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Wood Volume Calculation of Eucalyptus Using Robotic Total Station with Terrestrial Laser Scanner Application

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Abstract: The accurate quantification of wood volume is essential for effective timber production management, impacting decisions such as silvicultural treatments, harvesting, and supply chain logistics. Recently, laser scanning has emerged as a promising technology in forest measurement, offering efficiency and accuracy comparable to traditional inventory methods. Terrestrial Laser Scanner (TLS) plays a pivotal role by providing three-dimensional data of tree stems for wood volume calculation.This study evaluates the potential of Light Detection and Ranging (LiDAR) for estimating eucalyptus wood volume, comparing rigorous cubic measurement methods (actual volumes) with indirect methods (predicted volume). Statistical analysis, including Root Mean Square Error (RMSE), RMSE%, standard deviation, and correlation between measured volumes, was conducted to assess the accuracy of laser scanning.The Robotic Total Station (RTS) was employed to measure Diameter at Breast Height (DBH) with precision under 10%, utilizing raw point cloud data. A correlation of 0.761 was observed between volumes obtained through rigorous cubic measurement and those calculated from stem surface data. These findings highlight the potential of LiDAR and TLS technologies in accurately quantifying wood volume, crucial for efficient forest management.

Keywords: Eucalyptus, Wood Volume, Diameter at Breast Height (DBH) through Indirect Measurements, Point Cloud

1 INTRODUCTION

The forestry sector faces a shortage of effective techniques and methodologies for precision forestry, as highlighted by (Sobrinho et al., 2018). Classical methods, such as Tree scaling with Huber, Newton and Smalian formulas, are robust and well-established, but require the felling of the tree, resulting in high costs and the need for qualified professionals (Floriano, 2021). Another traditional method, widely recognized for its accuracy, but considered expensive, is xylometry. In this procedure, the wood log is submerged in a tank leveled with water, and the volume of displaced water is measured. This displaced volume directly represents the volume of wood (G. C. P. Lima et al., 2016).

Brazil, one of the world's leading producers of Eucalyptus, has invested in research and development to optimize the production of charcoal, paper and pulp. Technologies such as the Terrestrial Laser Scanner have gained prominence, allowing the profiling and obtaining of three-dimensional data (X, Y, Z) of the tree trunk and calculation of the volume of wood. This three-dimensional data can be processed by robust algorithms, such as RANSAC, designed to identify geometric shapes, including planes, spheres, rings, cones and cylinders in point clouds (Fonseca, 2018).

Lingnau et al., 2008 demonstrated that this technology provides accurate results in measuring height in different sections and in pruning and thinning simulations, as long as they are well planned. Equipment with LiDAR technology performs three-dimensional scans with high precision, surpassing traditional methodologies in the forestry sector (Almeida, 2018).

According to Buck et al., 2012, laser surveying for determining volume, through three-dimensional modeling, has shown promise in comparison to the water displacement method (Xylometer). Robotic Total Stations (RTS) with laser scanners offer precise control during field surveys and automatically obtain dendrometry variables such as stem height and diameter at breast height (dbh) (Buck et al., 2019).

Despite the advantages of LiDAR, there are still challenges in modeling and calculating timber volume. Data interpretation requires technical expertise, and the quality of estimates can be affected by stand density, the presence of obstacles, and the distance between the sensor and the target (Martins Neto et al., 2013; Lima, 2023).

Hypothesis: The use of technologies based on LiDAR sensors, combined with robust point cloud processing algorithms, can overcome the limitations of traditional methods of quantifying timber volume, such as xylometry and manual tree scaling, providing more accurate and cost-effective estimates for Eucalyptus sp. trees, even in high-density forest environments with obstacles.

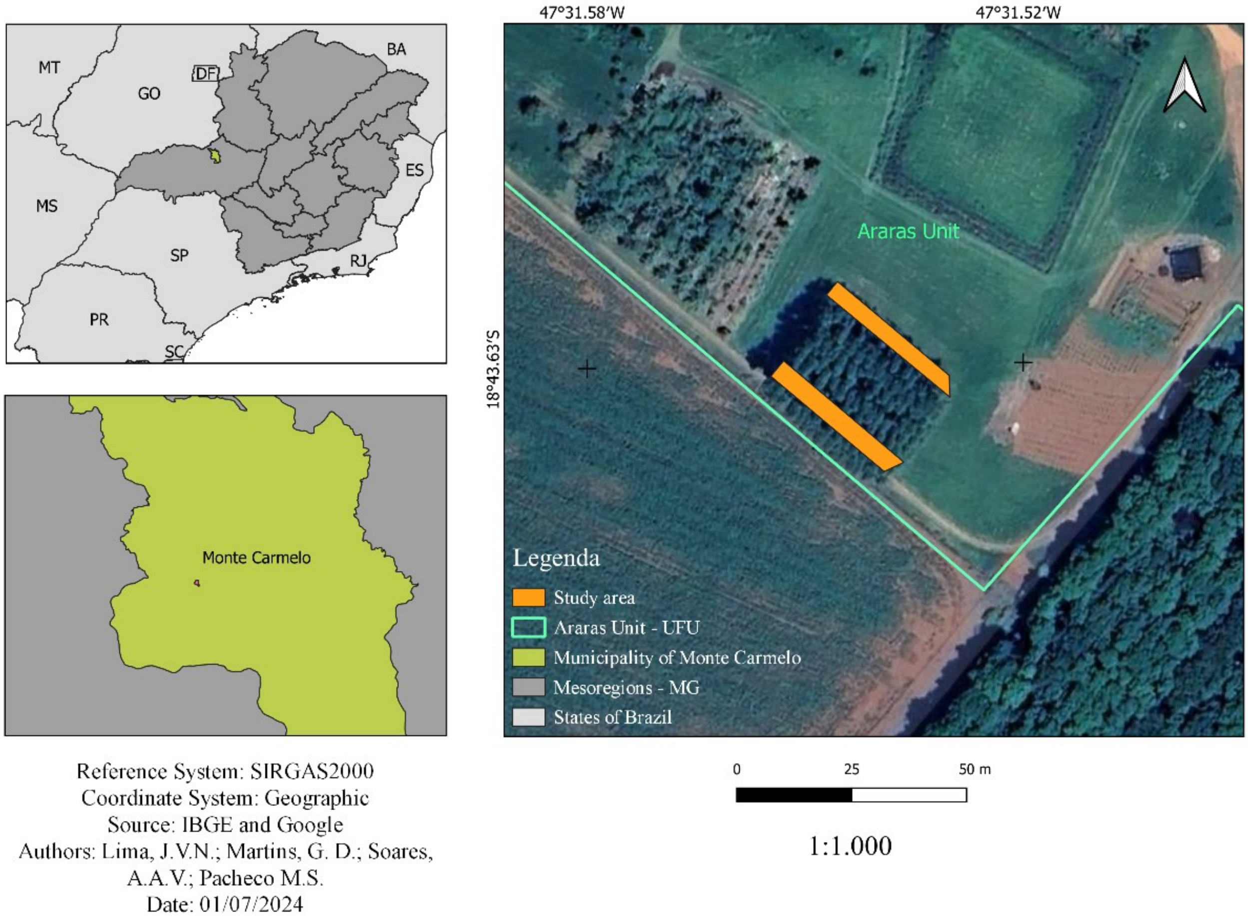
Objective: To develop and evaluate the efficiency of methodologies based on LiDAR sensors (RTS) for quantifying the volume of wood from Eucalyptus sp. trees, using three-dimensional data obtained in the field. The study will seek to optimize the processing of these data through algorithms to propose accurate, replicable and economically viable models, comparing the results with traditional methods widely used in forestry.

2 DEVELOPMENT

2.1 Study Area

For the development of this study, the experimental area located at the Araras Unit, Monte Carmelo Campus, Federal University of Uberlândia, in the municipality of Monte Carmelo - MG (figure 1) was used. Where, the plot contains 224 trees of a clone of Eucalyptus sp. In this study, only the two lateral lines containing a total of 50 trees were used, since the population is dense and it was not possible to scan the other trees.

Figure 1– Map of the location area.



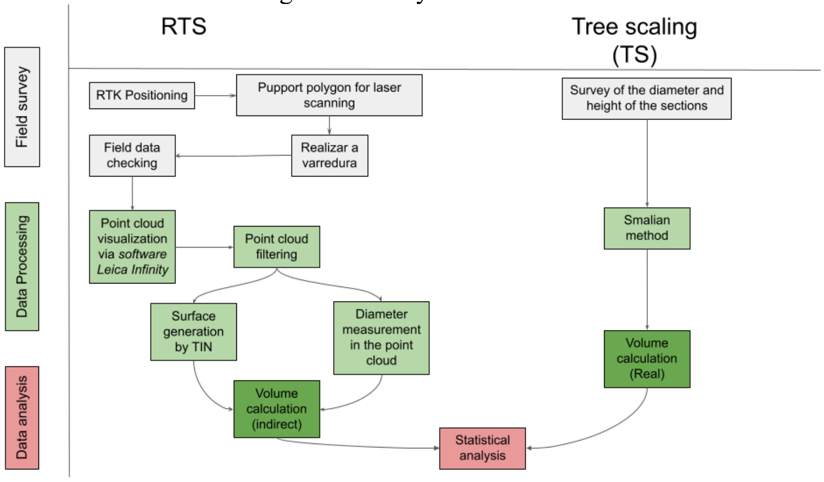
Source: The authors (2024).

The field surveys were conducted under weather conditions that significantly influenced the quality of the data obtained. During April 14 and 15, 2023, considerable movement of the treetops due to the wind was observed, which resulted in less accurate surfaces generated by the Leica Infinity software. The influence of weather conditions was continuously monitored, and the data collected reflect the need to perform scans on days with lower wind incidences to minimize estimation errors.

2.2 Material and Methods

The study methodology is shown in Figure 2.

Figure 2– Study flowchart.



Source: The Authors(2024)

2.2.1 MATERIALS

The following materials were used to perform the work:

The ETR MS50 was used for laser scanning: The RTS specifications include: angular accuracy of 1'', linear accuracy of 1 mm + 1.5 ppm with prism and 2 mm + 2 ppm without prism and has several applications, including three-dimensional scanning, direct and inverse position measurements, location, connectivity with GNSS receivers, automatic recognition of prisms and error compensators. In addition, the equipment has features that allow for the correction of vertical index error, collimation error, compensator index error and secondary axis inclination.

For the geodetic survey, the GNSS Hiper V RTK was used. This receiver has tracking of 226 channels of the dual-frequency GPS and GLONASS constellations. Using only L1, the horizontal error is 3 mm + 0.8 ppm and the vertical error is 4 mm + 1 ppm; Using L1 and L2 in static mode, the horizontal error is 3 mm + 0.1 ppm and the vertical error is 3.5 mm + 0.4 ppm; Using L1 and L2 in real-time kinematic mode, the horizontal error is 10 mm + 1 ppm and the vertical error is 15 mm + 1 ppm.

A 50-meter tape measure and a 3-meter millimeter tape measure were used to measure the circumference of the trees.

2.3 Field Survey

2.3.1 TREE SCALIN

Initially, marks were made on the 50 trees (25 trees in line 1 and 25 trees in line 2) of the outermost rows of the plantation (Figure 3), using white chalk and a tape measure, at the following heights: 0.5 m; 1.0 m; 1.3 m; 1.5 m; 2.0 m; 2.5 m; 3.0 m; 3.5 m; 4.0 m; 4.5 m and 5.0 m. Subsequently, with the aid of a millimeter tape measure, the circumferences were measured at these heights. Tree scaling was carried out up to a height of 5.0 m due to the operational impossibility of taking measurements above this height with the trees standing.

Figure 3 – Photo of Tree scaling of Standing Trees.

Source: The Authors(2024).

The circumference measurements recorded in a notebook were entered into an electronic spreadsheet and calculations were made to transform the circumference into diameter (1). For each section, the sectioned

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area was calculated (2), assuming that the sectioned area was a circle, followed by the calculation of the volume of the sections using the Smalian formula (3). Then, the volumes of the sections were added to obtain the volume of wood up to 5 meters in height, for later comparison between the Tree scaling and RTS methods.

$$d_i = \frac{c_i}{\pi} \tag{1}$$

$$g_i = \frac{\pi {d_i}^2}{40000} \tag{2}$$

$$Vh = \left(\frac{g_1 + g_2}{2}\right) L \tag{3}$$

Where di is the diameter at height i along the trunk, in centimeters, ci is the circumference at height i along the trunk, in centimeters, gi is the cross-sectional area at height i along the trunk, in square meters and L is the length of the section, in meters.

2.3.2. TOPOGRAPHIC SURVEY

The GNSS receiver was used to collect coordinates in the Universal Transverse Mercator (UTM) system. These coordinates served as support for the adjustment of open polygons and for the georeferencing of point clouds in the Brazilian Geodetic System.

The Robotic Total Station (RTS) used in this study was the MS50, with high angular accuracy specifications of 1", linear accuracy of 1 mm + 1.5 ppm with prism and 2 mm + 2 ppm without prism, in addition to features such as systematic error correction and three-dimensional scanning. As illustrated in Figure 4, the open traverse was adopted to ensure that the equipment maintained internal calibration throughout the data collection process, minimizing accumulated errors. The support points were strategically positioned to maximize coverage of the field edges and ensure the acquisition of high-quality point clouds.

Figure 4 – Open traverse planning.

Source: The Authors(2024).

The distance between the rows and between the trees is dense (0.8 m between trees and 2.5 m between rows) and therefore did not favor scanning, since the RTS has a restriction in which it is not able to obtain three-dimensional coordinates for distances smaller than 1.5 meters from the sensor, so only the edge rows were scanned. The decision in not to perform additional scans within the stand was due to the limitation of the

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spacing between trees (0.8 m) and between rows (2.5 m), which would make it difficult to capture data without significant overlap or occlusion caused by branches and canopies. In addition, the RTS restriction on capturing three-dimensional data at a minimum distance of 1.5 m made accurate measurements impossible in some internal positions. This decision aimed to ensure the quality and reliability of the captured data, avoiding compromising the results due to the high density of the stand and the structural characteristics of the plot. For future studies, it is recommended to explore hybrid scanning methods or additional sensors that can overcome these limitations.

Three-dimensional scans were performed at each support point, with a defined scanning area towards the trees (Figure 4), maintaining a spacing between the points of the point cloud of 1 centimeter horizontally and 3 centimeters vertically. It is important to note that in line 2 only 4 support points were made, due to the different spacing between the trees in this line compared to line 1.

2.4 Data Processing

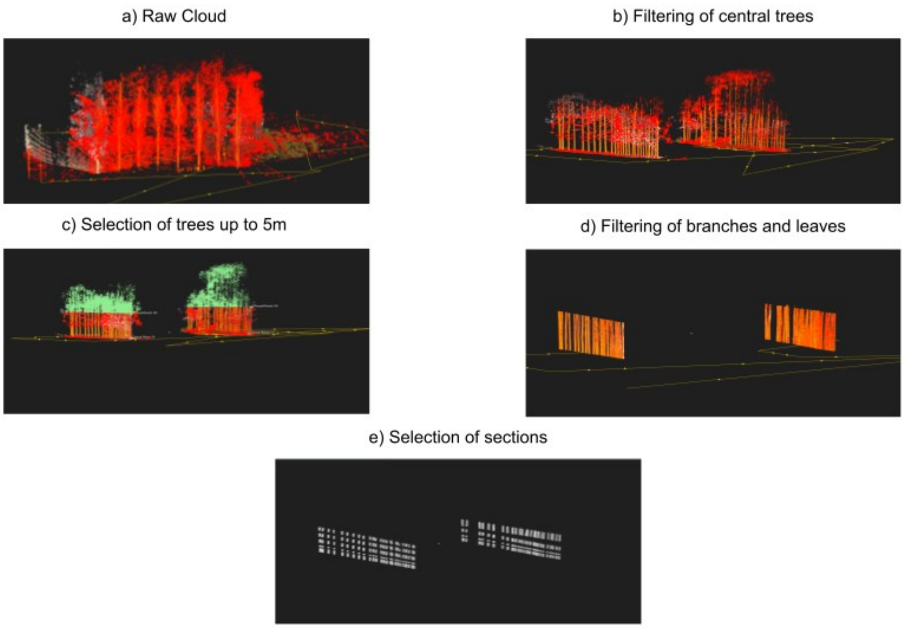
2.4.1 RTS PROCESSING

The processing of the point clouds obtained by the Terrestrial Laser Scanner was carried out using the Leica Infinity software. Manual filters were applied to remove points that represented branches and treetops, focusing exclusively on the trunk. The generation of the TIN (Triangulated Irregular Network) surface was performed to calculate the volumes of wood, using the 'Stockpile' function of the software. This procedure ensured an accurate representation of the geometry of the trunk, allowing a detailed and comparative analysis with the Tree scaling methods.

Two techniques were adopted to calculate timber volume. The first used a TIN surface around the tree, and the second used distance measurements between points on the trunk in the raw point cloud.

The point cloud filtering processes (Figure 5) were performed using Leica Infinity software. This was done by manually selecting and deleting all points representing tree branches and crowns. Specifically, for this study the manual filtering process was performed with the aim of removing points from the cloud that represented tree branches and crowns, focusing exclusively on the trunk. This procedure was carried out through careful manual selection, ensuring that only points corresponding to the trunk were included in the analysis. Filtering was essential to minimize interferences that could compromise the accuracy of the volumetric models generated.

Figure 5 – Point Cloud Filtering.



Source: The Authors(2024).

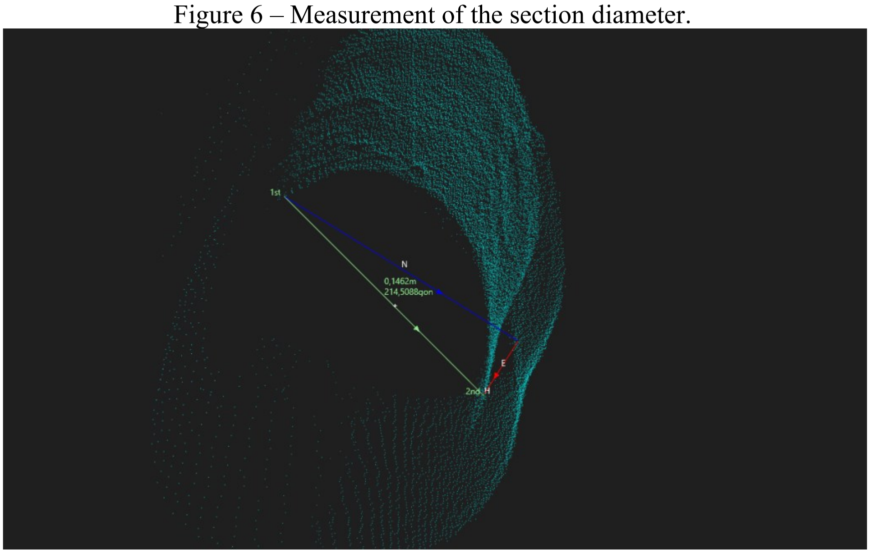
After selecting the points representing the stem, a surface was generated using a triangular irregular network (TIN - Triangulated Irregular Network). In the TIN (Triangulated Irregular Network) surface creation stage, the software's default configuration was used, without the application of additional parameters. The choice of a default TIN was due to the simplicity and replicability of the method, ensuring that the stem geometry was faithfully represented. However, future studies could explore the influence of different parameter configurations on the quality of volume estimates, especially in scenarios with greater structural variability in the trees. Wood volume calculations were performed using the "Stockpile" function of the Leica Infinity software. This function is capable of calculating the volume of stacks, as long as the surface is modeled in a way.

Next, statistical analyses were conducted to assess the accuracy, precision, and correlation of the volumes obtained in comparison with the volumes measured through Tree scaling. This allows the assessment of the precision and accuracy of the proposed method, providing a clearer understanding of the validity and reliability of the wood volumes obtained.

In order to measure the diameters based on the point clouds, diameter measurements were taken along the stem in the point cloud (Figure 6) using the Measure Point to Point tool of the Leica Infinity Software. The measurements were made at the same heights as in the Tree scaling.

Then, the volume of the sections was calculated using the Smalian formula (3). Afterwards, statistical analyses were performed to compare the diameters obtained through this method with the diameters measured by Tree scaling.

Figure 6 – Measurement of the section diameter.



Source: The Authors(2024).

2.5 Data Analysis

Statistical analyses of RMSE (root mean square error) (4), RMSE% (5) and Pearson correlation (6) of Volume and Diameter were performed. Tree scaling, being a classic technique and proven effective in previous studies in relation to the Xylometry method, was considered as the real timber volume and the field diameter measurements were taken as the real measurement for the real diameter.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Vpredicted_i - Vreal_i)^2}{n}} \quad (4)$$

$$RMSE\% = \frac{\sqrt{\frac{\sum_{i=1}^{n}(Vpredicted_i - Vreal_i)^2}{n}}}{\sum_{i=1}^{n} Vreal_i} * n * 100 \quad (5)$$

$$r = \frac{\sum_{i=1}^{n}(Vpredicted_i - \overline{V}predicted)(Vreal_i - \overline{V}real)}{\sqrt{\sum_{i=1}^{n}(Vpredicted_i - \overline{V}predicted)^2 \sum_{i=1}^{n}(Vreal_i - \overline{V}real)^2}} \quad (6)$$

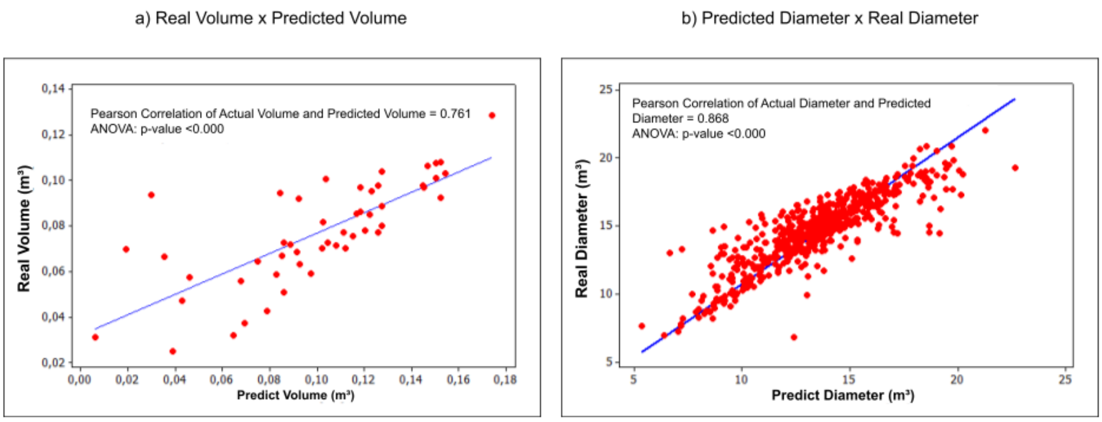
Where Vpredicted is the volume calculated from the point cloud and Vreal is the volume calculated by the Smalian formula. The same equations will be used for the diameter, that is, the "predicted" is the diameter derived from the point cloud and the "real" is the diameter measured in the field. The value of n is the number of trees (50 trees). And r is the value of the Pearson correlation.

3 RESULTS

3.1 Correlation

Figure 7 shows the correlation graphs that illustrate the relation between the wood volumes and diameters measured using RTS and the volumes and diameters obtained by Tree scaling methods.

Figure 7 – Correlation Graph.

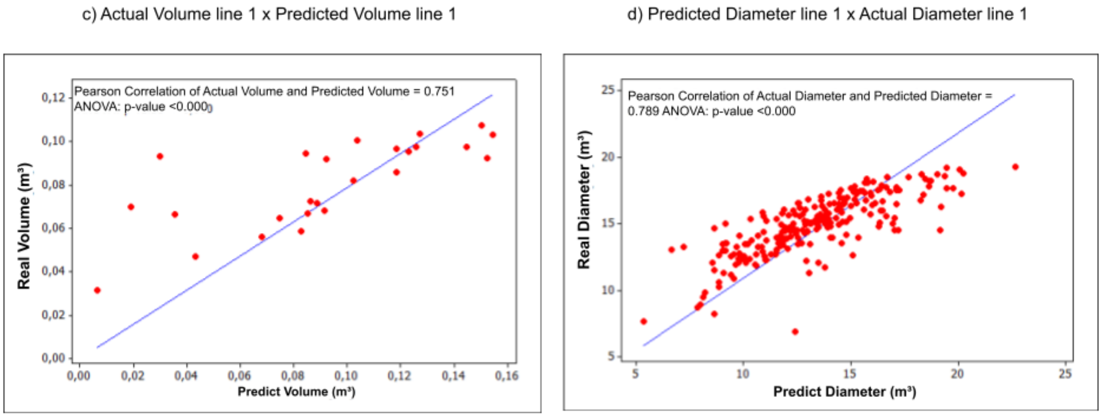


Source: The Authors(2024).

The graphs (Figure 7a and 7b) show that there was a positive correlation between the variables analyzed, with coefficients of 0.761 for wood volume and 0.868 for diameter, indicating a strong relation between the data collected by the two methods. In addition, the ANOVA test demonstrated a p-value of less than 0.05, indicating that, with a 95% confidence level, the timber volume and diameter obtained by RTS (predicted volume and predicted diameter) are statistically equivalent to the actual volume and diameter.

The Figure 8 shows correlation graphs for line 1 that illustrate the relationship between the wood volumes and diameters measured using RTS and the volumes and diameters obtained by Tree scaling methods.

Figure 8 – Correlation Graph for line 1.

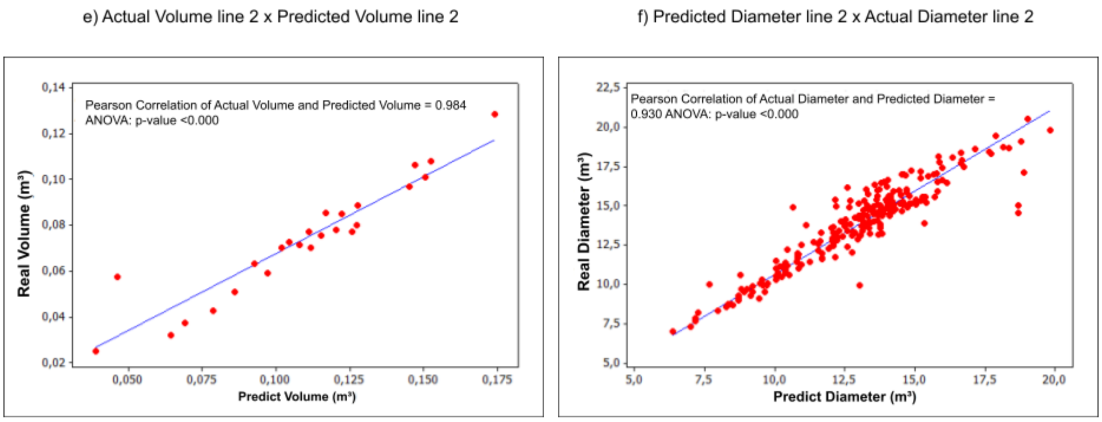


Source: The Authors (2024).

The graphs (Figure 8c and 8d) show that there was a positive correlation between the variables analyzed, with coefficients of 0.751 for the wood volume of line 1 and 0.789 for the diameter of line 1, indicating a strong relation between the data collected by the two methods.

The Figure 9 shows correlation graphs for line 2 that illustrate the relationship between the wood volumes and diameters measured using RTS and the volumes and diameters obtained by Tree scaling methods.

Figure 9 – Correlation Graph for line 2.



Source: The Authors (2024).

Os gráficos (Figura 9e e 9f) apresentam que houve correlação positiva entre as variáveis analisadas, com coeficientes de 0,984 para o volume de madeira da linha 2 e 0,930 para o diâmetro da linha 2, indicando uma relação fortíssima entre os dados coletados pelos dois métodos. Além disso, o teste de ANOVA demonstrou um valor de p (p-value) inferior a 0,05 para ambas as linhas, indicando que, com um nível de confiança de 95%, o volume madeireiro e diâmetro obtido pela ETR (volume predito e diâmetro predito) são estatisticamente equivalentes ao volume e diâmetro real para as linhas 1 e 2.

3.2 RMSE and RMSE% of Volume

Table 1 presents the RMSE (Root Mean Square Error) and RMSE% values for the volumes obtained through two methods: Tree scaling (actual volume) and the volume estimated by the robotic method using the Robotic Total Station (ETR) in both lines evaluated (Line 1 and Line 2).

Table 1 – Analysis of RMSE and RMSE% between Real Volume and Predicted Volume in m³.

Statistics	Both lines	Line 1	Line 2
RMSE	0,0254	0,03162	0,0201
RMSE%	32,9701%	37,6692	23,2306

Source: The Authors (2024).

Values lower than 33% were obtained for both lines. It is noteworthy that it was observed that line 2 presented a smaller error when compared to line 1. It is observed that Line 2 presented a smaller RMSE (0.0201 m³) compared to Line 1 (0.03162 m³), indicating that the estimates for Line 2 were closer to the real value. Again, Line 2 stands out for having a smaller RMSE% (23.2306%) compared to Line 1 (37.6692%), suggesting that the estimates in Line 2 are relatively more accurate than in Line 1.

3.3 RMSE and RMSE% of Diameter

3.3.1 LINE 1 AND 2

Table 2 provides a detailed analysis of the errors associated with diameter measurements along the stem of trees in Line 1, comparing the real values obtained by Tree scaling with the values estimated by point cloud analysis.

Table 2 – Analysis of RMSE and RMSE% between Real Diameter and Predicted Diameter in cm.

Section	RMSE	RMSE%
0,5 m	1,585	8,83%
1,0 m	1,044	6,12%
1,3 m	1,543	9,15%
1,5 m	1,777	10,75%
2,0 m	2,100	13,02%
2,5 m	2,232	14,23%
3,0 m	2,828	18,52%
3,5 m	2,849	19,13%
4,0 m	3,313	22,95%
4,5 m	3,374	23,90%
5,0 m	2,496	18,24%

Source: The Authors(2023)

The Table 2 shows that the error increases progressively as the height along the trunk increases, with a lower RMSE in the lower sections (1.044 cm to 1 meter) and a higher RMSE in the higher sections (3.3749 cm to 4.5 meters). This pattern indicates that the accuracy of the measurements decreases at higher heights. Similar to the RMSE, the RMSE% also increases with height, ranging from 8.83% at 0.5 meters to 23.90% at 4.5 meters. This indicates that the robotic method is more reliable for diameter estimates at lower heights and less accurate for higher heights.

The Table 3 follows the same format as Table 2, but presents the analysis of the diameters measured in Line 2. The results are compared with the actual values obtained by Tree scaling.

Table 3 – Analysis of RMSE and RMSE% between Actual Diameter and Predicted Diameter in cm.

Section	RMSE	RMSE%
0,5 m	0,834	5,00%
1,0 m	0,798	4,98%
1,3 m	1,017	6,46%
1,5 m	1,064	6,84%
2,0 m	1,025	6,74%
2,5 m	1,012	6,78%
3,0 m	1,103	7,50%
3,5 m	1,112	7,81%
4,0 m	1,198	8,64%
4,5 m	1,198	8,87%
5,0 m	1,403	10,57%

Source: The Authors (2023)

Similar to Table 2, the RMSE increases with height, ranging from 0.798 cm at 1 meter to 1.403 cm at 5.0 meters. However, the RMSE values in Line 2 are generally lower than those observed in Line 1, suggesting greater accuracy in the measurements of Line 2. The RMSE% in Line 2 is also lower compared to Line 1, ranging from 4.98% at 1 meter and increasing to 10.57% at 5.0 meters. These values suggest that Line 2 has a superior performance in estimating diameters along the stem.

4 DISCUSSION

The graphs in Figure 7 demonstrate that, although there is a reasonable correspondence between the methods, there is a scatter in the points, especially for extreme values, suggesting that, although the LiDAR technology coupled with RTS is effective, there are still variations and possible inaccuracies compared to Tree scaling, especially in more complex conditions or in higher sections of the shaft. These results reinforce the validity of using RTS for indirect measurements, but also indicate the need for improvements and adjustments to increase accuracy and reduce the differences observed in the correlation graphs.

The graphs in Figures 8 and 9 illustrate the correlation between volume and actual diameter, as well as between volume and predicted diameter. These results demonstrate that the Pearson correlation was higher in Line 2 compared to Line 1. This behavior can be attributed to the difference in spacing between the trees in the two lines, with the spacing in Line 1 being different from that observed in Line 2.

The diameters estimated by point cloud processing better represent the stem than conventional measurements made with a caliper or tape measure (Saarinen et al., 2017). This is because conventional Tree scaling methods do not consider the geometry of the stem, but rather solids of revolution that approximate the shape of the trees (Machado & Figueiredo Filho, 2006 cited by Buck et al., 2019).

Overall, the RMSE and RMSE% results indicated that, although both methods presented an acceptable level of accuracy, Line 2 presented better performance, with smaller absolute and percentage errors. Several factors may have contributed to the better performance of Line 2 compared to Line 1, resulting in lower absolute and percentage errors in volume calculations and diameter measurements. To this end, it is worth highlighting possible causes observed in the field:

The difference in stand density, in this case, Line 2 had a lower density of trees and a more spaced arrangement among the trees, which facilitated scanning and the acquisition of more accurate three-dimensional data. Thus, less interference among trees resulted in cleaner and less overlapping point clouds, allowing for more accurate measurements. In other words, the lower density and the absence of obstacles such as intertwined branches provided better visibility conditions for the LiDAR sensor, ensuring that more measurement points were captured accurately.

The arrangement and positioning of the support points in Line 2 may also have been more appropriate, resulting in better alignment of the measurements and less distortion in the point clouds. As observed in the field, this may have helped to minimize geometric errors that could otherwise have occurred during scanning. It is also worth noting that in Line 2, the support points allowed a more horizontal view (smaller vertical angle) of the tree trunks, which is generally associated with greater precision in measurements made with the RTS. Sharper angles, such as those used in Line 1, were more susceptible to parallax errors and other geometric distortions.

Furthermore, according to Faggion (2006), an error in the line of sight refers to the deviation in orthogonality between the secondary, main and collimation axes. It was confirmed that sights at vertical angles greater than 45° can affect the horizontal angle by approximately 24.8”. The scans performed on lines 1 and 2 showed sights with vertical angles greater than 45°, approaching 90° on line 1.

The RMSE% of the diameter at 1.30 m on line 1 and line 2 was less than 10%, suggesting that the ETR performs precise measurements with an accuracy level of 10% compared to the DAP. This is in line with the observation of Faggion (2006), since the RTS is usually positioned at a height of 1.3 to 1.7 meters, keeping the vertical angle close to the horizon, where the collimation error is smaller.

As demonstrated in Tables 2 and 3, it was evident that diameter measurements along the shaft have a higher accuracy in the lower parts, with a decrease in accuracy as the sections become higher. These results highlight the variation in accuracy of diameter measurements along the stem, suggesting that the method may be particularly useful for measurements at heights closer to the ground, but faces challenges at higher heights. Problems related to loss of accuracy in the highest regions are related to environmental, biotic and geometric factors of the forest itself.

On April 14 and 15, 2023, when the field surveys were carried out with the RTS, considerable movement of the tree canopy was observed due to the wind. This movement of the trees resulted in less accurate surfaces generated by the Leica Infinity Software (Figure 6), being another factor that contributed to the high RMSE.

For Liang et al. (2016), terrestrial laser scanning can be put into practice in forest inventories because the RTS operational processes can be carried out interactively, such as automated tree mapping processes, three-dimensional modeling and extraction of dendrometric variables. The authors add that point cloud data can be highly valuable for silviculture operations, as these data offer details that are not provided by automated tools.

Regarding biotic factors, another factor that influenced the inaccuracy of diameters in higher sections was the occlusion of the point cloud by trees and branches, due to the excessive density of branches in the forest. This caused the RTS view to be blocked, resulting in inaccuracies in the method. Furthermore, at these higher heights, solar illumination influenced the LiDAR sensor's ability to capture accurate reflections. According to the analysis of the point cloud, excessive reflections and shadows cast by branches interfered with data collection, resulting in less accurate measurements at higher heights.

As shown by Buck et al. (2019), point occlusion prevented the total trunk volume from being obtained, suggesting that total coverage of the trunk surface should be required to increase volume estimates. He also showed that, for conventional and TIN methods, the error in the estimated volume also increases as the height of the tree increases.

In general, the volumes of a species are calculated using dendrometric variables such as height and DBH (Gatziolis et al., 2010 cited by Silva et al., 2013) and are adjusted in equation models where these variables are difficult to acquire, sometimes using destructive methods (felling the tree) for collection. Therefore, the terrestrial laser scanner has proven to be a very valuable tool for accurately determining volume (Silva et al., 2013).

5 CONCLUSION

Based on the above, it can be concluded that the Robotic Total Station (RTS) is capable of performing diameter measurements at a height of 1.30 m (DBH) with an accuracy of less than 10% compared to direct measurements (Tree scaling).

Factors such as wind have a direct influence on the quality of the point cloud obtained by the RTS, causing inaccuracies in the method. Angles that are too close to the Zenith or Nadir of the equipment also introduce errors in indirect measurements. In addition, very long distances also affect the method of obtaining indirect measurements.

Although the entire field survey was carried out in a period of 9 hours, if any future work requires only the DBH, the RTS demonstrates an accuracy that allows a survey in less time compared to direct measurement techniques, such as tapes and calipers.

For future work, it is recommended that laser scans do not present such an abrupt elevation of the vertical angle, that the distances between the ETR and the target be smaller, and that the project include more control points for different scanning angles of the stem. As well as, it is important to better monitor the wind, which was a significant contributing factor to the error, suggesting that the scans be performed on days with less wind.

In addition, the application of algorithms that automatically filter noise present in the point clouds, such as those caused by branches, canopies or spurious reflections, should be evaluated, as this can significantly improve the accuracy of the stem modeling. Machine learning-based methods, such as neural networks trained for stem segmentation, or algorithms such as RANSAC adjusted for cylindrical structures, can be particularly useful. Investing in the automation of manually performed steps, such as filtering unwanted points and generating the TIN surface, can increase the efficiency and replicability of the method.

Programming and processing tools in specialized software, such as Python or MATLAB scripts, could be integrated into the workflow.

Finally, it is important to emphasize that this study used a Robotic Total Station with Laser Scanner application, which has limitations when compared to Terrestrial Laser Scanners appropriate for precise scanning.

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Author Contributions

J.V.N. Lima contributed to data acquisition, conceptualization and writing – first draft. A.A.V. Soares contributed to conceptualization and review. M.S.Pacheco contributed to data acquisition and conceptualization. G.D. Martins contributed to conceptualization, review and writing.

Conflicts of Interest

The authors declare no conflict of interest.

References

Almeida, G. J. F. D. (2018). *Uso do laser scanner terrestre na estimativa de parâmetros biométricos em povoamentos florestais* [Mestrado em Recursos Florestais, Universidade de São Paulo]. https://doi.org/10.11606/D.11.2018.tde-02032018-094924

Buck, A. L. B., Lingnau, C., Péllico Neto, S., Machado, Á. M. L., & Martins-Neto, R. P. (2019). Stem Modelling of Eucalyptus by Terrestrial Laser Scanning. *Floresta e Ambiente*, *26*, e20160125. https://doi.org/10.1590/2179-8087.012516

Buck, A. L. B., Silva, M. N., Lingnau, C., Machado, Á. M. L., Neto, R. P. M., & Pesck, V. A. (2012). Avaliação da modelagem tridimensional do tronco de Pinus elliottii a partir de dados laser terrestre Evaluation of three-dimensional trunk modeling of Pinus elliottii from terrestrial laser data. *AMBIÊNCIA*, *8*(4), Artigo 4.

FAGGION, P. L. (2006). *Considerações sobre a instrumentação topográfica*. Curso de Pós-Graduação em Ciências Geodésicas, Departamento de Geomática ….

Floriano, E. P. (2021). *Dendrometria*. Universidade Federal de Alagoas. http://www.repositorio.ufal.br/jspui/handle/123456789/13967

Fonseca, A. L. B. (2018). *Estimação de volume de madeira em povoamento de eucalipto utilizando dados de Laser Scanner Terrestre*. https://locus.ufv.br//handle/123456789/27647

Gruber, T., & Willberg, M. (2019). Signal and error assessment of GOCE-based high resolution gravity field models. *Journal of Geodetic Science*, *9*(1), 71–86. https://doi.org/10.1515/jogs-2019-0008

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

Lima, G. C. P., Kohler, S. V., Silvestre, R., Navroski, M. C., Bonazza, M., Allegretti, G., & Scarioti, R. (2016). ACURACIDADE DE MÉTODOS DE CUBAGEM PARA ESTIMATIVA DO VOLUME DE Pinus taeda L. *BIOFIX Scientific Journal*, *1*(1). https://www.researchgate.net/profile/Marcelo-Bonazza/publication/312542839_ACURACIDADE_DE_METODOS_DE_CUBAGEM_PARA_ESTIMATIVA_DO_VOLUME_DE_Pinus_taeda_L/links/59a40e79a6fdcc490a476288/ACURACIDADE-DE-METODOS-DE-CUBAGEM-PARA-ESTIMATIVA-DO-VOLUME-DE-Pinus-taeda-L.pdf

Lima, J. V. do N. (2023). *Cálculo de volume madeireiro de eucalyptus a partir de estação total robótica com aplicação de laser scanner terrestre*. https://repositorio.ufu.br/handle/123456789/38328

Lingnau, C., Silva, M. N., Santos, D. S. dos, Machado, Á., & Lima, J. G. dos S. (2008). Mensuração de alturas de árvores individuais a partir de dados laser terrestre Individual tree height mensuration with laser terrestrial data. *AMBIÊNCIA*, *4*(4), Artigo 4.

Martins Neto, R. P., Buck, A. L. B., Silva, M. N., Christel, L., Machado, Á. M. L., & Pesck, V. A. (2013). Avaliação da varredura laser terrestre em diferentes distâncias da árvore para mensurar variáveis dendrométricas. *Boletim de Ciências Geodésicas*, *19*(3), 420–433. https://doi.org/10.1590/S1982-21702013000300005

Saarinen, N., Kankare, V., Vastaranta, M., Luoma, V., Pyörälä, J., Tanhuanpää, T., Liang, X., Kaartinen, H., Kukko, A., Jaakkola, A., Yu, X., Holopainen, M., & Hyyppä, J. (2017). Feasibility of Terrestrial laser scanning for collecting stem volume information from single trees. *ISPRS Journal of Photogrammetry and Remote Sensing*, *123*, 140–158. https://doi.org/10.1016/j.isprsjprs.2016.11.012

Silva, M., Buck, A., Lingnau, C., Machado, A., Pereira Martins-Neto, R., & Pesck, V. (2013). Terrestrial Laser Scanner for Forestry Measurements – Principles and Applications. *1143-1152*.

Sobrinho, M., Corte, A., Vasconcellos, B., Sanquetta, C., & Rex, F. (2018). USO DE VEÍCULOS AÉREOS NÃO TRIPULADOS (VANT) PARA MENSURAÇÃO DE PROCESSOS FLORESTAIS. *Enciclopédia Biosfera*, *15*(27), 117–129. https://doi.org/10.18677/EnciBio_2018A80

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