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Accuracy of tree stem circumference estimation using close range photogrammetry: Does point-based stem disk thickness matter?

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A R T I C L E I N F O

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A B S T R A C T

There is an increase in the use of photogrammetric point clouds for tree attribute mensuration. Stem diameter and circumference can be estimated from point clouds using stem disks of varying thicknesses along the bole. However, there is a dearth of information on the effect of the thickness of point cloud-based stem disks on the accuracy of diameter and circumference estimations. In this study, we outlined a GIS-based procedure for analysing Structure from Motion-derived photogrammetric point clouds with a view to providing an optimal disk thickness for accurate circumference estimates. Geo-referenced point clouds were created from photographs of 30 trees belonging to five savanna species. For each tree, 20 horizontal stem disks, with increasing thicknesses of 1 to 20 mm were made at breast height using the open source QGIS software. The resulting cross-sections were manually delineated and digitised. The difference between reference (manually measured) and point cloud-based circumferences at breast height was expressed as mean absolute percent error (MAPE) and compared across tree species, size and disk thickness. We found significant effects of species identity, tree size and disk thickness on MAPE. A stem disk of 7 mm in thickness provided consistently lower MAPE values (< 6%). This suggests that the accuracy of tree stem circumference estimations from photogrammetric point clouds depends on stem disk thickness.

1. Introduction

There is increased interest in the application of photogrammetric point clouds in forest inventories based on individual trees (Morgenroth and Gomez, 2014; Miller et al., 2015; Surový et al., 2016), and entire sample plots (Liang et al., 2014; Mikita et al., 2016; Mokroš et al., 2018a). The relatively new, user-friendly and reliable approach which combines Structure from Motion and Multi-View Stereophotogrammetry, SfM-MVS (Szeliski, 2010) to produce high-quality tridimensional point clouds has formed the basis of these studies, in line with the context of precision forestry. Iglhaut et al. (2019) have summarised the principles and practical considerations underpinning the use of SfM-MVS in forest biometry and highlighted its potential benefits for this field.

Although a number of software packages have been developed for the implementation of SfM-MVS algorithms at varying financial costs (Bemis et al., 2014), Agisoft Metashape (Agisoft LLC St. Petersburg, Russia), formerly known as Agisoft PhotoScan seems to be a much prized tool. Previous studies have shown its suitability for the generation of tridimensional tree models (e. g., Morgenroth and Gomez, 2014; Miller et al., 2015; Surový et al., 2016; Mikita et al., 2016; Mokroš et al., 2018b; Roberts et al., 2018) However, there has been a focus on diameter estimation to the detriment of other important tree stem attributes as suggested by the limited number of studies on stem circumference (Mikita et al., 2016; Surový et al., 2016) and taper (Fang and Strimbu, 2017). Moreover, because stems are often assumed to have a circular cross-section, which is scarcely so, circumference may be a more descriptive and reliable biophysical attribute than diameter, especially for irregularly shaped trees (West, 2015). Thus, the use of SfM-MVS point clouds for the sole purpose of diameter estimation may underestimate the potentials of this technique, which is inherently not constrained by irregular geometrical objects (Bauwens et al., 2017).

A few researchers have estimated tree stem circumferences from SfM-MVS-derived point cloud (Mikita et al., 2016; Bauwens et al., 2017; Mokroš et al., 2018a). The methodological approach used in these studies is based on horizontal cross-sectional stem disks created in a tridi-

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Table 1
Tape-measured estimates of breast height circumference of sample trees.

Metric	Species	Mean	SD	CV%	Minimum	Maximum
CBH (cm)	*A. leiocarpa*	135.40	78.70	58.14	46.50	275.00
	B. costatum	127.30	60.30	47.36	44.00	198.00
	S. birrea	130.50	72.80	55.79	51.00	239.00
	T. laxiflora	131.10	53.30	40.63	61.50	202.00
	V. paradoxa	125.60	53.90	42.93	43.70	195.00
	Total	130.10	60.40	46.62	43.70	274.90

CBH: Breast height circumference, SD: Standard deviation, CV: Coefficient of variation ($n = 6$).

mensional point cloud at known stem heights. However, The accuracy of this approach depends on the stem disk thickness and point cloud density (Koreň et al., 2017). It is not clear what thickness produces accurate circumference estimates. Previous analyses of point clouds have been implemented manually (Surový et al., 2016), and automatically (Mikita et al., 2016; Bauwens et al., 2017; Mokroš et al., 2018a) in a variety of point cloud processing packages. For example, to evaluate the circumference at breast height using point clouds obtained within forest plots, Surový et al. (2016) created cross-sectional disks using Devdept Eyeshot. These workers reported results close to those measured in the field. However, stem disk thickness underlying these results was not specified in their study. Mikita et al. (2016) estimated breast height from forest stands by means of methods for automatic stem delineation based on circle-fitting algorithms and convex hulls, and reported more robust results with convex hull for stem disks of 1 cm. In another study, Bauwens et al. (2017) used a novel approach to estimate cross sections of buttressed tropical trees at different stem heights. First, they created stem skeletons by manually digitising the contours of successive, 2 cm-thick disks made along the stem axis. Then, they automatically derived circumferences from convex hulls simulating tape measurements around buttressed trees by superimposing the previously created tree skeletons to SfM-MVS point clouds. Similarly, Mokroš et al. (2018b) applied convex hull algorithms to 2 cm-thick stem disks of four species in a GIS software to determine breast height diameter. The somewhat arbitrary use of the same stem disks thickness by these authors, though in different contexts, i.e., temperate trees (Mokroš et al., 2018b) and tropical trees (Bauwens et al., 2017) underscores the need for a comprehensive assessment of the optimal point cloud-based stem disk thickness to be used for accurate stem circumference measurements.

Although tree stem circumference may be a less biased metric compared to diameter, there is a paucity of studies focusing on the estimation of this metric from photogrammetric point clouds. Furthermore, species-specific differences have not been explored in this context. In this study, we sought to identify the stem disk thickness for which accurate breast height circumferences can be derived based on photogrammetric point clouds.

2. Materials and methods

2.1. Site description

This study was conducted in the buffer area of the W National Park (11° 26′ – 12° 25′ N; 2° 48′ – 3° 05′ E) in Northern Benin. This area is located within the Sudanian tropical climate zone. It is characterized by a mosaic of open forests and savannas. Here, rainfall varies between 600 mm to 700 mm, and average annual temperature is about 40 °C. Temperature is lowest (12 °C – 25°C) from November to March, during the harmattan (Zakari et al., 2015).

2.2. Manual and image data acquisition

The experiment was based on the five most abundant tree species in the study area; namely *Sclerocarya birrea, Bombax costatum, Anogeissus leiocarpa, Terminalia laxiflora* and *Vitellaria paradox*a. For each species, six trees were randomly selected, each within breast height diameter ranges (DBH) of 10 – 20 cm, 20 – 30 cm, 30 – 40 cm, 40 – 50 cm, 50 – 60 cm and > 60 cm. Stem circumference was measured at breast height (1.3 m) using a graduated tape. This measurement level was specified by a red line drawn around the stem. Breast height circumference of the sampled trees are given in Table 1.

Images were taken at 15° intervals on a full circle around each tree using a Canon 77 D digital camera equipped with a Canon EF 50 mm f/1.8 STM lens. A distance of 1 m was maintained between the stem and the camera. At each shooting position, highly overlapping photographs were captured from the base of the tree to the top. The camera was held in portrait orientation to ensure a maximum coverage of the stem. The operator endeavoured to capture vertically overlapping images, parallel to the stem from the base up before moving to the next shooting position. Images were acquired at the highest resolution (6000 × 4000 pixels) with the aperture priority mode (f/3.2) to avoid blurriness. The camera was set to the lowest ISO value (100) to minimize noise in images. A 1.5 m ruler, which served as scale was vertically pinned to the stem prior to image acquisition.

2.3. Image processing

Images were processed into dense point clouds using Agisoft PhotoScan Professional 0.9.1 (Agisoft LCC, St. Petersburg, Russia), which implements SfM-MVS algorithms. The main steps in the PhotoScan workflow include 1) photo alignment, at the end of which a sparse point cloud is created, 2) sparse point cloud densification, 3) polygonal mesh model generation and 4) digital elevation model construction. However, due to limited processing power, only the first two steps of the model building workflow were implemented. At these stages PhotoScan simultaneously and automatically identifies matching points in a set of overlapping images, estimates camera locations for each image and generates a tridimensional dense point cloud model. The highest accuracy was selected for photo alignment to obtain the best estimates of camera positions. Because we used an un-calibrated camera, the pair pre-selection mode, which controls feature matching across image pairs was set to "Generic". Key point and Tie point limits were left at their default values (40,000 and 1000, respectively). The tridimensional sparse point cloud model resulting from this step was densified using recommended settings (https://www.agisoft.com/). Finally, to determine the geographic coordinates of individual points in the model, a spatial scale was assigned to it based on the major divisions of the ruler. This manual scaling procedure is described in detail by Mokroš et al. (2018a). Models were carefully cleaned by manually removing all points that significantly deviated from the external limits of the tree (Fig. 1). The final model was exported to XYZ format for stem circumference delineation using a GIS software.

2.4. Stem circumference estimation

We used the open source software QGIS 2.18 (https://www.qgis.org/) for point cloud processing and circumference estimation. There

Fig. 1. A photograph of *Bombax costatum* (left panel) and its scaled tridimensional model (right panel).

are several stem cross-section delineation methods depending on the noise in the point cloud, outliers and computational power. Automatic circle-fitting and convex hull methods have been used for more or less regular stem cross sections (e. g. Mikita et al., 2016) but remain largely untested in irregularly shaped stems. Text files containing the spatial coordinates of photogrammetric points were imported in QGIS and "cut" at breast height by filtering all point for which $Z \approx 1300$ mm. Additional cuts were made in order to create a set of 20 disks with increasing thicknesses (i.e., $1300 \le Z \le 1301$, $1300 \le Z \le 1302$, …, $1300 \le Z \le 1320$). Then, each disk was manually digitised into a multiple convex polygon. Owing to the irregular nature of most stem contours, we chose to delineate stem cross-sections manually. We interactively created polygons to closely reconstruct stem cross-sectional contours by zooming in on successive points and connecting them with a segment (Fig. 2). Finally, disk circumference was measured for each polygon in QGIS.

2.5. Data analysis

The difference between field-measured breast height circumferences and those estimated from point clouds was assessed by means of the relative bias (B%) and percent root mean square error (MAPE%) as defined in Eqs. (1) and (2), respectively.

$$B = 100 \times \left[\frac{1}{n} \sum_{i=1}^{n} \left(\frac{C_i - \hat{C}_i}{\hat{C}_i} \right) \right] \quad (1)$$

$$MAPE = 100 \times \left[\frac{1}{n} \sum_{i=1}^{n} \left| \frac{C_i - \hat{C}_i}{\hat{C}_i} \right| \right] \quad (2)$$

where $\hat{C}$ and C are the reference (tape-measured) and point cloud-derived circumferences respectively, and n the number of trees.

The effect of species identity, DBH range and disk thickness on MAPE was assessed using mixed models in the *lme4* package. Species identity was taken as random factor while fixed factors were DBH range and disk thickness. Mean absolute percent error values were $arcsine(\sqrt{x})$ transformed prior to analysis. Significance of fixed factor interactions and random factor was assessed using the *lmerTest* package. Data were analysed using R version 3.2.

3. Results

3.1. Optimal disk thickness

We obtained a very high rate (571 out of 600) of useful disks at most DBH ranges except for the last one (> 60 cm) in *T. laxiflora* where slicing failed (Table 2). The 30 – 40 cm breast height DBH range in *B. costatum* produced only 11 disks out of the expected 20. Mean absolute percent errors varied greatly across species, DBH class range and disk thickness, and there was a significant three-way interaction of the tested factors as shown in Tables 3 and 4.

The variation in biais in relation to species diametre range and stem disk thickness is shown in Fig. 3. There was an exponential decrease in biais for disk thicknesses between 1 – 4 mm, 1 – 5 mm and 1 – 6 mm in *A leiocarpa* and *T. laxiflora, V. paradoxa and B. costatum, and S. birrea* respectively. Then, biais decreased asymptotically between 5 – 20 mm, 6 – 20 mm and 7 – 20 mm in *A leiocarpa* and *T. laxiflora, V. paradoxa* and *B. costatum,* and *S. birrea* respectively. In the second phase, MAPE values were below 6% while bias values across DBH ranges were less than 2%. Mean absolute percent error and bias were lowest with a disk thickness of 7 mm regardless of species and breast height diametre ranges.

3.2. Reference and point cloud based circumferences at breast height

Reference and point cloud-derived circumference estimates for 7 mm-thick stem sections are compared in Fig. 4. Regardless of species and diameter size, reference values were almost similar to values obtained in QGIS.

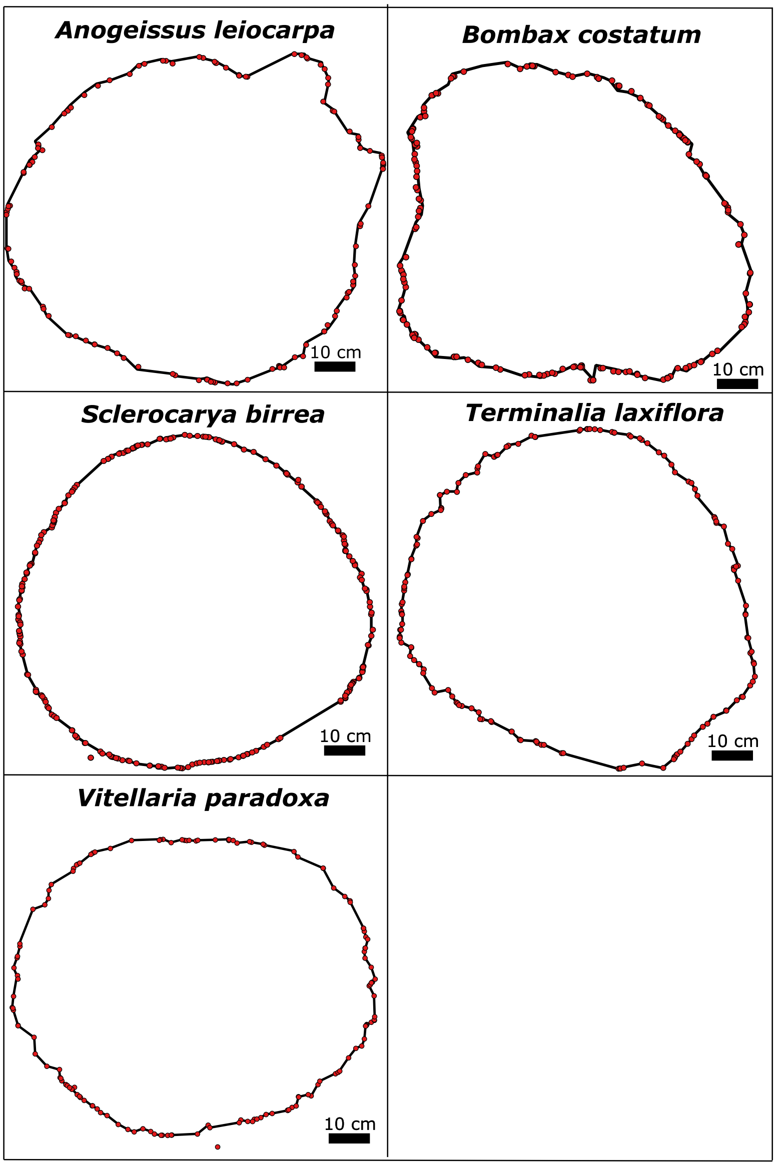

Fig. 2. Digitised stem cross-sections of the study species. The red dots are point clouds obtained with a stem disk of 7 mm in thickness.

Table 2
Number of stem disks in relation to breast height diameter and species

Species	Breast height diameter ranges (cm) [10–20[	[20–30[	[30–40[	[40–50[	[50–60[	[60- ∞[	Total
A. leiocarpa	20	20	20	20	20	20	120
B. costatum	20	20	11	20	20	20	111
S. birrea	20	20	20	20	20	20	120
T. laxiflora	20	20	20	20	20	0	100
V. paradoxa	20	20	20	20	20	20	120
Total	100	100	91	100	100	80	571

4. Discussion

Tree breast height diameter is a fundamental variable in forest measurements and inventories. Allometric equations using this variable are an important element in forest growth models for improved monitoring and management strategies (Burkhart and Tomé, 2012). The conventional, direct approach for circumference measurements by means of a graduated tape may misestimate this metric, especially in trees with irregularly shaped stems. Fortunately, this limitation can be overcome by means of SfM photogrammetry (Bauwens et al., 2017). Our study exploited the advantages of this technique in conjunction with an open source GIS software to prescribe the optimum stem disk thickness for which circumference estimation from point cloud models is adequate.

The effect of the thickness of point cloud-based stem disks on tree circumference estimation has been recognized (Koreň et al., 2017); while thinner stem disks may not capture a useful number of points for circumference estimation (Forsman et al., 2016), thicker disks can lead to inaccuracies in circumference estimation due to vertical changes bole size. Although optimal disk thickness was species-dependent in our study, we recorded consistently lower bias and mean absolute percent error values

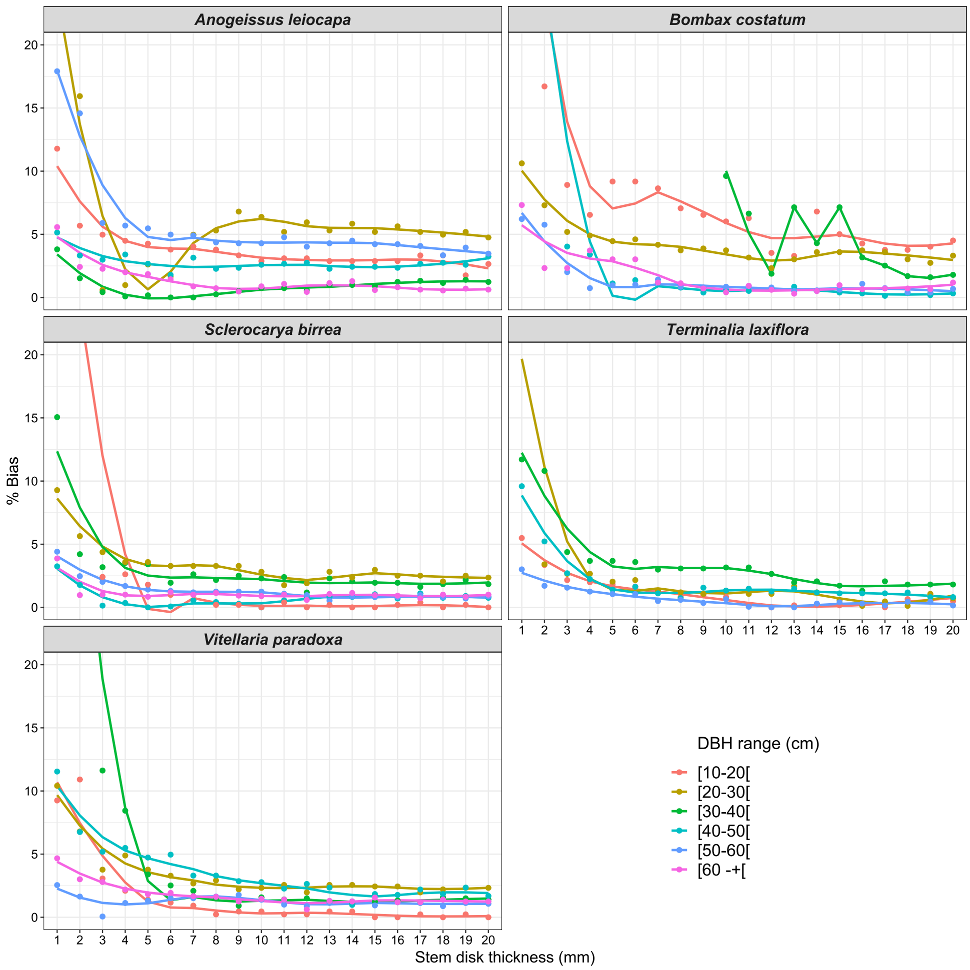

Fig. 3. Variation of the relative bias in relation to stem slice thickness for 7 mm thickness.

Table 3
Analysis of variance summary testing the variation in MAPE that is explained by species identity, breast height diameter range, disk thickness and their interactions.

Source of variation	Df	χ^2	*P value*
Species	1	13.177	<0.001
Species × Disk thickness	1	0.000	1.0000
Species × Disk thickness × DBH range	1	25.788	<0.001

Table 4
Analysis of variance summary for linear mixed models testing the variation in MAPE that is explained by species identity, breast height diameter range, disk thickness and their interactions.

Source of variation	df	*F*	*P value*
Disk thickness	19	17.283	<0.001
Diameter range	5	7.272	<0.001
Disk thickness × DBH range	95	0.959	0.589

with 7 mm-thick stem disks across the five study species. Previous works on temperate (Surový et al., 2016) and tropical trees (Bauwens et al., 2017; Mikita et al., 2016) were based on 1 and 2 cm-thick disks. Thicker disks (5 cm) at breast height were applied on point cloud derived from forest plots of *Fagus sylvatica* (Mokroš et al., 2018a). This difference may be explained by point cloud density or species identity, and suggests that thicker disks may be more suitable for plot levels studies than when individual trees are considered. Reliable stem delineation depends more on the number of point included in a disk (Koreň et al., 2017). Moreover, it is noteworthy that depending on species, stem disks more than 7 mm-thick may provide better circumference estimates given the asymptotic trend of relative bias in relation to disk thickness reported in this study. However, thicker disks may also lead to misleading stem circumference estimates due to digitization errors. In effect, for thicker disks (for example 17 mm), we obtained clusters of points that made digitisation more difficult even in the absence of outliers. This would be a drawback to automatic stem delineation methods as additional steps aimed at point cloud filtering may be required for optimal results (Koreň et al., 2017). Thus, the presence of a cluster of points inherent to thicker disks may lead to overestimations of stem circumference.

This study showed that regardless of species and diameter size, circumferences estimated from point clouds were almost similar to those measured on the filed with a tape. This is in agreement with the findings of Bauwens et al. (2017) who showed that there was no significant difference in cross-sectional based diameter estimations of buttressed, rainforest trees using both methods. These results highlight the robustness of SfM-MVS photogrammetry for measuring irregular tree stem. The accuracy of point cloud-based circumference and diameter estimations was also investigated by Mokroš et al. (2018a). With their manual GIS-based circumference delineation, these authors found no significant differences between destructively obtained and photogrammetric values (bias 0.66 cm). However, this bias was found to slightly increase (0.86 cm) using an automatic stem delineation method specifically developed from the manual method. In a related study, higher biases on stem circumference (1.87 cm) were reported by Surový et al. (2016). Similarly, root mean square errors varying from 4.41 cm to 5.98 cm were reported by Mokroš et al. (2018a) based on a circle-fitting algo-

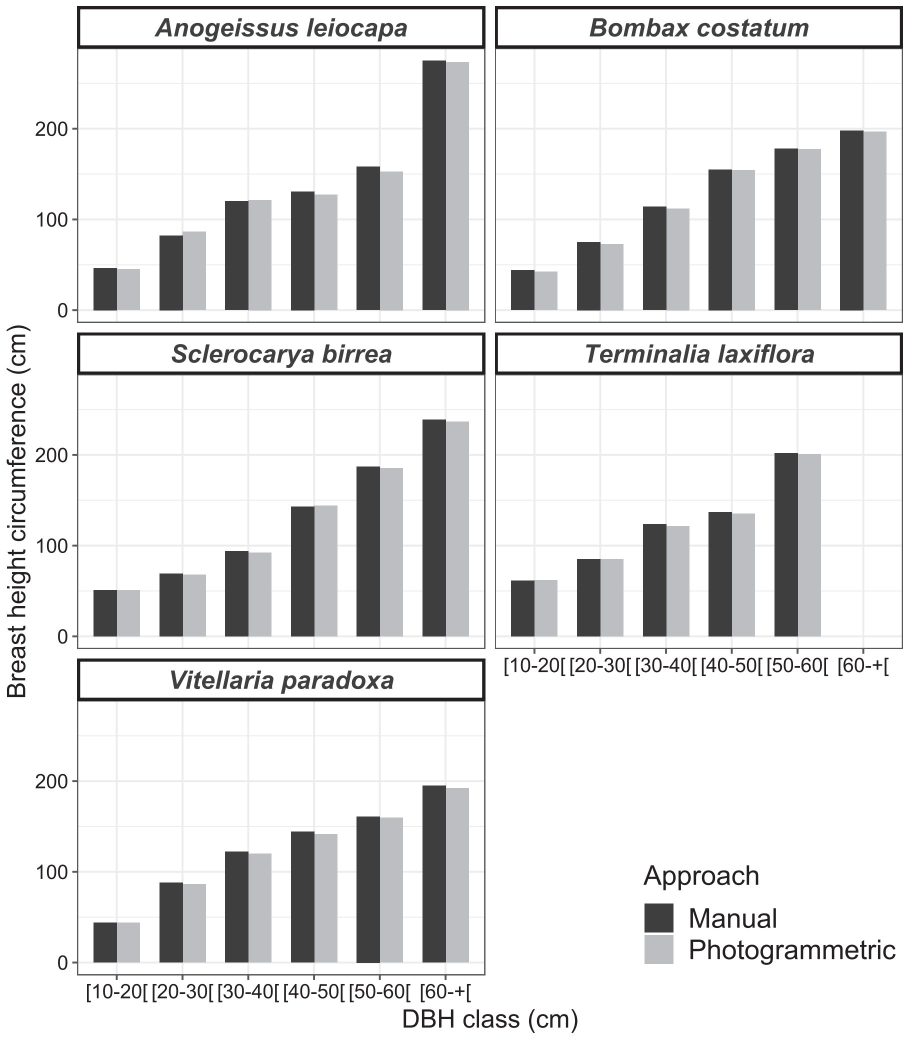

Fig. 4. Comparison of photogrammetrically estimated reference and point coud-derived circumferences at breast height for a stem disk of 7 mm.

rithm to estimate DBH of European beeches at the plot level. Although more uncertainties may be associated with automatic stem delineation methods, their supporting algorithms would improve with advances in point cloud cleaning procedures.

One obvious limitation of the application of SfM-MVS photogrammetry in forestry is that this technique is dependent on study system. So far, most successes with results comparable to LIDAR-based applications have been recorded in managed temperate forests plots in which lightning conditions and mobility are generally propitious for image acquisition (Liang et al., 2014; Mokroš et al., 2018b; Piermattei et al., 2019), or on trees within urban areas (Morgenroth and Gomez, 2014; Roberts et al., 2018) as opposed to tropical forests (Bauwens et al., 2017). To the best of our knowledge, the work of Bauwens et al. (2017) is the first application of SfM-MVS in extreme forest conditions. Their main finding, illustrated by a relatively low success rate (79%) in rendering photographed trees highlights the challenges in image acquisition in such conditions. In our case, image capture was easily conducted from all defined angles around trees because of the sparsely vegetated nature of tropical savannas, and deserts in the study of Huang et al. (2018).

5. Conclusion

This study identified the optimal horizontal stem disk thickness for estimating tree circumference from photogrammetric point clouds. Our results suggest that a disk of 7 mm in thickness provided less biased estimates of stem circumference in savanna trees. This value was not affected by tree species and size thereby underscoring the robustness of SfM-MVS photogrammetry in forest biometry. Owing to its accuracy, the proposed manual method is recommended for small sample sizes given its inherently higher post-processing times compared with automatic methods. However, many limitations remain to be overcome for a widespread application of this technique.

Declaration of Competing Interest

We have no competing interests to declare.

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