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Diameter at Breast Height (DBH) Estimation and Stem Cross-Section Shape Analysis of Eucalyptus Trees Using LiDAR Data after Noisy Removal

Estimativa do Diâmetro à Altura do Peito e Análise da Forma da Seção Transversal do Tronco de Árvores de Eucalipto Utilizando Dados LiDAR após a Remoção de Ruídos

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Abstract: LiDAR data offer new possibilities for obtaining geometric parameters of forest areas, such as diameter at breast height (DBH), basal area, height, volume, biomass, and carbon stock. Terrestrial Laser Scanning (TLS) is highly accurate and can be used to obtain the shape of a tree stem. This paper proposes a method for automatically eliminating noisy points, classifying the cross-section shape of eucalyptus trees into circular and non-circular, and identifying insufficient sampling. In addition, an analysis is made of the relationship between the shape of the cross-section and the circumference adjustment, which is traditionally used to estimate DBH. Based on the proposed method, the DBH estimated from TLS data showed a Root Mean Square Error (RMSE) of 0.7 cm for trees with a cross-section considered circular and an RMSE of 3.7 cm for cross-sections considered non-circular. The results showed that the shape of the cross-section is relevant for estimating biometric parameters such as DBH and that additional evaluations are needed for precise applications, such as volume estimation for trees with non-circular cross-sections.
Keywords: Photogrammetry. Dendrometry. LASER. Mapping. Forest Inventory.

Resumo: Os dados LiDAR oferecem novas possibilidades para a obtenção de parâmetros geométricos de áreas florestais, como o diâmetro à altura do peito (DAP), a área basal, a altura, o volume, a biomassa e o estoque de carbono. Nesse contexto, os escâneres a laser terrestres são altamente precisos e podem ser utilizados para obter a forma dos troncos das árvores. Este artigo propõe um método para a eliminação automática de pontos ruidosos, seguido da classificação da forma da seção transversal de árvores de eucalipto, em circular e não circular, além de identificar troncos com amostragem insuficiente. Adicionalmente é realizada uma análise da relação da forma da seção transversal e o ajuste da circunferência, tradicionalmente utilizado para o cálculo do DAP. Com base no método proposto, o DAP estimado a partir dos dados LiDAR apresentou raiz do erro médio quadrático (REMQ) de 0,7 cm para árvores com seção transversal consideradas circulares e REMQ de 3,7 cm para seções transversais consideradas como sendo não circulares. Os resultados indicaram que a forma da seção transversal é um fator relevante na estimação de parâmetros biométricos como o DAP e, que são necessárias avaliações adicionais para aplicações precisas, como a estimativa de volume para árvores com seções transversais não circulares.
Palavras-chave: Fotogrametria. Dendrometria. LASER. Mapeamento. Inventário Florestal.

1 INTRODUCTION

Estimating forest parameters is essential for sustainable conservation practices. It is also an important task in controlled plantations to optimize wood production. Point clouds obtained by terrestrial laser scanning (TLS) or close-range photogrammetry can be valuable sources of information for these applications, as they provide highly detailed three-dimensional data on forest structure (Bauwens et al., 2017; Koreň et al., 2020). TLS data have been gaining prominence in applications related to the extraction of geometric parameters from trees, such as diameter at breast height (DBH), basal area, height, and volume (Li et al., 2023), aiming at the quantification of carbon stock (Qin et al., 2021) and biomass (Eto et al., 2020).

Previous studies have established correlations between LiDAR (Light Detection and Ranging) point cloud measurements and traditional measurement methods (e.g., caliper, clinometer, and measuring tape), indicating the potential of the LiDAR technology for forest inventory (Muir et al., 2018). In addition, LiDAR data offer new possibilities for estimating variables that are challenging to quantify using conventional techniques, such as the volume of living vegetation (Li; Liu, 2019) and the height of trees (Solares-Canal et al., 2023).

Tree parameters extraction typically assumes a cylindrical stem with a circular cross-section at breast height. However, this simplification can introduce significant uncertainties in estimating biometric attributes for trees with irregular shapes (Nogueira; Nelson; Fearnside, 2006). Bauwens et al. (2017) analyzed the stem morphology of two species, *Celtis mildbraedii* (Ulmaceae) and *Entandrophragma cylindricum* (Meliaceae), showing that trees with irregular shapes can generate high uncertainties in biomass estimation. Puletti et al. (2019) evaluated poplar stems' eccentricity (deviation from circular shape) as an essential and economical factor in wood production.

Some studies have explored alternative methods for modeling trees with irregular cross-sections in DBH estimation. These methods include parametric curves (Wang et al., 2017), ellipses (Bu & Wang, 2016), polygons (Eto et al., 2020), and splines (Witzmann et al., 2022). The main objective of these alternative methods is to improve the accuracy of DBH estimation for irregular tree shapes. Other works have investigated the relationship between cross-section modeling approaches, the tree species' characteristics, and the data collected. Liu et al. (2018) evaluated the performance of DBH algorithms in natural secondary forest and plantation environments. Their findings indicate that tree characteristics influence the accuracy of DBH estimation. Fan et al. (2021) further confirmed that the quality of point cloud data, such as the incompleteness of point sampling, affects the performance of DBH estimation algorithms. These studies highlight that selecting the most suitable model for DBH estimation depends on several factors, including species characteristics, data completeness, and noise in the data.

This paper proposes a method for individual analysis of tree cross-sectional shapes within an urban forest plot. The data was collected using a terrestrial laser scanner from FARO Technologies, Inc., USA. The analysis involves three steps: i) Pre-processing of LiDAR point cloud to segment the trees' cross-section points into clusters and eliminate noisy points (caused by multi-path or objects near the trees); ii) Estimation of the DBH by the general least squares method (LSM) using the circular model and; iii) Evaluation of the suitability of the DBH estimation considering the cross-section shape analysis. In this last step, two evaluations are proposed. The first evaluation assesses the portion of the stem cross-section sampled by the TLS (out of a possible 360º). This ensures that the data is not incomplete and has information from all directions around the tree. The second evaluation assesses how closely the shape of the tree cross-section resembles a perfect circle.

The main contribution of the proposed strategy is the development of an automatic approach for classifying tree cross-sections obtained from three-dimensional data, considering some factors related to its shape, such as the roundness. Additionally, the results are evaluated using qualitative and quantitative analyses to demonstrate the influence of shape on DBH estimation. Metrics and correlation analysis quantify discrepancies between LiDAR data and field measurements.

The content of this article is subdivided as follows: Section 2 presents a brief description of the study area used in this work, technical descriptions of the laser scanner, and the point cloud generated. The proposed methodology is presented in Section 3. In Section 4, the results are shown, while in Section 5, a brief discussion takes place. Finally, Section 6 presents the conclusions and recommendations for future work. This paper is an extended version of Silva et al. (2023), presented at the XXIV Brazilian Symposium on GeoInformatics (GEOINFO, 2023), and includes the following improvements over the previous one:

- The proposition of a procedure for the automatic removal of noisy points.
- A more comprehensive analysis is conducted to verify whether the circular model adequately represents the shape of each tree, including the roundness and the sampling angle metrics.

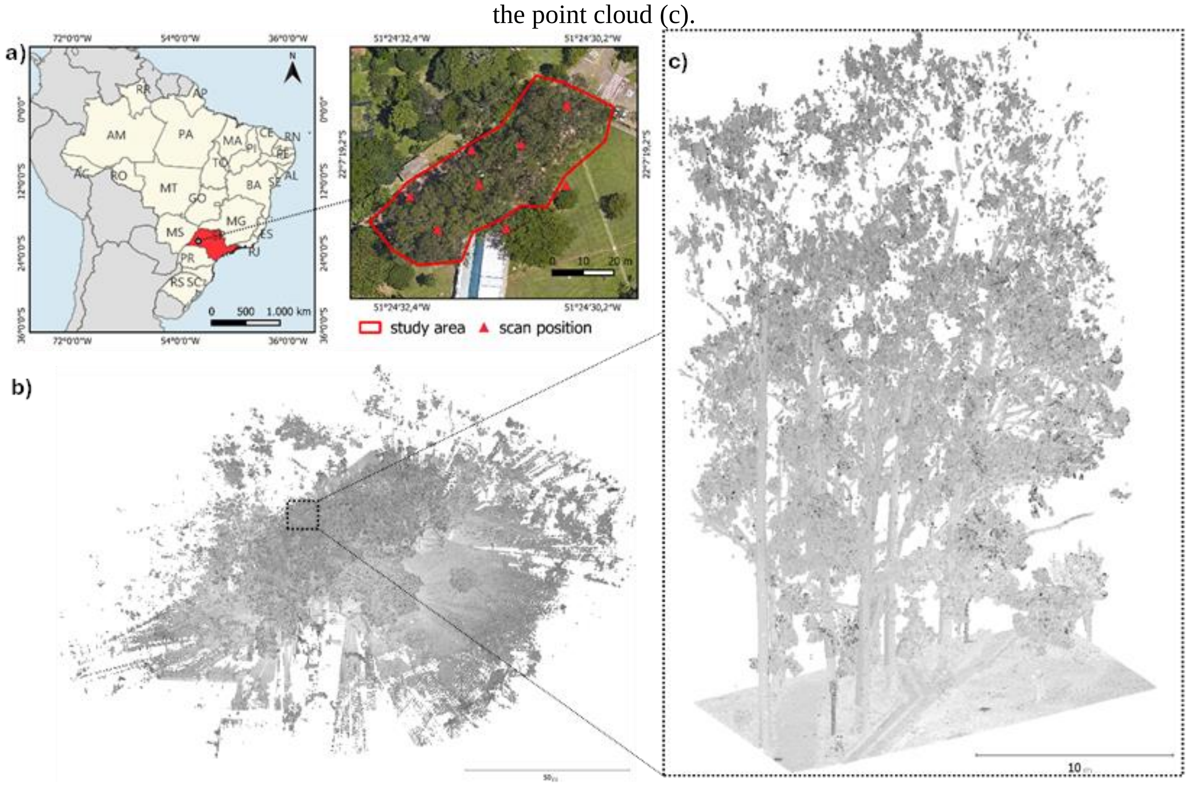
2 STUDY AREA AND DATASET

The experiments were carried out in a study area at the UNESP campus in Presidente Prudente, São Paulo (SP) (Figure 1(a)). This area includes 58 *Eucalyptus spp*. trees (with varying ages, heights, and trunk shapes) and has the characteristics of an urban forest landscape, covering approximately 2322.760 m^2 and containing artificial structures such as buildings and lampposts.

The LiDAR data were acquired in July 2023 with the FARO Focus Premium laser scanner. This LiDAR system can scan objects at up to 350 m, achieving an accuracy of ± 1 mm for distances between 10 m and 25 m, assuming a white surface with 90% reflectivity. It operates in the near-infrared spectral range (λ = 1553.5 nm), emitting a beam with a divergence of 0.3 mrad. The field of view covers 360º horizontally and 300º vertically, with an angular precision of 19 arcsec. For data collection, the scanner was configured to capture up to 400,000 points per second (1/5 of the maximum possible) and a quality of 4x to measure the coordinates of the points. The manufacturer recommends these settings for outdoor environments.

Eight scanning stations were established and distributed throughout the study area to ensure comprehensive coverage, illustrated by red triangles (Figure 1(a)). In addition, unique geometric targets such as cubes and spheres were used to register the point clouds generated by different scans in a local coordinate system. Data collection for all eight stations lasted approximately one hour. The registration step was performed manually using FARO Scene software, resulting in a point cloud of roughly 100 million points (Figures 1(b) and (c)). Manual measurements of DBH were derived from the perimeter of the cross-sections measured in the field with a measuring tape (with a reading interval of 1 mm) at a height of 1.30 m to the ground.

Figure 1 – Study area and collected point cloud. Study area at the UNESP campus and spatial distribution of the eight scanning stations (a); perspective view of the point cloud colored according to LiDAR intensity (b); zoom-in view of the point cloud (c).



Source: The Authors (2024).

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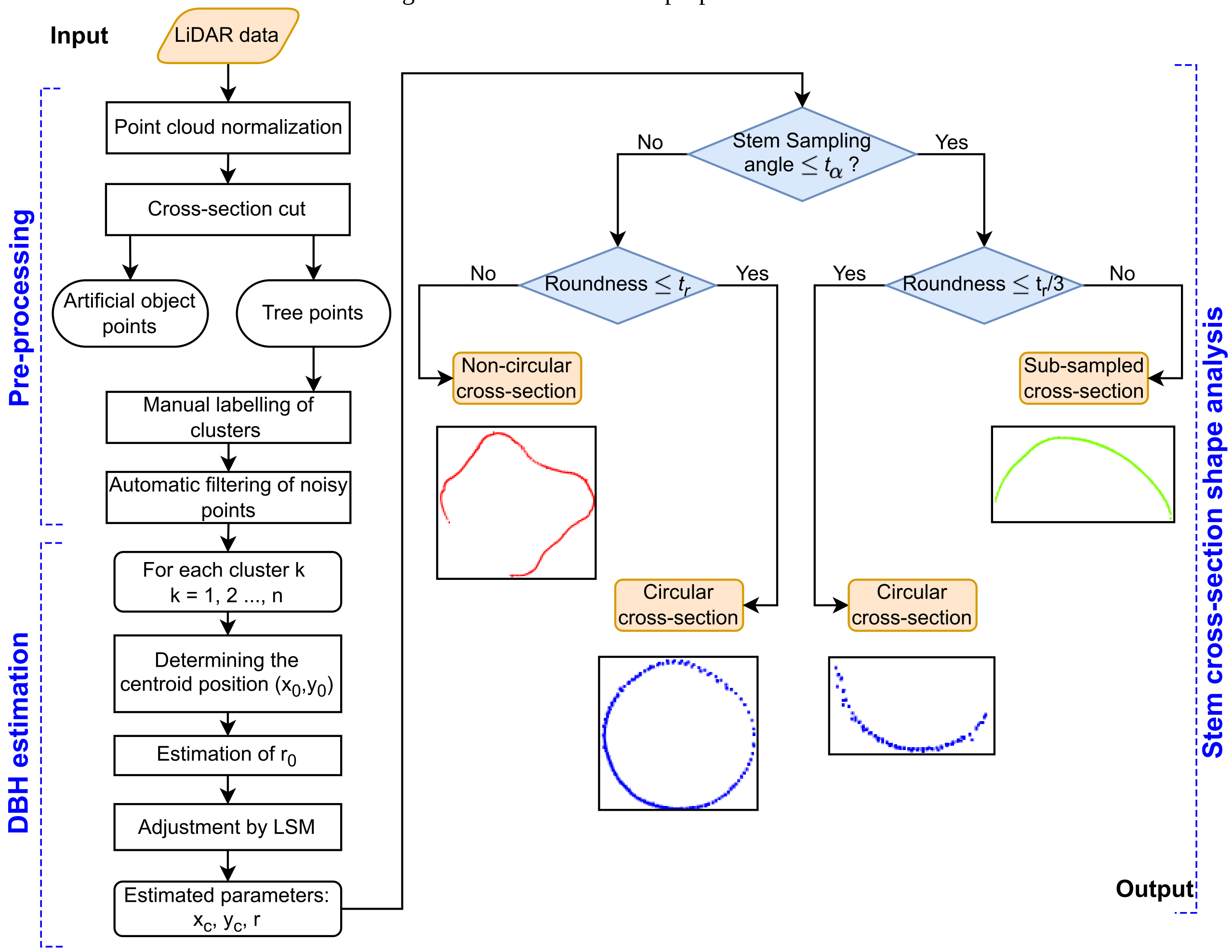
3 PROPOSED METHOD

Figure 2 shows a simplified flowchart representation of the proposed strategy, divided into three main steps. The first step involves pre-processing the LiDAR data to extract the points corresponding to the stem at breast height, then labeling the points into clusters representing individual mapped trees. In the second step, a least squares adjustment is performed to extract the DBH measurement for each cluster. In the final step, a shape analysis assesses the relationship between the extracted DBH measurement, trunk characteristics, and the circular model. The second and third steps were implemented in the GNU Octave environment.

Figure 2 - Flowchart of the proposed method.



Source: The Authors (2024).

3.1 LiDAR Data Pre-processing

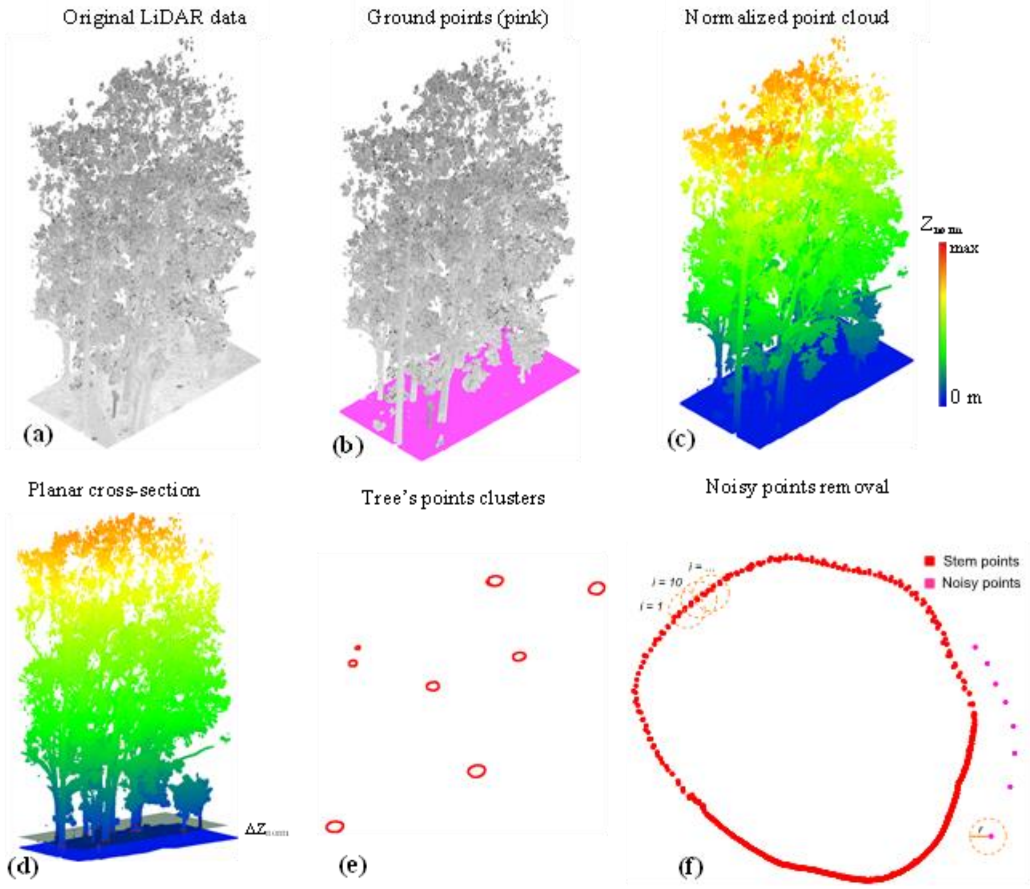
Terrestrial LiDAR data is a 3D representation of objects in the mapped environment, including anthropogenic objects, vegetation, and ground (Figure 3(a)). To extract points corresponding to the tree's stem at the breast height (1.30 m), the point cloud normalization is performed using the adaptive cloth simulation ground filtering algorithm (LIN et al., 2021). This algorithm improves the efficiency of the original cloth simulation (Zhang et al., 2016) to produce a realistic DTM (Digital Terrain Model) in areas with sparse point distribution along the ground (Figure 3(b)). Following ground filtering, a normalized height point cloud is derived, representing the point's elevation relative to the ground (Figure 3(c)). In this representation, ground points have zero elevation, whereas the object points have an elevation corresponding to their vertical distance from the ground.

After normalizing the original point cloud, a planar cross-section of the point cloud is selected at the breast height (Figure 3(d)). In this stage, an interval of 1 cm above and below breast height was considered, i.e., 1.30 m ± 1 cm. Manual labeling is carried out to obtain individual cross-sections for each tree (Figure

3(e)).

An automatic noise removal approach is adopted to remove undesirable points. These noisy points are typically related to multi-path effects or non-stem objects near eucalyptus stems, such as bark, branches, and leaves. Two parameters are considered: the radius of a circular neighborhood (r_{cn}) and the minimum number of points (m_{np}) within this neighborhood. For each point p_i (i = 1, …, n) in each cluster, a verification is carried out using a circle of radius r_{cn}. If the number of points within this circle is less than the minimum number established (m_{np}), that point is considered a noisy point and is removed from the cluster. Figure 3(f) illustrates an example of a noisy removal strategy. Other variations of noisy filtering algorithms can be seen in Carrilho, Galo, and Santos (2018).

Figure 3 – LiDAR data pre-processing. Original point cloud (a). Filtered ground points (pink) (b). Normalized point cloud (c). Planar cross-section at breast height (d). Tree cross-section clusters (e). Removal of noisy points (f).



Source: The Authors (2024).

3.2 DBH Estimation by Non-linear Least Square Method

The adjustment of indirect observations determines the stem DBH. The general least squares technique is applied to handle observations and parameters, which makes it possible to deal with correlated measurements, including those of unequal precision (Mikhail & Gracie, 1981; Gemael et al., 2015). The underlying mathematical model is based on the circle equation (Equation 1), which is based on three parameters: coordinates of the circle center (x_c, y_c) and radius (r). The observations consist of the plane coordinates (x_i, y_i) of all points within the cross-section at breast height.

$$F(x_i, y_i) = (x_i - x_c)^2 + (y_i - y_c)^2 - r^2 = 0 \tag{1}$$

The mathematical model (Equation 1) is non-linear and requires a linearization process based on series expansions. Taylor's linearization was adopted, and considering only the zero-order and first-order terms, the iterative LSM process was carried out. The centroid position (x_0, y_0) is estimated as the arithmetic mean of the coordinates of the cross-section points at the breast height of each tree (Equation 2). The approximate value of the radius (r_0) is obtained by calculating the maximum Euclidean distance between the center (x_0, y_0) and the points in each cross-section (Equation 3).

$$(x_0, y_0) = \left(\frac{\sum_{i=1}^{n} x_i}{n}, \frac{\sum_{i=1}^{n} y_i}{n}\right) \tag{2}$$

$$r_0 = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} \tag{3}$$

The unique solution to the parameters is based on the fundamental criteria of the least squares method (Equation 4), which states that the best estimate is consistent with the model, and it is as close as possible to the sample values of the observations, considering their stochastic properties (Mikhail, 1976; Gemael et al., 1995), i.e.,

$$\Phi = V^T W V \longrightarrow minimum \tag{4}$$

where W is the weight matrix of the observations, and V is the vector of residuals.

3.3 Stem Cross-section Shape Analysis

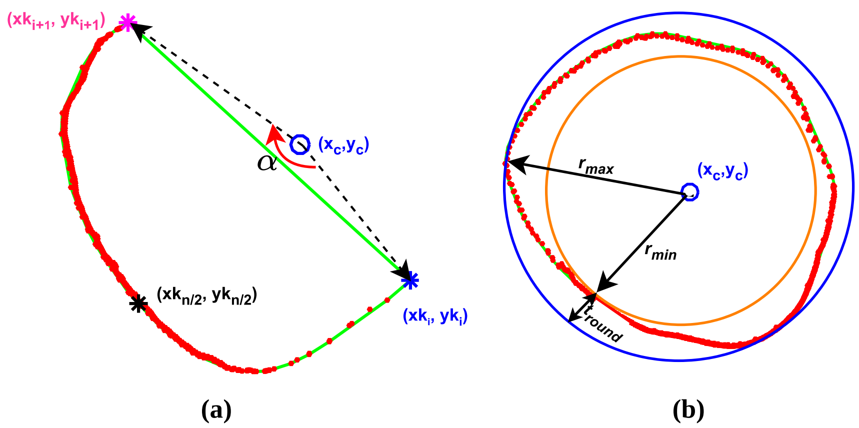
In the proposed strategy, two criteria are considered when assessing the shape of the cross-section: the minimum sampling angle and roundness. The first criterion considers the possibility of obstructions in the LiDAR data caused by objects or due to the scanner's position about the object of interest, making it difficult to assess the entire cross-section shape. The stem sampling angle indicates the portion of the cross-section that has been sampled about the maximum possible (360º). For example, if the sampling angle of a section is 180º, it means that half of the original stem shape has been sampled. The second criterion evaluates how similar the cross-section is compared to a perfect circle, the model traditionally used to estimate DBH in forest applications.

The convex hull function (*https://docs.octave.org/v4.4.1/Convex-Hull.html*) is used to extract the convex segments containing the set of points in each cross-section. This function produces a vector (k) whose points are ordered counterclockwise. For partially sampled sections, as shown in Figure 4(a), the points in the vector with the largest distance between them (asterisks in blue and magenta) will be considered the ends of the cross-section arc in analysis. Given three points, the farthest points in the vector of convex segments, and the central position of the stem obtained by the LSM adjustment (Section 3.2), the angle (α) that contains all the sample points for each stem can be calculated using the cosine law.

The roundness criterion analysis is based on the difference between the distances from the estimated center and the points in the cross-section. The minimum (r_{min}) and maximum (r_{max}) distances between the estimated center (x_c,y_c) and the points on the cross-section are calculated to verify the shape of each cross-section. Ideally, the difference between r_{max} and r_{min} for a perfect circle cross-section would be zero. Assuming that the observations are affected by random errors, a roundness threshold is set (t_{round}). Then, if the roundness error (r_{max} - r_{min}) is less than this value (t_{round}), the investigated section can be considered a circle; otherwise, it indicates that the shape of the tree section under analysis cannot be considered a circle. Figure 4(b) illustrates the roundness threshold (t_{round}) and the minimum and maximum radius of the circles associated with r_{max} and r_{min}, respectively. This roundness assessment is also relevant in other areas of engineering, such as mechanics and robotics, where this principle is used to determine the regularity of industrially produced objects (Sui & Zhang, 2012; Jiang et al., 2022).

In the analysis outlined in the flowchart in Figure 2, the sampling angle is first assessed to indicate whether sampling one specific stem meets a minimum threshold (t_α). If this is true, the roundness is evaluated using the predefined threshold (t_{round}). Sections that meet both criteria (roundness and stem angle threshold) are classified as circular. Otherwise, one-third (1/3) of the original roundness threshold is used for a secondary assessment. So, stem cross-sections that exceed this threshold are then classified as sub-sampled.

Figure 4 – Diagram of the criteria considered in the cross-section shape analysis. Stem sampling angle (α), segments of the convex hull vector (green), points that make it up (blue, magenta, and black asterisks), and center estimated from the LSM (a). The roundness principle for one cross-section shows r_{min}, r_{max} and t_{round} (b).



Source: The Authors (2024).

3.4 Evaluation of DBH Estimation

The results were evaluated considering qualitative and quantitative criteria. The qualitative assessment was conducted visually to determine whether the proposed approach adequately classified cross-sections into circular, non-circular, and sub-sampled. The quantitative evaluation was carried out for circular and non-circular cross-sections. To evaluate the accuracy of the DBH derived from the LiDAR point cloud obtained by TLS, field-measured diameters obtained from the perimeters measured using a measuring tape were used for this comparison. The diameter discrepancy (*δ)* was calculated as the absolute difference between the estimated diameter (*DBHe*) and the field-measured diameter (*DBHf*). The bias was obtained as the mean of the differences, and accuracy was determined by the RMSE (Root Mean Square Error). In addition, a linear regression was calculated to compare the estimated diameters with the corresponding field-measured diameters.

4 RESULTS

The proposed approach adopts four parameters (r_{cn}, m_{np}, t_α, t_{round}), as specified in Sections 3.1 and 3.3. These values were established based on geometric characteristics of LiDAR data (point spacing, distance accuracy, sampling pattern) and *a priori* knowledge of the study area. In the noisy point filtering step, the thresholds were set to r_{cn} = 2 cm and m_{np} = 3 neighborhoods. In the cross-section shape analysis step, the minimum sampling angle threshold (t_α) was set to 180º (half of the cross-section) and the roundness threshold (t_{round}) to 6 cm to distinguish trees with circular cross-sections from those with other shapes. Silva et al. (2023) adopted the same threshold for the roundness analysis.

Table 1 shows the metrics estimated to assess the DBH obtained for the two categories of cross-sections (circular and non-circular), according to the roundness assessment. This table presents the number of trees evaluated in each category, the bias, the maximum discrepancy between the estimated DBH and the field-measured value, the RMSE, and the coefficient of determination (R^2). In addition, Figure 5 illustrates the linear regression by comparing the estimated and field measurements.

Table 1 – DBH estimation metrics for circular and non-circular cross-sections.

	Nº trees	Bias (cm)	Max δ* *(cm)*	RMSE (cm)	R^2
Circular cross-section	33	0.5	2.27	0.70	0.998
Non-circular cross-section	20	2.7	9.93	3.76	0.934

* $\delta = |DBHe - DBHf|$

Source: The Authors (2024).

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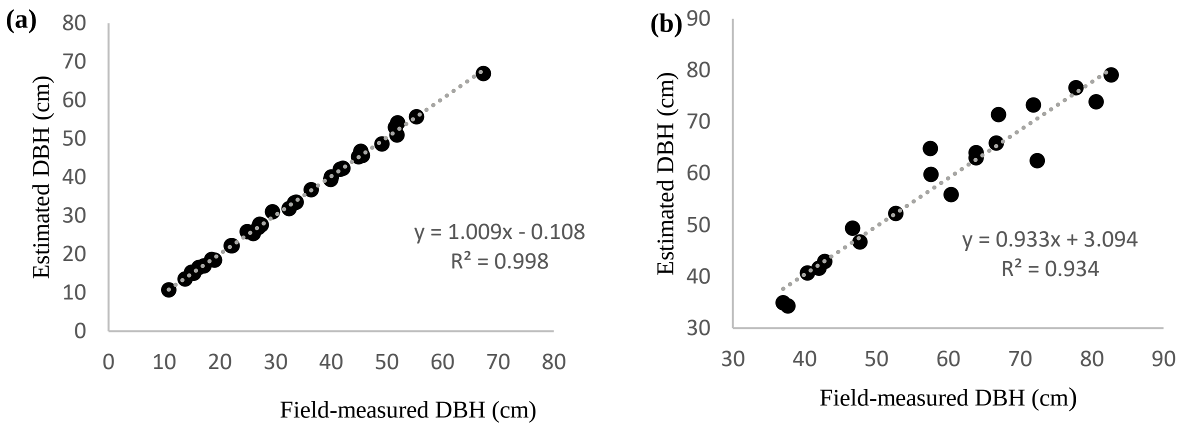
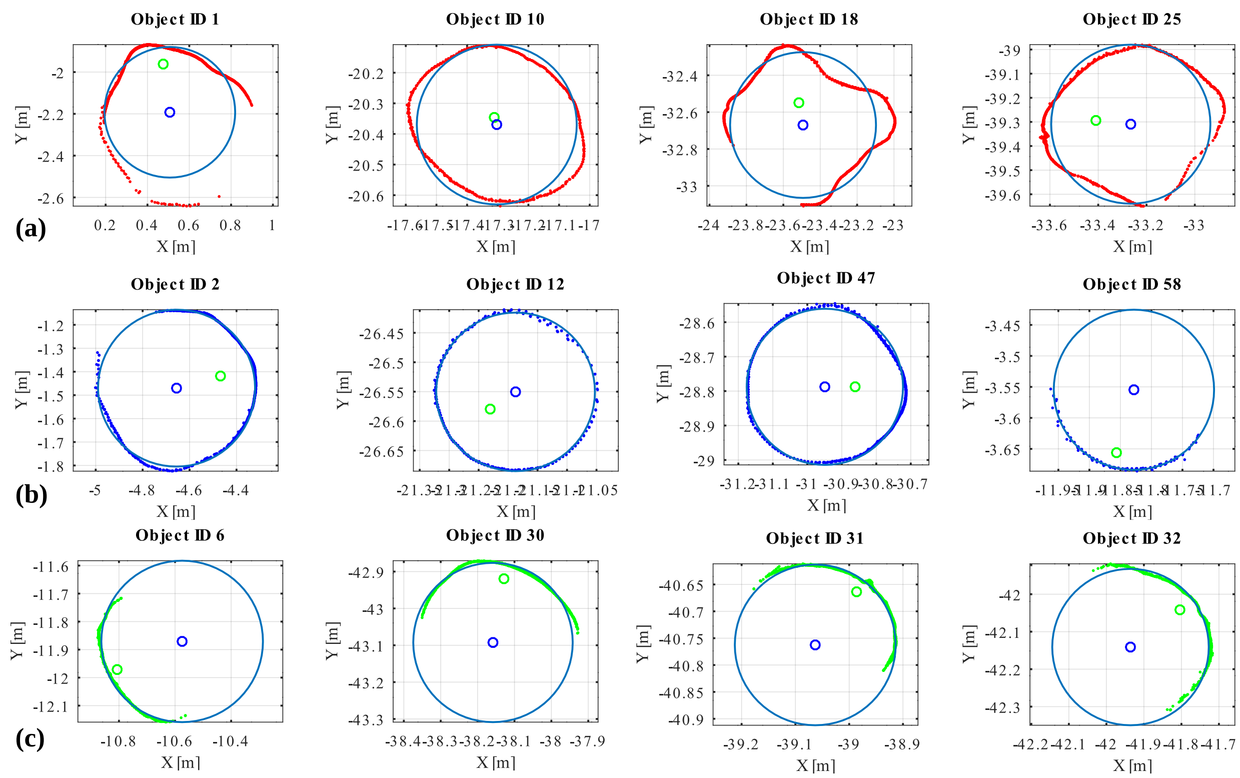
Figure 5 – Correlation graphs between estimated and field-measured diameters: (a) circular cross-section trees and (b) non-circular cross-section trees.



Source: The Authors (2024).

Figure 6 illustrates some examples of the 58 cross-sections categorized through shape analysis. In Figure 6(a), non-circular sections are highlighted, i.e., those that do not meet the adopted roundness criteria. Figure 6(b) shows circular sections, whereas Figure 6(c) shows sections with a sampling angle less than t_{α} and a roundness value exceeding one-third of t_{round}. For this last class, it is considered that the sampled data is insufficient to evaluate the tree's shape.

Figure 6 - Examples of cross-sections classified using the shape analysis approach. Non-circular cross-sections (a). Circular cross-sections (b) and sub-sampled cross-sections (c). The position of the center of the adjusted circle is shown in blue and the centroid in green, respectively.



Source: The Authors (2024).

5 DISCUSSION

The results shown in Table 1 indicate that the DBH estimated by TLS data is consistent with those acquired by the traditional method, in this case, direct tape measurement. A low RMSE and a high R^2 for circular and non-circular cross-sections evidence this. These results corroborate previous studies that also used

LiDAR data to measure dendrometric variables, as shown in Koreň et al. (2017), Wang et al. (2017), Fan et al. (2021) and Wu et al. (2024).

In the current case, an RMSE of 0.7 cm for trees with circular cross-sections and 3.76 cm for those with non-circular cross-sections was obtained. The R-squared (R^2) value was 0.998 for circular cross-sections and 0.934 for non-circular cross-sections. These results suggest that other models should be considered for non-circular cross-sections. The scatter plots in Figure 5 support this conclusion by demonstrating a clear link between the shape of the cross-sections and the quality of the circular model fit. The points representing non-circular sections exhibit greater dispersion around the fitted line than those for circular sections.

Our analyses suggest that future research should investigate contour adjustment methods that accurately extract measurements from non-circular cross-sections, supporting basal area calculations. This assessment is critical because advanced sensors, such as laser scanners, provide more accurate modeling than traditional forest inventory techniques. Furthermore, evaluating the shape of multiple cross-sections may be necessary for estimating other parameters, such as volume, which can be calculated as the sum of the basal area of various cross-sections. According to Witzmann et al. (2022), errors in cross-section shape modeling propagate to volume estimation, reinforcing the importance of appropriate modeling.

Although the focus of this paper was not on the relationship between tree position and stem shape, it is essential to note that this information can be easily obtained by TLS data and correlated with other variables such as tree spacing, presence of chemical elements in the soil, availability of light and water, exposure to wind, soil fertility (Plomion et al. 2001; Wang et al. 2017), among other variables. The proposed method for evaluating tree cross-sectional shapes can be equally valuable in managing plantations. Pulleti et al. (2019) emphasized the economic significance of this factor and the proposed method offers a tool to directly assess it.

6 CONCLUSIONS

This paper aimed to investigate the relationship between tree stem cross-section shape and the accuracy of DBH estimation using LiDAR data acquired from TLS. In the proposed approach, based on the LSM method applied to adjust points at the DBH height to a circular model, as done in Silva et al. (2023), the automatic elimination of outliers and the analysis of sampling quality were also incorporated. The assessment of the suitability of the circular model for DBH estimation demonstrated that trees with non-circular cross-sections exhibit significantly higher errors in estimated DBH compared to trees with circular cross-sections. This finding highlights the importance of considering shape analysis for improving the accuracy of DBH estimation, particularly in applications such as forest inventory for volume and biomass estimation that require precise information.

For future research, we suggest examining the influence of error propagation on variable estimation for these applications. Furthermore, the method's performance could be evaluated using data from other sources, including photogrammetric point clouds and mobile laser scanners, to improve trunk sampling and reduce obstructions in LiDAR data. Additionally, automatic modeling of the cross-sectional shape of trees with highly eccentric trunks is recommended to correctly estimate the variables in these situations.

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Author’s Contribution

Conceptualization, M.F.S., R.C.S., A.M.G.T., and M.G.. Data curation: M.F.S.. Formal Analysis: M.F.S., R.C.S., and M.G.. Methodology: M.F.S., R.C.S., A.M.G.T., and M.G.. Software: M.F.S., R.C.S., and

M.G.. Supervision: R.C.S., A.M.G.T., and M.G.. Validation: M.F.S.; Writing initial minute, M.F.S.; All authors contributed to the final revision and edition of the manuscript.

Conflicts of Interest

The authors have no conflicts of interest to declare.

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