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Research article

Assessment of Eucalyptus Stem Diameter Estimation Using Terrestrial Laser Scanning

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Abstract

Stem diameter plays a pivotal role in forest mensuration, encompassing applications in growth assessment, stand density estimation, wood production, and carbon sequestration. Traditionally measured with diameter tape or calipers through ground-based methods, the advent of Terrestrial Laser Scanning (TLS) has introduced a non-destructive 3D modeling technology for precise measurements. In this study, we aimed to assess the accuracy and precision of eucalyptus stem diameter estimation using TLS in comparison to ground-based diameter tape measurement. The results showed an average diameter at breast height (dbh) of 13.840 cm and an average height of 18.5 m for the sample trees. Stem curves from TLS were automatically derived from the 3D Forest program analyses of standing eucalyptus trees. Our analysis reveals that the average Root Mean Square Error (RMSE) for estimated stem diameter using TLS was 4.34 cm for the first ten sections of the tree from the ground. The measurement of stem size in eucalyptus trees using TLS tends to show increased RMSE in the upper sections of the stem. Our research underscores the high accuracy achieved in estimating stem diameters, particularly for the lower portions of the trees, even under light wind conditions.

Keywords: eucalyptus; point cloud; stem curve; terrestrial laser scanning; three-dimensional model of tree

1. Introduction

Terrestrial Laser Scanning (TLS), a ground-based LiDAR (Light Detection and Ranging) technology, emits laser pulses towards a target and measures the return time of the light to calculate distance, resulting in the creation of a 3D point cloud representation. This technology enables the precise capture of geometric details, rendering it applicable for forest inventory, stand structure assessment, and accurate estimation of stem diameter (Calders, 2015; Liang et al., 2016; Bournez et al., 2017; Åkerblom & Kaitaniemi, 2021; Hu et al., 2021). Stem diameter serves as a fundamental measurement that provides crucial

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insights into the growth and development of trees, enabling us to make informed decisions regarding forest management, resource utilization, and conservation efforts. Utilizing TLS, stem diameter can be extracted with enhanced precision at various tree heights without the need to fell the tree, thereby enabling non-destructive and accurate measurements (Saarinen et al., 2017; Forsman, 2018; Buck et al., 2019).

Eucalyptus holds an outstanding position among the commercial tree species in Thailand due to its rapid growth rate and remarkable adaptability to various environmental conditions. With a relatively short rotation period of 3 to 5 years, eucalyptus stands out as an efficient resource for timber production and other purposes. Depending on the size of its stem, eucalyptus timber assumes crucial significance as a valuable resource for the pulp and paper industry, plywood manufacturing, wood energy fuel, and residential building construction (Kaur & Monga, 2021). The stem curve or stem size can serve as indicators to ascertain the potential applications of eucalyptus, aiming to optimize profitability (Cerqueira et al., 2019).

The 3D Forest program, an open-source software, features a user-friendly graphical interface and was created by Trochta et.al. (2017). This application automates the estimation of tree parameters including diameter at breast height (DBH), height, stem curve, and crown attributes. The 3D Forest program estimates DBH using two methods: i) Randomized Hough Transform (RHT) for circle detection with adjustable iterations, and ii) Least Square Regression (LSR) with algebraic circle estimation and squared distance reduction. Both use a subset of tree point cloud within a 1.25-1.35 m height slice (DBH cloud). At least 4 points are needed for successful circle fitting. Methods were tested for data sensitivity and efficiency optimization. The stem curve, a function in the 3D Forest program, calculates stem diameters at various heights starting from 0.65 m, 1.3 m, and 2 m, followed by each successive meter above the terrain. This software has found application in numerous research studies (Wan et al., 2019; Eker et al., 2022; Panagiotidis et al., 2022; Viana et al., 2022).

This paper utilizes the 3D Forest program to estimate DBH and stem diameters derived from TLS and compares them with ground measurements in a eucalyptus plantation. Point cloud data from TLS was collected under typical weather conditions. The findings demonstrate the 3D Forest program's capability in estimating eucalyptus stem diameter, aiding inventory data and wood assortment tasks. The results from this study can serve as guidelines for employing TLS and the 3D Forest program in other forest regions.

2. Materials and Methods

2.1 Study area

Wang Nam Khiao Forestry Student Training Station is situated within Wang Nam Khiao District, Nakorn Ratchasima Province, with connectivity to Prachinburi Province, Thailand. The study area is located at a latitude of 14.494413°, a longitude of 101.942632°, and an altitude of 376 m above sea level. The research station is in proximity to the Sakaerat Environment Research Station. The study area experiences a moist to dry climate characterized by three distinct seasons. The dry season spans from March to May, with the peak heat observed in April at 33ºC. The cold season is from November to January, with the lowest temperature recorded around 18ºC. The transitional period, encompassing the middle part of the year, is the rainy season, featuring an average measured rainfall of 247 mm. The research station's elevation from mean sea level averages at 418 m. The prevailing wind registers an average of around 1.2 m/s, corresponding to light wind levels at a height of around 10 m from the ground.

The research station encompasses an extensive forest complex that transitions between a mixed-deciduous forest and a dry evergreen forest. This study area is situated on a small plateau and is characterized by the presence of *Eucalyptus* spp. The eucalyptus trees have surpassed three years of age during their second growth cycle. The designated sampling site comprises a eucalyptus plantation spanning a 20x20 m area. The tree arrangement is spaced at 2 x 3 m intervals, accommodating a total of 62 trees. These trees are organized in rows, each containing 12 trees, and columns extending from north to south, with 7 trees in each column (Figure 1).

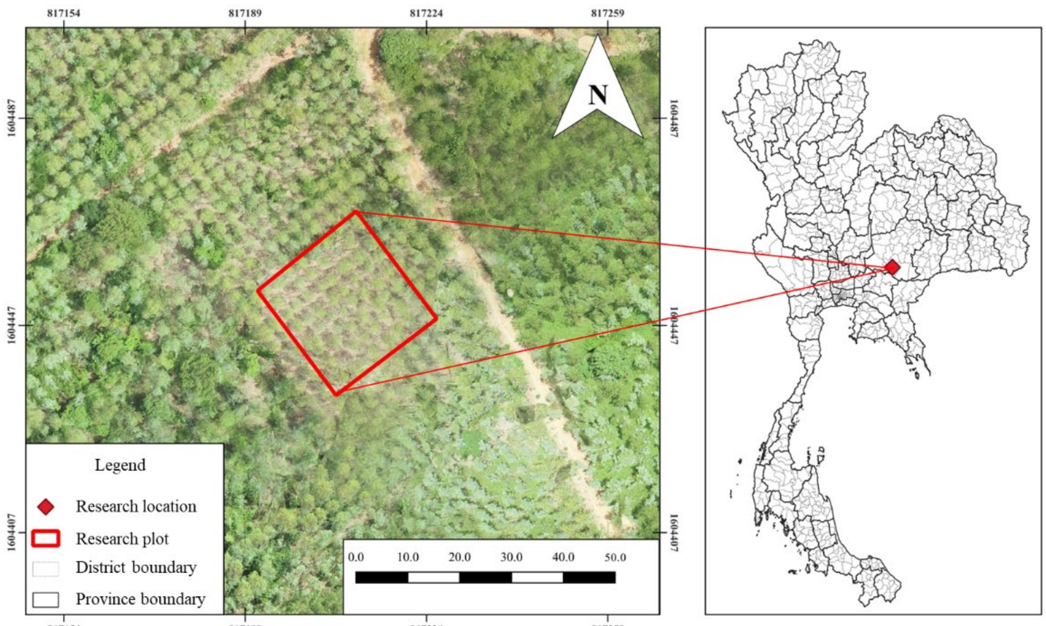

Figure 1. Research plot at Wang Nam Khiao Forestry Student Training Station, Thailand

2.2 Methodology

The methodology was structured into three distinct phases: field data collection, data processing, and result evaluation (Figure 2). The initial phase involved field measurements of tree diameter at breast height (1.3 m above the ground) using a diameter tape. Subsequently, the research plot was subjected to scanning through a terrestrial laser scanner. The scanning procedure was executed utilizing the Faro S150 equipment, with maintenance of a constant scanning resolution of 3.1 mm over a 10 m distance and an acquisition rate of 2,000,000 points per second. To facilitate the registration of scans, white spherical targets with a diameter of 200 mm were positioned on tripods. A minimum of three targets in each scan station was established as a prerequisite for accurate observation. For this study, the research plot was scanned from a total of nine positions, encompassing the four corners, the four sides, and the central location. After the completion of scanning, the next step involved felling 15 trees and measuring their

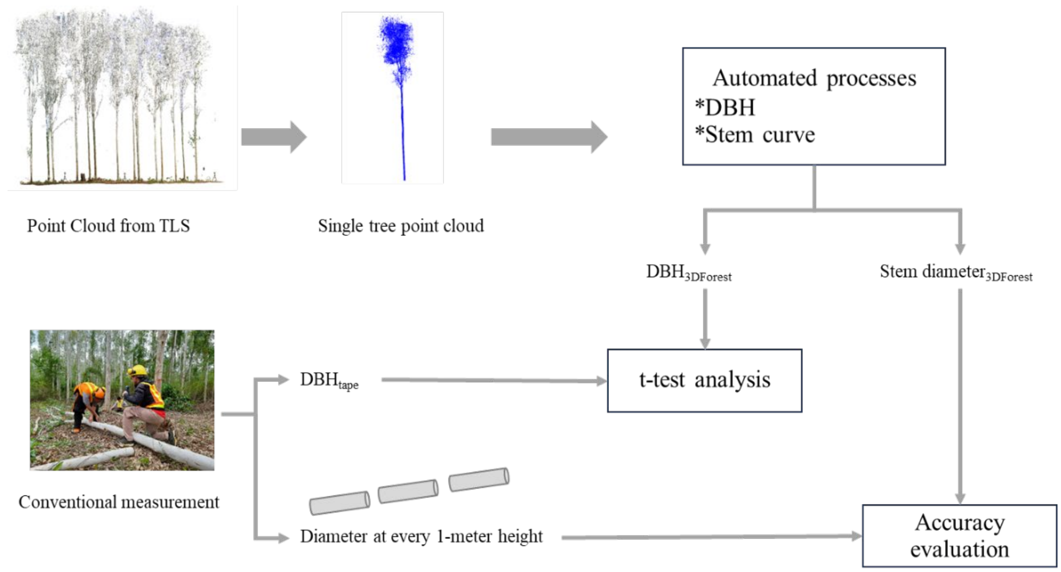

Figure 2. Methodology workflow

diameter at one-meter intervals using a diameter tape. The following phase encompassed the processing of point cloud data obtained from TLS and include the extraction of individual tree data for the 15 felled trees. Afterwards, an automated procedure within the 3D Forest program (Trochta et al., 2017) was employed to eliminate terrain. This was followed by the application of the DBH and stem curve functions to derive both the DBH and stem diameter values along the tree's height.

To assess the practicality of the 3D Forest program, the accuracy of DBH estimation was examined. The statistical tool used for this comparison was the t-test, which assesses the significance of differences between the means of two datasets: the estimated DBH from 3D Forest program and the reference DBH from field measurement. To further assess the agreement between the 3D Forest program and field measurements for DBH estimation, a Bland-Altman analysis was conducted. Equations (1) and (2) were employed to assess the diameter at various heights. Bias was utilized to characterize the systematic distinction between the estimated values and the observed actual values. Analysis encompassed the comparison between the diameter estimated from the 3D Forest (D_{3D}) and the reference diameter (D_{ref}). Root mean square error (RMSE) was employed to evaluate the disparity between referenced and estimated diameters.

$$\text{Bias} = \frac{\sum(D_{3D} - D_{ref})}{n} \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{\sum(D_{3D} - D_{ref})^2}{n}} \quad (2)$$

Where n is the number of observations.

3. Results and Discussion

3.1 Diameter at breast height (DBH) estimation

DBH estimates were calculated using the DBH function within the 3D Forest program, utilizing point cloud data from TLS. The estimated DBH values were subjected to statistical testing through a t-test, revealing a significant difference between the 3D Forest estimates and field measurements obtained with diameter tape. The mean DBH obtained from the point cloud was 14.053 cm, while the diameter tape measurements resulted in an average of 13.840 cm (Table 1).

Table 1. Comparison of diameter at breast height (DBH) statistics between 3D Forest and diameter tape methods

Method	Mean	Variance	N	df	t	p
3D Forest	14.053	6.774	15.000	14.000	1.562	0.140
Diameter tape	13.840	6.766	15.000	14.000		

The presented t-value of 1.562 and p-value of 0.140 indicate that, at a significant level of 0.05, there is no statistically significant difference in mean DBH values between the 3D Forest method and the diameter tape method.

The Bland-Altman plot indicates a mean difference of 0.21 cm, indicating that TLS measurements, on average, slightly overestimate DBH compared to diameter tape measurements (Figure 3). The limits of agreement are 1.24 cm and -0.82 cm. These values indicate that 95% of the differences between the methods fall within this range, demonstrating the consistency and acceptability of the differences across the measured values. The plot shows no extreme outliers and does not exhibit any clear patterns of bias variation with different measurement sizes, indicating a stable agreement across the range of DBH values measured.

Figure 4 illustrating the correlation between DBH values from diameter tape measurements and estimates derived from the 3D Forest method exhibits a notable R-squared (R^2) value of 0.96. This indicates that approximately 96% of the variation in estimated DBH can be attributed to the linear relationship between the two methods. The Root Mean Square Error (RMSE) of 0.55 cm also reflects the average magnitude of differences between observed and estimated DBH values. This high R^2 value and relatively low RMSE collectively underscore the substantial agreement between diameter tape measurements and the 3D Forest method, highlighting its efficacy in providing accurate DBH estimates.

3.2 Stem diameter

Fifteen felled trees displayed an average height of 18.5 m. The eucalyptus taper model illustrated in Figure 5 demonstrates the gradual reduction in stem diameter as height increases from ground level to the tree's apex.

The study compared stem diameter estimations from the 3D Forest method with those obtained through the conventional diameter tape. The stem diameter estimation results obtained from the 3D Forest method show limitations in estimating diameters in the upper regions of the tree, particularly when the height exceeds 12 m from the ground.

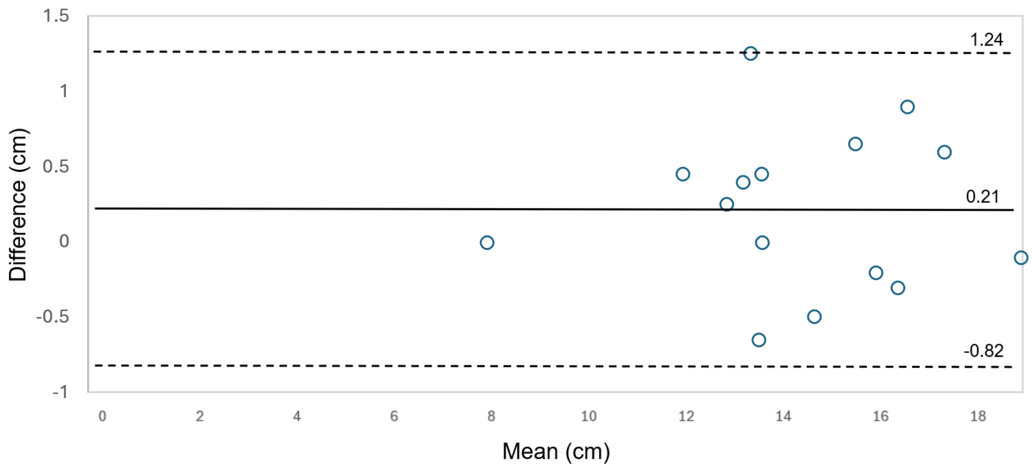

Figure 3. The Bland-Altman plot of DBH measurements comparing TLS and diameter tape methods

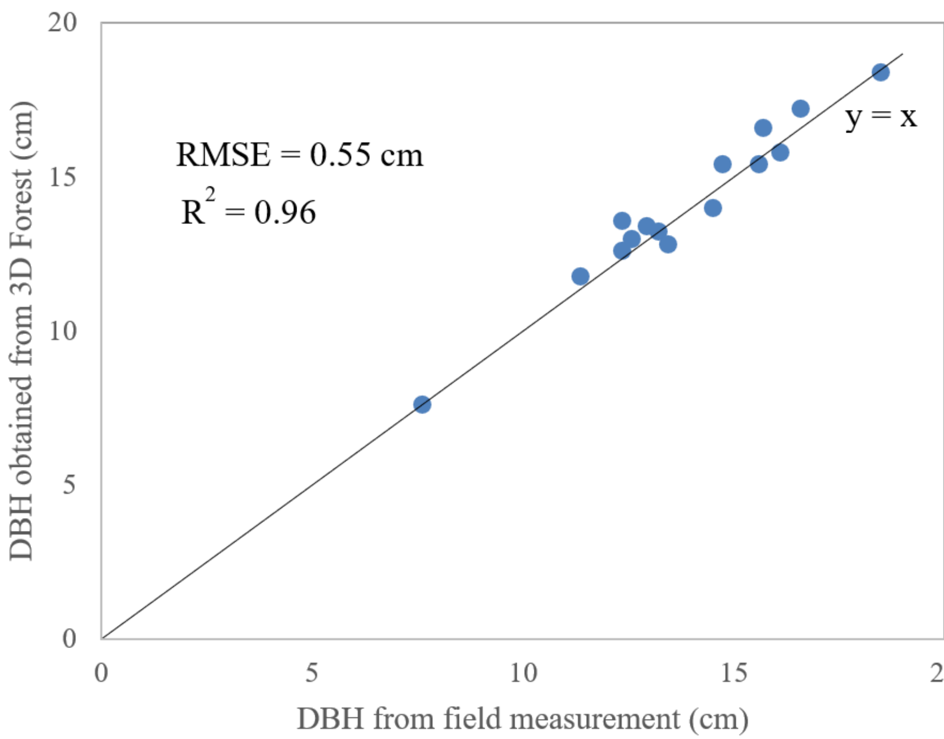

Figure 4. Scatter plot for DBH from field measurement and 3D Forest program

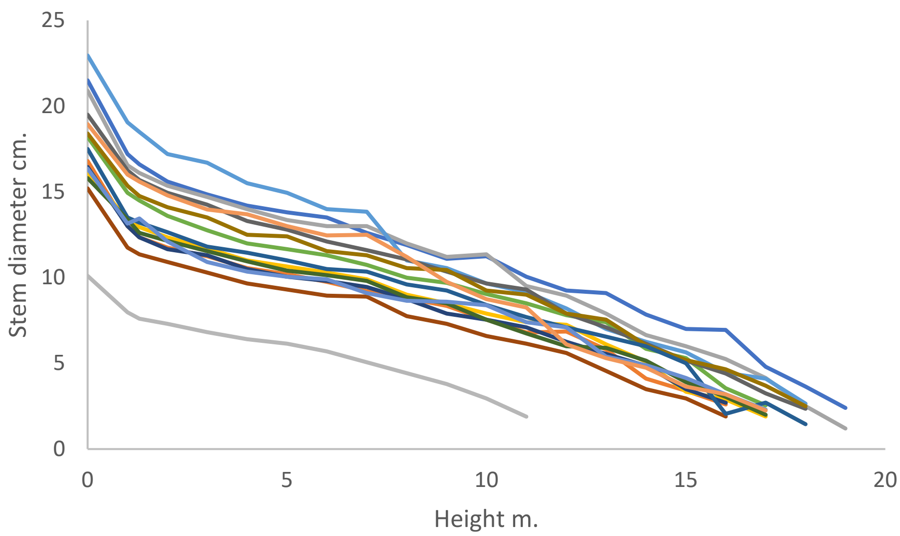

Figure 5. The relationship between tree height and stem diameter in this study

However, the estimated stem diameter results show that the analysis revealed an increasing estimation error in stem diameter as the sections were located higher above the ground. Most of the estimated errors exhibited positive bias, indicating consistent overestimation of the actual values. However, in the height range of 2 m to 4 m above ground, the diameter estimation errors were predominantly negative, with an average underestimation ranging between -0.18 cm and -0.30 cm (Figure 6). In other parts of the tree, diameter estimation errors predominantly exhibited positive values, resulting in an average overestimation ranging between 0.56 cm and 7.33 cm. The bias value of 1.60 cm indicates that stem diameter estimation from TLS was consistently higher than the conventional diameter tape method.

The mean RMSE for the initial 10 sections is 4.34 cm (Figure 7). Stem positions higher above the ground exhibited overestimated stem diameters due to point cloud dispersion caused by wind effects. The upper portion of a eucalyptus tree leads to increased RMSE following an exponential function, as described in equation 3. The predictions of the stem diameter become less accurate as the height increases.

$$\text{RMSE} = 0.3829e^{0.3547x} \quad (3)$$

Where *x* is the tree section height from the ground.

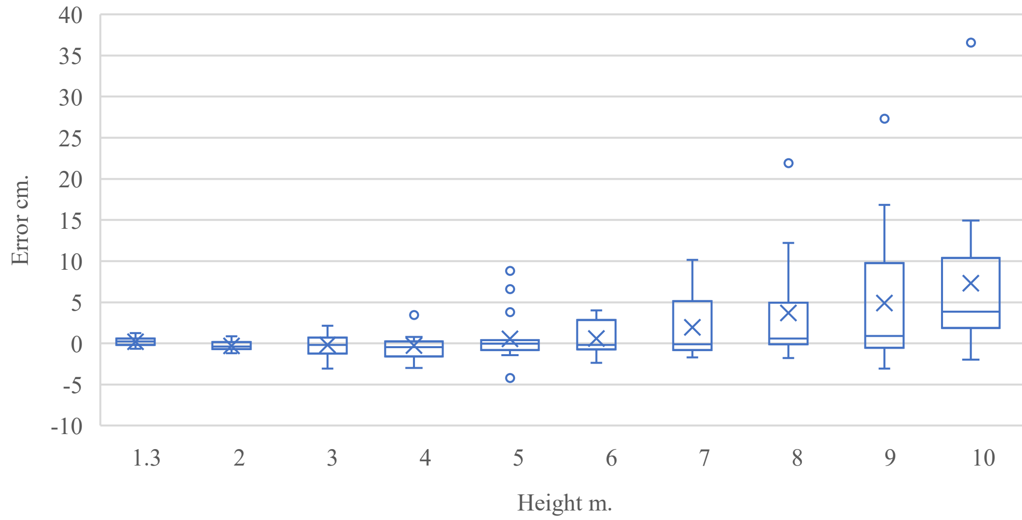

Figure 6. Estimation errors of diameter in point cloud across different sections

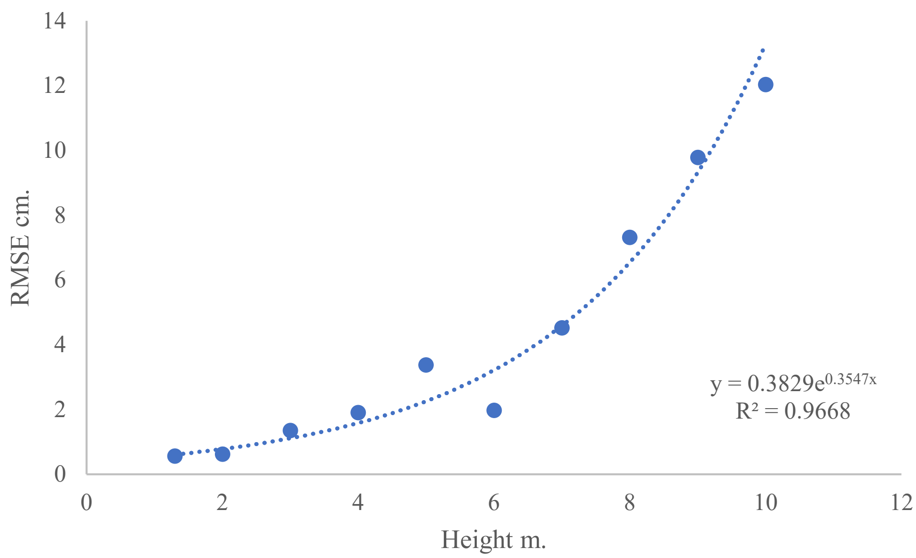

Figure 7. Root Mean Squared Error (RMSE) of stem diameter at various heights

3.3 Discussion

The three-dimensional eucalyptus tree model acquired through TLS offers the capability to measure various parts of the tree. This study employed the 3D Forest software to assess the automation of obtaining DBH and stem diameter for eucalyptus trees under normal weather conditions, aligning with suggestion of Eker et al. (2022). In this study, the DBH results revealed a robust correlation between field measurements and 3D Forest-estimated values from TLS. Our findings align with previous research (Yurtseven et al., 2019; Viana et al., 2022), showcasing the close resemblance of DBH estimation between TLS point cloud in 3D Forest and conventional methods, with a determination coefficient (R^2) of 0.99. This result substantiates the high accuracy of DBH measurements using TLS-derived point clouds processed in 3D Forest. However, estimating stem diameter using 3D Forest faces challenges in higher cross sections above the ground. The automated function encounters difficulties in the upper regions of slender trees affected by wind-induced swaying. The findings indicate that the Root Mean Square Error (RMSE) increases exponentially with tree height, highlighting a significant relationship. Figure 8 illustrates the point cloud data around the stem at heights of 1.3 m and 7 m above the ground. The point cloud at 1.3 m resembles a circular shape as the basic background of 3D Forest software, while the point cloud at 7 m from the ground exhibits a non-circular stem form. This suggests that as tree height rises, the accuracy of stem diameter predictions diminishes when conducted with small trees in light wind levels.

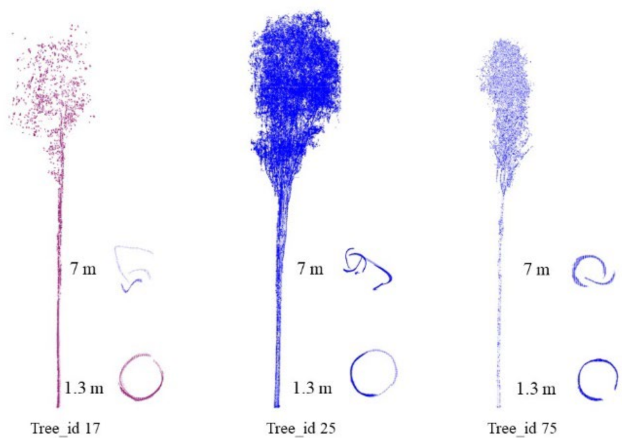

Figure 8. The point cloud data surrounding the stem at heights of 1.3 m and 7 m above the ground

The findings of Vaaja *et al*. (2016) underscore the significance of considering wind effects in the analysis of TLS tree measurements. While TLS offers improved accuracy and efficiency in forest inventories, its error analysis has often neglected wind-induced deformations that impact tree stem parameter estimation. Our result aligns with Vaaja et al. (2016) observations of wind-induced inaccuracies in tree stem measurements especially the upper portions of trees. Solares-Canal et al. (2023) highlights that wind can significantly affect the stability and accuracy of TLS data. Wind-induced movement not only complicates the automatic detection of tree attributes but also introduces errors in the derived measurements such as tree height and stem diameter. This underlines the necessity of accounting for wind effects in TLS studies and suggests that strategies such as timing scans to coincide with calmer weather conditions or employing advanced algorithms capable of correcting for movement-induced distortions could enhance measurement reliability. Previous studies have also highlighted the influence of wind on the upper tree section and trunk movement (Dassot et al., 2011; Pitkänen et al., 2019; Eto et al., 2020). While this study encountered wind speeds of 1.2 m/s, it is important to note that recommendations in the range of approximately 5 m/s have been mentioned in previous studies (Seidel et al., 2011; 2012). Even light winds can have an impact, particularly on small trees, which should be considered when analyzing point cloud data obtained from TLS.

4. Conclusions

In conclusion, this study provides valuable insights into the assessment of eucalyptus stem diameter estimation using TLS and the 3D Forest program. The analysis demonstrates that TLS is a reliable tool for measuring stem diameter, particularly in the lower sections of eucalyptus trees, with a mean RMSE of 4.34 cm for the first 10 sections from the ground. However, the accuracy of stem diameter estimation decreases as tree height increases, highlighting challenges in capturing precise measurements for the upper portions of trees due to factors such as reduced point cloud density and potential effects of wind. Despite these limitations, this study underscores the potential of TLS and 3D Forest as effective tools for forest management applications, offering precise and non-destructive measurements of stem diameter. Future research should focus on increasing sample size, expanding the study to multiple sites with diverse environmental and structural conditions, and refining algorithms to improve accuracy, particularly for the upper sections of trees. Addressing these challenges will further enhance the applicability and reliability of TLS in forest inventory and management.

5. Acknowledgements

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6. Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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