Improving tree diameter measurements above irregularities in Central African forests: a Close-Range Photogrammetric approach

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Accurate measurement of tree diameter in forests is essential for sustainable management of forest resources, ecological assessment, and scientific research. However, most trees in tropical forests have irregularities at the base of the trunk, making it challenging to measure the trunk diameter above them with a tape measure. To meet the increasing demand for data accuracy and reliability, approaches using three-dimensional (3D) point clouds offer a valuable new source of data for tree measurements. This study examines the accuracy of diameter measurements above irregularities using the Close-Range Photogrammetric approach, with diameter tape serving as the reference. A total of 212 trees measured in the north of the Republic of Congo were reconstructed in three dimensions (3D), including 128 trees in semi-deciduous forest and 84 trees in evergreen forest. Comparisons were made in terms of dependence (simple linear regression), correlation (Pearson, Kendall, and Spearman tests), agreement (Bland and Altman method), and difference (Mean Absolute Error - MAE, Root Mean Square Error - RMSE, bias - BIAS, and coefficient of variation - CV). In addition to a near perfect match, a strong association of diameter measurements and a good degree of agreement, the results indicated the presence of differences between diameter measurement approaches in semi-deciduous forest (MAE = 9.25 cm, RMSE = 16.95 cm, BIAS = 7.45 cm) and evergreen forest (MAE = 3.88 cm, RMSE = 8.47 cm, BIAS = 2.37 cm). These differences are minor in the evergreen forest. The magnitude of the differences found is mostly due to the size of the large-diameter classes. In addition, the coefficients of variation (CV) of diameter obtained from the Close-Range Photogrammetric approach were lower than those obtained from the classic conventional approach in both forests, indicating the higher accuracy of the former approach. Further studies could use larger data samples to provide more accurate estimates and verify the limits of these applications' measurement capabilities.

Keywords: Diameter, Irregular Trunk Trees, Measuring Accuracy, Close-range Photogrammetric Approach

Introduction

Diameter is the most commonly measured tree attribute, whether for inventory, management, or forest monitoring purposes (West 2015). It is a crucial indicator of forest health and functionality (Haq et al. 2023). However, measuring the diameter at breast height of tropical trees using conventional dendrometric tools is biased when the trunk has irregularities at its base (Clark 2002). In this case, we recommend moving the diameter measurement point above the irregularities until the trunk has a geometrically cylindrical shape (Alder & Synnott 1992, Picard & Gourlet-Fleury 2008). Nonetheless, in some situations, it may not be possible to raise the point of diametric measurement above the irregularities using conventional dendrometric tools, which means the forester must visually measure or determine the trunk diameter (Grogan & Schulze 2008, Celes et al. 2019). Measurements of this kind yield values that differ from the actual tree sizes (Celes et al. 2019).

To address the inaccessibility of diameter measurement above irregularities, many instruments using the indirect approach (no contact with the tree) have been proposed in the literature (Clark et al. 2000, Weaver et al. 2015, Ucar et al. 2022). These instruments can be differentiated based on cost, accuracy, precision, and ease of use (Clark et al. 2000, West 2015, Paul et al. 2017, Mokroš et al. 2018b). However, indirect approaches are imprecise or time- and resource-intensive (Liu et al. 2011, Weaver et al. 2015, Ucar et al. 2022).

To meet the increasing demands for data accuracy and robustness, three-dimensional (3D) point clouds are a valuable new source of data for tree measurements (Mokroš et al. 2018a). 3D tree data can be subdivided into two primary acquisition methods: Terrestrial Laser Scanning (TLS) and Close-Range Photogrammetry (CRP) (Liang et al. 2016, Surovy et al. 2016). TLS is a technology that uses light detection and rang-

ing (LiDAR) to characterise individual stems at plot or tree scale more effectively, providing accurate estimates of stem diameter, height, volume, and biomass (Calders et al. 2020). However, TLS units are expensive and often difficult to handle (Liang et al. 2016). A quicker and cheaper alternative for obtaining similar data for use in the forest inventory is the Close-Range Photogrammetric (CPR) approach (Liang et al. 2016, Mokroš et al. 2018b). CRP allows to obtain 3D point cloud data from sequential images based on the principle of multi-view geometry (Iglhaut et al. 2019, Zhu et al. 2021, Kuzelka & Surovy 2021). At present, the dominant method of 3D reconstruction is Structure from Motion (SfM) (Bauwens et al. 2017, Akpo et al. 2020, Eliopoulos et al. 2020). Based on SfM, recent studies have demonstrated the success of CRP in reconstructing individual stems at tree or plot scale to estimate diameter, volume, above-ground biomass (Forsman et al. 2016, Bauwens et al. 2017, Mokroš et al. 2018a, 2018b, Mulverhill et al. 2019, Marzulli et al. 2020, Han et al. 2023), detect trunk shape (Bauwens et al. 2017), establish taper equations (Bauwens et al. 2021, Cushman et al. 2021) and monitor tree diameter growth (Nguila Bakala et al. 2023).

The potential of using CRP to estimate tree diameter has been widely demonstrated in temperate and boreal forests (Forsman et al. 2016, Mokroš et al. 2018a, 2018b, Piermattei et al. 2019, Wu et al. 2019, Eliopoulos et al. 2020, Marzulli et al. 2020). These studies show that the precision (RMSE) of diameter estimates varies from 0.21 to 3.1 cm at the tree scale (Surovy et al. 2016, Wu et al. 2019, Eliopoulos et al. 2020) and from 1.21 to 7.2 cm at the plot scale (Forsman et al. 2016, Mokroš et al. 2018a, Piermattei et al. 2019, Marzulli et al. 2020). However, in tropical regions, very little in-

formation is currently available on measuring the diameter of trees above irregularities using the CRP approach (Bauwens et al. 2017, Celes et al. 2019). Furthermore, studies using the CRP approach for diameter measurement over irregularities in the tropics have focused on a single forest type (Bauwens et al. 2017, Celes et al. 2019). Therefore, further analysis on diameter accuracy as a function of diameter class size and within different forest types is needed to understand the usefulness of the CRP approach in forest management and biodiversity conservation.

This study aims to detect possible biases when using the Close-Range Photogrammetric approach and the classic conventional approach to measure tree diameters above irregularities. We seek to answer the following questions: (i) Do the measurements of diameter above irregularities using the Close-Range Photogrammetric approach and the classic conventional approach differ significantly? (ii) How accurate is the measurement of diameter above irregularities using the CPR approach compared with the classic conventional approach?

Material and methods

Study sites and sampling

The study was carried out at two forest sites characteristic of the primary forest types in the Congo Basin, as described by Réjou-Méchain et al. (2021): a semi-deciduous forests (Semi-F) and an evergreen forest (Ever-F) in the north of the Republic of Congo. The Loundoungou site, located at 17° 31′ - 17° 34′ E, 02° 18′ - 02° 22′ N, belongs to Semi-F and is dominated by light-demanding deciduous tree species, notably of the genus *Celtis* (Fayolle et al. 2014), while the Ngombé site (15° 20′ - 16° 38′ E,

00° 27′ - 01° 48′ N, Ever-F) is characterised by species belonging to the Meliaceae and Fabaceae families (Lanfranchi & Schwartz 1990). The forest sites are dominated by clay soils (Lanfranchi & Schwartz 1990, Fayolle et al. 2012). The climate at forest sites is humid tropical, with a dry season (December-February) and a long rainy season (March-November). On average, annual rainfall ranges from 1700 to 1900 mm, and the average yearly temperature is 25 °C. The two forest sites have gentle topography, with average altitudes of 400-460 m a.s.l.

In each forest site, fieldwork was carried out within an 800-ha experimental set-up (DynAfFor project – https://www.dynaffor.org) described by Forni et al. (2019). Using DynAfFor forest inventories, we targeted 11 species of irregular-trunk trees (n=9 species for Semi-F and n=5 for Ever-F, with three species shared between the two sites) belonging to 11 genera and eight families (Tab. S1 in Supplementary material). For each species, we sampled an average of 20 individuals (range: 5 to 47 trees), totaling 307 trees (181 in Semi-F and 126 in Ever-F).
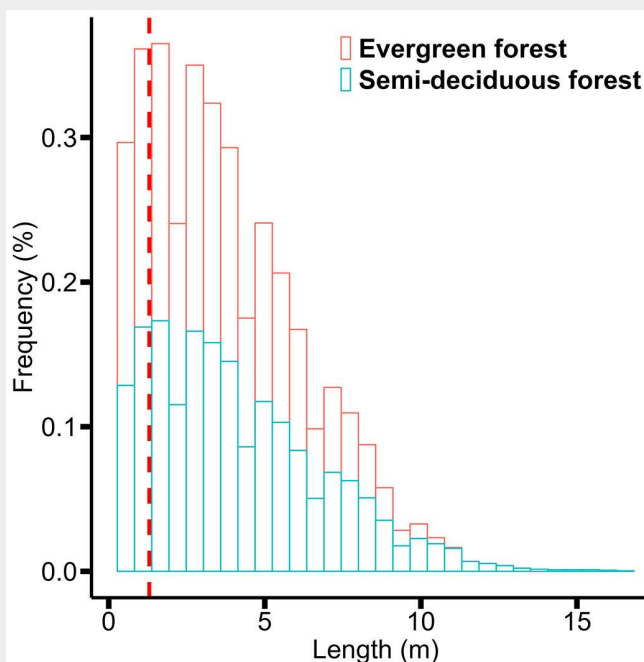
Photogrammetric measurements and processing

The image acquisition procedure consisted of removing all small plants and lianas within a 3 m radius around each tree. Four photogrammetric targets were placed at the four cardinal points around each tree at a distance of less than 1 m. The reference target was placed to the south to avoid backlighting. Targets were used to improve image alignment and point cloud scaling. The Nikon D5600™ digital SLR camera was used with a fixed zoom lens with a focal length of 16 mm. The camera (focus, ISO, and shutter speed) has been set to automatic mode. All trees were photographed with these settings. A series of photographs was taken around each tree using an image-acquisition method similar to the "one panorama at each stage" approach (Bauwens et al. 2017). At each step around the tree (1 m), photographs were taken with a substantial overlap (vertical panorama) and convergent images. The distance from the image-taking point to the tree was 3 m.

The Agisoft Metashape Professional (Agisoft LCC, St Petersburg, Russia) software was used to process the images. 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) point cloud densification, and (6) mesh construction.

The photogrammetric workflow can be summarised as follows. Once the target has been detected (phase 1), the Meta-

Fig. 1 - Distribution of cross-sections at different heights along the trunk in semi-deciduous and evergreen forests. The red line indicates the measurement point at 1.30 m above the ground.

Fig. 2 - Distribution of trees whose height has achieved the diameter measurement point in (a) semi-deciduous forest and (b) evergreen forest.

shape software automatically calculates lens calibration parameters using the SfM algorithm. The final product of phase 2 is a scattered point cloud of the tree trunk with camera locations. In the third phase (3), the point cloud is scaled using coded targets automatically detected on the photogrammetric test patterns from phase 1. The resulting 3D point cloud after scaling was optimised to adjust the camera's intrinsic and extrinsic parameters in the fourth phase. Phase 4 brings back the cloud of points scattered along the trunk. Before the point clouds were densified to create the mesh, ill-fitting point clouds along the trunk were removed to reduce processing time. Then, thanks to the image network's geometric knowledge, it was possible to produce a dense point cloud, including the calculation of a corresponding 3D point for almost every image pixel using the Multi-View Stereo (MVS) algorithm (phase 5). Finally, the mesh (phase 6) was generated, saved, and exported as a "mesh" file containing the XYZ coordinates to obtain the cross-sections in RStudio.

The method was applied using a computer equipped with an AMD Ryzen 9 5900X processor (12 cores, 3.7/4.8 GHz, 70 MB cache), an Asus Prime X570-Pro motherboard with an AMD X570 chipset, and 64 GB of DDR4 memory. From the 3D mesh, cross-sections along the trunk were generated following the workflow detailed in Bauwens et al. (2017) using the R packages "sp", "Raster", and "lidR". The workflow produces 2 cm-thick cross-sections every 20 cm along the trunk's Z axis. The workflow was successfully implemented on 88% (n = 160) of the 181 Semi-F trees and 91% (n = 115) of the 126 Ever-F trees, and failed on the remaining trees, which were therefore discarded from the analysis.

The data was automatically saved in a structured CSV file, significantly reducing data entry time and minimizing the risk of transcription errors. The generated file included essential information, such as tree ID, species, forest type, and cross-sections at different heights, facilitating data analysis and management.

Before estimating the photogrammetric variables, a preliminary analysis was carried out on the cross-sections obtained along the trunks of the 3D-generated trees (Fig. 1), as well as on the 3D models that had reached the diameter measurement height above the irregularities (Fig. 2) in each forest site. Fig. 1 shows the distribution of cross-sections obtained along the trunk in the forest sites. Examination of these frequency histograms reveals the most significant proportion of cross-sections between 1.30 and 6 m in height in the semi-deciduous forest (60.38% with an average height ± standard deviation of 4.12 ± 2.75 m) and in the evergreen forest (64.01% with an average height of 3.55 ± 2.28 m). Fig. 1 also shows that cross-sections were obtained from some trees up to 16.30 m in the semi-deciduous forest and 10.30 m in the ever-
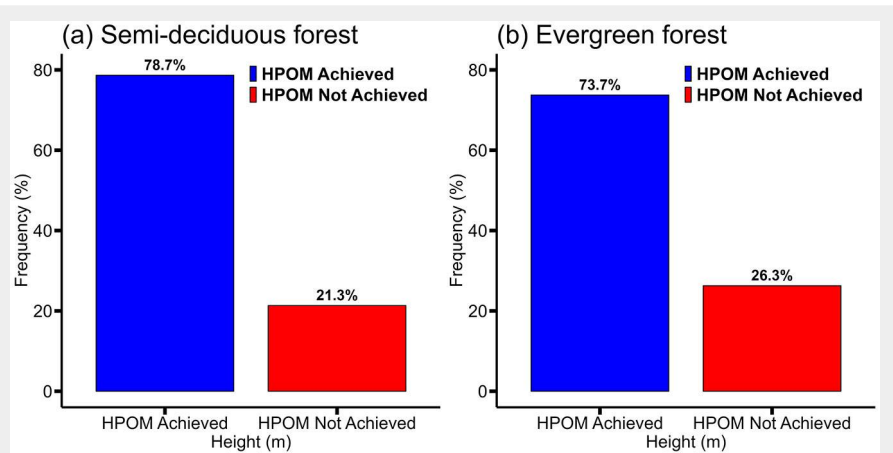
green forest. In the semi-deciduous forest, 128 of the 160 trees reconstructed in 3D reached the point of measurement (POM) for diameter (HPOM). Fig. 2a shows that 78.7% of trees achieved HPOM, with an average height of 4.52 ± 2.14 m in the semi-deciduous forest. On the other hand, in the evergreen forest, 84 of the 115 trees reconstructed in 3D reached the HPOM. Fig. 2b shows that HPOM was achieved by 73.7% of trees, with an average height of 2.31 ± 1.34 m in the evergreen forest.

Only trees for which the 3D model reached the diameter measurement height (HPOM) were taken into account. Fig. S1 (Supplementary material) show a sample of the shape of the cross-sections obtained 30 cm above the irregularities. For each cross-section, the disc area ("Darea") and disc perimeter ("Dperim") were calculated. Since diameter is more frequently used than basal area to quantify tree size in forestry science, the area and perimeter of cross-sections were converted into diameter. Previous studies have already shown

that Darea is a better predictor of aboveground biomass than Dperim (Bauwens et al. 2017, Han et al. 2023). In this study, Darea was considered equivalent to the point-of-measurement (POM) for diameter. The photogrammetric workflow is shown in Fig. 3.

Tree diameter measurements

In addition to Close-Range Photogrammetric measurements, diameter measurements were obtained at the tree level. The diameter of the trees (D, in cm) was measured with a tape at a height of 30 cm above any deformation (Picard & Gourlet-Fleury 2008). A single person took all the diameter measurements. This process enabled avoiding differences between individuals, even slight ones (Elzinga et al. 2005).

Data analysis

To support statistical comparisons between diameter measurement methods above irregularities, the mean and stan-
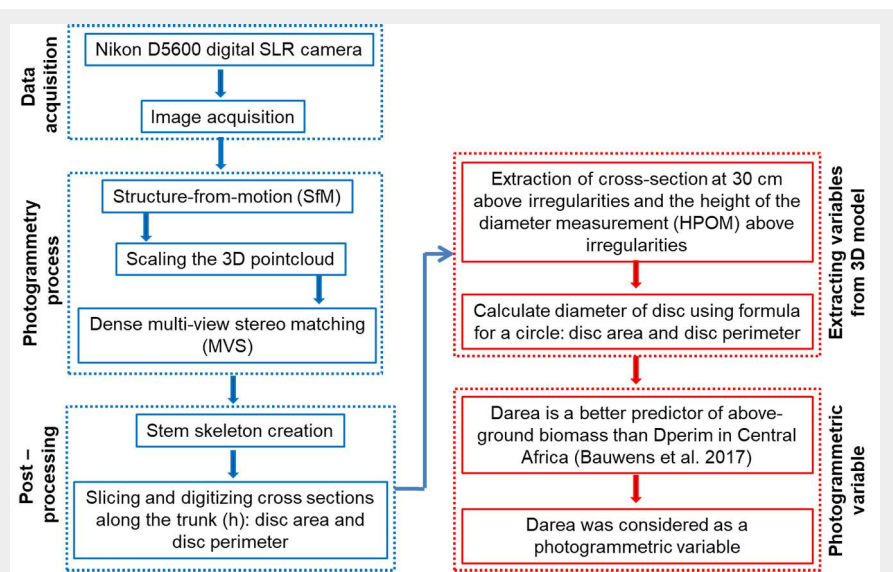

Fig. 3 - Photogrammetric workflow.

dard deviation were calculated for all data as a function of diameter class sizes. To detect differences between the diameter obtained using the Close-Range Photogrammetric approach (Darea) and the diameter obtained using the classic conventional approach (DPOM), the Wilcoxon pairwise test was performed on all data, and according to diameter class (D < 70: smaller diameter class, D > 70: larger diameter class). In addition, a complete correlation analysis was carried out on all data and as a function of diameter class sizes, using Pearson (r), Spearman (ρ), and Kendall (τ) tests (Zar 2010), complemented by a graphical representation of association and dependence (causality) in the data and the development of simple linear regression models. These models and their key statistics were used to assess whether there were general trends in the data fit and their magnitudes. These analyses were carried out on the entire data set and by diameter class.

To examine the accuracy of diameter measurement using the Close-Range Photogrammetric approach (Darea) versus the classic conventional approach (DPOM), Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and bias were estimated for all data and as a function of diameter class size (D < 70: smaller diameter class, D > 70: larger diameter class). Absolute differences between diameters and relative differences between diameters were also estimated. As a measure of error, MAE is a statistical measure used to quantify the accuracy of a measurement method by comparing predicted or estimated values with reference or absolute values (eqn. 1):

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |y_i - \hat{y}_i| \qquad (1)$$

where n is the total number of observations, y_i is the real (or reference) value, and $\hat{y}_i$ is the estimated or measured value.

RMSE is calculated as the square root of the mean of the squared deviations between measured and reference values in a given sample (eqn. 2):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2} \qquad (2)$$

Finally, BIAS is calculated as the mean of the differences between measured and reference values (eqn. 3):

$$BIAS = \frac{1}{n} \sum_{i=1}^{n} y_i - \hat{y}_i \qquad (3)$$

When the precision of the two sets of estimates is uncertain, these error measures can be interpreted as differences between them and present different sensitivities to the magnitude of differences found in the data; thus, the RMSE is more sensitive to a large magnitude of differences in the data, unlike the MAE (Willmott & Matsuura 2005). On the other hand, BIAS measures the average estimation error of new data relative to reference data (Giavarina 2015) and also accounts for the direction of the estimation error. In addition, the agreement between the measurement methods compared was analyzed using the method developed by Bland and Altman. Bland-Altman plots are generally used to assess agreement between two measurements of the same variable when it is uncertain whether the measurements are free of error (Giavarina 2015). This statistical method is handy for finding out whether a new measurement method will achieve acceptable accuracy compared with a reference method, provided that acceptable limits of agreement can be set in advance (Bland & Altman 1995, Giavarina 2015, Borz et al. 2024). Typically, it plots the absolute difference between two variables with respect to their mean values in a space defined by two limits of agreement (upper and lower limits of agreement) that includes an identity line (zero differences) and the line characterizing the mean of the differences (Bias). When the difference values are clustered around the Bias within two standard deviations of their mean (i.e., the limits of agreement), measurement agreement between the methods being compared is generally achieved. Although this approach assumes that the differences are normally distributed, the fact that they are not is less severe than in other statistical contexts. Given that the method estimates a fixed bias, it may be necessary to test for heteroscedasticity, which can be done using several techniques (Giavarina 2015), to verify the presence of a proportional bias (Ludbrook 2010, Mansournia et al. 2021). The statistical measures taken in this study to check the agreement between the measurement methods consisted of (i) checking the normality of the data in absolute differences, (ii) checking the homoscedas-

ticity of the data, and (iii) developing Bland-Altman graphs. As recommended in previous studies (Mansournia et al. 2021), it is helpful to check for a correlation between the differences and the mean values of a given pair of data sets before performing a Bland-Altman analysis. This statistical step used the same correlation measures as mentioned above for all compared data sets. Data homoscedasticity can be checked using Breusch-Pagan tests (Breusch & Pagan 1979). Statistical analyses of method agreement using the Bland-Altman method were carried out at the sample level. The coefficients of variation of the diameters obtained from the two diameter measurement approaches were also compared. Finally, the one-sample Student's t-test was performed to detect differences between coefficients of variation (CV%).

Departure from normal distribution of data and homogeneity of variances were tested using the Shapiro-Wilk, d'Agostino-Pearson, and Bartlett tests, respectively, before carrying out the analyses (see Tab. S2 in Supplementary materials).

Results

Comparison of tree diameter measurements above irregularities

The average diameters measured in each forest type and the associated measurement approaches are presented in Tab. 1. In general, the results show that the diameter obtained from the classic conventional approach is superior to that obtained from the Close-Range Photogrammetric (CPR) approach in both forest types and as a function of diameter class size (Tab. 1). In addition, the results of the Wilcoxon pairwise test showed no significant difference (Fig. S2) between measurements of tree diameter above irregularities made using the classic conventional approach and the Close-Range Photogrammetric approach in semi-deciduous forest (W = 7978, p-value = 0.1482) and evergreen forest (W = 4135.5, p-value = 0.8079). Similar trends were observed in small-diameter class sizes in semi-deciduous forest (W = 650.5, p-value = 0.176) and evergreen forest (W = 1480, p-value = 0.8949), but also in large-diameter class sizes in evergreen forest (W = 711.5, p-value = 0.478). The absence of differences in tree diameters indicates that diameter-measurement methods have little influence on measurements over irregularities. However, significant differences were observed in large-diameter class size in the semi-deciduous forest (W = 4461.5, p-value < 0.05). The significant differences observed in the size of the large-diameter class in the semi-deciduous forest strongly indicate that diameter measurements change statistically as a function of the measurement approach in the forest type from which the sample was drawn.

The relationship between diameter measurements and correlation coefficients for each forest type is shown in Fig. 4 and Tab.

Tab. 1 - Means ± standard deviation of the diameter of irregular trunk trees in semi-deciduous and evergreen forests. Different letters indicate significant (p<0.05) differences after Wilcoxon pairwise test.

Site	Diameter type	All data	D < 70 cm	D > 70 cm
Semi-deciduous forest	DPOM	94.74 ± 38.38 [a]	53.64 ± 11.34 [a]	110.33 ± 33.11 [a]
	Darea	87.28 ± 33.74 [a]	50.56 ± 11.11 [a]	101.21 ± 28.55 [b]
Evergreen forest	DPOM	76.12 ± 36.69 [a]	51.14 ± 14.45 [a]	113.58 ± 26.48 [a]
	Darea	73.74 ± 32.67 [a]	51.10 ± 13.97 [a]	107.71 ± 20.99 [a]

S3 (Supplementary material). In addition, Tab. S4 shows the parameters fitted using simple linear regression. As shown in Fig. 4a, the Darea and DPOM measurements are more dispersed around the reference line (red line), indicating greater differences between the two diameter measurement methods in the upper diameter range, generally above 70 cm. Correlation coefficients above 0.70 indicate the two methods are most closely associated for the data set (Fig. 4a) and for diameter class size (Tab. S3). The coefficients of determination (R^2 – Tab. S4) confirm the high degree of dispersion of the diameter values compared in the semi-deciduous forest.

In contrast, the results in Fig. 4b show smaller differences between the two measurement methods around the reference line (red line). The correlation results show a similar trend (Tab. S3 in Supplementary material), placing the values of both methods in the closest association in the evergreen forest. Similar trends can be observed for the regression statistics presented in Tab. S4, where the response in Darea as a linear function of DPOM gave the highest coefficients of determination (R^2 – Tab. S4), and a slope close to 1 and an intercept close to 0.

The relationship between diameter measurements proved less sensitive to small-diameter class sizes and to evergreen forests, with closer correlation coefficients. In addition, the correlation between the diameter measurements was relatively linear, indicating a proportional change in Darea as the reference data (DPOM) varied. This applied to forest types and is confirmed by comparing the Pearson's (r) and Spearman's (ρ) correlation coefficients, which were close in value (Tab. S3 in Supplementary material). Given that the diameter measurement data did not follow the normal distribution, Spearman's correlation coefficient (ρ) might be more robust in characterizing the association between the data being compared. The regression trends shown in Fig. 4 indicate that Darea underestimates DPOM in semi-deciduous and evergreen forests. Simple linear regression with a slope of exactly 1 indicates a general deterministic trend in which the increase in the response variable perfectly corresponds to the increase in the independent variable. The slopes of the Darea-DPOM comparisons were < 1.

At first glance, these results indicate good agreement between diameter measurement methods (Fig. 4), particularly in the evergreen forest (Fig. 4b).

Accuracy of tree diameter estimates above irregularities

The main results of agreement between diameter measurement methods are presented in Fig. 5, Fig. 6, and Tab. 2. Supporting data and additional results are included in Tab. S4 (Supplementary material) and Fig. S3-S6. Fig. 5 shows the Bland-Altman plots comparing the diameter measure-
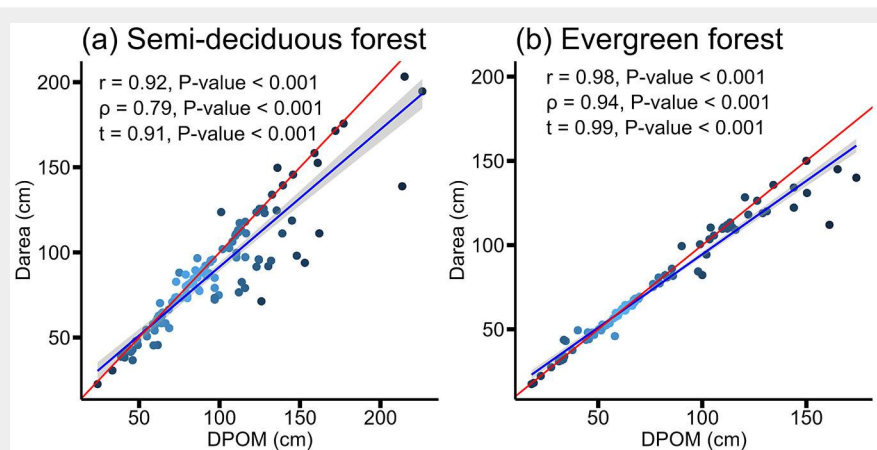

Fig. 4 - Linear relationship between diameter above irregularities (DPOM) and equivalent diameter derived from the Close-Range Photogrammetric approach (Darea) in semi-deciduous and evergreen forest. Pearson's correlation coefficient (r), Kendall's correlation coefficient (ρ), Spearman's correlation coefficient (τ), and p-value are shown.
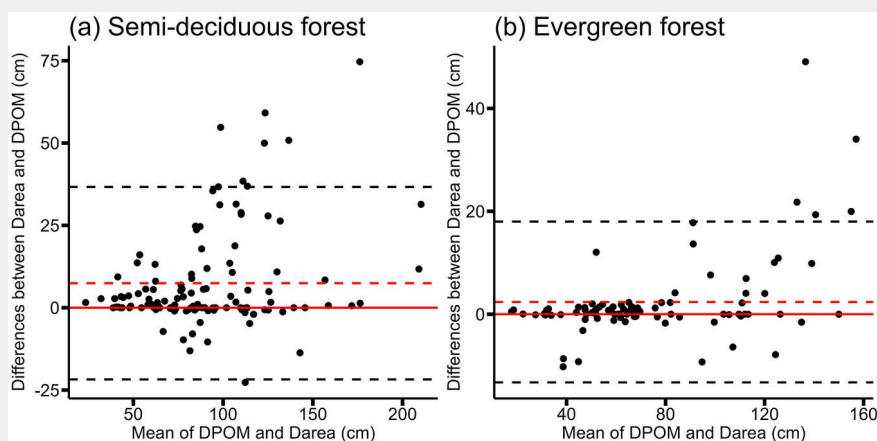

Fig. 5 - Bland-Altman plot of Darea and DPOM concordance. Absolute differences between Darea and DPOM taking as reference DPOM in semi-deciduous forest and evergreen forest. The dotted black lines indicate the lower and upper limits of agreement, calculated from two standard deviations. The dotted red line indicates the bias of the comparison, constructed as the mean of the absolute differences. The solid red line is the identity line.
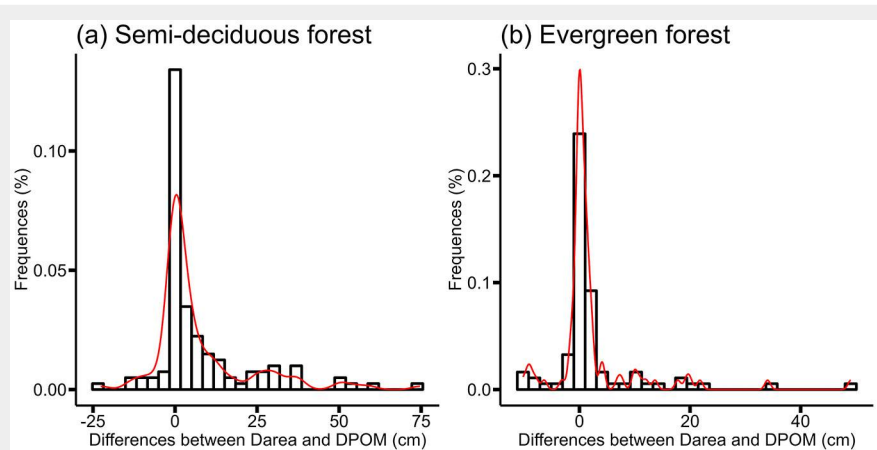

Fig. 6 - Distribution diagram of differences between Darea and DPOM measurements in semi-deciduous forest and evergreen forest. The red line shows a non-parametric kernel density estimate of the data distribution.

Tab. 2 - Differences between diameter measurement methods using error measurements.

Site	Diameter type	All data (cm)			D < 70 cm (cm)			D > 70 cm (cm)		
		MAE	RMSE	Bias	MAE	RMSE	Bias	MAE	RMSE	Bias
Semi-deciduous forest	Darea$_{vs}$DPOM	9.25	16.95	7.45	3.11	5.27	3.08	11.57	19.64	9.11
Evergreen forest	Darea$_{vs}$DPOM	3.88	8.47	2.37	1.45	2.92	0.05	7.52	12.91	5.86

ment methods by forest type. Correlation analysis between differences and mean measurement values yielded low correlation coefficients in semi-deciduous forest (r = 0.30, p-value < 0.001) and evergreen forest (r = 0.49, p-value < 0.001), respectively, although both were statistically significant. In the Darea-DPOM comparison, a general trend of overestimation was observed, characterized on average by a bias of 7.45 cm in the semi-deciduous forest (Fig. 5a) and 2.37 cm in the evergreen forest (Fig. 5b). In other words, compared with the reference measurements (DPOM), the Darea measurement underestimated the semi-deciduous forest by an average of 7.45 cm and the evergreen forest by 2.37 cm (Tab. 2). Only for this comparison treatment and only for absolute differences, the normality test was validated by the Shapiro-Wilk test (Fig. 6, Tab. S2 in Supplementary material) and heteroscedasticity was observed in diameter measurements (Fig. S5) in the semi-deciduous forest (BP = 17.764, df = 1, p-value < 0.001) and evergreen forest (BP = 12.128, df = 1, p-value < 0.001), respectively.

As with the complete data set, Fig. S3 (Supplementary material) depicts the Bland-Altman plots of the diameter measurement methods compared against diameter size classes in the two forest types. In the Darea-DPOM comparison, similar trends were observed in diameter class sizes, with DPOM overestimating Darea. Compared with the reference measurements (DPOM), the underestimation of the Darea measurement is low in the small-diameter class size in both semi-deciduous and evergreen forests (Tab. 2).

Tab. 2 presents the main results on differences between the diameter measurement methods and the commonly used error measurements. When comparing the Darea with the DPOM for the data sample considered in the study, these error measures yield values of 9.25 cm (MAE) and 16.95 cm (RMSE) in the semi-deciduous forest, and 3.88 cm (MAE) and 8.47 cm

(RMSE) in the evergreen forest. In terms of diameter class sizes, the most significant differences were measured by MAE and RMSE for large-diameter class sizes in semi-deciduous and evergreen forests (Tab. 2). However, these errors appeared to be smaller in the evergreen forest. Fig. S6 (Supplementary material) shows the distribution of relative errors (in percent) for the diameter measurement methods compared. These were of the order of ± 42% in the semi-deciduous forest (Fig. S6a) and ± 30% in the evergreen forest (Fig. S6b). These relative errors were also low in the evergreen forest. Overall, the percentage error tended to increase with increasing diameter, particularly in the evergreen forest. The results on coefficients of variation (CV) for the differences found between diameter measurement methods are presented in Tab. 3. Overall, our results show that the coefficients of variation for Darea are significantly lower than those for DOPM in both forest types and as a function of diameter class size (Tab. 3). Furthermore, the results of the one-sample Student's *t*-test showed no significant difference between measurements of tree diameter above irregularities made using the classic conventional approach and the CRP approach in semi-deciduous forests (t = 42.795, df = 1, p-value = 0.014) and evergreen forests (t = 23.718, df = 1, p-value = 0.026). Similar trends were observed for small-diameter classes in semi-deciduous forest (t = 51.333, df = 1, p-value = 0.012) and evergreen forest (t = 60.435, df = 1, p-value = 0.010), but also for large-diameter classes in semi-deciduous forest (t = 32.344, df = 1, p-value = 0.019). These results indicate the accuracy of diameter measurement with the Darea. However, no significant differences were observed in the size of the large-diameter classes in the evergreen forest (t = 11.204, df = 1, p-value = 0.05). The absence of a significant difference in the coefficient of variation for large-diameter class size in the evergreen

forest indicates the accuracy of the measurement approaches used.

Discussion

Factors affecting the difference in diameter measurements above irregularities

Overall, the results show no difference in diameter measurements of trees above irregularities between the classic conventional approach and the Close-Range Photogrammetric approach, except for the size of the large-diameter class in the semi-deciduous forest. These results are comparable to those of Celes et al. (2019) in South America, who also found no significant difference in diameter between the Close-Range Photogrammetric and conventional approaches. However, significant differences in class size at large diameters in semi-deciduous forests indicate that forest type influences measurement accuracy across the methods used. These differences could be explained by several factors that affect the nature of the differences between measured diameters, including tree size, species-specific characteristics, and individual spacing (Liu et al. 2011, Paul et al. 2017). Tree size, divided into two diameter classes, was the main factor studied in this analysis. In addition, the inaccessibility of the point of measurement of diameter could be a factor influencing the nature of diameter differences measured above irregularities. For example, in a semi-deciduous forest, some trees with highly irregular trunks require diameter measurements taken at heights over 6 m, making it difficult to use a tape measure. In this case, it is challenging to stretch the tape around the tree's transverse perimeter and position it perpendicular to the trunk. These results underscore the importance of accounting for the environmental and morphological constraints specific to each forest type when selecting approaches to measure the diameters of irregular-trunk trees.

The results presented in Fig. 4 show a reasonable correspondence between the conventional and Close-Range Photogrammetric approaches for diameter measurement across both forest types and diameter classes. However, the photogrammetric approach tended to underestimate measurements relative to the conventional approach by approximately 7.45 cm in semi-deciduous forest and 2.37 cm in evergreen forest. This difference is mainly attributable to the non-cylindrical shape of the trunk at the point of measurement (Fig. S1 in Supplementary material). Indeed, the tape

Tab. 3 - Coefficient of variation (%) of the diameter of irregular trunk trees in semi-deciduous and evergreen forests. Different letters indicate significant (p<0.05) differences among values after Wilcoxon pairwise test.

Site	Diameter type	Coefficient of variation (%)		
		All data	D < 70 cm	D > 70 cm
Semi-deciduous forest	DPOM	40.51 [a]	21.98 [a]	30.01 [a]
	Darea	38.66 [b]	21.14 [b]	28.21 [b]
Evergreen forest	DPOM	48.20 [a]	28.26 [a]	23.31 [a]
	Darea	44.30 [b]	27.34 [b]	19.49 [a]

measure, by hugging the convex envelope of the cross-section, overestimates diameter measurement, particularly in semi-deciduous forests. Conversely, the disc surface derived from the photogrammetric point cloud provides a more faithful estimate of the trunk's geometric reality, which could explain the relative underestimation observed using this approach. Despite these differences, diameters measured above irregularities show a strong linear relationship ($R^2 > 0.80$) between the two diameter measurement approaches (Tab. S4). However, the intensity of this relationship varies according to forest type: in semi-deciduous forest, the coefficient of determination R^2 reaches 0.84, while it is 0.96 in evergreen forest. These variations could be explained by the heterogeneity of tree dimensions within each forest type.

Large-diameter trees affect the accuracy of diameter measurement above irregularities

The results of this study confirm the high accuracy of the Close-Range Photogrammetric approach for measuring the diameters of irregular-trunk trees. However, a bias of 7.45 cm in semi-deciduous forest and 2.37 cm in evergreen forest was observed. Analysis of the biases as a function of diameter classes reveals that these deviations are smaller for small diameters, a finding consistent with the observations of Bauwens et al. (2017) in Central Africa and Celes et al. (2019) in Amazonia, who reported better accuracy of photogrammetric measurements on small-diameter trees with trunk irregularities.

Measurement accuracy (RMSE) was higher in the evergreen forest than in the semi-deciduous forest (Tab. 2). The results show that the RMSE reached 8.47 cm in the evergreen forest and 16.95 cm in the semi-deciduous forest. These values are higher than those reported by Terryn et al. (2022), who reported an RMSE of 4.8 cm for diameter measurements above irregularities in Australian tropical forests from TLS across all diameter classes combined. These discrepancies could be explained by differences in forest structure and stand density, which influence the detection of trunk contours and the accuracy of 3D reconstructions. Based on diameter classes, our results indicate that accuracy (RMSE) is higher for small diameters than for large diameters in each forest type (Tab. S2 in Supplementary material), a pattern similar to that reported by Bauwens et al. (2017) in Central Africa. These results indicate that irregularities on trunks make large trees challenging to model accurately.

In small diameter classes, the Mean Absolute Error (MAE) was less than 2 cm in the evergreen forest. However, relative diameter differences reached 42% in semi-deciduous forest and 30% in evergreen forest, comparable to the results of Celes et al. (2019), who observed similar variations in Amazonian forests due to the morphological complexity of irregular trunks. Analysis of measurement differences using the Bland-Altman graphical method (Bland & Altman 1995, Giavarina 2015) revealed perfect agreement between the two measurement methods at the threshold of 7.45 cm and 2.37 cm in semi-deciduous and evergreen forests, respectively. These results are in line with the work of Borz et al. (2024) in Eastern Europe, who also demonstrated good agreement between these measurement methods. It should be noted that the linear regression and agreement assessment techniques are neither superimposable nor redundant; rather, they are complementary and serve different purposes (Ilunga et al. 2019). While correlation between two measurement methods indicates an association, agreement requires the regression line to be as close as possible to the equivalence (1:1) line (Fig. 5).

Many taper models for irregular stem trees rely exclusively on the diameter above to predict the diameter at 1.30 m from the ground in the tropics (Bauwens et al. 2021, Cushman et al. 2021). Overall, the results show that the coefficients of variation obtained from the Close-Range Photogrammetric approach are lower than those from the classic conventional approach, indicating that the former approach can provide reasonable results with less bias in taper models predicting diameter at 1.30 m above ground. In addition, the Close-Range Photogrammetric approach has the advantage of automatically recording measurements in an online database, saving technicians time in data entry and avoiding transcription errors (Ahamed et al. 2023).

Research limitations

The Close-Range Photogrammetric approach has been applied in forest research sites in the tropics. These forest sites have closed canopies and dense understories, creating challenging conditions for detecting point clouds in images acquired during photogrammetric processing. In addition to dense understory and closed canopies, point cloud detection on acquired images is also affected by conditions such as fog/haze and low sunlight angles. These different environmental conditions limit the height of the model reconstituted in three dimensions (3D), as shown in Fig. 2. To solve the problem of limiting the height of the 3D model, it is advisable to photograph the trees very early in the morning or late in the day and take the images at two different heights (view height and 4 m high at using a milestone) in central Africa (Bauwens et al. 2017) or at three different heights (2 m, 3 m and 5 m) in Europe (Mulverhill et al. 2019). Future studies should consider these tips to improve the photogrammetric process for irregular-trunk trees in tropical forests.

Conclusions

This study demonstrates that the Close-Range Photogrammetric approach is an accurate and suitable method for measuring the diameters of irregular-trunk trees in tropical forests. The results show a strong correlation between measurements obtained using this approach and those obtained with the conventional approach, with relatively minor differences, particularly in evergreen forests. The Close-Range Photogrammetric approach thus offers an effective alternative to overcome the limitations of classic dendrometric tools, particularly when the diameter measurement point is difficult to access.

Because of its accuracy and its ability to reduce errors associated with conventional measurements, this method could be incorporated into forest inventories and allometric models to improve estimates of biomass and volume for irregular trees. However, further studies are needed to explore the limitations of this approach across different environmental conditions and to refine its use in operational contexts of forest management and the conservation of tropical ecosystems.

List of abbreviations

MAE: Mean Absolute Error, RMSE: Root Mean Square Error, TLS: Terrestrial Laser Scanning, CRP: Close-Range Photogrammetry, SfM: Structure from Motion, Semi-F: semi-deciduous forests, Ever-F: evergreen forests, MVS: Multi-View Stereo, POM: Point of Measurement.

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References

Ahamed A, Foye J, Poudel S, Trieschman E, Fike J (2023). Measuring tree diameter with photogrammetry using mobile phone cameras. Forests 14 (10): 2027. - doi: 10.3390/f14102027

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: 121-136. - doi: 10.3390/f11010121

Alder D, Synnott T (1992). Permanent sample plot techniques for mixed tropical forest. Oxford Forestry Institute, University of Oxford, UK, pp. 124.

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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. - doi: 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 (8): 881. - doi: 10.1002/eap.2451

Bland JM, Altman DG (1995). Comparing methods of measurement: why plotting difference against standard method is misleading. The Lancet 346: 1085-1087. - doi: 10.1016/S0140-6736(95)91748-9

Borz SA, Toaza JMM, Proto AR (2024). Accuracy of two LiDAR-based augmented reality apps in breast height diameter measurement. Ecological Informatics 81: 102550. - doi: 10.1016/j.ecoinf.2024.102550

Breusch TS, Pagan AR (1979). A simple test for heteroscedasticity and random coefficient variation. Econometrica 47: 1287-1294. - doi: 10.2307/1911963

Calders K, Adams J, Armston J, Bartholomeus H, Bauwens S, Bentley LP, Chave J, Danson FM, Demol M, Disney M, Gaulton R, Krishna Moorthy SM, Levick SR, Saarinen N, Schaaf C, Stovall A, Terryn L, Wilkes P, Verbeeck H (2020). Terrestrial laser scanning in forest ecology: Expanding the horizon. Remote Sensing of Environment 251: 112102. - doi: 10.1016/j.rse.2020.112102

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

Clark NA, Wynne RH, Schmoldt DL (2000). A review of past research on dendrometers. Forest Science 4: 570-576. - doi: 10.1093/forestscience/46.4.570

Clark DA (2002). Are tropical forests an important carbon sink? Reanalysis of the long-term plot data. Ecological Applications 12: 3-7. - doi: 10.1890/1051-0761(2002)012[0003:ATFAIC]2.0.CO;2

Cushman KC, Bunyavejchewin S, Cárdenas D, Condit R, Davies SJ, Duque A, 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. - doi: 10.1111/btp.12994

Eliopoulos NJ, Shen Y, Nguyen ML, Arora V, Zhang Y, Shao G, Woeste K, Lu Y-H (2020). Rapid tree diameter computation with terrestrial stereoscopic photogrammetry. Journal of Forestry 118: 355-361. - doi: 10.1093/jofore/fvaa009

Elzinga C, Shearer RC, Elzinga G (2005). Observer variation in tree diameter measurements. Western Journal of Applied Forestry 20: 134-137. - doi: 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: e42381. - doi: 10.1371/journal.pone.0042381

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

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 [New-generation permanent devices for monitoring forest dynamics in Central Africa: assessment in the Republic of Congo]. Bois et Forêts des Tropiques 341: 55-70. [in French] - doi: 10.19182/bft2019.341.a31760

Forsman M, Börlin N, Holmgren J (2016). Estimation of tree stem attributes using terrestrial photogrammetry with a camera rig. Forests 7 (3): 61. - doi: 10.3390/f7030061

Giavarina D (2015). Understanding Bland-Altman analysis. Biochemia Medica 25: 141-151. - doi: 10.11613/bm.2015.015

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. - doi: 10.1017/S0376892908004554

Han T, Raumonen P, Sánchez-Azofeifa GA (2023). A non-destructive approach to estimate buttress volume using 3D point cloud data. Ecological Informatics 77: 102218. - doi: 10.1016/j.ecoinf.2023.102218

Haq SM, Waheed M, Khoja AA, Amjad MS, Bussmann RW, Ali K, Jones DA (2023). Measuring forest health at stand level: a multi-indicator evaluation for use in adaptive management and policy. Ecological Indicators 150: 110225. - doi: 10.1016/j.ecolind.2023.110225

Iglhaut J, Cabo C, Puliti S, Piermattei L, O'Connor J, Rosette J (2019). Structure from motion photogrammetry in forestry: a review. Current Forestry Reports 5: 155-168. - doi: 10.1007/s40725-019-00094-3

Ilunga C, Mbayu F, Boyemba F, Sabongo P, Nshimba H, Ndjele L (2019). Relation précipitations et croissances des arbres tropicaux dans les forêts semi- décidues de la région de Kisangani en RD Congo: cas de *Milicia excelsa* (Welw.) C.C.Berg et *Pericopsis elata* (Harms) Meuwen [Relationship between rainfall and growth of tropical trees in the semi-deciduous forests of the Kisangani region in DR Congo: the case of *Milicia excelsa* (Welw.) C.C.Berg and *Pericopsis elata* (Harms) Meuwen]. Revue Scientifique et Technique Forêt et Environnement du Bassin du Congo 12: 22-34. [in French]

Kuzelka K, Surovy P (2021). Mathematically optimized trajectory for terrestrial close-range photogrammetric 3D reconstruction of forest stands. ISPRS Journal of Photogrammetry and Remote Sensing 178: 259-281. - doi: 10.1016/j.isprsjprs.2021.06.013

Lanfranchi R, Schwartz D (1990). Évolution des paysages de la Sangha (RP du Congo) au Pléistocène supérieur. Bilan des observations archéologiques, géomorphologiques, pédologiques et paléobiologiques [Landscape evolution in the Sangha (RP of Congo) during the Late Pleistocene. Assessment of archaeological, geomorphological, pedological and palaeobiological observations]. In: "Paysages Quaternaires de l'Afrique Centrale Atlantique". ORSTOM, Paris, France, pp. 248-259. [in French]

Liang X, Kankare V, Hyyppä J, Wang Y, Kukko A, Haggrén H, Yu X, Kaartinen H, Jaakkola A, Guan F (2016). Terrestrial laser scanning in forest inventories. ISPRS Journal of Photogrammetry and Remote Sensing 115: 63-77. - doi: 10.1016/j.isprsjprs.2016.01.006

Liu S, Bitterlich W, Cieszewski CJ, Zasada MJ (2011). Comparing the use of three dendrometers for measuring diameters at breast height. Southern Journal of Applied Forestry 35: 136-141. - doi: 10.1093/sjaf/35.3.136

Ludbrook J (2010). Confidence in Altman-Bland plots: a critical review of the method of differences. Clinical and Experimental Pharmacology and Physiology 37: 143-149. - doi: 10.1111/j.1440-1681.2009.05288.x

Mansournia MA, Waters R, Nazemipour M, Bland M, Altman DG (2021). Bland-Altman methods for comparing methods of measurement and response to criticisms. Global Epidemiology 3: 100045. - doi: 10.1016/j.gloepi.2020.100045

Marzulli MI, Raumonen P, Greco R, Persia M, Tartarino P (2020). Estimating tree stem diameters and volume from smartphone photogrammetric point clouds. Forestry 93: 411-429. - doi: 10.1093/forestry/cpz067

Mokroš M, Liang X, Surovy P, Valent P, Cernava J, Chudy F, Tunák D, Salon S, Merganič J (2018a). Evaluation of close-range photogrammetry image collection methods for estimating tree diameters. ISPRS International Journal of Geo-Information 7: 93. - doi: 10.3390/ijgi7030093

Mokroš M, Vybošt'ok J, Tomaštík J, Grznárová A, Valent P, Slavík M, Merganič J (2018b). High precision individual tree diameter and perimeter estimation from close-range photogrammetry. Forests 9: 696. - doi: 10.3390/f9110696

Mulverhill C, Coops NC, Tompalski P, Bater CW, Dick AR (2019). The utility of terrestrial photogrammetry for assessment of tree volume and taper in boreal mixedwood forests. Annals of Forest Science 76: 83. - doi: 10.1007/s13595-019-0852-9

Nguila Bakala MM, Yoka J, Loumeto J-J (2023). Monitoring the diameter growth of irregular trunk trees in the Celtis forest in Northern Republic of Congo. International Journal of Biosciences 23: 24-39. dx. - doi: 10.12692/ijb/23.5.24-39

Paul KI, Larmour JS, Roxburgh SH, England JR, Davies MJ, Luck HD (2017). Measurements of stem diameter: implications for individual- and stand-level errors. Environmental Monitoring and Assessment 189: 416. - doi: 10.1007/s10661-017-6109-x

Picard N, Gourlet-Fleury S (2008). Manuel de référence pour l'installation de dispositifs permanents en forêt de production dans le Bassin du Congo [Reference manual for the installation of permanent devices in production forests in the Congo Basin]. COMIFAC, Yaoundé, Cameroon, pp. 271. [in French]

Piermattei L, Karel W, Wang D, Wieser M, Mokroš M, Surovy P, Koren M, Tomaštík J, Pfeifer N, Hollaus M (2019). Terrestrial structure from mo-

tion photogrammetry for deriving forest inventory data. Remote Sensing 11: 950. - doi: 10.3390/rs11080950

R Core Team (2022). R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. [online] URL: http://www.r-project.org

Réjou-Méchain M, Mortier F, Bastin J-F, Cornu G, Barbier N, Bayol N, Bénédet F, Bry X, Dauby G, Deblauwe V (2021). Unveiling African rainforest composition and vulnerability to global change. Nature 593: 90-94. - doi: 10.1038/s41586-021-03483-6

Surovy P, Yoshimoto A, Panagiotidis D (2016). Accuracy of reconstruction of the tree stem surface using terrestrial close-range photogrammetry. Remote Sensing 8: 123. - doi: 10.3390/rs8020123

Terryn L, Calders K, Akerblom M, Bartholomeus H, Disney M, Levick S, Origo N, Raumonen P, Verbeeck H (2022). Analysing individual 3D tree structure using the R package ITSMe. Methods in Ecology and Evolution 14: 231-241. - doi: 10.1111/2041-210X.14026

Ucar Z, Degermenci AS, Zengin H, Bettinger P (2022). Evaluating the accuracy of remote dendrometers in tree diameter measurements at breast height. Croatian Journal of Forest Engineering 43: 185-197. - doi: 10.5552/crojfe.2022.1016

Weaver SA, Ucar Z, Bettinger P, Merry K, Faw K (2015). Assessing the accuracy of tree diameter measurements collected at a distance. Croatian Journal of Forest Engineering 36: 73-83. [online] URL: http://hrcak.srce.hr/136130

West PW (2015). Tree and forest measurement. Springer International Publishing AG, Switzerland, pp. 214. - doi: 10.1007/978-3-319-14708-6

Willmott CJ, Matsuura K (2005). Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. Climate Research 30: 79-82. - doi: 10.3354/cro30079

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. - doi: 10.1016/j.compag.2019.104875

Zar JH (2010). Biostatistical analysis (5th edn). Pearson Prentice Hall, USA, pp. 960.

Zhu R, Guo Z, Zhang X (2021). Forest 3D reconstruction and individual tree parameter extraction combining close-range photo enhancement and feature matching. Remote Sensing 13: 1633. - doi: 10.3390/rs13091633

Supplementary Material

Tab. S1 - Characteristics of the species studied, including scientific names, family, and sampling effort.

Tab. S2 - Normality check and distribution of the data. Results of normality check by Shapiro-Wilk and d'Agostino-Pearson tests.

Tab. S3 - Pearson's correlation coefficient (r), Kendall's correlation coefficient (ρ), Spearman's correlation coefficient (τ) for all data and as a function of diameter class size.

Tab. S4 - Main statistics of simple linear regression on all data and as a function of diameter class size.

Fig. S1 - Illustration of a sample of the shape of cross-sections obtained 30 cm above irregularities using the close-range photogrammetric approach.

Fig. S2 - Diameter variation according to diameter measurement methods within each forest type.

Fig. S3 - Bland-Altman plot of the agreement between Darea and DPOM as a function of diameter class size: absolute differences between Darea and DPOM using DPOM in semi-deciduous and evergreen forest as reference.

Fig. S4 - Distribution diagram of differences between Darea and DPOM measurements as a function of diameter class sizes in semi-deciduous and evergreen forests.

Fig. S5 - Results of heteroskedasticity tests in the Darea using the Breusch-Pagan test, taking as a reference DPOM in semi-deciduous and evergreen forest.

Fig. S6 - Distribution of percentual errors (differences) in Darea, taking as a reference DPOM.

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