INNSPUB

International Journal of Biosciences | IJB |
ISSN: 2220-6655 (Print), 2222-5234 (Online)
http://www.innspub.net
Vol. 23, No. 5, p. 24-39, 2023

RESEARCH PAPER OPEN ACCESS

Monitoring the diameter growth of irregular trunk trees in the Celtis forest in Northern Republic of Congo

Melain Merland Nguila Bakala*, Joseph Yoka, Jean-Joël Loumeto

Laboratoire de Biodiversité, De Gestion des Ecosystèmes de l'Environnement, Faculté des Sciences et Techniques, Université Marien Ngouabi, Republic of The Congo

Key words: Point of measurement, Growth, Irregular trunk tree, Tropical forests, Close-range photogrammetric approach, Central Africa

http://dx.doi.org/10.12692/ijb/23.5.24-39 Article published on November 03, 2023

Abstract

Information on the growth of tropical trees is essential for the management of tropical forests. However, tree diameter measurements taken over irregularities result in negative diameter growth due to trunk shrinkage over time. The use of the close-range photogrammetric approach to harmonise diameter measurements of irregular trunk trees is likely to improve the diameter growth of these trees. This study uses close-range photogrammetric point cloud data and conventional measurements collected on 72 irregular trunk trees at Loundoungou to examine the diameter growth of irregular trunk trees in the Celtis forest in northern Republic of Congo. Significant differences were observed in the diameter above the irregularities and at 1.30 m from the ground between 2014 and 2021, suggesting the evolution of the trunk from 2014 to 2021. The relative change in diameter above the irregularities was 4 times greater than the diameter at 1.30 m above ground. Variations in trunk diameter growth were observed within each diameter type, with the rate of diameter growth above irregularities higher for the data set and for larger diameter trees. Diameter growth models using diameter at 1.30 m above ground were best (lowest AIC and BIC), suggesting that diameter at 1.30 m above ground is, therefore, the most appropriate predictor for irregular trunk trees. The results of this study highlighted the ability of the close-range photogrammetric approach to detect diameter growth at 1.30 m above ground, which is important for improving forest carbon balance estimates and decision-making in tropical forest management.

* **Corresponding Author:** Melain Merland Nguila Bakala ✉ nguilabakalamelainmerland@gmail.com

Introduction

Knowledge of tree growth is essential for understanding the dynamics of tropical forests (Clark and Clark, 1999; Clark *et al.*, 2019). This information is often used to examine the growth response of tree species to anthropogenic and natural environmental variations (Clark *et al.*, 2003; Nath *et al.*, 2006; Feeley *et al.*, 2007; Gourlet-Fleury *et al.*, 2013; Fétéké *et al.*, 2016). Tree growth is influenced both by intrinsic factors-ontogeny (Shen *et al.*, 2014) and genotype (King *et al.*, 2013) - and by extrinsic factors such as climate, altitude (Bonada *et al.*, 2022), soil nutrients (Baribault *et al.*, 2012), competition with surrounding trees (Aakala *et al.*, 2018; Rozendaal *et al.*, 2020), strong winds (Coomes and Allen, 2007) and diseases (Lyytikäinen-Saarenmaa and Tomppo, 2002).

In forest dynamics, tree growth can be defined as the increase in size of an individual tree over time (Weiskittel *et al.*, 2011; Bowman *et al.*, 2013). Among the most commonly measured dimensions for tree growth, such as height, volume, biomass and basal area, diameter is the most important and commonly used variable in forest management decisions (Kunstler *et al.*, 2016; Wu *et al.*, 2019). Diameter has many advantages, including the ease of having close relationships with other tree attributes such as height, volume and biomass (Chave *et al.*, 2005, 2014; Feldpausch *et al.*, 2011). Therefore, to describe natural forest dynamics, information on diameter growth is essential (Nath *et al.*, 2006; Feeley *et al.*, 2007; Scolforo *et al.*, 2017; Pereira *et al.*, 2021).

Irregular trunk trees pose a particular challenge in monitoring diameter growth (Sheil, 1995; Clark and Clark, 1996; Clark, 2002; Phillips *et al.*, 2002; Metcalf *et al.*, 2009; Cushman *et al.*, 2014; Muller-Landau *et al.*, 2014; Talbot *et al.*, 2014). Many tropical trees have irregularities that extend well beyond the standard measurement height of 1.3 m. In this case, it is recommended to take diameter measurements above the irregularities, but as the height of the irregularities increases with the diameter of the tree, it is often necessary to change the Point of Measurement (POM) of the diameter (Alder and Synnott, 1992; Sheil, 1995; Condit, 1998; Picard and Gourlet-Fleury, 2008). The new POM is generally located at a higher point, where the trunk has a smaller diameter due to the diameter shrinking as the height of the irregularities increases over time (Sheil, 1995; Clark and Clark, 1996; Metcalf *et al.*, 2009). Thus, a diameter taken at a new height will not be comparable to the initial diameter (Phillips *et al.*, 2002; Metcalf *et al.*, 2009; Muller-Landau *et al.*, 2014) and considering them as such would lead to significant biases in estimates of biomass change (Clark and Clark, 1996; Cushman *et al.*, 2014; Bauwens *et al.*, 2021).

The development of remote sensing technology such as Terrestrial Laser Scanning (TLS) and Close-Range Photogrammetry (CRP) has opened up new possibilities for obtaining diameter measurements at different heights along the trunk of tropical trees (Nölke *et al.*, 2015; Bauwens *et al.*, 2017, 2021; Momo Takoudjou *et al.*, 2018; Celes *et al.*, 2019; Martin-Ducup *et al.*, 2020; Akpo *et al.*, 2020, 2021; Cushman *et al.*, 2021; Witzmann *et al.*, 2022). They have proven to be promising technologies for harmonizing the diameter measurement of irregular trunk trees at 1.30 m above the ground in the tropics (Nölke *et al.*, 2015; Bauwens *et al.*, 2017, 2021; Cushman *et al.*, 2021; Witzmann *et al.*, 2022). Both remote sensing technologies (TLS and CRP) use overlapping images to generate three-dimensional (3D) point clouds. Currently, TLS and CRP are becoming powerful technologies for monitoring tree growth over time (Kaasalainen *et al.*, 2014; Srinivasan *et al.*, 2014; Sheppard *et al.*, 2017; Hess *et al.*, 2018; Luoma *et al.*, 2019; Mokroš *et al.*, 2020; Yrttimaa *et al.*, 2020, 2022, 2023). Several studies have shown the ability of TLS and CRP to characterise changes in tree trunk shape in temperate forests during monitoring periods ranging from 9 months to 9 years (Luoma *et al.*, 2019; Mokroš *et al.*, 2020; Yrttimaa *et al.*, 2020, 2022, 2023). However, it is not known whether TLS and CRP can be used to detect changes in the trunk shape of irregular trunk trees over time in tropical forests.

A better understanding of the growth of irregular trunk trees could improve our knowledge of the dynamics of tropical forests in the face of anthropogenic pressure and climate change. Despite the advantages offered by new remote sensing technologies (TLS and CRP), little attention has been paid to the potential of these approaches in monitoring changes in the shape of irregular trunk trees over time (Bauwens *et al*., 2021). Therefore, we do not know if the diameter of irregular trunk trees obtained directly from close-range remote sensing can change over time, especially in Central Africa, which remains a relatively understudied area. The aim of this study is to examine the diameter growth of irregular trunk trees in the Celtis forest in the northern Republic of Congo. We addressed three research questions: (i) do the diameters obtained above the irregularities and at 1.30 m from the ground differ between 2014 and 2021? (ii) does the diameter growth obtained at 1.30 m from the ground differ from the diameter growth obtained above the irregularities? (iii) what is the best predictor of diameter growth between the diameter at 1.30 m above the ground and above the irregularities?

Materials and methods

Study site and sampling

The study site was located in the Loundoungou-Toukoulaka forest concession (17°31'17°34" E, 02°18'02°22" N) managed by the company CIB-Olam in the north of the Republic of Congo. Annual rainfall averages 1600 mm with a distinct dry season (December to March), and the average annual temperature is 25°C. The topography is slightly undulating, with an altitude varying between 400 and 460 m. The geological substratum consists of alluvial deposits (Fayolle *et al*., 2012). The vegetation of the area belongs to the Central African rainforests (Fayolle *et al.* 2014a) and, more specifically, to the Celtis semi-deciduous forest (Fayolle *et al.* 2014b).

On this site, fieldwork was carried out in an 800-ha experimental set-up (DynAfFor project, www.dynaffor.org), which was described by Forni *et al.* (2019). Using DynAfFor forest inventories, we targeted 6 species of irregular trunk trees belonging to 6 genera and 4 families in 2014 and 2021 (Table 1). For each species, we sampled an average of 12 individuals (range: 10 - 13 trees), representing a total of 72 trees.

Photogrammetric measurement

The images were acquired twice at the study site to cover a period of 7 years. The first was carried out in 2014 and the second in 2021. The same image acquisition procedure was followed for both periods. The procedure involved removing all small plants and vines up to 2 m high around each tree within a 3 m radius, prior to image acquisition. Four photogrammetric targets were placed at the four cardinal points around each tree at a distance of less than 1m. The reference target was placed to the south to avoid backlighting and its height was measured using a pentadecameter. The targets were used to improve the alignment and scaling of the images. The diameter at breast height (DBH) was marked with blue paint, which provided additional information during model calibration.

For image acquisition, two Nikon D90 and Nikon D5600 digital SLR cameras with a fixed zoom lens with a focal length of 16 mm were used in 2014 and 2021, respectively. The cameras (focus, ISO and shutter speed) were set in automatic mode. All trees were photographed with these settings. A series of photographs were taken all around each tree following an image acquisition method similar to the "one panorama at each step" approach of Wenzel *et al.* (2013). At each step around the tree (1 m), photographs were taken with a high overlap (vertical panorama) and converging images. The lateral shooting distance around the tree was 2-3 m.

Diameter measurement

In addition to the phtogrammetric measurements, non-destructive quantitative diameter measurements were obtained at the tree level in 2014 and 2021. Tree diameter (DAB; in cm) was measured using a tape at chest height for less irregular trunks or 30 cm above any deformation (Picard and Gourlet-Fleury, 2008).

Photogrammetric processing

For image processing, Agisoft Metashape Professional software (Agisoft LCC, St Petersburg, Russia) was used. Each series of tree photos was loaded into the software without any additional information. The photogrammetric workflow of this software consists of six phases, namely (1) target detection, (2) image alignment and sparse cloud generation, (3) scaling of the constructed 3D point clouds, (4) optimization of the sparse point clouds, (5) densification of the point clouds and (6) mesh construction. More details on the process of reconstructing these trees in three dimensions are described in Bauwens *et al.* (2017). The final product is a dense three-dimensional (3D) mesh point cloud containing XYZ coordinates. Finally, the generated mesh was saved and exported to Rstudio software to perform the cross-sections. The method used was carried out on a computer equipped with an AMD Ryzen 9 5900X processor (12 cores - 3.7/4.8 GHz - 70 MB cache) with an Asus Prime X570-Pro - AMD X570 chipset and 64 GB DDR4 memory.

To make the cross-sections along the trunk, Rstudio software was used to obtain cross-sections along the trunk using the packages 'sp' (Pebesma *et al.*, 2012), 'Raster' (Hijmans *et al.*, 2013), 'lidR' (Roussel *et al.*, 2020). Firstly, the stem skeleton was created by digitising the contours of discs with a thickness varying between 2 and 5 cm every 20 cm along the z-axis of the stem. The contours of the discs were automatically delimited. Each contour of the point clouds obtained using the splines function was then smoothed to generate a polygon. For sections of the disc where the smoothing was poorly adjusted due to occlusions, we proceeded by eliminating these occlusions and manually correcting the smoothing on the contour of the point clouds. The centre of each disc was automatically calculated as the point furthest from the edges of the polygon. All the resulting layers were saved in a "gpkg" file. The specific process details of this study are shown in Fig. 1.

Before estimating the photogrammetric variables (diameter of the trees above the irregularities and at 1.30 m from the ground), we first analysed the height of the trees generated from the 3D models in 2014 and 2021. Fig. 2 shows the distribution of trees generated in 3D according to height classes in 2014 and 2021. All the trees had an irregular structure, i.e., a bell shape in 2014 and 2021. Tree heights ranged from 4.1 to 19.90 m in 2014 and from 2.1 to 16.3 m in 2021. Height classes III, II and V are better represented, with 21, 18 and 10 trees, respectively, in 2021 than in 2014. However, height class VIII was better represented in 2014 with 9 trees than in 2021. However, in 2021, no trees were generated in height classes VI, VII and VIIII. In 2014, all the trees were generated at heights greater than 2.9 m. The imbalance in the height of the trees in 2014 and 2021 meant that it was not possible to follow the cross-sections above the irregularities during the growth period. This led us to consider the cross-section at 1.30 m from the ground. In addition, the perimeter and surface area of the cross-sections were calculated for each tree. Since diameter is the variable more frequently used than basal area to quantify tree size in forestry science, the area and perimeter of each cross-section at 1.30 m from the ground was converted into diameter. The area and perimeter of cross-sections were converted to diameter by calculating the diameter of a disc with the same area as the surface of the disc (Darea) and the diameter of a disc with the same perimeter as the perimeter of the disc (Dperim). The work of Bauwens *et al.* (2017) has already shown that Darea is a better predictor of above-ground biomass than Dperim. In this study, Darea was considered as an equivalent photogrammetric variable in 2014 and 2021.

Monitoring changes and growth in irregular trunk trees

Two variables describing tree size were taken into account in 2014 and 2021, namely DAB and Darea. Of the 72 irregular trunk trees measured, 19.44% and 43.05% of the trees whose diameters were obtained at 1.30 m above the ground (Darea) and above the irregularities (DAB), respectively were affected by the change in the point of measurement (POM). In order to work only with data free of any inconsistencies, we eliminated the trees whose diameters were affected by the change in the point of measurement (POM). To monitor changes in tree diameters over the growing season, relative changes in diameter were first assessed on the remaining trees. Relative changes were evaluated using equation 1.

$$Change\ (\%) = \frac{D_{2021} - D_{2014}}{D_{2014}} \times 100 \qquad \text{(Equation 1)}$$

Where, change (%): the relative change in diameter above irregularities (DAB) or at 1.30 m above ground level (Darea), D: the diameter obtained in 2014 and 2021.

Diameter growth was then calculated from DAB and Darea using equation 2.

$$\Delta d\ (cm/an) = \frac{D_{2021} - D_{2014}}{2021 - 2014} \qquad \text{(Equation 2)}$$

With, Δd: Diameter growth above irregularities (DAB) or at 1.30 m from the ground (Darea), D: the diameter obtained in 2014 and 2021.

Data analysis

To detect differences in tree diameters (DAB and Darea) between 2014 and 2021, the paired Student's t-test was performed to assess significant differences in DAB and Darea.

To detect differences in tree diameter growth, analysis of variance (ANOVA) was performed with diameter types as a random factor and diameter growth as a fixed factor for (1) the entire data set and (2) the two tree diameter size classes, namely, (i) the lower and middle stratum, with small and large trees, most of which reached the canopy (D < 70 cm), (ii) the upper stratum corresponding to the largest trees, which were either in the canopy or emerging, with a diameter D > 70 cm.

In order to identify the best predictor of diameter growth, the polynomial mixed effects model was fitted to the data. This was the polynomial mixed-effects model fitted to (i) all tree diameter class sizes, (ii) the lower and middle stratum tree diameter size class (D < 70 cm) and (iii) the upper stratum tree size class (D > 70 cm) with a random 'species' effect. DAB and Darea were predictors of diameter growth. The following mixed-effects polynomial model (equation 3) was fitted to the data:

$$\Delta d = \beta + \alpha_1 \times D_i + \alpha_2 \times D^2{}_i + \beta \times Species[i]$$

Equation 3)

With Δd: the diameter growth obtained above irregularities or at 1.30 m from the ground (cm/year), D is one of the diameter predictors mentioned above (in cm); β and α are the intercept and slope of the model, respectively. Models were selected using the Akaïke Information Criterion (AIC) and the Bayesian Information Criterion (BIC). The best models are those with the lowest AIC and BIC.

All statistical analyses were performed with the open-source environment R (R Core Team, 2022) and using the packages 'lme4' for fitting linear mixed models (Bates *et al.*, 2014), and 'ggplot2' for graphical output. The conditions of normality and homogeneity of variances were tested using the Shapiro-Wilk and Bartlett tests respectively before proceeding with the analyses.

Results

Relative changes in tree diameters during the growing period

Changes in the diameters of irregular trunk trees were observed between 2014 and 2021. There were significant differences with DAB (t = 6.884; df = 40; P-value < 0.001) between 2014 and 2021 and with Darea (t = 11.509; df = 57; P-value < 0.001) between 2014 and 2021, suggesting that trunk changes could be detected from the diameter above irregularities and the diameter 1.30 m ground obtained using the photogrammetric approach. The relative change in the DAB was 4 times greater than that of the Darea (Fig. 3), suggesting that the diameter above the irregularities changed faster than the diameter at 1.30 m above ground level during the growth period.

Differences in diameter growth according to diameter measurement methods

Diameter growth varied considerably between diameter measurement methods (Fig. 4a). Diameter growth obtained from the DAB was greater than that obtained from the Darea, suggesting that the rate of diameter growth obtained above the irregularities was greater than that obtained at 1.30 m above ground level. Diameter growth (Fig. 4b) also varied according to tree diameter class. For the diameter size class of trees in the lower and middle stratum (D < 70 cm), no significant difference was observed between the two diameter types (P - value = 0.167).

Nevertheless, the Diameter growth obtained from the DAB was higher than that obtained from the Darea. For the size class of large diameter trees (D > 70 cm), significant differences were observed in diameter growth (P - value < 0.001). Diameter growth obtained from DAB was greater than that obtained from Darea, suggesting that the growth rate of large trees obtained from DAB was greater than that obtained from Darea.

Table 1. Characteristics of the species studied, including scientific names, family and sampling effort (n, number of trees sampled and diameter range) in 2014 and 2021. With DAB, diameter above irregularities in 2014 and 2021.

Scientific names	Families	n	DAB in 2014	DAB in 2021
Piptadeniastrum africanum (Hook. f.) Brenan	Fabaceae	10	[33 – 123.31]	[40.60 – 123]
Celtis mildbraedii Engl.	Ulmaceae	12	[38 – 84.94]	[35 – 81.49]
Manilkara mabokeensis Aubrev.	Sapotaceae	12	[45.75 – 119.71]	[45.34 – 143.43]
Pterocarpus soyauxii Taub	Fabaceae	13	[19.42 – 87.26]	[24.20 – 102.36]
Entandrophragma cylindricum (Sprague) Sprague	Meliaceae	13	[69.67 – 185.08]	[59.30 – 175.45]
Erythrophleum suaveolens Brenan	Fabaceae	12	[71.22 – 112.43]	[67.96 – 142]

Predictors of diameter growth in irregular trunk trees

In all cases, the diameter growth models using Darea were better (lowest AIC and BIC) than the models using DAB (Table 2). These results based on a small number of samples suggest that the diameter growth model using Darea could significantly reduce the error in the diameter growth of irregular trunk trees. The Darea variable is therefore the most appropriate predictor for irregular trunk trees.

Discussion

Changes in tree diameter over the growing period

Our results show changes in tree diameters between 2014 and 2021. In general, paired Student's t-tests show that diameters (DAB or Darea) in 2021 are higher than in 2014, suggesting that trunk changes can be detected from the diameter above the irregularities and the diameter obtained at 1.30 m from the ground using the photogrammetric approach. These results are similar to those of Yrttimaa *et al.* (2020) in boreal forests, who also detected changes in tree diameter over time using the conventional method and the Terrestrial Laser Scanner (TLS) point cloud.

The relative change in DAB was greater than that of Darea, suggesting that the diameter above the irregularities changed faster than the diameter at 1.30 m above ground level during the growing period.

The rate of change in DAB relative to the rate of change in Darea could be explained by the shrinkage of the tree trunk due to the increase in the height of the irregularities during the growing period (Sheil, 1995; Clark and Clark, 1996; Metcalf *et al.*, 2009). This means that the diameters of these trees above the irregularities have decreased more than the diameter at 1.30 m from the ground. Taking such diameters into account is likely to lead to biases in the estimates of forest tree growth and, therefore, the AGB and carbon pools and fluxes (Sheil, 1995; Phillips *et al.*, 2002; Cushman *et al.*, 2014; Muller-Landau *et al.*, 2014; Talbot *et al.*, 2014).

Table 2. Results of diameter growth models (Δd) obtained above irregularities (DAB) and at breast height (Darea). With MG: general model fitted with all data, D < 70 cm: model fitted using data from the size classes of small and medium diameter trees, D > 70 cm: model fitted using data from the size classes of large diameter trees. AIC: Akaïke information criterion, BIC: Bayesian information criterion. The best model is shown in bold.

Type	Models	Fixed effect			Random effect		AIC	BIC
		Intercept	D	D^2	Species	Residual		
MG	Δd_{DAB}	-0.4898	0.0649	-0.00035	0.1795	3.3542	188.21	196.53
	Δd_{Darea}	0.6555	1.1e-04	8.095e-06	0.0217	0.2384	124.44	134.75
D < 70 cm	Δd_{DAB}	10.471	-0.484	0.006084	1.598	5.095	70.57	72.56
	Δd_{Darea}	-0.220	0.058	-0.000760	0.000	0.413	48.32	50.31
D> 70 cm	Δd_{DAB}	13.7216	-0.2026	0.0008825	0.02333	4.68062	155.23	162.24
	Δd_{Darea}	-0.5230	1.9e-02	-6.70e-05	0.003872	0.223424	101.82	111.07

Although it can be stated that changes in trunk shape do occur, the relative changes in DAB and Darea are not sufficient to explain the evolution of the shape of irregular trunk trees over the growing period. This study should be continued by taking into account indices ("taper", form factor, normal form quotient, stem slenderness) describing the shape of the trunk of irregular trunk trees in order to improve our knowledge of the evolution of the trunk over a long period of growth. In this study, the close-range photogrammetric approach was used to obtain diameter measurements. However, this approach showed its limitations in fully modelling the tree trunk due to occlusions caused by lianas on the trunk, backlighting phenomena or blurring in certain images under tropical forests (Bauwens *et al.*, 2017; Cushman *et al.*, 2021). In the future, it will be essential to use terrestrial or mobile lidar technology to improve the modelling of tropical tree trunks.

Influence of tree size on diameter growth

Diameter growth varied considerably between the diameter measurement methods, with the mean diameter growth obtained from the DAB higher than that obtained from the Darea, suggesting that the rate of diameter growth obtained above the irregularities was greater than that obtained at 1.30 m above ground level and highlighting the influence of the diameter point of measurement. These results differ from those of Metcalf *et al.* (2009) in South America, which showed that Darea increased more than DAB. The differences observed could be explained by the fact that these authors (Metcalf *et al.*, 2009) have taken into account the trees affected by the changes in point of measurement.

These mean ± Sd diameter growths were 2.55 ± 2.3 cm/year with DAB and 0.75 ± 0.49 with Darea for all trees. Estimates of diameter growth with Darea alone ranged from 0.048 to 1.141 cm/year in Brazil (da Silva *et al.*, 2002), from 0.5 to 1.8 cm/year in La Selva, Costa Rica (Clark and Clark, 1999) and from 0.71 to 0.92 cm/year in Panama (Condit *et al.*, 1995).

Diameter growth also varied according to the size class of large diameter trees (D > 70 cm), with DAB diameter growth higher than that of Darea, suggesting that the growth of large trees obtained from DAB was higher than that obtained from Darea. These differences could be explained by changes in DAB during the growth period as shown previously. The increase in the height of the irregularities could also explain the differences in DAB and Darea growth, as the size of the irregularities on the trunk was found to grow allometrically at faster rates than the tree trunks (Newbery *et al.*, 2009), which would influence the rate of increase in DAB during the growth period. Even after eliminating the negative diameter growth due to changes in the diameter point of large trees, the use of the DAB continues to overestimate the diameter growth of irregular trunk trees. These overestimates can be explained by errors in measuring the diameter of large trees with the tape measure.

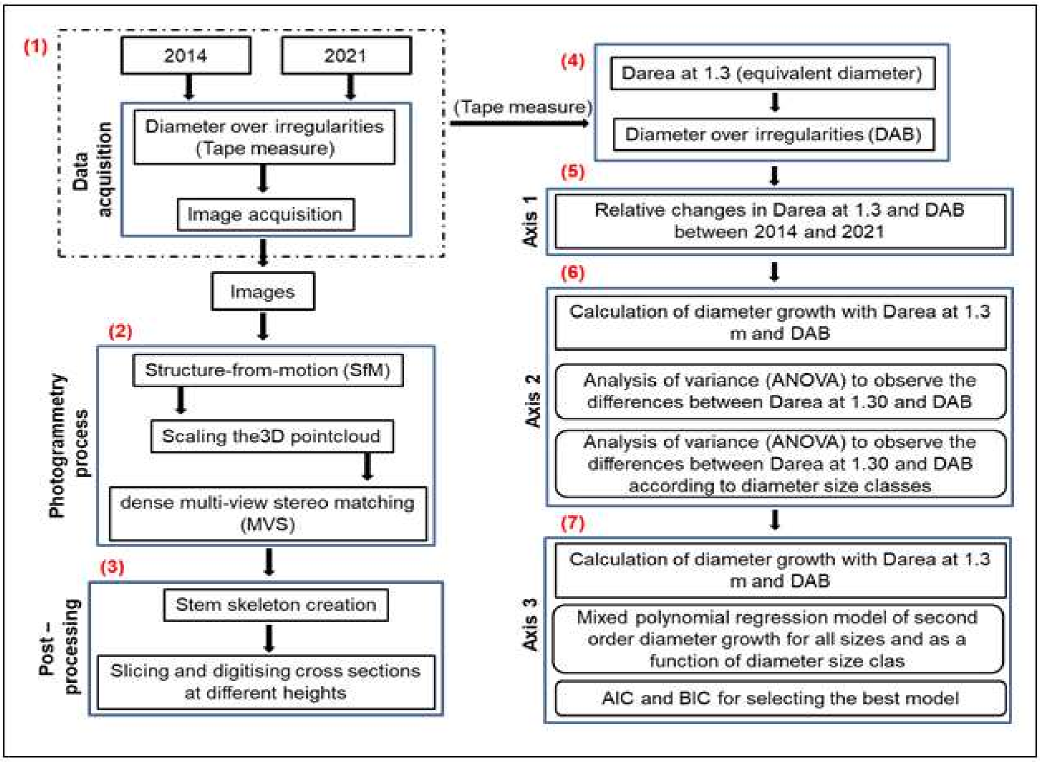

Fig. 1. Flow chart of this study.

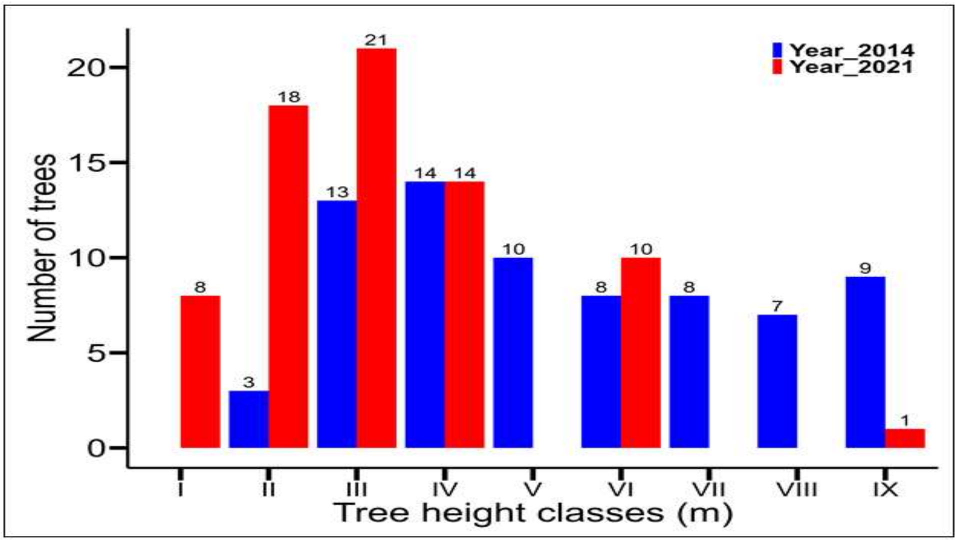

Fig. 2. Distribution of trees according to height classes in m in 2014 and 2021. With class I: [1-2.9]; class II: [3-4.9]; class III: [5-6.9]; class IV: [7-8.9]; class V: [9-10.9]; class VI: [11-12.9]; class VII: [13-14.9]; class VIII: [15-16.9]; class IX: > 17 m.

Previous studies comparing repeated diameter measurements on the same trees have already reported measurement errors with the tape measure when the measuring tool is not oriented perpendicular to the vertical axis of the stem (Clark, 2002; Phillips *et al.*, 2002; Elzinga *et al.*, 2005; Grogan and Schulze, 2008; Butt *et al.*, 2013). Visual estimates of diameter, for which diameter measurements on the irregularities of large trees are not accessible, even with the use of a scale, also lead to significant errors (Grogan and Schulze, 2008; Muller-Landau *et al.*, 2014; Celes *et al.*, 2019). In addition, these types of measurements are notoriously unreliable and lead to significant overestimates of the diametric growth of irregular trunk trees (Clark and Clark, 1996; Muller-Landau *et al.*, 2014).

Our results showed no difference in the DAB and Darea increases for the diameter size class of trees in the lower and middle strata ($D < 70$ cm), suggesting that the diameter measurement point does not influence the diameter growth of trees in the lower and middle strata.

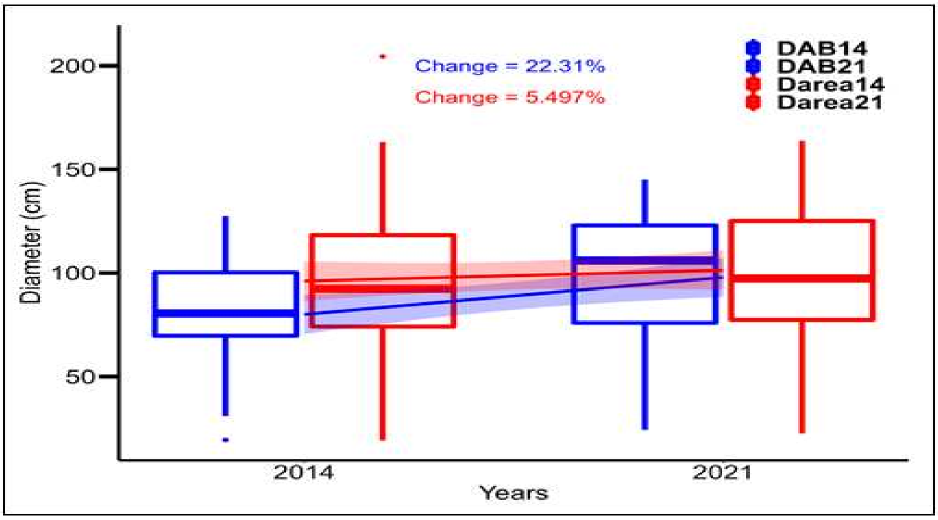

Fig. 3. Relative change in tree size attributes in 2014 and 2021. With blue colour: the relative change in diameter obtained above irregularities and red colour: the relative change in diameter obtained at breast height. The regression lines indicate the increase in attributes over the growth period. With DAB, diameter above the irregularities in 2014 (DAB14) and in 2021 (DAB21); Darea, diameter at 1.30 m from the ground in 2014 (Darea14) and in 2021 (Darea21).

Best predictor of diameter growth

Models predicting diameter growth from Darea are best with the lowest AIC and BIC, suggesting that Darea may reduce errors in diameter growth. The importance of Darea has also been demonstrated in improving above-ground biomass growth in tropical forests in Central Africa (Bauwens *et al.*, 2021) and South America (Cushman *et al.*, 2014).

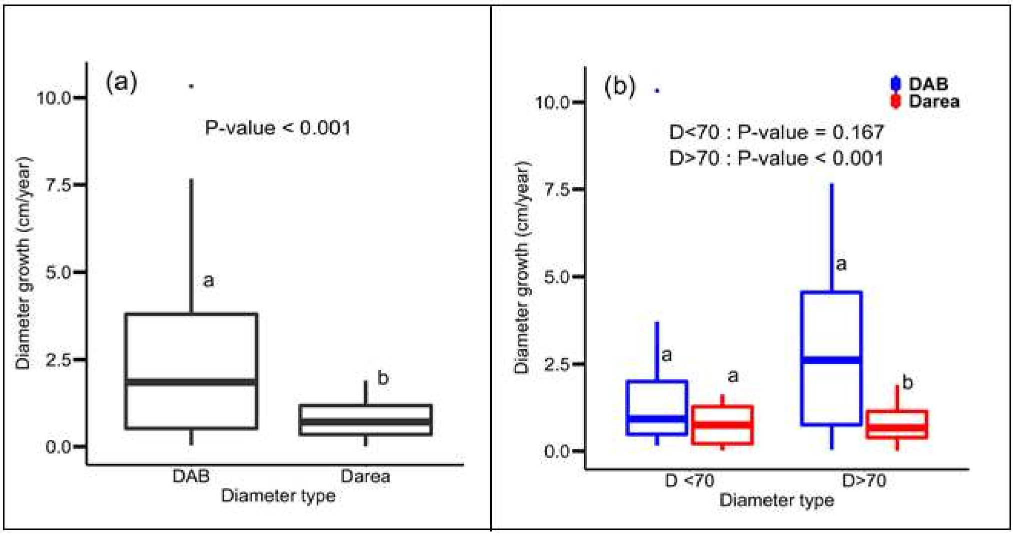

Fig. 4. Variation in diameter growth according to diameter measurement methods. With (a) variation in diameter growth obtained from diameter above irregularities and diameter at breast height, (b) variation in diameter growth according to the two diameter classes ($D < 70$: small and medium diameter class, $D > 70$: large diameter class) . The significance level (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$) is indicated and the individual letters constitute the one-factor ANOVA test.

The results clearly show that standardising the diameter at 1.30 m from the ground would eliminate the errors in measuring the diameter of large irregular trunks trees, which are sometimes excluded from the analyses because of the problem of shrinkage of the tree trunk (Condit *et al.*, 1993; Nath *et al.*, 2006; Dong *et al.*, 2012; Ligot *et al.*, 2022).

As a result, measuring the diameter of irregular trunks at 1.30 m from the ground becomes the only alternative for improving the diameter growth of irregular trunk trees (Sheil, 1995; Metcalf *et al.*, 2009; Cushman *et al.*, 2014; Muller-Landau *et al.*, 2014). Reducing uncertainties in the Diameter growth of irregular trunk trees would increase the overall carbon sink of tropical forests. This is very promising for monitoring tropical forests, which contain around 55% of large-diameter irregular trunk trees (Ploton *et al.*, 2020).

Conclusion

This study has provided new information on monitoring changes and Diameter growth in irregular trunk trees. Changes in the diameters of irregular trunk trees were observed between 2014 and 2021, with the relative change from the DAB greater than that from the Darea. The diameter growth obtained from the DAB was greater than that obtained from the Darea for all tree sizes and for the large diameter size class. No difference in diameter growth from DAB and Darea was observed for the diameter size class of trees in the lower and middle strata. The use of a diameter of 1.30 m from the ground in monitoring irregular trunk trees, therefore, becomes an opportunity to improve tree growth in tropical forests. Harmonising the measurement of the diameter of irregular trunk trees at 1.30 m above the ground and taking this into account in the development of allometric models in the tropics would, therefore, be a promising solution for improving estimates of the carbon balance of tropical forests.

Data availability statement

Data will be made available on request.

Conflict of interest

The authors declare that they have no competing interests.

Funding statement

This research project was funded by the International Science Foundation (grant NO. I-1-D-6295-1), the Conservation Action-Research Network (2020) and the "Eugen Ionescu" PhD scholarship from the Agence Universitaire de la Francophonie of the Romanian government. The fieldwork for this study was carried out in the permanent plots of the DynAfFor project.

Acknowledgments

The authors would like to thank the members of the CIB-Olam forestry company team, who greatly facilitated the work on the forestry sites. The authors would also like to thank Mr Eric Forni, CIRAD, France; Professors Olivier Bouriaud, Laura Bouriaud, University Ştefan cel Mare, Faculty of Sylviculture, Romania, for their technical support.

References

Aakala T, Berninger F, Starr M. 2018. The roles of competition and climate in tree growth variation in northern boreal old-growth forests. Journal of Vegetation Science **29,** 1040–1051. https://doi.org/10.1111/jvs.12687

Akpo HA, Atindogbé G, Obiakara MC, Adjinanoukon AB, Gbedolo M, Fonton NH. 2021. Accuracy of common stem volume formulae using terrestrial photogrammetric point clouds: a case study with savanna trees in Benin. Journal of Forestry Research **32,** 2415–2422.

Akpo HA, Atindogbé G, Obiakara MC, Adjinanoukon AB, Gbedolo M, Lejeune P, Fonton NH. 2020. Image data acquisition for estimating individual trees metrics: Closer is better. Forests **11(1),** 121 - 136. https://doi.org/10.3390/f11010121

Alder D, Synnott T. 1992. Permanent sample plot techniques for mixed tropical forest. Oxford Forestry Institute, University of Oxford, 141 p.

Baribault TW, Kobe RK, Finley AO. 2012. Tropical tree growth is correlated with soil phosphorus, potassium, and calcium, though not for legumes. Ecological Monographs **82,** 189–203. https://doi.org/10.1890/11-1013.1

Bates D, Mächler M, Bolker B, Walker S. 2014. Fitting linear mixed-effects models using lme4. arXiv preprint arXiv:1406.5823.

Bauwens S, Fayolle A, Gourlet-Fleury S, Ndjele LM, Mengal C, Lejeune P. 2017. Terrestrial photogrammetry: a non-destructive method for modelling irregularly shaped tropical tree trunks. Methods in Ecology and Evolution **8,** 460–471. https://doi.org/10.1111/2041-210X.12670

Bauwens S, Ploton P, Fayolle A, Ligot G, Loumeto JJ, Lejeune P, Gourlet-Fleury S. 2021. A 3D approach to model the taper of irregular tree stems: making plots biomass estimates comparable in tropical forests. Ecological Applications **31,** 1 - 12. https://doi.org/10.1002/eap.2451

Bonada A, Amoroso MM, Gedalof Z, Srur AM, Gallo L. 2022. Effects of climate on the radial growth of mixed stands of Nothofagus nervosa and Nothofagus obliqua along a precipitation gradient in Patagonia, Argentina. Dendrochronologia **74,** 125961. https://doi.org/10.1016/j.dendro.2022.125961

Bowman DMJS, Brienen RJW, Gloor E, Phillips OL, Prior LD. 2013. Detecting trends in tree growth: not so simple. Trends in Plant Science **18,** 11–17. https://doi.org/10.1016/j.tplants.2012.08.005

Butt N, Slade E, Thompson J, Malhi Y, Riutta T. 2013. Quantifying the sampling error in tree census measurements by volunteers and its effect on carbon stock estimates. Ecological Applications **23,** 936–943. https://doi.org/10.1890/11-2059.1

Celes CHS, Araujo RF de, Emmert F, Lima AJN, Campos MAA. 2019. Digital approach for measuring tree diameters in the Amazon forest. Floresta e Ambiente **26,** 1–10. https://doi.org/10.1590/2179-8087.038416

Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, Fölster H, Fromard F, Higuchi N, Kira T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia **145,** 87–99. https://doi.org/10.1007/s00442-005-0100-x

Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan MS, Delitti WB, Duque A, Eid T, Fearnside PM, Goodman RC. 2014. Improved allometric models to estimate the above-ground biomass of tropical trees. Global change biology **20,** 3177–3190. https://doi.org/10.1111/gcb.12629

Clark DA. 2002. Are Tropical Forests an Important Carbon Sink? Reanalysis of the Long-Term Plot Data. Ecological Applications **12,** 3–7. https://doi.org/10.1890/1051-0761(2002)012[0003:ATFAIC]2.0.CO;2

Clark DA, Clark DB. 1999. Assessing the Growth of Tropical Rain Forest Trees: Issues for Forest Modeling and Management. Ecological Applications **9,** 981–997. https://doi.org/10.1890/1051-0761(1999)009[0981:ATGOTR]2.0.CO;2

Clark DA, Piper SC, Keeling CD, Clark DB. 2003. Tropical rain forest tree growth and atmospheric carbon dynamics linked to interannual temperature variation during 1984–2000. Proceedings of the national academy of sciences **100,** 5852–5857. https://doi.org/10.1073/pnas.0935903100

Clark DB, Clark DA. 1996. Abundance, growth and mortality of very large trees in neotropical lowland rain forest. Forest Ecology and Management **80,** 235–244. https://doi.org/10.1016/0378-1127(95)03607-5

Clark DB, Ferraz A, Clark DA, Kellner JR, Letcher SG, Saatchi S. 2019. Diversity, distribution and dynamics of large trees across an old-growth lowland tropical rain forest landscape. PLOS ONE **14(11),** 1 - 23. https://doi.org/10.1371/journal.pone.0224896

Condit R. 1998. Tropical forest census plots: methods and results from Barro Colorado Island, Panama and a comparison with other plots. Springer Science & Business Media, 97 p.

Condit R, Hubbell SP, Foster RB. 1995. Demography and harvest potential of Latin American timber species: data from a large, permanent plot in Panama. Journal of Tropical Forest Science **7(4),** 599–622.

Condit R, Hubbell SP, Foster RB. 1993. Mortality and growth of a commercial hardwood 'el cativo', Prioria copaifera, in Panama. Forest Ecology and Management **62,** 107–122. https://doi.org/10.1016/0378-1127(93)90045-O

Coomes DA, Allen RB. 2007. Effects of size, competition and altitude on tree growth. Journal of Ecology **95,** 1084–1097. https://doi.org/10.1111/j.1365-2745.2007.01280.x

Cushman KC, Bunyavejchewin S, Cárdenas D, Condit R, Davies SJ, Duque Á, Hubbell SP, Kiratiprayoon S, Lum SK, Muller-Landau HC. 2021. Variation in trunk taper of buttressed trees within and among five lowland tropical forests. Biotropica **53,** 1442–1453. https://doi.org/10.1111/btp.12994

Cushman KC, Muller-Landau HC, Condit RS, Hubbell SP. 2014. Improving estimates of biomass change in buttressed trees using tree taper models. Methods Ecol Evol **5,** 573–582. https://doi.org/10.1111/2041-210X.12187

Da Silva RP, dos Santos J, Tribuzy ES, Chambers JQ, Nakamura S, Higuchi N. 2002. Diameter increment and growth patterns for individual tree growing in Central Amazon, Brazil. Forest Ecology and Management **166,** 295–301. https://doi.org/10.1016/S0378-1127(01)00678-8

Dong SX, Davies SJ, Ashton PS, Bunyavejchewin S, Supardi MNN, Kassim AR, Tan S, Moorcroft PR. 2012. Variability in solar radiation and temperature explains observed patterns and trends in tree growth rates across four tropical forests. Proc Biol Sci **279,** 3923–3931. https://doi.org/10.1098/rspb.2012.1124

Elzinga C, Shearer RC, Elzinga G. 2005. Observer variation in tree diameter measurements. Western Journal of Applied Forestry **20,** 134–137. https://doi.org/10.1093/wjaf/20.2.134

Fayolle A, Engelbrecht B, Freycon V, Mortier F, Swaine M, Réjou-Méchain M, Doucet J-L, Fauvet N, Cornu G, Gourlet-Fleury S. 2012. Geological Substrates Shape Tree Species and Trait Distributions in African Moist Forests. PLOS ONE **7,** 1 - 10. https://doi.org/10.1371/journal.pone.0042381

Fayolle A, Picard N, Doucet J-L, Swaine M, Bayol N, Bénédet F, Gourlet-Fleury S. 2014a. A new insight in the structure, composition and functioning of central African moist forests. Forest Ecology and Management **329,** 195–205. https://doi.org/10.1016/j.foreco.2014.06.014

Fayolle A, Swaine MD, Bastin J-F, Bourland N, Comiskey JA, Dauby G, Doucet J-L, Gillet J-F, Gourlet-Fleury S, Hardy OJ. 2014b. Patterns of tree species composition across tropical African forests. Journal of Biogeography **41,** 2320–2331. https://doi.org/10.1111/jbi.12382

Feeley KJ, Davies SJ, Ashton PS, Bunyavejchewin S, Nur Supardi MN, Kassim AR, Tan S, Chave J. 2007. The role of gap phase processes in the biomass dynamics of tropical forests. Proceedings of the Royal Society B: Biological Sciences **274,** 2857–2864. https://doi.org/10.1098/rspb.2007.0954

Feldpausch TR, Banin L, Phillips OL, Baker TR, Lewis SL, Quesada CA, Affum-Baffoe K, Arets EJ, Berry NJ, Bird M. 2011. Height-diameter allometry of tropical forest trees. Biogeosciences **8,** 1081–1106. https://doi.org/10.5194/bg-8-1081-2011

Fétéké F, Fayolle A, Dainou K, Bourland N, Dié A, Lejeune P, Doucet J-L, Beeckman H. 2016. Variations saisonnières de la croissance diamétrique et des phénologies foliaire et reproductive de trois espèces ligneuses commerciales d'Afrique centrale. Bois & Forêts des Tropiques **330,** 3–21.
https://doi.org/10.19182/bft2016.330.a31315

Forni E, Rossi V, Gillet J-F, Bénédet F, Cornu G, Freycon V, Zombo I, Alberny E, Mayinga M, Istace V, Gourlet-Fleury S. 2019. Dispositifs permanents de nouvelle génération pour le suivi de la dynamique forestière en Afrique centrale : bilan en République du Congo. Bois & Forêts des Tropiques **341,** 55 - 70.
https://doi.org/10.19182/bft2019.341.a31760

Gourlet-Fleury S, Mortier F, Fayolle A, Baya F, Ouédraogo D, Bénédet F, Picard N. 2013. Tropical forest recovery from logging: a 24 year silvicultural experiment from Central Africa. Philosophical Transactions of the Royal Society B: Biological Sciences **368,** 1–10.
https://doi.org/10.1098/rstb.2012.0302

Grogan J, Schulze M. 2008. Estimating the number of trees and forest area necessary to supply internationally traded volumes of big-leaf mahogany (Swietenia macrophylla) in Amazonia. Environmental Conservation **35,** 26–35.
https://doi.org/10.1017/S0376892908004554

Hess C, Härdtle W, Kunz M, Fichtner A, von Oheimb G. 2018. A high-resolution approach for the spatiotemporal analysis of forest canopy space using terrestrial laser scanning data. Ecology and evolution **8,** 6800–6811.
https://doi.org/10.1002/ece3.4193

Hijmans RJ, Van Etten J, Mattiuzzi M, Sumner M, Greenberg JA, Lamigueiro OP, Bevan A, Racine EB, Shortridge A. 2013. Raster package in R. Version.
https://mirrors.sjtug.sjtu.edu.cn/cran/web/packages/raster/raster.pdf.

Kaasalainen S, Krooks A, Liski J, Raumonen P, Kaartinen H, Kaasalainen M, Puttonen E, Anttila K, Mäkipää R. 2014. Change detection of tree biomass with terrestrial laser scanning and quantitative structure modelling. Remote Sensing **6,** 3906–3922.
https://doi.org/10.3390/rs6053906

King GM, Gugerli F, Fonti P, Frank DC. 2013. Tree growth response along an elevational gradient: climate or genetics? Oecologia **173,** 1587–1600.
https://doi.org/10.1007/s00442-013-2696-6

Kunstler G, Falster D, Coomes DA, Hui F, Kooyman RM, Laughlin DC, Poorter L, Vanderwel M, Vieilledent G, Wright SJ. 2016. Plant functional traits have globally consistent effects on competition. Nature **529,** 204–207.
https://doi.org/10.1038/nature16476

Ligot G, Gourlet-Fleury S, Dainou K, Gillet J-F, Rossi V, Mazengué M, Ekome SN, Nkoulou YS, Zombo I, Forni E, Doucet J-L. 2022. Tree growth and mortality of 42 timber species in central Africa. Forest Ecology and Management **505,** 119889.
https://doi.org/10.1016/j.foreco.2021.119889

Luoma V, Saarinen N, Kankare V, Tanhuanpää T, Kaartinen H, Kukko A, Holopainen M, Hyyppä J, Vastaranta M. 2019. Examining changes in stem taper and volume growth with two-date 3D point clouds. Forests **10,** 382–396.
https://doi.org/10.3390/f10050382

Lyytikäinen-Saarenmaa P, Tomppo E. 2002. Impact of sawfly defoliation on growth of Scots pine Pinus sylvestris (Pinaceae) and associated economic losses. Bulletin of Entomological Research **92,** 137–140.
https://doi.org/10.1079/BER2002154

Martin-Ducup O, Ploton P, Barbier N, Momo Takoudjou S, Mofack G, Kamdem NG, Fourcaud T, Sonké B, Couteron P, Pélissier R. 2020. Terrestrial laser scanning reveals convergence of tree architecture with increasingly dominant crown canopy position. Functional Ecology **34,** 2442–2452.
https://doi.org/10.1111/1365-2435.13678

Metcalf CJE, Clark JS, Clark DA. 2009. Tree growth inference and prediction when the point of measurement changes: modelling around buttresses in tropical forests. Journal of Tropical Ecology **25,** 1–12. https://doi.org/10.1017/S0266467408005646

Mokroš M, Výbošt'ok J, Grznárová A, Bošela M, Šebeň V, Merganič J. 2020. Non-destructive monitoring of annual trunk increments by terrestrial structure from motion photogrammetry. PloS one **15,** 1–14. https://doi.org/10.1371/journal.pone.0230082

Momo Takoudjou S, Ploton P, Sonké B, Hackenberg J, Griffon S, De Coligny F, Kamdem NG, Libalah M, Mofack GI, Le Moguédec G. 2018. Using terrestrial laser scanning data to estimate large tropical trees biomass and calibrate allometric models: A comparison with traditional destructive approach. Methods in Ecology and Evolution **9**, 905–916.

Muller-Landau HC, Detto M, Chisholm RA, Hubbell SP, Condit R. 2014. Detecting and projecting changes in forest biomass from plot data. Forests and global change **17,** 381–416.

Nath CD, Dattaraja HS, Suresh HS, Joshi NV, Sukumar R. 2006. Patterns of tree growth in relation to environmental variability in the tropical dry deciduous forest at Mudumalai, southern India. Journal of Biosciences **31,** 651–669. https://doi.org/10.1007/BF02708418

Newbery DM, Schwan S, Chuyong GB, van der Burgt XM. 2009. Buttress form of the central African rain forest tree Microberlinia bisulcata, and its possible role in nutrient acquisition. Trees **23,** 219–234.

Nölke N, Fehrmann L, I Nengah SJ, Tiryana T, Seidel D, Kleinn C. 2015. On the geometry and allometry of big-buttressed trees - a challenge for forest monitoring: new insights from 3D-modeling with terrestrial laser scanning. iForest-Biogeosciences and Forestry **8,** 574–582. https://doi.org/10.3832/ifor1449-007

Pebesma E, Bivand R, Pebesma ME, RColorBrewer S, Collate AAA. 2012. Package 'sp.' The Comprehensive R Archive Network.

Pereira IRC, Morais VM de C, Emmert F, Nascimento RGM. 2021. Size, Ecology, and Seasonality Affect the Monthly Diametric Growth of Trees in a Secondary Forest. Floresta Ambient. **28,** 1–10. https://doi.org/10.1590/2179-8087-FLORAM-2021-0009

Phillips OL, Malhi Y, Vinceti B, Baker T, Lewis SL, Higuchi N, Laurance WF, Vargas PN, Martinez RV, Laurance S, Ferreira LV, Stern M, Brown S, Grace J. 2002. Changes in Growth of Tropical Forests: Evaluating Potential Biases. Ecological Applications **12,** 576–587. https://doi.org/10.1890/1051-0761(2002)012[0576:CIGOTF]2.0.CO;2

Picard N, Gourlet-Fleury S. 2008. Manuel de référence pour l'installation de dispositifs permanents en forêt de production dans le Bassin du Congo. COMIFAC, 271 p.

Ploton P, Mortier F, Barbier N, Cornu G, Réjou-Méchain M, Rossi V, Alonso A, Bastin J-F, Bayol N, Bénédet F, Bissiengou P, Chuyong G, Demarquez B, Doucet JL, Droissart V, Kamdem NG, Kenfack D, Memiaghe H, Moses L, Sonké B, Texier N, Thomas D, Zebaze D, Pélissier R, Gourlet-Fleury S. 2020. A map of African humid tropical forest above-ground biomass derived from management inventories. Sci Data **7,** 221–234. https://doi.org/10.1038/s41597-020-0561-0

R Core Team. 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing. version 4.2.1 (2022-06-23 ucrt). Vienna, Austria. http://www.R-project.org

Roussel J-R, Auty D, Coops NC, Tompalski P, Goodbody TRH, Meador AS, Bourdon J-F, de Boissieu F, Achim A. 2020. lidR: An R package for analysis of Airborne Laser Scanning (ALS) data. Remote Sensing of Environment **251,** 112061-112076. https://doi.org/10.1016/j.rse.2020.112061

Rozendaal DMA, Phillips OL, Lewis SL, Affum-Baffoe K, Alvarez-Davila E, Andrade A, Aragão LEOC, Araujo-Murakami A, Baker TR, Bánki O, Brienen RJW, Camargo JLC, Comiskey JA, Djuikouo Kamdem MN, Fauset S, Feldpausch TR, Killeen TJ, Laurance WF, Laurance SGW, Lovejoy T, Malhi Y, Marimon BS, Marimon Junior B-H, Marshall AR, Neill DA, Núñez Vargas P, Pitman NCA, Poorter L, Reitsma J, Silveira M, Sonké B, Sunderland T, Taedoumg H, ter Steege H, Terborgh JW, Umetsu RK, van der Heijden GMF, Vilanova E, Vos V, White LJT, Willcock S, Zemagho L, Vanderwel MC. 2020. Competition influences tree growth, but not mortality, across environmental gradients in Amazonia and tropical Africa. Ecology **101,** 1–11. https://doi.org/10.1002/ecy.3052

Scolforo HF, Scolforo JRS, Thiersch CR, Thiersch MF, McTague JP, Burkhart H, Ferraz Filho AC, de Mello JM, Roise J. 2017. A new model of tropical tree diameter growth rate and its application to identify fast-growing native tree species. Forest Ecology and Management **400,** 578–586. https://doi.org/10.1016/j.foreco.2017.06.048

Sheil D. 1995. A critique of permanent plot methods and analysis with examples from Budongo Forest, Uganda. Forest Ecology and Management **77,** 11–34. https://doi.org/10.1016/0378-1127(95)03583-V

Shen Y, Santiago LS, Shen H, Ma L, Lian J, Cao H, Lu H, Ye W. 2014. Determinants of Change in subtropical tree diameter growth with ontogenetic stage. Oecologia **175,** 1315–1324. https://doi.org/10.1007/s00442-014-2981-z

Sheppard J, Morhart C, Hackenberg J, Spiecker H. 2017. Terrestrial laser scanning as a tool for assessing tree growth. iForest: Biogeosciences and Forestry **10**, 172–179.

Srinivasan S, Popescu SC, Eriksson M, Sheridan RD, Ku NW. 2014. Multi-temporal terrestrial laser scanning for modeling tree biomass change. Forest Ecology and Management **318,** 304–317.

Talbot J, Lewis SL, Lopez-Gonzalez G, Brienen RJ, Monteagudo A, Baker TR, Feldpausch TR, Malhi Y, Vanderwel M, Murakami AA. 2014. Methods to estimate above-ground wood productivity from long-term forest inventory plots. Forest Ecology and Management **320,** 30–38.

Weiskittel AR, Hann DW, Kershaw Jr JA, Vanclay JK. 2011. Forest growth and yield modeling. John Wiley & Sons, 85 p.

Wenzel K, Rothermel M, Fritsch D, Haala N. 2013. Image acquisition and model selection for multi-view stereo. Int. Arch. Photogramm. Remote Sens. Journal of Spatial Information Science **40,** 251–258.

Witzmann S, Matitz L, Gollob C, Ritter T, Kraßnitzer R, Tockner A, Stampfer K, Nothdurft A. 2022. Accuracy and precision of stem cross-section modeling in 3D point clouds from TLS and caliper measurements for basal area estimation. Remote Sensing **14,** 1923–1950.

Wu X, Zhou S, Xu A, Chen B. 2019. Passive measurement method of tree diameter at breast height using a smartphone. Computers and Electronics in Agriculture **163**, 104875–104886. https://doi.org/10.1016/j.compag.2019.104875

Yrttimaa T, Junttila S, Luoma V, Calders K, Kankare V, Saarinen N, Kukko A, Holopainen M, Hyyppä J, Vastaranta M. 2023. Capturing seasonal radial growth of boreal trees with terrestrial laser scanning. Forest Ecology and Management **529,** 120733–120743. https://doi.org/10.1016/j.foreco.2022.120733

Yrttimaa T, Luoma V, Saarinen N, Kankare V, Junttila S, Holopainen M, Hyyppä J, Vastaranta M. 2022. Exploring tree growth allometry using two-date terrestrial laser scanning. Forest Ecology and Management **518,** 120303–120316.
https://doi.org/10.1016/j.foreco.2022.120303

Yrttimaa T, Luoma V, Saarinen N, Kankare V, Junttila S, Holopainen M, Hyyppä J, Vastaranta M. 2020. Structural Changes in Boreal Forests Can Be Quantified Using Terrestrial Laser Scanning. Remote Sensing **12,** 2672–2692.
https://doi.org/10.3390/rs12172672