees [7]. Furthermore, selecting the most appropriate model is essential to improve accuracy [8], yet identifying the best-performing equation is not always straightforward [9].

While volume estimation is critical for forest management and timber commercialization, the demand for biomass estimation has significantly increased over the past decade due to its relevance in climate change mitigation [10]. In the Congo Basin countries, the establishment of robust Measurement, Reporting, and Verification (MRV) protocols is hindered by the lack of data necessary for developing allometric equations. This data gap is particularly critical for plantations, which remain among the most effective strategies for mitigating climate change [11]. Developing region-specific equations can significantly improve biomass estimation and MRV protocols [7].

In the Republic of Congo, agroforestry and forestry plantations play a key role in reforestation programs, where they are at the heart of ecological restoration and carbon sequestration strategies [12,13]. They also contribute substantially to wood and energy production, meeting the rapidly growing urban demand for firewood and charcoal [14,15]. In 2013, the government of the Republic of Congo took a proactive approach to afforestation and reforestation, notably through the National Afforestation and Reforestation Program (PRONAR), which aimed to establish 1 million hectares of forest and agroforestry plantations [15–17]. Among the species used, *Acacia mangium* is particularly prominent due to its rapid growth, tolerance of nutrient-poor and acidic soils, and ability to fix atmospheric nitrogen through symbiotic associations

with *Rhizobium* bacteria, making it particularly suitable for the long-term success of afforestation initiatives [13,18–22]. In addition, it stands out for its substantial potential in terms of timber and energy production, making it even more attractive for planting programs in tropical areas [13,23,24].

In this context, this study aims to develop and test allometric equations adapted to *Acacia mangium* plantations for tree volume and aboveground biomass on the Batéké Plateau, Republic of Congo. This study has two specific objectives to: i) develop allometric equations for estimating wood volume and aboveground biomass of trees; and ii) Assess the impact of applying allometric equations for volume and AGB to these plantations. This study will enable significant advances in several fields: forest inventory, carbon stock assessment and sustainable management of *Acacia mangium* plantations on the Batéké Plateau and overall the Central Africa.

MATERIALS AND METHODS

Study sites

This study was conducted in the plantation of *Acacia mangium* Willd. (Fabaceae) located on the Batéké Plateau in the Republic of Congo. The Batéké Plateau of the Republic of Congo consists of four distinct savannah sub-plateaus : Koukouya, Djambala, Nsa-Ngo and Mbé/Batéké [25,26]. Fieldwork for this study was carried out in three sites representing three main topography types in the Batéké Plateau landscape. The first site (Site 1: 3°52'2''S, 15°31'5''E) was located on the Mbé plateau with a stable topography. The second site (Site 2: 3°37'44''S, 15°20'9''E) was assigned to a transition area, with an undulating topography, between the Mbé plateau and the hills. The third site (Site 3: 2°39'27''S, 15°51'6''E) has been described as an area with a succession of hills (Figure 1). All three sites are characterized by tropical transitional climate with an average annual rainfall of 1500–1800 mm. There is a main dry season from June to September and a shorter one in January and February. The average annual temperature is 25°C. The soils are predominantly ferrallitic, sandy with low clay content, leached with low organic matter and mineral content, classifying them as low fertility soils [25,26].

[Insert Figure 1 here]

Figure 1. Location of study sites on the Batéké Plateau in Republic of Congo.

Experiment design and tree sampling

The experimental design was based on pre-existing forest inventory data, comprising 2,722 measurements of diameter at breast height (DBH) collected across the three sites with trees aged 25, 42, and 66 months old. Specifically, Site 1 (66 months old) contributed 85 DBH measurements, Site 2 (25 and 42 months old) contributed 640 measurements, and Site 3 (25 months old) contributed 1,997 measurements. DBH values ranged from 2 cm to 23 cm. Site 3 was subdivided into two sub-units due to pronounced differences in growth observed between two plantation zones, despite their identical age.

The pre-existing tree DBH measurements data were divided into four classes corresponding to the quartiles of the stand's DBH distribution (Supporting Information Figure S1). DBH values below 4 cm were excluded from the sampling frame, as they are younger trees planted to replace dead ones and should have specific allometric equation [27]. The sampling intensity in term of number of tree for each class was proportionally adjusted on the standard deviation of basal area [6]. A total of 54 trees from all diameter classes and plantation ages were selected in all three sites (Table 1). This number of sampled trees exceeds the recommended minimum (30) for homogeneous plantation stands [6,28,29] and should ensure sufficient precision for the resulting models.

Table 1. Number of trees according to DBH class and plantation age in each site.

DBH classes	Site 1	Site 2		Site 3		Total
	<i>(plantation age in month)</i>	<i>(plantation age in month)</i>		<i>(plantation age in month)</i>		
	66	42	25	25	25	
1 [4 ; 6.5]	2	1	1	2	2	8
2 [6.5 ; 9]	2	2	1	3	3	11
3 [9 ; 11.5]	5	4	3	2	2	16
4 [11.5 ; DBH _{max}]	6	5	2	3	3	19
Total	15	12	7	10	10	54

Tree measurements

Prior to felling, non-destructive tree diameter and height measurements were performed in 2024. The diameter at breast height (DBH) was measured at 1.30 m above the ground using a diameter tape (Richter model: 283D/5) for single-stem trees and multi-stemmed trees (number of stems ranged from 1 to 6). For multi-stemmed tree, the diameter was calculated as the root mean square of stems diameter [30]. Each stem with a DBH of at least 1 cm at breast height was measured. For each standing tree, total height was measured three times from three different positions using a SUUNTO clinometer (SUUNTO model: PM-5/1520 PC), ensuring that the operator stands at a minimum distance equivalent to the height of the tree to be measured.

Destructive sampling was carried out using a chainsaw. Each tree was cut down at 10 cm from the base. The length of felled tree was measured before being cut into four compartments: trunks and large branches (> 4 cm diameter), small branches (1-4 cm diameter), foliage and stump. The trunks and large branches were cut into chunks less than 2 m long [6]. The length and diameter (butt and butt end) of each chunk were measured for each felled tree.

For each compartment, the fresh mass was measured in the field using a 500g precision mechanical balance. Representative samples (trunk: discs of 5 cm at both ends and every 2 m; branches divided into 4 diameter classes: on average, 5 fixed-length samples per class; phyllodes: 3 bags of 10 liters each) were collected and weighed on a 1 g precision balance. These samples were then dried in a circulating air oven at 105°C (for stems, large branches and small branches) or 70°C (for foliage) until their mass stabilized [6,31]. The dry mass of each representative sample was measured using the 1 g precision balance.

For each tree, the observed volume (V_{obs}) was calculated as the sum of the chunks and stump volumes. The volume of each chunk was calculated using Smalian's formula [32] and the volume of the stump using the truncated cone formula [33]. The observed dry aboveground biomass (AGB_{obs}) was calculated as the sum of the dry aboveground biomass of all the compartments. The dry biomass of each compartment, except the stump, was calculated by multiplying the fresh mass of the compartment by the dry mass/fresh mass ratio determined from the dried samples. The stump biomass was estimated from its volume using the relationship: $AGB_{stump} = V_{stump} * d$, where d is the anhydrous density (0.507 g/cm³) of *Acacia mangium* [34].

Data analysis

To develop the allometric equations, both non-destructive measurements (diameter at breast height, D , and total height, H) and the destructive measurements (observed volume, V_{obs} , and aboveground biomass, AGB_{obs}) were used. Allometric models using D as a predictor have been widely used in allometric studies due to their simplicity and operational applicability [31,13,7,35]. However, integrating total height with diameter (D^2H) in the allometric models can significantly improve the accuracy of AGB estimates [8,36–38]. Since tree height measurements are difficult in tropical forest [39,40], we first evaluated how accurate are non-destructive tree height measurements in comparison with destructive measurements on felled trees. Given the strong correlation (Pearson's $r = 0.98$, p -value < 0.001) and no significant difference between the non-destructive and destructive height measurements (p -value > 0.05; repeated measures analysis of variance; see supporting information Table S1, and Figure S2),

the non-destructive height measurement is confidently used to establish volume and AGB allometric equations.

For each predictor (D in cm or D²H in m³), four allometric models (linear, power, exponential and logarithmic) commonly used worldwide to estimate volume or aboveground biomass were tested [35]. The modelling approach used the following equation based on the diameter (D) and total height (H) of a tree *i* belonging to all three sites:

$$Y_i = a \times D_i + b + \varepsilon_i \quad \text{or} \quad Y_i = a \times D_i^2 \times H_i + b + \varepsilon_i \quad \text{linear model}$$

$$Y_i = a \times D_i^b + \varepsilon_i \quad \text{or} \quad Y_i = a \times (D_i^2 \times H_i)^b + \varepsilon_i \quad \text{power model}$$

$$Y_i = a \times e^{b \times D_i} + \varepsilon_i \quad \text{or} \quad Y_i = a \times e^{b \times (D_i^2 \times H_i)} + \varepsilon_i \quad \text{exponential model}$$

$$Y_i = a \times \ln(D_i) - b + \varepsilon_i \quad \text{or} \quad Y_i = a \times \ln(D_i^2 \times H_i) - b + \varepsilon_i \quad \text{logarithmic model}$$

where a and b are the fitted coefficient or exponent, Y_i is alternatively the observed tree volume (V_{obs} in m³) or the aboveground biomass (AGB_{obs} in Mg) and ε_i is the error.

For the power and exponential models, initial parameter values were derived from linear regressions on log-transformed data. These starting values were then used to fit the final models directly to the untransformed data using the “nls()” function, thereby avoiding correction of retransformation bias [41,42].

The biomass expansion factor (BEF) which represents the part of biomass contained in the small branches ($D < 4$ cm) and phyllodes is useful to convert tree volume to aboveground biomass [43]. It was obtained from the linear regression: $AGB_{\text{obs}} = BEF * (V_{\text{obs}} * d)$, where V_{obs} is of the tree volume, and d the dry density (0.507) of *A. mangium* [34].

Model selection was based on the following criteria: (a) the coefficient of determination (R^2), representing the proportion of explained variance; (b) model performance indicators, including root mean square error (RMSE) and prediction bias; (c) Akaike’s Information Criterion (AIC), and Bayesian Information Criterion (BIC) which balances model accuracy and complexity. A lower AIC or BIC value indicates a better model fit [44]. To estimate the predictive performance of the selected models, a leave-one-out cross validation (LOO-CV) was computed and evaluate the mean absolute error (MAE), the mean relative error (MRE), and the mean bias of the models. The LOO-CV compares the model’s predictions with independent variables that were not used during model fitting [45–47].

To assess the impact of volume and AGB allometric equations developed in this study, forest inventory data were converted into volume and AGB using the best fitted models. The forest inventory data consisted of eight permanent sample plots (PSP), with two PSP established in

194 Site 1 (64 months old) and six in Site 2 (40 months old for 4 PSP and 28 months old for 2 PSP).
 195 Each PSP corresponds to three lines of thirty spots, i.e. approximately 0.0907 ha. The tree
 196 density was estimated at approximately 715 trees/ha in the Site 1 and 880 trees/ha in the Site 2.
 197 The forest inventory data (DBH and H) for all living trees (a total of 634 trees) in the PSP was
 198 collected in March 2024. These forest inventory data were used to assess the impact of these
 199 equations for plantation ages ranging from 25 to 66 months. A linear regression was fitted
 200 between the estimated volume or AGB, and plantation age to assess the validity of allometric
 201 equations across the plantation age range (25-66 months).
 202 All statistical analyses were computed using the open-source R environment (R version 4.4.2,
 203 R Core Team, 2024).

RESULTS

Overview of sampled trees

The 54 sampled trees have a mean diameter at breast height (DBH) of 11.0 ± 4.5 cm and a mean height (H) of 10.3 ± 3.8 m (Table 2). DBH and H ranged from 4.5 to 23.8 cm and 5.3 to 20.2 m respectively, indicating the range of validity of the allometric models. The observed stem volume and aboveground biomass (AGB) of felled trees ranged from 0.007 to 0.477 m³ (mean = 0.073 ± 0.091 m³) and from 0.004 to 0.284 Mg (mean = 0.052 ± 0.059 Mg), respectively (Table 2).

Table 2. Mean $\pm$ standard deviation of the tree measurements (DBH, total height, volume, and AGB) in each study site.

Site	Plantation age (month)	Mean DBH (cm)	Mean height (m)	Mean volume of felled tree (m ³)	Mean AGB of felled tree (Mg)
Site 1	66	12.7 ± 5.7	14.6 ± 3.8	0.135 ± 0.142	0.089 ± 0.093
Site 2	42	12.0 ± 4.4	10.3 ± 1.6	0.041 ± 0.027	0.032 ± 0.021
	25	9.9 ± 2.8	8.4 ± 1.4	0.070 ± 0.055	0.050 ± 0.036
Site 3	25	9.7 ± 4.4	9.2 ± 1.8	0.048 ± 0.051	0.038 ± 0.039
	25	9.5 ± 3.3	6.3 ± 1.1	0.030 ± 0.027	0.028 ± 0.023
mean	44	11.0 ± 4.5	10.3 ± 3.8	0.073 ± 0.091	0.052 ± 0.059

The allocation of tree AGB varied with plantation age (Figure 2). The proportion of AGB allocation increased for the trunk and large branches and decreased for small branches and phyllodes according to plantation age from 25 months to 66 months.

[Insert Figure 2 here]

Figure 2. Distribution of the AGB allocation according to the compartments (Trunk and large branch, small branch, phyllode and Stump) and plantation ages.

The proportion of biomass contained in the small branches ($D < 4$ cm) and phyllodes, which represents the biomass expansion factor ($AGB = BEF \cdot (V_{obs} \cdot d)$), varied significantly with stand age (Table 3). At 25 months, the BEF reached 1.57 ± 0.04 and progressively decreased with age, being 1.36 ± 0.06 at 42 months and 1.28 ± 0.05 at 66 months. Model fits were very strong, with coefficients of determination ranging from 0.977 to 0.983.

When all ages were considered together, the global model (mean age of 44 months, $n = 54$) yielded a BEF of 1.32 ± 0.03 ($R^2 = 0.974$). This overall value is close to that obtained at 42

months and well reflects the general trend, namely a progressive decline in BEF with increasing stand age.

Table 3. Biomass Expansion Factor (BEF) by stand age and for the global model.

Stand age (months)	n	BEF ($\pm$ SE)	R ²
25	27	1.57 $\pm$ 0.04	0.983
42	12	1.36 $\pm$ 0.06	0.978
66	15	1.28 $\pm$ 0.05	0.977
mean (44)	54	1.32 $\pm$ 0.03	0.974

Values are expressed as the mean BEF $\pm$ standard error (SE), with the number of observations (n) and the coefficient of determination (R²) reported for stand age. The mean corresponds to all ages combined (mean age = 44 months).

Allometric models for volume and aboveground biomass

Models using D²H as a predictor exhibited better performance than those using only D², except for the exponential model (Table 4). These findings indicate that D²H provides a more accurate representation of the variability in observed tree volume and aboveground biomass. The power model with D²H as predictor (Model 4: $Y = a(D^2H)^b$) demonstrated the best overall performance for both volume and AGB allometric equations (Table 4).

For tree volume, Model 2 (linear) and Model 4 (power) showed comparable performance. Their respective goodness-of-fit statistics were: R² = 0.98 for both models; AIC = -310.89 and -310.80; BIC = -304.92 and -304.83; RMSE = 0.012867 m³ and 0.012878 m³; and bias = -3.98 % and -1.29 %, respectively (Table 4).

Results from the leave-one-out cross-validation (LOOCV) indicated a mean relative error (MRE) of 13.45 % for the linear model (Model 2) and 12.28 % for the power model (Model 4). The mean absolute error (MAE) was nearly identical for both models (0.0080 m³ and 0.0081 m³, respectively). Prediction bias remained negligible, with values of -0.0001 m³ for Model 2 and -0.0005 m³ for Model 4.

For the aboveground biomass (AGB), the model 4 “ $AGB = a(D^2H)^b$ ” exhibited the best performance with the highest R² (0.97), the lowest AIC (-335.49) and BIC (-229.53), and the lowest RMSE (0.010245) and bias (-3.66). The LOOCV results further confirmed the robustness of model 4, with a MAE of 0.0076 Mg, an MRE of 19.08%, and a negligible mean bias of -0.0001 Mg, indicating good predictive accuracy at the individual tree level (Table 4).

Table 4. Allometric equations for tree volume (V) and aboveground biomass (AGB).

Models	N° Equation	Coefficient and exponent		Performance criteria				
		a	b	R ²	AIC	BIC	RMSE	Bias
1	$V = aD + b$	0.01785	-0.12377	0.79	-184.40	-178.43	0.041507	40.83
	$AGB = aD + b$	0.01191	-0.07889	0.83	-243.14	-237.17	0.024094	33.23
2	$V = a(D^2H) + b$	0.40053	0.00167	0.98	-310.89	-304.92	0.012867	-3.98
	$AGB = a(D^2H) + b$	0.25869	0.00630	0.97	-333.17	-327.20	0.010469	-12.48
3	$V = aD^b$	0.00005	2.89288	0.92	-234.45	-228.49	0.026112	5.28
	$AGB = aD^b$	0.00007	2.60588	0.93	-291.51	-285.54	0.015396	3.09
4	$V = a(D^2H)^b$	0.40115	0.98435	0.98	-310.80	-304.83	0.012878	-1.29
	$AGB = a(D^2H)^b$	0.25917	0.90017	0.97	-335.49	-329.53	0.010245	-3.66
5	$V = ae^{bD}$	0.00753	0.17491	0.92	-234.26	-228.30	0.026158	-33.43
	$AGB = ae^{bD}$	0.00676	0.16063	0.92	-283.48	-277.51	0.016584	-30.54
6	$V = ae^{b(D^2H)}$	0.04470	2.18624	0.85	-202.16	-196.19	0.035214	-102.42
	$AGB = ae^{b(D^2H)}$	0.03350	2.04148	0.82	-238.80	-232.84	0.025081	-87.28
7	$V = a \ln(D) - b$	0.18079	-0.34663	0.63	-154.84	-148.87	0.054576	42.87
	$AGB = a \ln(D) - b$	0.12180	-0.23032	0.68	-208.92	-202.95	0.033076	39.46
8	$V = a \ln(D^2H) - b$	0.07286	0.24022	0.72	-168.65	-162.69	0.048022	56.12
	$AGB = a \ln(D^2H) - b$	0.04797	0.16247	0.74	-219.03	-213.06	0.030120	37.69

For each model, the estimated coefficients (*a*, *b*) and performance criteria are reported, including coefficient of determination (*R*²), Akaike Information Criterion (*AIC*), Bayesian Information Criterion (*BIC*), root mean square error (*RMSE*), and bias. Volume is expressed in cubic meters (m³), AGB in megagrams (Mg), *D* in centimeters (cm), and *D*²*H* in cubic meters (m³).

Application of volume and AGB allometric models

The power model (model 4) was chosen as the best model to estimate volume and AGB. Using data from the eight permanent sample plots from 28 to 64 months, our results showed a progressive increase in volume and AGB with plantation age (Figure 3). The volume increased from 38.29 m³ ha⁻¹ at 28 months to 157.62 m³ ha⁻¹ at 64 months, with a mean annual increment from 16.41 m³ ha⁻¹ year⁻¹ to 29.78 m³ ha⁻¹ year⁻¹. Similarly, AGB varied from 29.41 Mg ha⁻¹ at 28 months to 105.51 Mg ha⁻¹ at 64 months, with a mean annual increment from 12.60 Mg ha⁻¹ year⁻¹ to 19.94 Mg ha⁻¹ year⁻¹. This indicates that the plantation is in an ascending growth phase.

[Insert Figure 3 here]

Figure 3. Volume and aboveground of 8 PSP located on Site 1 and 2

DISCUSSION

Aboveground biomass partitioning

Destructive sampling revealed that the trunk and large branches accounted for the majority of aboveground biomass (> 50%) across all plantation ages, consistent with findings for *A. mangium* in Indonesia [43] and *A. mearnsii* in Ethiopia [48]. The increasing allocation to these compartments with age supports the relevance of the selected diameter range for validating allometric equations, although the ontogenetic scope remains limited (4–24 cm DBH) compared to natural forests (> 200 cm). Consequently, this study will need to be updated to account for larger diameter classes.

The Biomass Expansion Factor (BEF) estimated in this study for the 54 sampled trees aged 25 to 66 months was 1.32. This value is very close to the estimate of 1.332 reported by Miyakuni [43] for *Acacia mangium* trees aged 36 to 96 months (3–8 years), suggesting a relative stability of BEF within this age range. However, both values are significantly lower than the default BEF value of 3.4 (range: 2.0–9.0) recommended by the Intergovernmental Panel on Climate Change (IPCC) guidelines for tropical forests, which includes *Acacia mangium* [49].

BEF is known to vary with multiple factors, including forest type, tree age, stand density, growth conditions, and climate [36]. It has been shown in this study, in agreement with the findings of Miyakuni [43], that BEF decreases with stand age. The use of age-class-specific BEF values is therefore regarded as a relevant approach to improve the accuracy of biomass estimates and to reduce uncertainties in carbon stock assessments. Nevertheless, BEF does not conform to any classical allometric model. As highlighted by Miyakuni [43] and further supported by the present study, no statistically robust relationships could be established between BEF and commonly used predictors such as D, H, or D²H (see Figure S3 in Supporting Information). This lack of predictive consistency underscores the empirical nature of BEF and suggests that its estimation should rely on direct measurements rather than on allometric surrogates.

Allometric equations for volume and aboveground biomass estimation

The choice of the allometric model is a critical step in the estimation of forest aboveground biomass [50,51]. As demonstrated in this study, several studies reported that the inclusion of multiple predictors in combination with tree diameter, provides a better estimate of tree volume and aboveground biomass [6,52]. The power model with D²H as predictor showed the best overall performance for the volume and AGB allometric equations. The leave-one-out cross-validation (LOOCV) results also showed a better predictive performance for the power model in terms of relative accuracy. Previous studies have also shown that power functions were able to estimate AGB with a high goodness of fit [53]. It is the most commonly used functional

form in allometric equations for estimating the tree volume and aboveground biomass in Central Africa [54,55,52], and used to describe the allometric relationships for a wide range of plants [56]. Power function models also express the allometry between different parts of the plant, such as the proportionality in the relative increments between stem biomass and girth of the trees [6].

CONCLUSION

This study provides a new destructive dataset for *Acacia mangium* Willd. plantations on the Batéké Plateau, covering the early growth stages (25–66 months). By integrating destructively sampled trees, power-law models based on D²H were identified as the most reliable predictors of tree volume and aboveground biomass. These equations improve the accuracy of biomass and carbon stock estimation compared to default IPCC values and are directly applicable to MRV systems for REDD+ and other forest-based mitigation initiatives. Although the results are constrained by a relatively narrow diameter range (4–24 cm), they provide an essential reference for forest plantations in the Congo Basin and highlight the need for further studies encompassing older stands and larger trees. Overall, this work strengthens the scientific basis for monitoring *A. mangium* Willd. plantations and contributes to more transparent and reliable reporting of forest carbon dynamics.

SUPPORTING INFORMATION

Figure S1. The stand's DBH distribution of pre-inventory data

[Insert Figure S1 here]

Figure S2. Regression between tree height non-destructive measurement and tree felled length

[Insert Figure S2 here]

Table S1. Comparison of total tree height measurements methods (repeated measures ANOVA).

Site	Age (months)	Mean DBH (cm)	Total height (Ht) of stand trees (m)				Total length of felled tree (m)
			<i>Position 1</i>	<i>Position 2</i>	<i>Position 3</i>	<i>Mean Position</i>	
Site 1	66	12.7 ± 5.7	14.4 ± 3.5	14.4 ± 3.8	15.0 ± 4.2	14.6 ± 3.8	14.7 ± 3.8
Site 2	42	12.0 ± 4.4	10.4 ± 1.7	10.3 ± 1.7	10.3 ± 1.5	10.3 ± 1.6	10.4 ± 1.5
	25	9.9 ± 2.8	8.6 ± 1.5	8.5 ± 1.3	8.1 ± 1.4	8.4 ± 1.4	8.5 ± 1.1
Site 3	25	9.7 ± 4.4	9.2 ± 1.9	9.3 ± 1.8	9.2 ± 1.7	9.2 ± 1.8	9.5 ± 1.5
	25	9.5 ± 3.3	6.2 ± 1.2	6.4 ± 1.1	6.2 ± 1.0	6.3 ± 1.1	5.7 ± 1.0
Average		11.0 ± 4.5	10.3 ± 3.7	10.3 ± 3.7	10.4 ± 4.0	10.3 ± 3.8	10.3 ± 3.9
repeated measures ANOVA			p-value = 0.911 (> 0.05); F(3,159) = 0.178; ges = 0.000064				

Raw distributions were non-normal (Shapiro–Wilk, $p \leq 0.001$ for all four methods), but normality was achieved after log transformation ($p = 0.097–0.219$). A repeated-measures ANOVA on log-transformed data showed no method effect ($F(3,159) = 0.178$, $p = 0.911$; generalized eta squared (ges) = 0.000064. These findings indicate that measures at Position 1, 2, 3, and Felled yield equivalent total height estimates

Figure S3. Relationship between BEF and D, H and D²H

[Insert Figure S3 here]

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329 AUTHOR CONTRIBUTIONS

Role	Contributor
Conceptualization	Chelton DESARMES, Grace Jopaul LOUBOTA PANZOU, Flore HIRSCH, Paul BERTAUX, Nicolas BAYOL
Data Curation	Chelton DESARMES
Formal Analysis	Chelton DESARMES, Grace Jopaul LOUBOTA PANZOU
Funding Acquisition	The logistical and operational supports (transportation, field teams, field equipment, and oven facilities) were provided by SPF2B; otherwise, no specific funding was received for this study.
Investigation	Chelton DESARMES
Methodology	Chelton DESARMES, Grace Jopaul LOUBOTA PANZOU, Flore HIRSCH, Paul BERTAUX, Nicolas BAYOL
Project Administration	Chelton DESARMES, Flore HIRSCH, Paul BERTAUX
Resources	Chelton DESARMES
Software	Chelton DESARMES
Supervision	Chelton DESARMES, Flore HIRSCH, Paul BERTAUX
Validation	Chelton DESARMES, Grace Jopaul LOUBOTA PANZOU, Flore HIRSCH, Paul BERTAUX, Nicolas BAYOL
Visualization	Chelton DESARMES, Grace Jopaul LOUBOTA PANZOU
Writing – Original Draft Preparation	Chelton DESARMES
Writing – Review & Editing	Chelton DESARMES, Grace Jopaul LOUBOTA PANZOU, Flore HIRSCH, Paul BERTAUX, Nicolas BAYOL.

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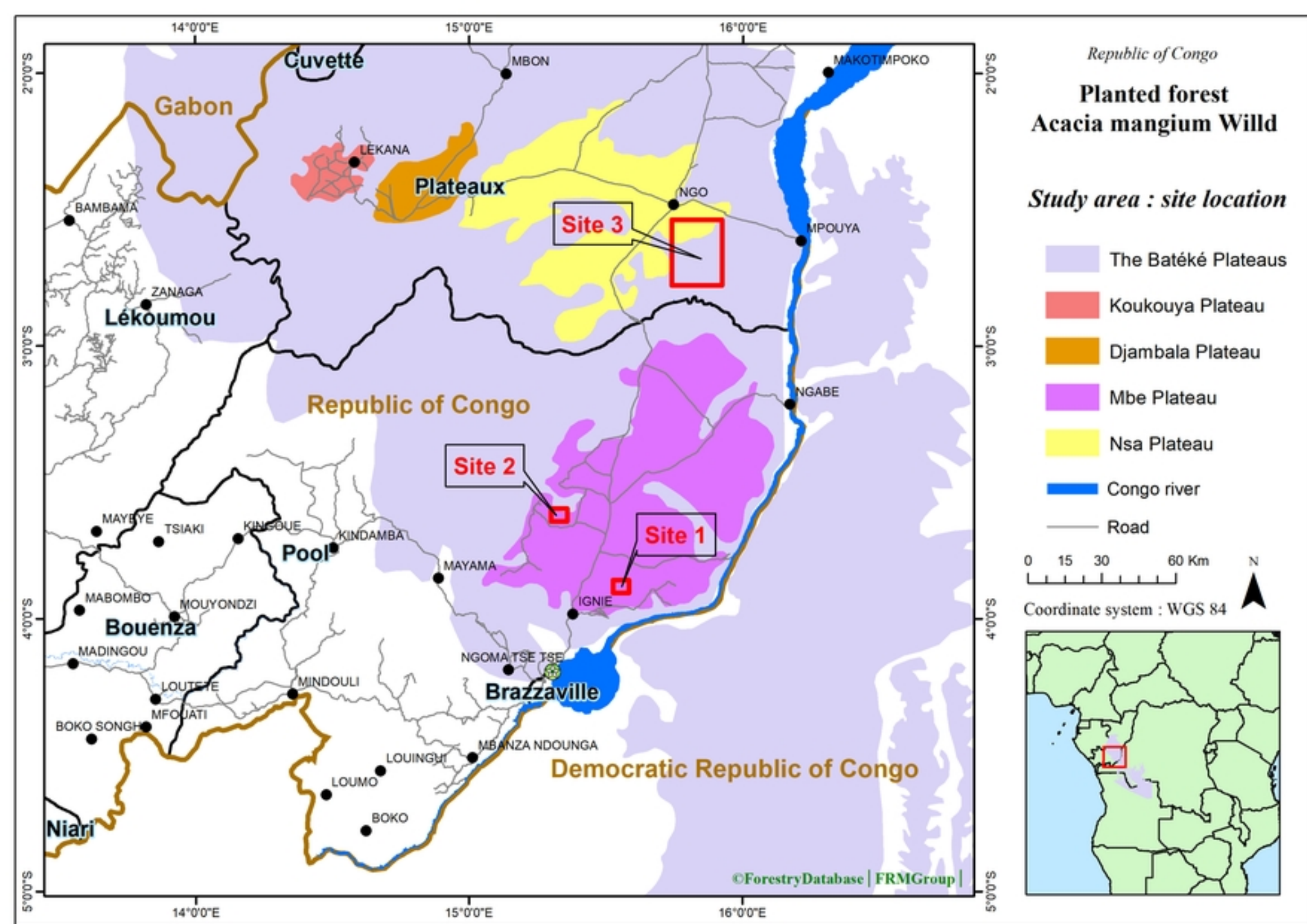
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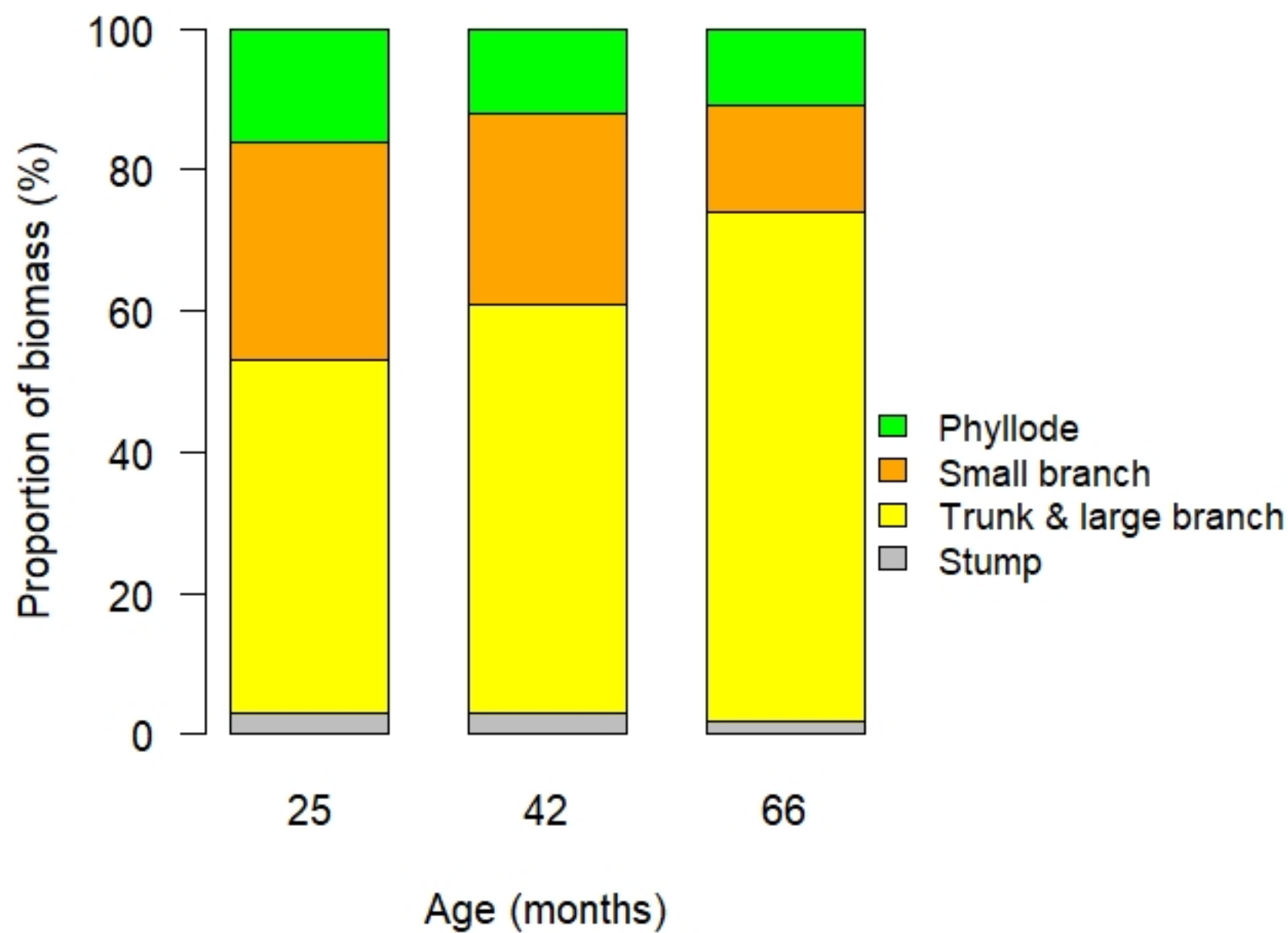


Figure 2

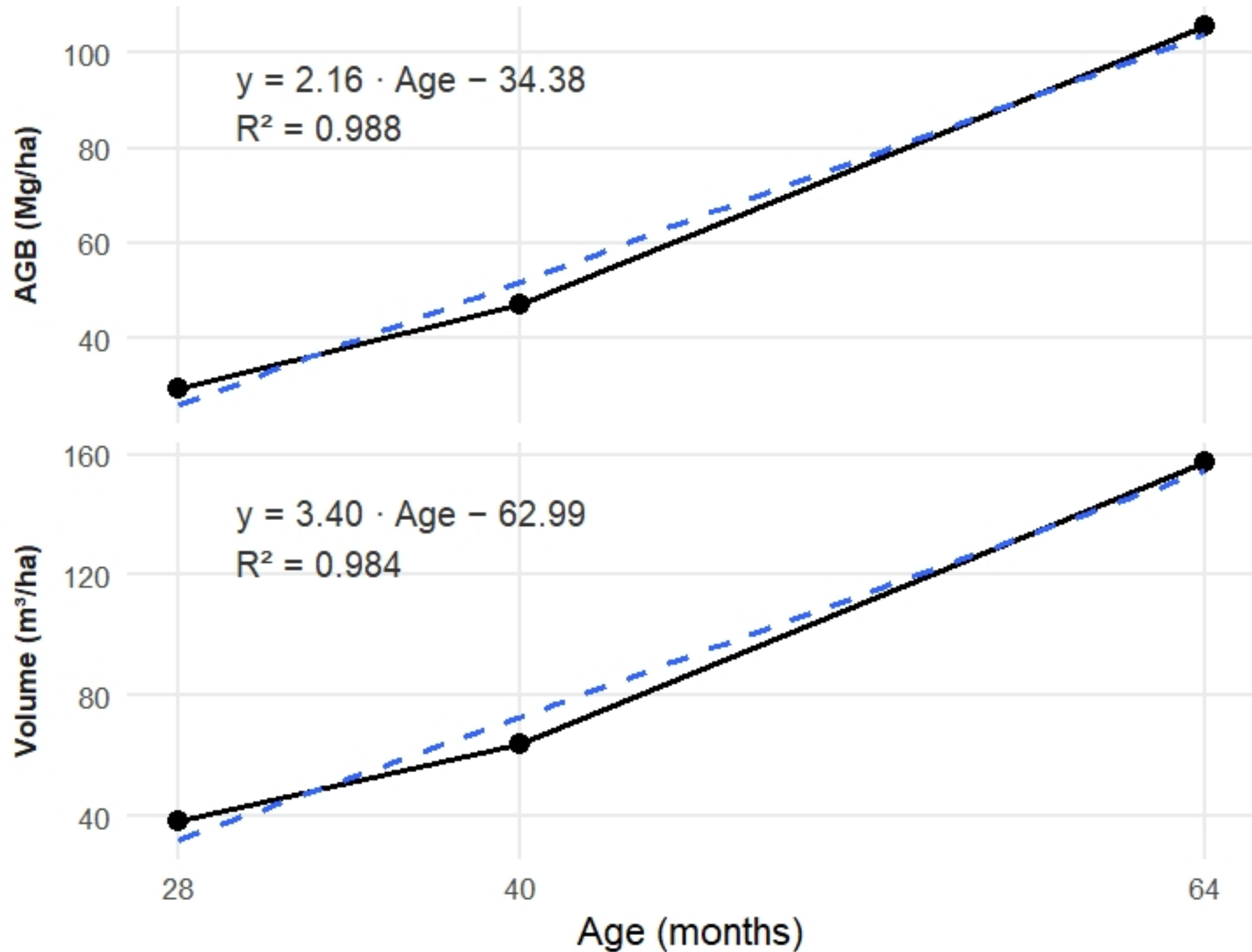


Figure 3

Frequency

200
100
0

5

10

15

20

25

DBH (cm)

1st Qu.

Median

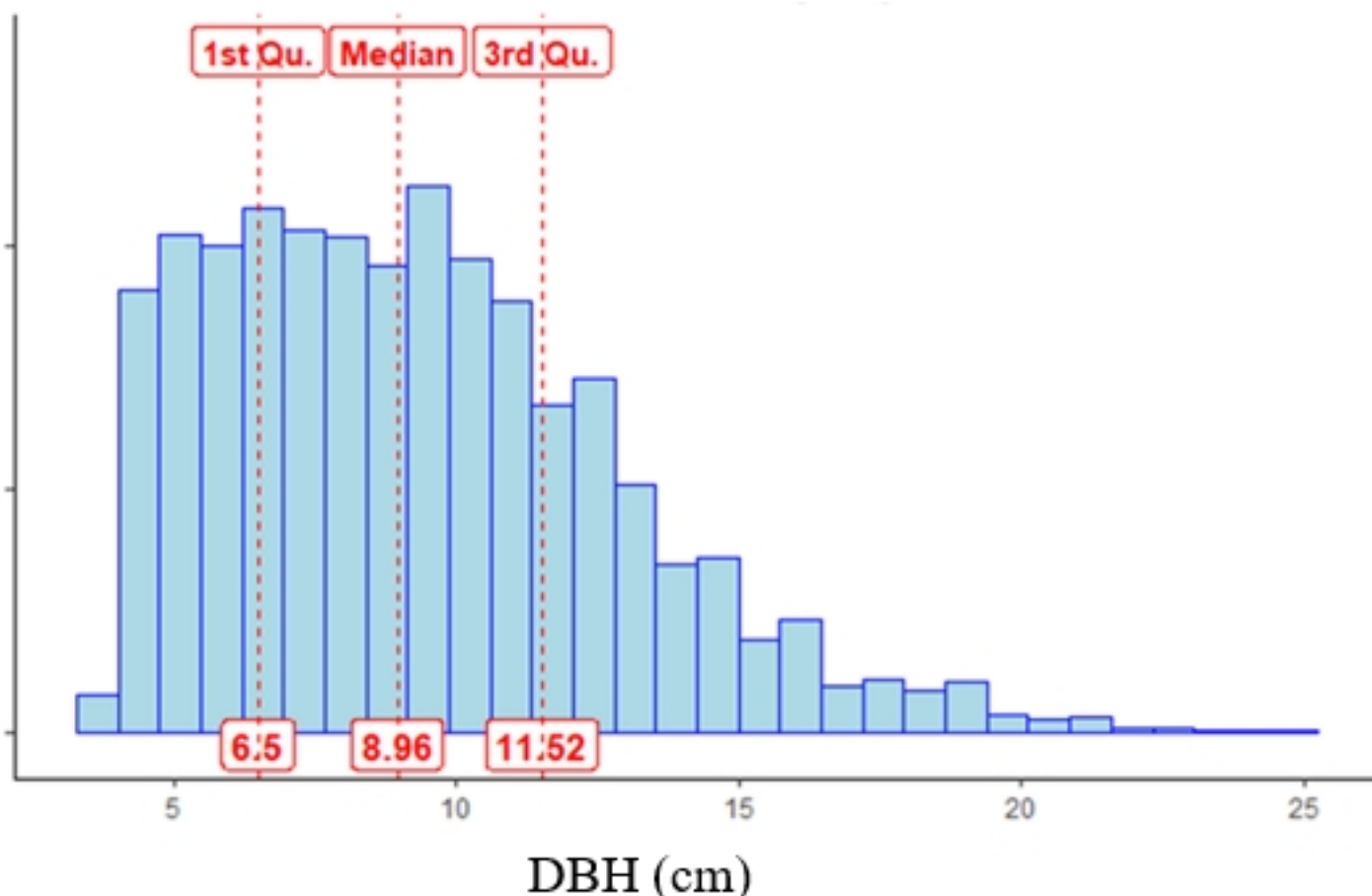
3rd Qu.

6.5

8.96

11.52

Figure S1



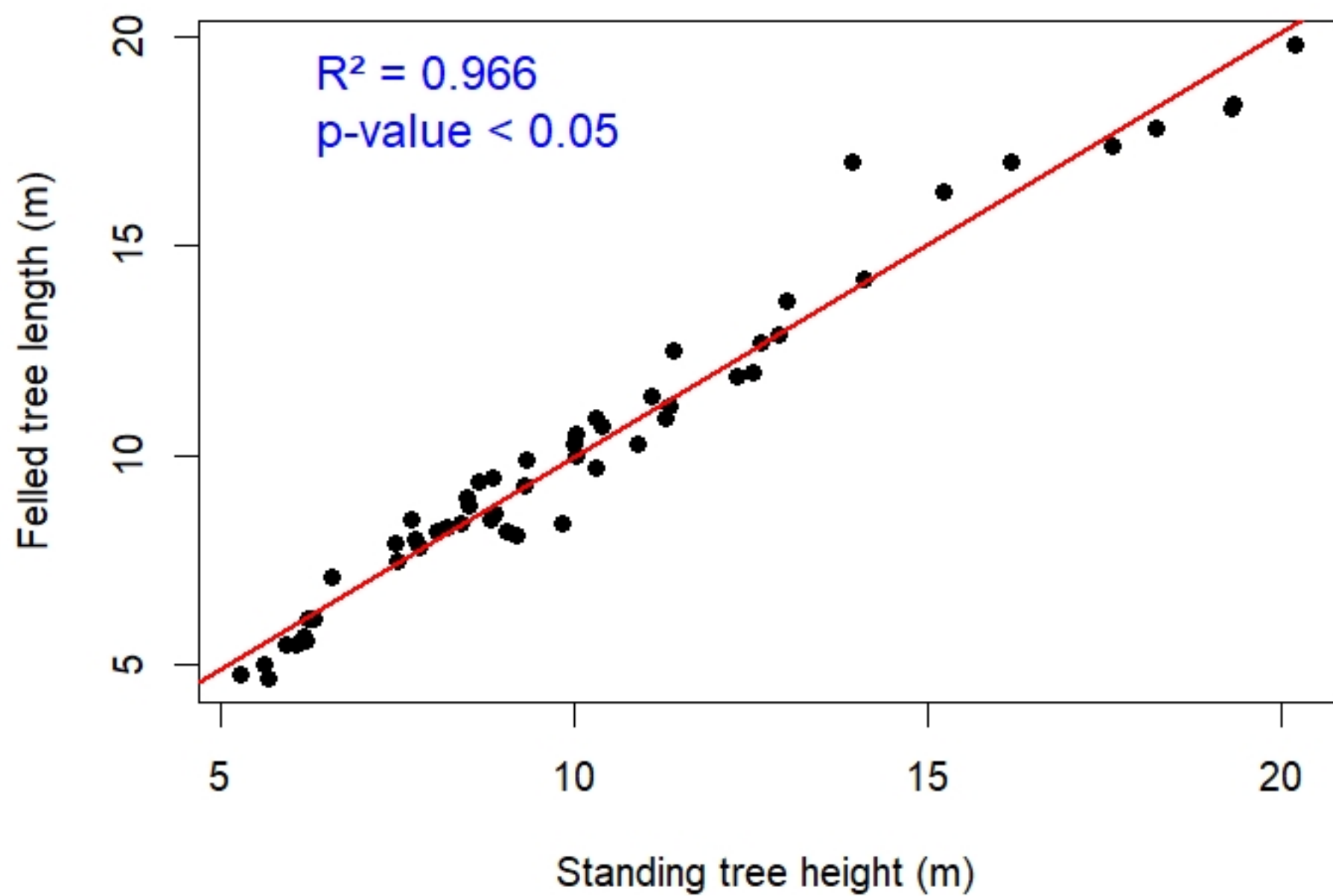


Figure S2

