Terrestrial Laser Scanning to Assess Eucalyptus Aboveground Biomass: A Surface Reconstruction Approach

Choeipo, S.,[1,2] Vaiphasa, C.[2*] and Meunpong, P.[3]
[1]Survey Engineering, Faculty of Engineering and Technology, Rajamangala University of Technology Isan, Suranarai Road, Naimuang Subdistrict, Muang District, Nakornratchasima 30000
E-mail: sukunya.c@gmail.com
[2]Department of Survey Engineering, Faculty of Engineering, Chulalongkorn University, Phayathai Road, Wangmai, Pathumwan, Bangkok 10330, E-mail: chaichoke@hotmail.com*
[3]Department of Silviculture, Faculty of Forestry, Kasetsart University, Phahonyothin Road, Ladyao Subdistrict, Chatuchak District, Bangkok 10900, E-mail: fforptm@ku.ac.th
**Corresponding Author*

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Abstract
Terrestrial laser scanners (TLS) provide an alternative to traditional field sampling for gathering accurate volumetric data about vegetations without destroying the tree samples. However, popular volumetric modeling approaches (e.g., those cylindrical methods) oversimplify vegetation structure by underutilizing surface undulations provided by the point cloud. Thus, this study aimed to test the capability of two specialized surface reconstruction methods against a traditional cylindrical method to obtain the stem volumes and masses from 3D-cloud points generated by terrestrial laser scanners under relatively controlled conditions in a eucalyptus plantation in Muang, Nakornratchasima Province, Thailand. The TLS point data were collected from the test plots, and then three algorithms, the Poisson Surface Reconstruction (PSR), the Screen Poisson Surface Reconstruction (SPSR), and the traditional Quantitative Structure Model (QSM) were applied in order to build volumetric models of the sample eucalyptus trees. It is notable that this is the first study to test the SPSR method on real tree samples (N=40). The results were then compared with the reference values measured by a water replacement method. The root means square errors (RMSE) were estimated between the xylometric referenced aboveground biomass (AGB) and the TLS three methods. The SPSR approach yielded the most accurate results (RMSE of 0.49 kg or 6.91%), while the PSR method resulted in an RMSE of 0.60 kg (8.37%). The QSM method had the worst results, with an RMSE of 1.09 kg (15.31%). Despite the occlusion problem that caused 20% systematic error, this outcome provides evidence that the use of two Poisson reconstruction methods (e.g., PSR and SPSR) provides effective alternatives to accurately quantify aboveground biomass for eucalyptus trees.

1. Introduction

Eucalyptus is one of the most important energies vegetations in many countries due to its accelerated growth rates and wood characteristics (Cunha et al., 2021 and Wongchai et al., 2020). The demand for generating electricity, and manufacturing biofuels and biochemicals has been growing substantially for the last decade (Cunha et al., 2021). Despite some conflicts, the production of such energy vegetations is supported by government and non-government organizations in order to alleviate greenhouse gas emissions as they can replace the use of fossil fuels (Gomiero et al., 2010 and Ostwald et al., 2013).

Remote sensing technology has been proven to be an effective tool that helps extract the needed information about eucalyptus for farmers and policymakers (Mohd Zaki and Abd Latif, 2017 and Timothy et al., 2016). According to the literature (Chao et al., 2019), the studies can be classified into five common categories: 1) statistical studies with vegetation indices, 2) applications of Synthetic Aperture Radar (SAR) on biomass modeling, 3) net primary productivity modeling, remote sensing platforms, satellite, aerial, and ground, offer different spatial- and temporal-resolution information for energy vegetation management, 4) vegetation height-based estimation, ground based remote sensing was the most suitable reference to establish calibration model of eucalyptus tree, and 5) the vegetation growth model. Although broad resolution remote sensing tools have proven to be sufficient for the study of eucalyptus at the regional scale, terrestrial laser scanners (TLS) are still required for specialized investigations of individual eucalyptus trees (Calders et al., 2015, Raumonen et al., 2015 and Stobo‑Wilson et al., 2021).

There have been a number of notable TLS applications for eucalyptus studies. First, the TLS instrument was used for habitat studies of the savanna glider in a eucalyptus forest. Stobo-Wilson et al., (2021) revealed fundamental details of the glider's habitats by utilizing the advantages of the TLS scanning capability (Stobo-Wilson et al., 2021). It was found that this TLS measurement technique is sufficient to distinguish the variations in den-tree selection between sites. Despite the cost of the TLS instrument, the authors confirmed that the method is effective for mapping animal habitats in eucalyptus forests. Next, there are two reports on the topic of forest fires. One is a report on how to perform a forest fuel structure classification in eucalyptus forests (Yang et al., 2016). The second report studied vertical fuel connectivity in the eucalyptus forests of Australia (Wilson et al., 2021). The outcomes of these studies provide crucial evidence that is useful in the debate about forest fire control and has helped scientists to investigate fire situations (i.e., fire intensity, spread rate, flame structure, and duration) more clearly using 3D modeling. The final topic is the quest for building accurate quantitative aboveground biomass models (QSM) of eucalyptus trees (Calders et al., 2015 and Raumonen et al., 2015). Initially, the most common method was to assemble the QSM by joining simplified geometric parts (i.e., frustum of a cylinder or a cone). This technique utilized the advantage of dense TLS cloud points for precise geometric parameter extraction in a non-destructive fashion (i.e., no tree cutting). These studies generally applied TLS based methods to extrapolate the estimated area to a larger area.

When looking specifically through the development of modern QSM techniques in recent plant studies other than eucalyptus (Brede et al., 2019, Gonzalez de Tanago et al., 2018 and Kükenbrink et al., 2021), the more recent QSM studies have taken a more advanced route than the use of basic geometric models (e.g., cylindrical shapes) to extract the information from the surface of the 3D cloud (Calders et al., 2015, Intarat and Vaiphasa, 2020 adnd Raumonen et al., 2015) .This pioneering research uses free form surfaces instead of cylinders to model the branch geometry more precisely as it fits better with the irregular shapes of tree branches in nature (Muumbe et al., 2021 and Zhu et al., 2021). Recent studies in this field have done quite a bit to advance the field of study. The first is the success of manually reconstructing the volumetric model of the tree by applying a mesh method with editing options (ellipse, ellipsoid, and convex hull) to fit the irregular shape of the tree (Takoudjou et al., 2018). Next, an automated reconstruction of convex hull polyhedral shapes was proposed and tested with a sample of 153 trees (Fan et al., 2020). This novel study claimed that the convex polyhedra can fit the tree branch better than the traditional cylindrical models (i.e., TreeQSM). In addition, PSR algorithms were successfully used for constructing a 3D model of complex coastal vegetation (Owers et al., 2018). The results showed that the PSR model is reliable and statistically comparable to the standard QSM algorithm. The PSR method had been previously tested against seven related surface reconstruction techniques, including the Triangular Irregular Network algorithm (TIN) (Kazhdan et al., 2006). It was found that the PSR algorithm can overcome noisy, non-uniform patterns and robustly recover fine detail from noisy real-world scans better than the TIN method. Unfortunately, there have been very few of this type of development eucalyptus trees. The only attempt found in the literature was the use of the original TIN algorithm to create 3D surface models (Buck et al., 2019). There is still room for improvement in this area as many unexplored implicit and explicit math models (Lim and Haron, 2014) could be matched up with the eucalyptus species, including SPSR, the successor to the PSR model.

This study further investigates the prospective combination of TLS technology and image processing technology for plant studies. It supports the notion that individual trees are different, and the TLS volumetric model should be appropriately customized for each type of plant. The objective of this work is to test the performance of the well-established PSR model, and its successor SPSR (Kazhdan et al., 2006 and Kazhdan and Hoppe, 2013), for building accurate 3D models of eucalyptus trees. The study site comprises a young eucalyptus plantation in Nakornratchasima Province, Thailand. The results are to be compared with the standard QSM method. The accuracy will be assessed with the measurement from the water replacement. It is anticipated that this study can be used as a guideline for building 3D models for supporting the sustainable management of eucalyptus vegetations.

2. Materials and Methods

2.1 Study Area

The study site is in a 1.5-year-old clonal *Eucalyptus spp* plantation (Figure 1) located in a rather flat area in Ban-Bu, Mueang, Nakhonratchasima Province, Thailand (N 15°02'31.9", E 102°09'59.5"). Tree spacing is about 2.5 m × 3.5 m. (Figure 2).

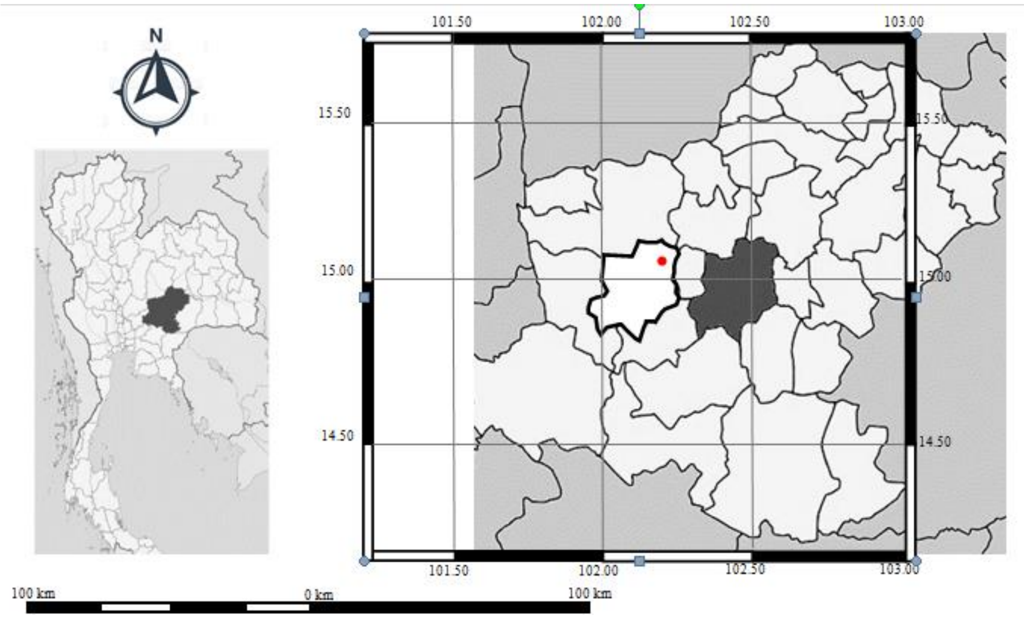
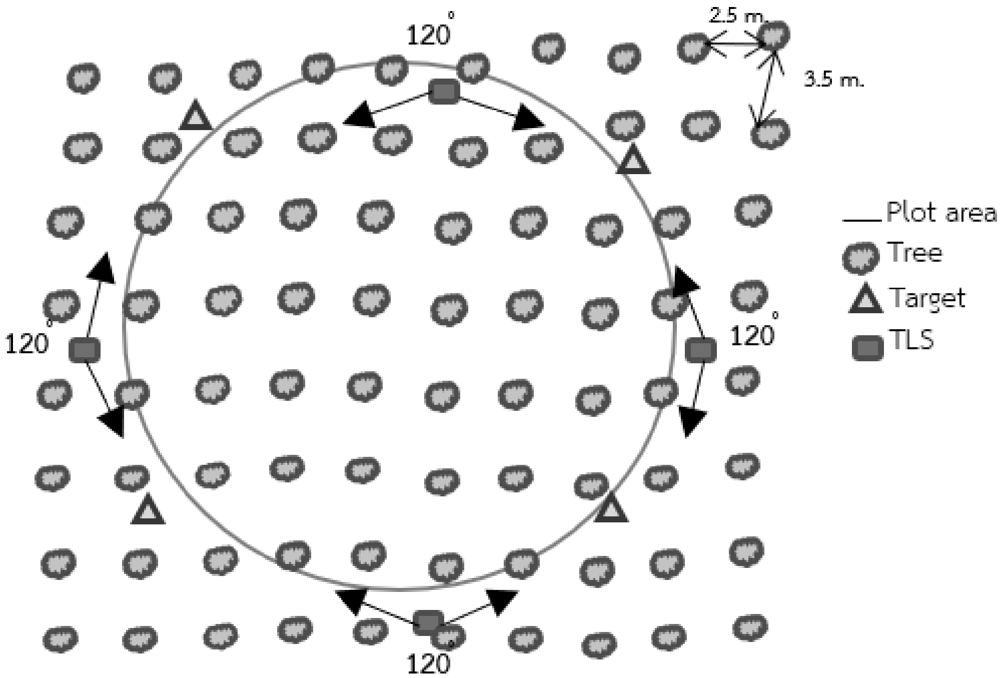


Figure 1: Map of Nakhonratchasima province with the study area by a red dot



* illustration not drawn to scale

Figure 2: A configuration of four TLS stations with four quadrilateral targets in a circular plot

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2.2 Acquiring the TLS Data

All scans were performed using the TOPCON GLS2000 equipment. The scanning resolution was fixed at 3.1 mm at a distance of 10 m between the TLS instrument and the tree. The acquisition rate was set at 120,000 points per second. The registration process was done by beaming at 400 x 550 mm quadrilateral checkerboard targets. At least three quadrilateral targets were used for each scan (Maas et al., 2008). As illustrated in Figure 2, four scans were performed in a circular plot of about 300 m^2. The angle of each scan was limited to 120° horizontal and 270° vertical due to the physical characteristics of the TLS instrument. The measurement was conducted on February 15, 2020, between 8 am and 5 pm. In total, 40 *Eucalyptus spp* samples (i.e., tree height > 5 m, diameter at breath height >0.04 m) were scanned, and each of them was numerically coded from 1 to 40. Finally, the Topcon MAGNET Collage software (Topcon, 2017) was used to merge all the laser cloud points. A Helmert transformation was applied under the 3D environment of the software. The point cloud transformation required at least three tie points. The registration residuals (i.e., root mean square errors) were limited to under 0.08 m. The whole scanning procedure was conducted under accepted guidelines (Buck et al., 2019, Feliciano et al., 2014 and Intarat and Vaiphasa, 2020). As an example, a merged point cloud measured by four TLS stations is illustrated in Figure 3a, and a point cloud of main stems is shown in Figure 3b.

2.3 Estimating the Volume of Main Stems

Stem volume modelling was performed using three selected methods: i) Quantitative Structure Model (QSM), ii) Poisson Surface Reconstruction (PSR) and iii) Screen Poisson Surface Reconstruction (SPSR). Firstly, the cylindrical based QSM scans were carried out using the 3D environment of the TreeQSM software (Figure 4a). The main stem was reconstructed through a least squares algorithm by fitting with different sizes of cylinders. The diameters and the volumes of the trunks were estimated by measuring these cylinders (Åkerblom et al., 2017, Calders et al., 2015 and Raumonen et al., 2013). Secondly, the PSR process was started by generating 3D triangular meshes of the entire main stem of the eucalyptus tree. Unlike typical surface fitting algorithms, these meshes can be constructed by transforming the oriented point samples into a continuous vector field and refining them with a best-fitted scalar function. Mathematical details of this scalar function were extensively elaborated in the literature (Kazhdan and Hoppe, 2013). Then, the meshed volume of the main stem was calculated by Cloud Compare software (Figure 4b) (Brouček, 2019, Panagiotidis and Abdollahnejad, 2021 and Šiljeg et al., 2021).

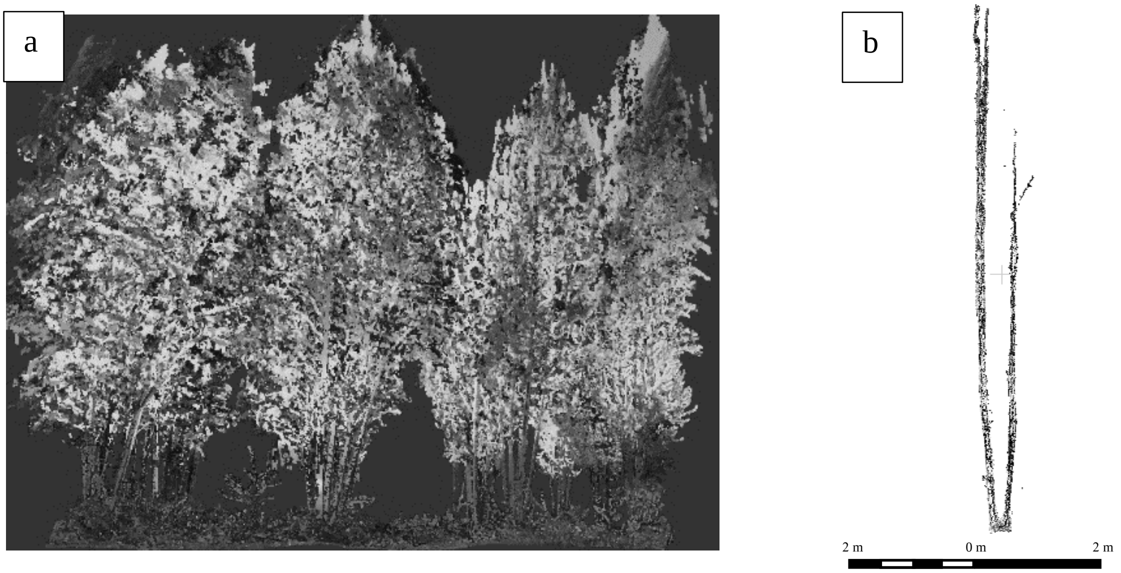

Figure 3: (a) A merged point cloud measured by multiple TLS stations; (b) An example of eucalyptus main stems from TLS point cloud

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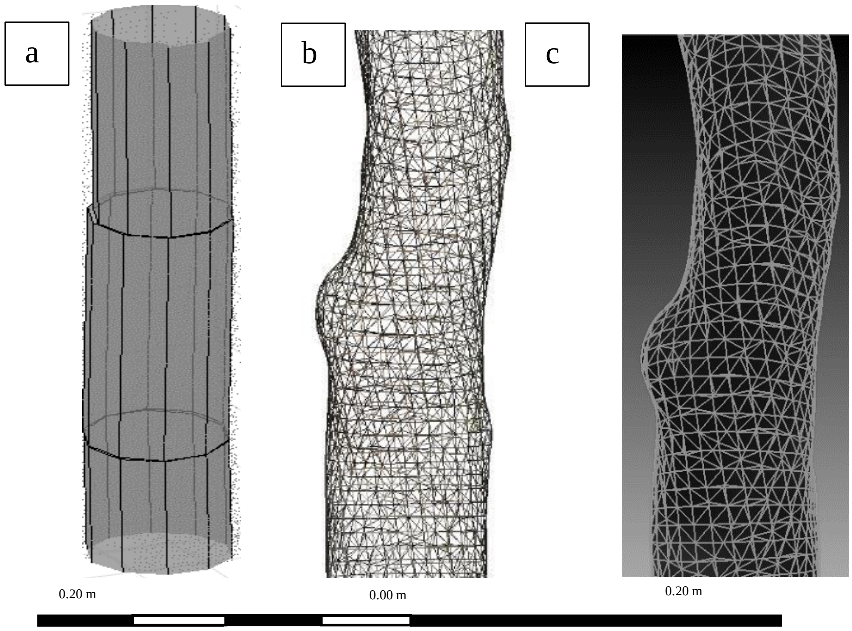


Figure 4: Examples of stem volume modelling was performed using (a) Quantitative Structure Model (QSM) results generated by the TreeQSM software, (b) Poisson Surface Reconstruction (PSR) created by the Cloud Compare software, and (c) Screen Poisson Surface Reconstruction (SPSR) produced by the MeshLab software.

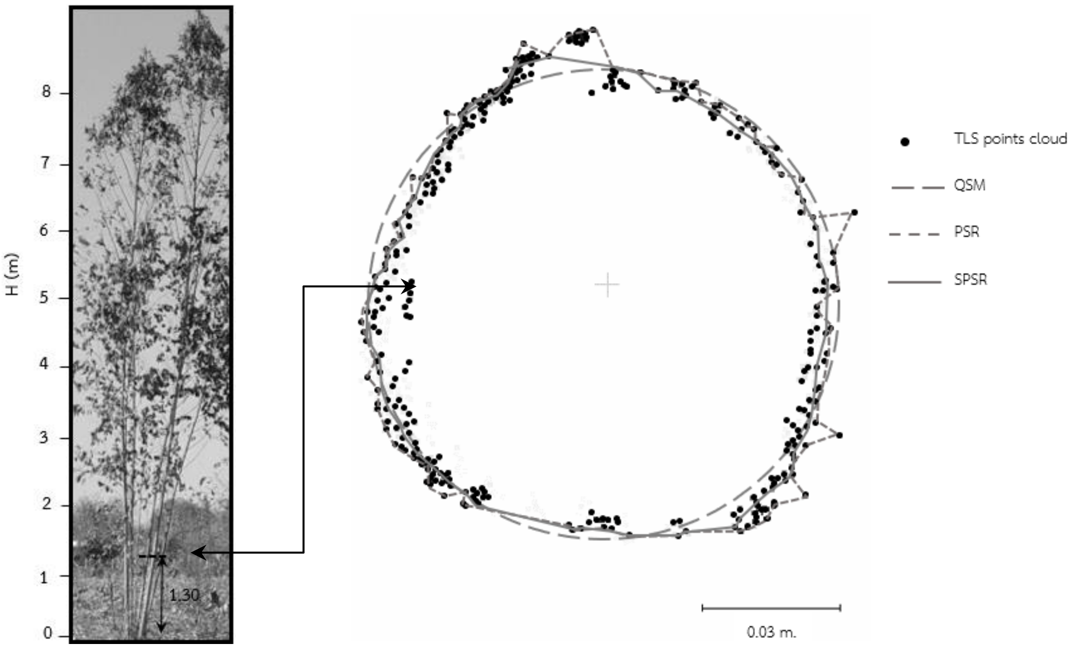


Figure 5: An example of cross-sectional rings produced by the three methods plotted against the TLS cloud points

Thirdly, the MeshLab software (Figure 4c) was used to generate the SPSR mesh. Unlike PSR, SPSR allows the edge of the tree surface to be specifically enhanced so as to build a finer detailed volumetric model, especially where the tree surfaces are rutted. The advantages of SPSR over PSR have been thoroughly discussed in some other original (Cignoni et al., 2008 and Kazhdan and Hoppe, 2013). Examples of cross section sectional rings produced by the three methods are illustrated in Figure 5 for the purpose of comparison.

2.4 Estimating Aboveground Biomass (AGB) from the TLS Data

There are two steps in calculating the total AGB of the *Eucalyptus spp* tree. First, the volume of the main stem is multiplied by the wood specific density (WSD), 0.487 g/cm^3 as shown in the equation below, this step results in the mass of the main stem ($AGB_{main\ stem}$).

$$AGB_{main\ stem} = Volume_{main\ stem}\ x\ Wood\ Specific\ Density$$

Equation 1

Where $Volume_{main\ stem}$ represents the volume of main stems in cubic centimeters (cm^3), calculated in the previous section, and the *Wood Specific Density* is the 0.487 g/cm^3.

2.5 Measuring and Referencing the Tree Volume

In this section, the real volumes of 40 *Eucalyptus spp* trees were assessed by a water displacement method (Berendt et al., 2021, Kunz et al., 2017 and Miller et al., 2015). First, the main stems were cut into 0.80 m pieces. Then, they were submerged in the xylometric tub. At this step, the stem volumes were measured by observing the changes of the water levels in the xylometric tub. Finally, the xylometric volumes were multiplied by the chosen WSD value (i.e., 0.487 g/cm^3) in order to get the masses of the main stems.

3. Results

3.1 Water Displacement Reference vs the TLS Estimations

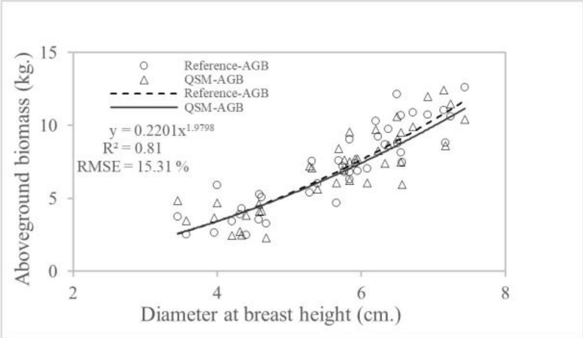
In Figure 6(a)-(c), the xylometric references are compared with the results of the TLS three algorithms, QSM, PSR and SPSR. The best results were achieved by the SPSR method (Figure 6c). As for the eucalyptus No.16,17,20,23,26,28,29,31 and 39 there was no difference between the results produced by the SPSR method and the reference values (i.e., the discrepancies are less than 0.01%). The QSM method generated the poorest results (Figure 6a). As for the eucalyptus No.10,22 and 26, it was found that the variances were more than 20% off the reference AGB values. The root means square errors (RMSE) between the xylometric referenced AGB and the TLS three methods were shown in Figure 6 a-c also confirmed this finding. The best RMSE of 6.91% belongs to the SPSR, and the poorest of 15.31 % belongs to the QSM. For the purpose of visualization, the outcomes of the TLS three methods are also plotted separately in Figure 6 a-c. The results of the TLS three methods are presented in solid lines, while the dashed lines represent the xylometric references. Although the results of the three methods look visually quite similar, the R-square and the RMSE point out that the SPSR results are actually the most accurate.

4. Discussion

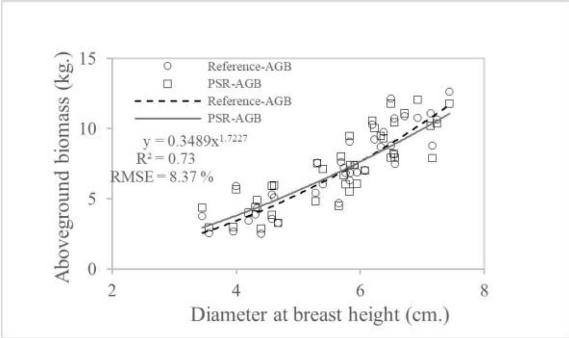
In this study, we explored the efficiency of combining the strength of the 3D scanning capability of the TLS instrument and the noise resistance ability of two well-established surface reconstruction model algorithms, PSR and SPSR (Kazhdan and Hoppe, 2013), to estimate the volumes and masses of 40 eucalyptus trees. The results were compared against xylometric references (i.e., water displacement measurements). According to the literature, the performance of these two Poisson methods have never before been tested with tall and almost single trunk trees like the eucalyptus. Our experiment found that both models were promising for this type of plant. The PSR and SPSR achievement was reported in terms of small root mean square errors (RMSE) of 6.91% and 8.37%, respectively (see Figure 6(a)-(c),). The two Poisson methods outperformed the traditional QSM method as the QSM had a much larger RMSE value of 15.31%. This evidence supports the claim that the Poisson basis functions can robustly recover fine 3D details from a noisy real-world dataset, overcoming the complexity level of the tangible eucalyptus data (Kazhdan et al., 2006 and Kazhdan and Hoppe, 2013). The outcome of this study also encourages the practitioner to believe that individual trees are different and deserve to be appropriately treated by customized models that do not oversimplify the point cloud data, thus gaining optimal accuracy. This statement is especially true for plants that have biological and economic value. This is a new field of research that has already been pioneered by a number of authors, including Buck et al., (2019), Muumbe et al., (2021), Owers et al., (2018), and Takoudjou et al., (2018).

Research into the effects of using different surface reconstruction methods on eucalyptus data is still in its infancy stage. In fact, only one related study was found in the literature (Buck et al., 2019). The authors explored a triangulated irregular network (TIN), which is a kind of explicit method (Lim and Haron, 2014). The algorithm fits small triangles on the tree surface; however, the noisy patterns of real-world data can cause problems in this method.

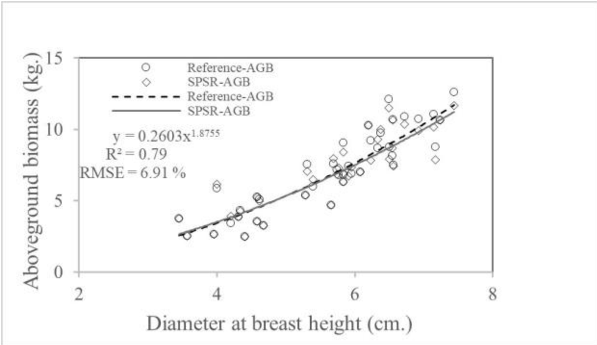
Referenced AGB and TLS - AGB from three techniques comparison



a)



b)



c)

Figure 6: Comparison of reference *Eucalyptus spp* aboveground biomass estimates derived from water displacement illustrated as a dashed line, and three 3-D surface reconstruction models using TLS-derived point cloud illustrated as a solid line; (a) Comparison of reference AGB vs QSM, (b) Comparison of reference AGB vs PSR, and (c) Comparison of reference AGB vs SPSR

In the study by Buck et al., (2019), the volume of each tree was calculated and compared with the field references measured by a caliper. Both Buck et al., (2019) and this current research agree that the TLS model evidently underestimates the eucalyptus volume. The experiments show that the estimation is about 20% smaller than the xylometric reference. Additionally, there were also underestimation reports found in the studies of other kinds of tall trees (Calders et al., 2015, Disney et al., 2020 anf Saarinen et al., 2017). In our opinion, it can be hypothesized that the underestimation problem of these tall trees may have been caused by occlusion on the laser signal by the branches and leaves in the upper sections. Further investigation should be done to confirm this hypothesis. Unfortunately, we cannot compare the results quantitatively to Buck et al. (2019) as the accuracy assessment schemes are different. Buck et al., (2019) did not use the water displacement reference but a caliper method. Moreover, the eucalyptus species in the two studies are not the same.

Although the SPSR made the best performance when compared with the xylometric reference and its estimation error was within a range reported in real practice (Pérez-Cruzado and Rodríguez-Soalleiro, 2011 and Picos et al., 2020), the SPSR method is still far from perfect. Its overfitting behavior is noticeable when facing with the real-world data and hence reducing the overall estimation performance (Kazhdan and Hoppe, 2013). Specifically, the estimation error could be induced by the following sources: registration error, occlusion, wind and noise, segmentation error, geometric structure error (Calders et al., 2015). This problem will need further refinements of the smoothing parameters to find the best-fitted reconstruction weights and constraints (Alliez et al., 2007 and Taubin, 2012). Unfortunately, this future study requires a near perfect field data and high computational resources that is beyond the scope to this study.

According to the benchmark study (Liang et al., 2018), the stand complexity of the study area that has 40 eucalyptus trees is rated easy to construct a volumetric model. Moreover, the shape of a eucalyptus tree is fairly elongated. The chosen multi-scan method (i.e., scanning a batch of trees from different angles) is a standard method that is therefore adequate for this moderate complexity (Liang et al., 2018). However, the exception is located at the top part of the tree where the occlusion occurs. The top section of the trunk is obscured by the stems and leaves make it hard for the reconstruction algorithms to fit the isosurfaces and construct an accurate watertight mesh. This occlusion causes a volumetric estimation error about the upper section of the eucalyptus trees as reported in the literature (Buck et al., 2019). For the case of highly complex stands (i.e., real forest stands), the occlusion problem is likely to affect the reconstruction process during the optimization of reconstruction weights and constraints (Kazhdan and Hoppe, 2013). Thus, it is recommended, for such complex scenarios, the volumetric modeling geometry should be kept simple (i.e., cylindrical models) as they are less sensitive to high variances caused by the noise and occlusion (Newnham et al., 2015).

This study was intended to be a preliminary study to test the performance of the PSR and SPSR methods. Due to the lack of budget for conducting extensive fieldwork, it was not intended to be a comprehensive comparison between many notable surface reconstruction model methods. The small number of tree samples (N=40) is not enough to build strong evidence to support the central limit theorem. By collecting more tree samples in the near future, we would be the first to re-test everything and also investigate the upper sections of the trees where the occlusions are typically found. Additionally, we would like to run more comparative tests between the PSR and SPSR methods as the PSR algorithm is expected to suffer from the over-smoothing problem (Owers et al., 2018) under the highly occluded conditions of the upper section. We expect to learn whether the new generation SPSR method can alleviate or overcome such a problem. The laser data density can also be reduced using a parametric tool such as Gaussian models (Miraki et al., 2021 and Senin et al., 2021) so as to see the sensitivity of the reconstruction algorithms to the sampling levels. Additionally, we would also like to split the trees in parts and use suitable surface reconstruction model methods on each part. This idea is inspired by the success of Owers et al., (2018).

5. Conclusion

The capability of two surface reconstruction methods has been tested against the traditional cylindrical method in this work. The selected test site was a relatively controlled eucalyptus plantation in Thailand. This is also the first study to test the SPSR method on real trees. When compared with water replacement references, the PSR and SPSR approaches yielded the most accurate results (i.e., smaller RMSE values), while the traditional QSM method produced a much higher RMSE value. Despite the systematic mass error of 20%, the results support the claim that both Poisson methods offer effective alternatives for quantifying volume and mass of eucalyptus trees. Thus, it is anticipated that our work should enhance the guidelines for 3D model estimations of eucalyptus trees for practitioners.

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