TIMBER VOLUME ESTIMATION BY USING TERRESTRIAL LASER SCANNING: METHOD IN HYPERDIVERSE SECONDARY FORESTS

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ABSTRACT – High accuracy in timber volume estimation in tropical forests is required to support sustainable management. Terrestrial laser scanners (TLS) can provide high-quality estimates from tree structural variables. We compared stem variable estimations obtained by TLS and traditional methods at tree level and adjusted volume equations using data of a secondary seasonal semideciduous forest (Atlantic Forest). We also discuss the feasibility of TLS in hyperdiverse and secondary forest fragments. Traditional measurements (Method I) and TLS-based measurements (Method II) were performed on 29 trees belonging to 10 species. Volume equations based on the Schumacher and Hall (SH) and Spurr models were generated. DBH (diameter at breast height) was equal for both methods. Total height (TH) was overestimated by Method II, and commercial height (CH) showed a low correlation between the two methods. The adjusted volumetric equations were different for both methods, and those based on the SH volume model showed the best fit. Our results lead us to infer that in hyperdiverse secondary forests, tree structural variables should be obtained via TLS. However, attention should be given to the occlusion of target trees by the regenerating understory and to height estimates, which can be biased by the crown characteristics of the dominant species.

Keywords: TLS; Atlantic Fores; Lidar.

ESTIMATIVA DE VOLUME DE MADEIRA POR USO DE VARREDURA A LASER TERRESTRE: MÉTODO EM FLORESTAS SECUNDÁRIAS HIPERDIVERSAS

RESUMO – A alta precisão na estimativa do volume de madeira em florestas tropicais é necessária para apoiar o manejo sustentável. Os scanners a laser terrestres (TLS) podem fornecer estimativas de alta qualidade a partir de variáveis estruturais de árvores. Comparamos estimativas de variáveis do fuste obtidas por TLS e métodos tradicionais em nível de árvore e equações de volume ajustadas usando dados para uma floresta semidecídua sazonal secundária (Mata Atlântica). Também discutimos a viabilidade do TLS em fragmentos florestais hiperdiversos e secundários. Medições tradicionais (Método I) e medidas baseadas em TLS (Método II) foram realizadas em 29 árvores pertencentes a 10 espécies. Foram geradas equações de volume baseadas nos modelos de Schumacher e Hall (SH) e Spurr. O DAP (diâmetro à altura do peito) foi igual para ambos os métodos. A altura total foi superestimada pelo Método II, e a altura comercial apresentou baixa correlação entre os dois métodos. As equações volumétricas ajustadas foram diferentes para ambos os métodos, e aquelas baseadas no modelo de volume SH apresentaram o melhor ajuste. Nossos resultados nos levam a inferir que em florestas secundárias hiperdiversas, as variáveis estruturais das árvores devem ser obtidas via TLS. No entanto, *atenção deve ser dada à oclusão das árvores alvo pelo sub-bosque em regeneração e às estimativas de altura, que podem ser influenciadas pelas características da copa das espécies dominantes.*

Palavras-Chave: TLS; Floresta Atlántica; Lidar.

1. INTRODUCTION

The monitoring of forest succession through floristic and structural surveys is extremely important for the management and conservation of natural forests. One of the technological advances that have made it possible to obtain and process data with precision is the laser scanning system (LiDAR - Light Detection and Ranging) (Görüm, 2019). The system´s working principle is to locate objects of interest using laser pulses with high repetition frequency that allow extending the highly accurate spatial analysis to the third dimension (z) where the coordinates of the points are given in a local or global coordinate system (Benedek, 2021). Recently, the terrestrial platform has become one of the platforms for LiDAR, generating a laser scanning system whose main instrument is the Terrestrial Laser Scanning (TLS) (Decuyper et al., 2018).

The TLS works like no other platform by scanning the stem surface to obtain the tree three-dimensional shap e with speed as well as high spatial resolution and therefore better trunk coverage for estimating the woody constituent (Molina-Valero et al., 2022). It is possible to model and measure diameters and heights without requiring tree overthrow (Cabo et al., 2018; Pitkänen et al., 2019) and also it is possible to estimate volumes and above-ground biomass (Takoudjou et al., 2018). The tree reconstitution in this system comes from a dense point cloud that can be analysed in a computational environment. The procedure culminates in the data collection automation, which allowing the elimination of possible human errors or adverse conditions in the field as illumination, though subtle distortion may occur due to fog and rain. (Jeong et al, 2020).

Laser scanning for the measurement of vegetation was used for the first time in forest sciences in studies on wood production, with the aim to obtain the density, height and DBH (Zimbres et al., 2020). This method is now widely used in ecological investigations of natural forests (Calders et al. , 2020 ; Danson et al., 2018), and studies have assessed the structures of denser forests (Meyer et al., 2018).

The characteristics of a secondary tropical forest environment with dense understory are different when compared to those of a forest plantation. Studies obtaining dendrometric variables with the use of TLS are mostly performed in forest plantations (Xu et al., 2018; Liu et al., 2018). TLS started to show it has been pronounced potential to extract DBH, tree height, stand density, leaf area index (LAI), leaf angle distribution, basal area, effective number of layers and AGB at both plot and individual tree scales (Xu et al., 2021, Takoudjou et al., 2018). Thus, we compared estimates of stem structural variables obtained through the traditional measurement method (Method I) and TLS (Method II) and adjusted volume equations using both data types for a secondary seasonal semideciduous forest (Atlantic Forest domain) in southeastern Brazil. We also discuss the feasibility of TLS-based volume estimation in secondary forests.

2. MATERIAL AND METHODS

2.1 Study area

The seasonal semideciduous forest fragment (42º 52 '30” W and 20º 46' 10” S) is located in Viçosa, Minas Gerais, Brazil, and belongs to the Federal University of Viçosa. According to the Brazilian legislation for the Atlantic Forest, the fragment which regeneration age is 86 years has woody species that diameters are between 10 and 20 cm and tree species are height between 5 and 12 m (Rocha et al., 2020).

According to the Köppen classification, the local climate is Cwa type, warm temperate, with hot summers and rainy and cold, dry winters (Dubreuil et al., 2018) In the period from 1968 to 2017, average temperature, humidity, and annual precipitation were 19.82°C, 82.2%, and 1,255 mm, respectively (UFV, 2018).

The predominant soil classes in the region are dystrophic Oxisols rich in aluminium, shallow and exchange Oxisols and nutrient-rich epieutrophic Cambisols (Ferreira Júnior et al., 2012).

The region´s topography is heavily rugged, ranging from strongly undulating to mountainous sites with narrow, humid valleys. The relief is strong, wavy and mountainous (Meira Neto, 1997).

2.2 Obtaining tree structural variables

To acquire the tree structural variables (diameter at breast height (DBH) and total height (TH)), 29 trees belonging to 10 species were selected in a plot of 10 x 50 m. Species selection was made based on the importance value index (IVI). The IVI was obtained by this formula IVI = aAr + aDr + aFr, where Ar is relative abundance, Dr is the relative dominance and Fr is the relative frequency (Queiroz et al., 2017). The data were from a forest inventory conducted in the area in May/2018. All 10 species were present in the sampling plot within one of the permanent plots in the forest fragment.

The following species were selected: *Albizia polycephala* (Benth.) Killip ex Record, *Anadenanthera peregrina* (L.) Speg, *Casearia ulmifolia* Vahl ex Vent., *Nectandra lanceolata* Nees, *Piptadenia gonoacantha* (Mart.) JF Macbr., *Rollinia laurifolia* Schltdll., *Rollinia sylvatica* (A. St.-Hil.) Mart., *Siparuna arianeae* MVL Pereira, *Siparuna guianensis* Aublet. and *Trichilia pallida* Swartz.

Two methods were established: the traditional measurement (Method I) and the TLS (Method II). In Method I, CBH (circumference at breast height), TH and commercial height (CH) were collected from the trees in the selected area, using a measuring tape and a Vertex model IV hypsometer (Haglof Inc. - Madison, Mississippi, USA) in a unique sample. For calculations, we convert CBH to DBH.

For tree scaling, the non-destructive method was used. The diameters along the stem were measured using a tree-climbing or Wheeler's pentaprism. The overbark diameter measurement heights were 0, 0.30, 0.70, 1.30 and, from this height, every 2 meters until the height at which it was possible to measure.

Stem volume determination for both methods, in each section, was performed using the Smalian formula:

$$Vcc = \frac{AS_1 + AS_2}{2} * L$$

Vcc – Gross volume, in m^3;

AS_1 – Sectional area of the stem lower part, in m^2;

AS_2 – Sectional area of the stem upper part, em m^2;

L – Stem length, in m.

For the TLS method, DBH, TH and CH data were acquired using the TLS equipment RIEGL VZ-1000 (RIEGL - Horn, Austria).

2.2.1 Equipment configuration

This TLS reads the distance from the sensor to the target using the ToF (time of flight) method with multiple returns, reaching up to 122,000 points per second (RIEGL, 2017).

The equipment was operated directly by the panel itself, configured in panorama 40 (that is, every 0.04º of rotation, a laser beam is fired); viewing angle (vertical scan angle) was 100º (60º upwards and 40º downwards from the phase centre – the place of laser beam emission) vertically and 360º horizontally.

2.2.2 Field data acquisition

TLS data are often displayed in the georeferenced point cloud format (x, y, z coordinates) calculated based on the original angle and the measurement range. ToF method has a high spatial resolution, which allows digitizing objects far from the laser phase center, such as tree crowns. The pulse is reflected by the surface so the distance to the pulse can be achieved using the ToF from emission to observation (Aubertin et al., 2021). However, this high spatial resolution can lead to an information redundancy from objects close to the scanner, making it essential to plan the field measurement for data sampling based on the size, shape and sample structure (Puttonen et al., 2013).

In this study, trees were digitised using the multiple scan system, where countless scans are carried out inside and even outside the plot to allow improved accuracy of vegetation structural metrics (Singh et al., 2020). Then, these scans are joined and recorded with the aid of artificial reference targets that are placed randomly within the plot.

2.2.3 Filtering and modelling data

Tree filtering and modelling were performed using the Riscan Pro version 2.1 software, the processing software for RIEGL's terrestrial scanner lasers (Rodríguez, 2017). In this process, points referring to an object, but coming from multiple clouds (different scans), were joined at a single point in the final cloud; this process is called “overlapping point clouds”. This process makes it possible to obtain information of objects evaluated at different angles, in addition to increasing the density of points.

First, in the so-called “pre-processing stage”, a point cloud co-registration was performed based on the laser scanner position coordinates that converts arbitrary coordinate systems into a common coordinate system (Dong et al., 2020) through a topographic survey by polygonation, using a Topcon Total Topographic Station model GTS 212.

The UTM coordinates (N, E, Z) of the polygonal starting point, as well as its reference point, were obtained with a Garmin GNNS receiver model ETREX 30 and are stored in the SIRGAS2000 Geodetic system. From these initial coordinates, as well as from the data from the topographic survey, laser scanner position coordinates were calculated in the topoGRAPH software (Ferraz, 2012). This was necessary due to tree canopy interference on the GNSS receiver, so the laser position survey was performed with an arbitrary coordinate, but the position was corrected later, with the position data collected outside the forest area.

As a reference in the rotation, artificial targets were used (Styrofoam balls or cardboard letters connected to 2-m PVC sticks fixed to the ground), trees with unique characteristics and trees with reflective bands making up the DBH (Miranda et al., 2018). For the dendrometric variable extraction at the tree level, it was necessary to cut the point cloud into several slices to speed up the interest tree identification.

Subsequently, it was necessary to manually identify and isolate each tree from the point cloud and perform a point filtering to remove points that did not belong to the target tree stem (such as understorey, noise points and limb). These procedures were performed using point cloud editing tools from the Riscan Pro software.

With the file of each tree, automatic terrain filtering was executed by the Terrain Filter function (Rodríguez, 2017) implemented in the Riscan Pro software, the filter uses the distance of points to determine what is or is not terrain, for that it uses the Base grid size, corresponding to the finest level. Number of levels, Tolerance factor, Percentile and Maximum slope angle = 90°. This procedure was performed to obtain the tree position in the software used to calculate dendrometric variables through the terrain point exclusion.

2.2.4 Dendrometric variable extraction and scaling

We used the 3D Forest software version 0.42 to extract the dendrometric variables. This version is the most current one allows the extraction of parameters such as position (x, y, z) and height and DBH of the stem Trochta et al. (2017). The 3D software functions used were Inverse Distance Weighted interpolation (IDW interpolation) in areas with missing terrain points, position by lowest point for calculating tree position and TH and Randomized Hough transformation (RHT) for the DBH calculation.

Scaling was done virtually using the 3D tree model (scaling by TLS), obtained in the data processing step. With this model, the tool “Measure distance between two points” of the Riscan Pro software was used, measuring the diameters and their respective heights along the stem cloud. The scaling by TLS volume was obtained using the Smalian formula, as described for Method I.

2.3 Volume equations

After obtaining the dendrometric variables by both methods, with volumes obtained by conventional (field) and virtual (TLS) scaling, volume equations were generated.

Adjustment was made based on two volumetric models: the Schumacher and Hall (SH) model (Schumacher and Hall, 1933) and the Spurr model (Spurr, 1952). In this way, four equations were generated (two for each method mentioned above). The equations were compared with each other to ascertain their accuracy with Method II data in relation to those adjusted with Method I data. Important in validating data verified in the field and by the virtual method.

2.4 Methods I and II approach

2.4.1 Among the dendrometric variables

It is important to highlight that for the approach among the methods, the same trees were used both in the conventional method and in the TLS point

Table 1 – Decision rules for comparing the observed values with the expected values from the L&O test.
Tabela 1 *– Regras de decisão para a comparação dos valores observados com os esperados do teste L&O.*

Situation	$F(H_0)$	$t\bar{e}$	rY_jY1	Decision
1	ns	Ns	$rY_jY1 \geq (1-\lvert\bar{e}\rvert)$	$Y_j = Y_1$
2	ns	Ns	$rY_jY1 \leq (1-\lvert\bar{e}\rvert)$	$Y_j \neq Y_1$
3	ns	*	$rY_jY1 \geq (1-\lvert\bar{e}\rvert)$	$Y_j \neq Y_1$
4	ns	*	$rY_jY1 \leq (1-\lvert\bar{e}\rvert)$	$Y_j \neq Y_1$
5	*	Ns	$rY_jY1 \geq (1-\lvert\bar{e}\rvert)$	$Y_j \neq Y_1$
6	*	Ns	$rY_jY1 \leq (1-\lvert\bar{e}\rvert)$	$Y_j \neq Y_1$
7	*	*	$rY_jY1 \geq (1-\lvert\bar{e}\rvert)$	$Y_j \neq Y_1$
8	*	*	$rY_jY1 \leq (1-\lvert\bar{e}\rvert)$	$Y_j \neq Y_1$

ns and * denote, respectively, not significant and significant at the α significance level.
*ns e * denotam, respectivamente, não significativo e significativo no nível α de significância.*

cloud. Thus, the sample number was the same in all methodologies and statistical tests.

The dendrometric variables obtained by both methods were compared by calculating the difference among the variables obtained by the traditional method and by TLS.

Subsequently, the L&O test (Leite et al., 2006) was applied to assess the identity hypothesis among the data obtained by Method I (standard method-Yi) and data obtained by Method II (alternative method-Yj). This test was used because it combines the results of the F (H0) statistic, modified from Graybill (Graybill, 1976) (H_0: $S^21 - S^22 = 0$), the mean error

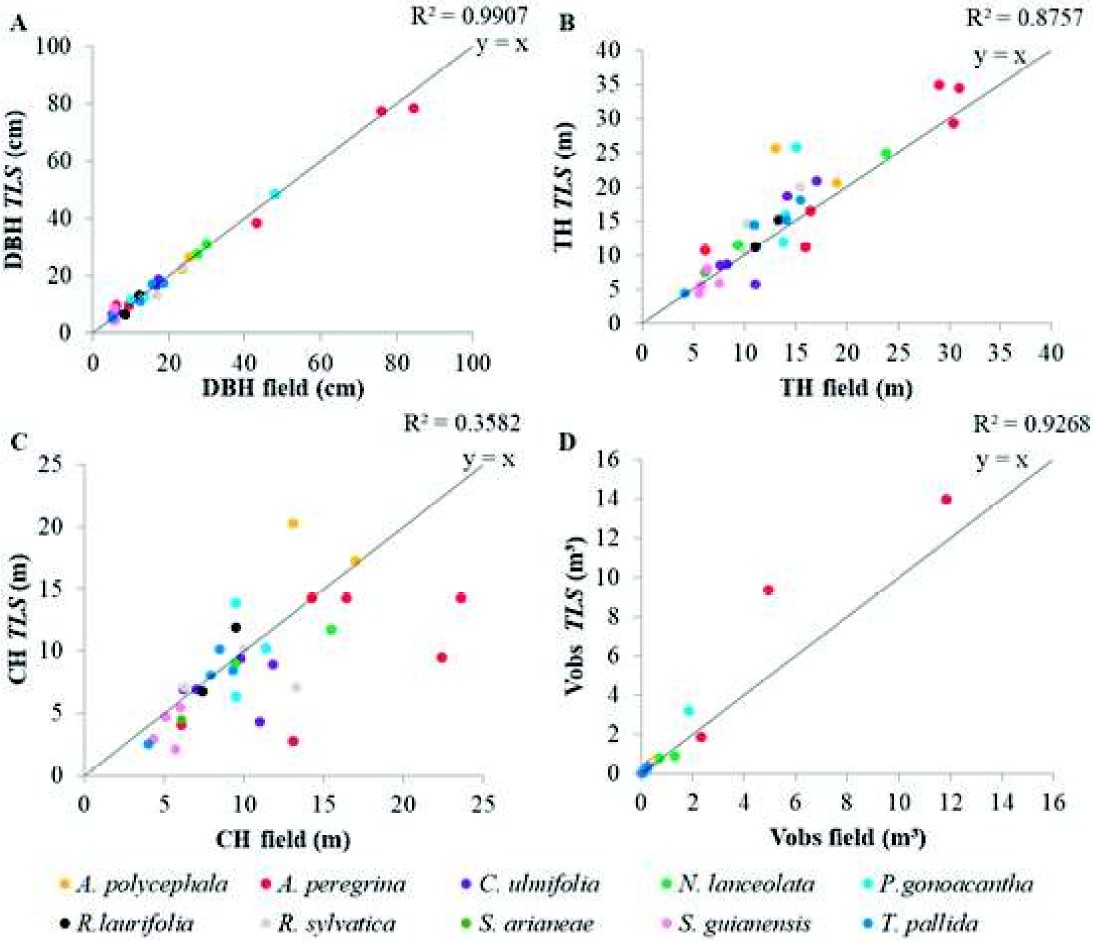

Figure 1 – Trend line among DBH (A), among TH (B), CH (C) and Vobs (D) obtained in a conventional method with those obtained with the 31-stem TLS in a seasonal semideciduous forest in Viçosa, Minas Gerais.
Figura 1 *– Ajuste da linha de tendência entre os DAP (A), entre as alturas totais (B), as alturas comerciais (C) e volume obtidos (D) obtidos de maneira convencional com aqueles obtidos com o uso do TLS de 31 fustes em uma Floresta Estacional Semidecidual em Viçosa, Minas Gerais.*

test (t) (H0: m_1-m_2 = 0) and the linear correlation coefficient (rYjY1).

The L&O test considers Y1 and Yj, two vectors of quantitative data obtained from two samples, in which j indicates the alternative method and 1 indicates the standard method, normally distributed with average 0 and variance σ^2. The relationship between Y1 and Yj can be metrically expressed for $Yj = Y1\beta + \epsilon$.

Thus, with n−2 degrees of freedom and at a significance level α, these statistics can be used to test the hypothesis H0: $\beta' = [0\ \ 1]$. If $F(H0) \geq F\alpha$ (2,n−2 d.f.), the hypothesis is rejected. On the other hand, if $F(H0) < F\alpha$(2,n−2 d.f.), the hypothesis is not rejected, admitting the identity between the two methods, that is, Yj = Y1 at level α of significance (Leite et al. 2006). Based on these statistics, a decision rule for the test is suggested (Table 1).

2.4.2 Volumetric equations

The volumetric equations for each model were compared with each other based on a model identity test proposed elsewhere (Santos et al., 2017). The adjusted equations based on the SH model were compared with the forest conventional data and the TLS data. Then, this procedure was performed with the adjusted equations based on the Spurr model.

If the equality between Equations 1 and 2 or 3 and 4 could not be verified, an equation for each method will be selected based on their performance in the precision statistics: percentage mean square root error and percentage bias.

3. RESULTS

3.1 Dendrometric variables and scaling volume

The DBH mean obtained by the conventional method was 19.58 cm (± 98.34%) and that obtained using TLS was 19.48 cm (± 94.99%) (Figure 1A). TH average for the conventional method was 13.47m (± 7.04%) and that obtained with the TLS was 15.36 m (± 8.63%) (Figure 1B). CH average found with the conventional method was 10.33 m (± 46.66%) and that obtained by TLS was 8.63 m (± 51.61%) (Figure 1).

DBH values determined with TLS were close to those obtained using the conventional method, with a determination coefficient (R^2) of 0.99. TH values showed a good fit among them.

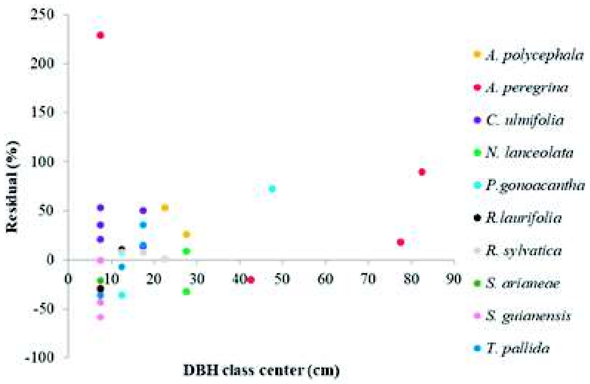

Figure 2 – Volume residuals obtained through scaling based on the DBH class centre of 31 stems in a seasonal semideciduous forest in Viçosa, Minas Gerais.
Figura 2 – *Resíduos dos volumes obtidos por meio da cubagem com base no centro de classe dos DAP de 31 fustes em uma Floresta Estacional Semidecidual em Viçosa, Minas Gerais.*

Regarding the volume obtained by scaling, the volume values obtained with the data collected using the conventional method, SH model and those obtained with the TLS data were similar. Trend line adjustment among them showed a strong correlation (Figure 1D). In a detailed analysis of the residual volume values, we observed that, there was a tendency to overestimate the TH values (Figure 2).

The L&O test summary used to compare the dendrometric variables showed that only the DBH variable was considered statistically equal for both methods (Table 2).

Table 2 – L&O test (for 1% significance level) for DBH, TH and volume obtained by Methods I and II, with Y_j being the DBH obtained by method II and, Y_i being the DBH obtained by Method I in 31 stems in a seasonal semideciduous forest in Viçosa, Minas Gerais.
Tabela 2 – *Teste L&O (para nível de significância de 1%) para DAP, Altura total e Volume obtidos pelos Métodos I e II, sendo Yj o DAP obtido pelo método II e, Yi sendo o DAP obtido pelo Método I em 31 hastes em floresta semidecídua em Viçosa, Minas Gerais.*

	DBH	TH	Volume
F(H0)	3.3512ns	8.8445*	14.4801*
t(e)	1.1204ns	2.6537 ns	1.4790 ns
rYjY1 ≥ 1-|ē|	Yes	No	Yes
p-value F(H0)	0.0491	0.0010	0.0000
p-value t(e)	0.2711	0.0124	0.1496
Conclusion	**Y_j equals Y_i**	**Y_j does not equal Y_i**	**Y_j does not equal Y_i**

*: significant; ns: not significant.
**: significativo; ns: não significativo.*

Table 3 – Volumetric equations for the Schumacher and Hall and Spurr models and their respective precision statistics for data obtained through a conventional forest inventory and using TLS for a fragment of seasonal semideciduous forest in Viçosa, Minas Gerais.
Tabela 3 *– Equações volumétricas ajustadas para os modelos Schumacher e Hall e de Spurr e suas respectivas estatísticas de precisão para os dados aferidos por meio de inventário florestal convencional e com o uso do TLS para um fragmento de Floresta Estacional Semidecidual no munícipio de Viçosa, Minas Gerais.*

Nº eq.	Method	Model	Equation	RMS (%)	BIAS (%)
1	I	SH	$V= 0.000002183 \cdot DAP^{2,283} \cdot H^{1,6322}$	8.48	9.57
2	I	Spurr	$V=0.0000005910 \cdot (DAP^{2} \cdot H)^{1,386}$	41.42	14.51
3	II	SH	$V=0.00001777 \cdot DAP^{2,644} \cdot H^{0,5853}$	7.34	3.48
4	II	Spurr	$V=0.00004542 \cdot (DAP^{2} \cdot H)^{1,036}$	46.71	-3.86

Regarding the comparison among the volumetric equations and considering a significance level equal to 1%, the model identity test indicated that there was not similarly among the equations adjusted by the SH model with the conventional data with those adjusted with the TLS (p-value = 1.20e-25). The model identity test also did not indicate similarly among the equations adjusted by the Spurr model; whose p-value was equal to 0.00006. As there was no equality among the equations, the best models adjusted, with the data obtained by both models, were those based on the SH model (Table 3).

4. DISCUSSION

Over 10 years, studies have been investigated the use of TLS in forest inventory (Vastaranta et al., 2009; Newnham et al., 2015; Berbert, 2016), with the aim to evaluate this approach as a tool for native forest management based, mainly, on tree dendrometric parameters, in preservation areas, for example, providing information about the regeneration of these areas, and the importance of their maintenance. However, in other fieldwork, relationships were made between what was verified in the field with the virtual method, especially in areas with permanent plots with mapped trees and identified species (Decuyper et al., 2018; Ojoatre et al., 2019).

The DBH values showed a better adjustment when compared to those derived from the TH and volume variables. The use of multiple scans can explain this strong correlation among the DBH values from the TLS processing and those obtained conventionally, because the multiple scans allow for better closure of the tree's circumference, and therefore, we have a higher density of points, making the reconstruction stem (Wilkes et al., 2017; Kumar et al., 2018).

In addition, noise absence (such as branches and understory vegetation) because of the manual data filtering procedure, favoured the obtaining of DBH by TLS. In situations with a strong understory, it is essential to develop algorithms to automate data filtering and to remove the understory in a consistent way (Buck et al., 2017).

Other important factors that contributed to the accurate measurement of DBH by TLS were the small wind interference and the laser scanner operating range (on average 1.50 m) close to the DBH height (Almeida, 2017). This was confirmed by the L&O test result, which indicated identity among the DBH values collected using the conventional method and those using the TLS. DBH was approved in the tree tests; however, total, and CH and volume also show significance for the t-test, i.e., the averages are equal at a confidence level of 1%.

We obtained similar results for TH through TLS and conventional measurement, although this similarity is not statistically significant. There were trends of over and underestimation of heights, which has already been observed by other authors (Brede, 2017; Liu et al., 2018; Vaglio Laurin et al., 2019).

The underestimation of these values can be explained with the low visibility in the treetops, caused by the occlusion of adjacent treetops, which coverage of the target tree (Bazezew et al., 2018). Other reasons are the high density and height of the surrounding vegetation and the understory, contributing to stem shading, as well as the fact that the highest point of the tree does not always coincide with that found in the crown centre, culminating in lower height values (Vaglio Laurin et al., 2019).

TH overestimation may have been caused by the fact that in dense plots, smaller trees are generally surrounded by larger trees, and part of the larger tree crowns were considered as parts of the smaller tree crowns (Cabo et al., 2018). Overlapping crowns, errors in positioning the equipment or filtering data can also result in TH overestimation (Srinivasan et al., 2015), including under or overestimated all vertical tree dimensions (Pitkanen et al., 2021).

The definition of the CH term is subjective and it can be attributed to stem height (Soares et al., 2011). However, CH was understood as the vertical distance from the ground to the height at which the first branch insertion occurs.

It is highly likely that the dense understory presents in the study area, combined with large tree species, made it difficult to describe the structure of the highest strata of the forest. Thus, the tree height readings made by the TLS generated inaccurate estimates of the canopy structure (Zimbres et al., 2020). The difference between the maximum total (15.36 m) and average (8.40 m) heights observed in the forest corroborates this idea.

Airborne LiDAR can better describe the forest canopy structure and estimate tree height than TLS, especially in the case of dense and tall formations (Zimbres et al., 2020). Therefore, the combination of terrestrial and airborne LiDAR data sets, obtained in the same locations, can more accurately delimit the understory and canopy structure in dense formations.

We observed a low linear correlation among the values obtained by conventional ways and those obtained using TLS. CH measurement in native forests is complex because of the subjectivity in the definition and detection of the first branch, which can vary among observers and among observations. In addition, there may have been an error in data filtering or the distance at which the laser was positioned for readings may have been too small.

The distance from the TLS to the tree is relevant for data accuracy. The shorter this distance, the more the equipment's angle of view will be inclined and, thus, the scan will cover overlapping branches, which makes it difficult not only to define the base height, but also to determine the entire crown (Martins Neto et al., 2013). In general, disagreements between the TLS- and the field-based tree height measurements increase with an increasing complexity of the forest stand (Wang et al., 2019). All these factors help to understand the statistical difference among the HC values obtained by the two different approaches.

Similar to previous findings, the R^2 value adjusted among the volume values obtained by the field scaling and that performed via TLS was high (Kunz et al., 2017). However, there was an underestimation for smaller trees and an overestimation for larger trees, following the same trend observed for TH. Because due to the terrestrial laser angulation, few points were acquired at the apex of the trees, making virtual processing difficult.

TH is one of the tree components that most significantly contribute to the stem volume, and it was therefore expected that stem volume would show a trend similar to that of TH (Torresan et al., 2018). In addition, considering the stem tapering pattern, larger diameters are closer to the target height, which culminates in smaller incidence angles (Buck, 2017; Almeida, 2017). With this variation in the accuracy of the data along the stem, the result of the L&O test confirmed the statistical difference among the volumes acquired using the two different methods.

It is important to note that the volume obtained via TLS is influenced by the terrain, such as slopes and gaps. In such places, fields surveys are not viable. In the case of sloping environments, the great difficulty lies in the considerable weight (± 15 kg) and in the internal components of the equipment, which are hypersensitive to friction, rain and winds (Wilkes et al., 2017). In openings, understory and dead material would impede the acquisition of the stem volume, promoting the occlusion of adjacent tree parts. Thus, stem volume and its extrapolation to the entire area may be inaccurate, in addition to the considerable intra- and interspecific variability of the forest. As an example, in our study, *A. peregrina* was dominant in the upper canopy, and its specific crown structure might bias the community's TH (and volume) identities between the methods. Thus, in hyperdiverse communities, the crown characteristics of the dominant tree species can lead to extrapolation errors.

Because the equations adjusted according to the SH and Spurr volumetric models for Methods I and II were not equal, the equations based on the SH volumetric model were chosen as the most adequate ones to obtain the volume in this forest formation. Previous studies have shown that equations based on the SH volumetric model describe a better fit for the data (Leal et al., 2015; Martins et al., 2015, Moreno et al., 2018), which reinforces the use of SH to estimate stem volume in secondary Neotropical forests.

Finally, it is recommended to develop algorithms for filtering and modelling the data so that the user can more easily interact with the interface, making processing efficient. Furthermore, it is essential that these algorithms can recognise and promote the distinction among a target tree and a shrub, a frequent component of the understory.

5. CONCLUSION

As expected, for the entire forest, DBH, TH and CH values obtained by TLS showed the same trends as those obtained by the traditional method. However, due to the high species diversity, as well as differences in successional stages and canopy densities, we infer that height measurement by TLS results in values that differ from those obtained by the traditional method, particularly in hyperdiverse secondary forests.

We emphasize the importance of the applicability of this non-destructive method in areas of conservation and sustainable management, allowing the verification of parameters and monitoring of the development of the area.

AUTHOR CONTRIBUTIONS

All authors contributed to the study.

Torres CMME, Amaral CH and Fernandes Filho EI: Conceptualization, Methodology, Supervision, Writing - review & editing. Soares CPB: Data Statistics, Writing - review & editing. Santana FC: Software, Data curation, Writing - review & editing. Timo LB: Field Measurement, Data Processing, Writing - review & editing. Rocha SJS: Field Measurement, Writing - review & editing. Viana ABT: Field measurement, Data Processing, Writing - original draft, Writing - review & editing.

6. REFERENCES

Almeida GJF. Uso do laser scanner terrestre na estimativa de parâmetros biométricos em povoamentos florestais Piracicaba. Escola Superior de Agricultura “Luiz de Queiroz”; 2017.

Aubertin JD, Hutchinson DJ, Diederichs M. Horizontal single hole blast testing – Part 1: Systematic measurements using TLS surveys. Tunnelling and Underground Space Technology. 2021;114(103985). doi: 10.1016/j.tust.2021.103985.

Bazezew MN, Hussin YA, Kloosterman EH. Int J Appl Earth Obs Geoinformation Integrating Airborne LiDAR and Terrestrial Laser Scanner forest parameters for accurate above-ground biomass / carbon estimation in Ayer Hitam tropical forest, Malaysia. Int J Appl Earth Obs Geoinf [Internet]. 2018;73(June 2017):638–52. doi: 10.1016/j.jag.2018.07.026.

Benedek C, Majdik A, Nagy B, Rozsa Z, Sziranyi T. Positioning and perception in LIDAR point clouds. Digital Signal Processing. 2021;119(103193). doi: 10.1016/j.dsp.2021.103193.

Berbert MLDG. Potencial do LiDAR terrestre como ferramenta para o manejo de florestas naturais. Federal Rural University of Rio de Janeiro; 2016.

Brede B. Canopy Height and DBH with Terrestrial LiDAR. 2017;1–16.

Buck ALB, Lingnau C, Machado ÁML, Netto SP. Detecção de árvores em nuvens de pontos de varredura laser terrestre. Bol Ciencias Geod. 2017;23(1):21–38.

Cabo C, Ordóñez C, López-Sánchez CA, Armesto J. Int J Appl Earth Obs Geoinformation Automatic dendrometry: Tree detection, tree height and diameter estimation using terrestrial laser scanning. Int J Appl Earth Obs Geoinf [Internet]. 2018;69(January):164–74. doi: 10.1016/j.jag.2018.01.011.

Calders K, Adams J, Armston J, Bartholomeus H, Bauwens S, Bentley LP, Chave J, Danson FM, Demol M, Disney M, Gaulton M, Moorthy SMK, Levick SR, Saarinen N, Schaaf C, Stovall A, Terryn L, Wilkes P, Verbeeck H. Terrestrial laser scanning in forest ecology: Expanding the horizon. Remote Sensing of Environment. 2020;251(112102). doi: 10.1016/j.rse.2020.112102.

Danson FM, Disney MI, Gaulton R, Schaaf C, Strahler A. The terrestrial laser scanning revolution in forest ecology. Interface Focus. 2018;8(20180001). doi: 10.1098/rsfs.2018.0001.

Decuyper M, Ayele K, Brede B, Calders K, Armston J, Rozendaal DMA, et al. Forest Ecology and Management Assessing the structural differences between tropical forest types using Terrestrial Laser Scanning. For Ecol Manage [Internet]. 2018;429(June):327–35. doi: 10.1016/j.foreco.2018.07.032.

Dong Z, Liang F, Yang B, Xu Y, Zang Y, Li J, Wang Y, Dai W, Fan H, Hyyppä J, Stilla U. Registration of large-scale terrestrial laser scanner point clouds: A review and benchmark. ISPRS Journal of Photogrammetry and Remote Sensing. 2020;163:327-342. doi: 10.1016/j.isprsjprs.2020.03.013.

Dubreuil V, Fante K.P, Planchon O, Sant'Anna Neto JL. Climate change evidence in Brazil from Köppen's climate annual types frequency. International Journal of Climatology. 2018;39(3):1446-1456. doi: 10.1002/joc.5893.

Ferraz AS. Estimação dos estoques de Biomassa e carbono na parte aérea de um fragmento de Floresta Estacional Semidecidual por meio de imagens de satélite Ikonos II; 2012.

Ferreira Júnior WG, Shaeffer CEGR, Silva AF. Uma visão pedomorfológica sobre as formações florestais da Mata Atlântica. In: Ecologia de florestas tropicais do Brasil. Viçosa, Brasil: Editora UFV; 2012;141–74.

Graybill FA. Theory and Application of the Linear Model Belmont, CA: Duxbury Press; 1976.

Görüm T, Landslide recognition and mapping in a mixed forest environment from airborne LiDAR data, Engineering Geology. 2019;258(105155). doi: 10.1016/j.enggeo.2019.105155.

Jeong J, Younggun C, Young-Sik S, Roh H, Kim A. Complex urban dataset with multi-level sensors from highly diverse urban environments. The International Journal of Robotics Research. 2019;38(6):642–657. doi: 10.1177/0278364919843996.

Kumar S, Sara R, Singh J, Agrawal S, Kushwaha SPS. Remote Sensing Applications: Society and Environment Spaceborne PolInSAR and ground-based TLS data modeling for characterization of forest structural and biophysical parameters. Remote Sens Appl Soc Environ [Internet]. 2018;11(June):241–53. doi: 10.1016/j.rsase.2018.07.010.

Kunz M, Hess C, Raumonen P, Bienert A, Hackenberg J, Maas HG, et al. Comparison of wood volume estimates of young trees from terrestrial laser scan data. IForest. 2017;10(2):451–8.

Leal FA, Cabacinha CD, Castro RVO, Matricardi EAT. Amostragem de árvores de Eucalyptus na cubagem rigorosa para estimativa de modelos volumétricos. Rev Bras Biometria. 2015;33(1):91–103.

Leite HG, Henrique F, Oliveira T De. Statistical procedure to test identity between analytical methods. Commun Soil Sci Plant Anal. 2006;33(7–8):1105–18.

Liu G, Wang J, Dong P, Chen Y, Liu Z. Estimating Individual Tree Height and Diameter at Breast Height (DBH) from Terrestrial Laser Scanning (TLS) Data at Plot Level. Forests. 2018;9(398):1–19.

Martins Neto RP, Buck ALB, Silva MN, Lingnau C, Machado ÁML, Pesck VA. Avaliação da varredura laser terrestre em diferentes distâncias da árvore para mensurar variáveis dendrométricas. Bol Ciencias Geod. 2013;19(3):420–33.

Martins RM, Leite MVS, Cabacinha CD, Assis AL de. Teste de identidade de modelos volumétricos para povoamentos de Eucalyptus sp. em sete Municípios de Minas Gerais. Enciclopédia Biosf. 2015;11(21):1818–33.

Meira Neto JAA. Estudos florísticos, estruturais e ambientais nos estratos arbóreo e herbáceo-arbustivo de uma floresta estacional semidecidual em Viçosa, MG. State University of Campinas; 1997.

Meyer V, Saatchi S, Clark DB, Keller M, Vincent G, Ferraz A, et al. Canopy area of large trees explains aboveground biomass variations across neotropical forest landscapes. 2018;3377–90.

Miranda GHB, Medeiros NG, Santos AP, Santos GR. Análise de qualidade de amostragem e interpolação na geração de MDE. Revista Brasileira de Cartografia. 2018;70(1):226-257.

Molina-Valero JA, Martínez-Calvo A, Villamayor MJG, Pérez MAN, Álvarez-González JG, Montes F, et al. Operationalizing the use of TLS in forest inventories: The R package FORTLS. Environmental Modelling & Software. 2022;150(105337). doi: 10.1016/j.envsoft.2022.105337.

Moreno N, Moreno R, Molina JR. Optimal harvest cycle on Nothofagus forests including carbon storage in Southern America: An application to Chilean subsidies in temperate forests. Land Use Policy. 2019;81:705-713. doi: 10.1016/j.landusepol.2018.10.026.

Newnham GJ, Armston JD, Calders K, Disney MI, Lovell JL, Schaaf CB, et al. Terrestrial laser scanning for plot-scale forest measurement. Curr For Reports. 2015;1(4):239–51.

Ojoatre S, Zhang C, Hussin YA, Kloosterman HE, Ismail M. Avaliando a incerteza da altura das árvores e da biomassa acima do solo a partir de scanner a laser terrestre e hipsômetro usando dados de LiDAR no ar em florestas tropicais. IEEE J Sel Top Appl Obs da Terra e Sensoriamento Remoto. 2019;12(10):4149–59.

Pitkänen TP, Raumonen P, Kangas A. Measuring stem diameters with TLS in boreal forests by complementary fitting procedure. ISPRS J Photogramm Remote Sens [Internet]. 2019;147(March 2018):294–306. doi: 10.1016/j.isprsjprs.2018.11.027.

Pitkänen TP, Raumonen P, Liang X, Lehtomäki M, Kangas A. Improving TLS-based stem volume estimates by field measurements. Computers and Electronics in Agriculture. 2021; 180 (105882). doi: 10.1016/j.compag.2020.105882.

Puttonen E, Lehtomäki M, Kaartinen H, Zhu L, Kukko A, Jaakkola A. Improved sampling for terrestrial and mobile laser scanner point cloud data. Remote Sens. 2013;5(4):1754–73.

Queiroz WT, Silva ML, Jardim FCS, Vale R, Valente, MDR, Pinheiro J. Índice de valor de importância de espécies arbóreas da floresta nacional do Tapajós via análises de componentes principais e de RIEGL. RIEGL VZ-1000 High-Resolution and Accurate 3D Measurements [Internet]. Data Sheet. 2017. p. 1–4. Available from: http://www.riegl.com/uploads/tx_pxpriegldownloads/DataSheet_VZ-1000_2017-06-14.pdf

RIEGL. Laser Measurement systems: Data Sheet RIEGL VZ-1000. 2017.

Rocha SJSS, Torres CMMET, Villanova PH, Schettini BLS, Jacovine LAG, Leite HG, et al. Drought effects on carbon dynamics of trees in a secondary Atlantic Forest. Forest Ecology and Management. 2020; 465(118097). doi: 10.1016/j.foreco.2020.118097.

Rodríguez ACC. Above ground biomass estimation in palm trees using terrestrial LiDAR and tree modelling. Wageningen University & Research; 2017.

Santos ACA., Fardin LP., Oliveira Neto RR. Teste de Hipótese em Análise de Regressão. Ed. Novas Edições Acadêmicas; 2017. 65 p.

Schumacher FX, Hall FS. Logarithmic expression of timber-tree volume. J Agric Res. 1933;47(9):719–34.

Singh J, Levick SR, Guderle M, Schmullius C. Moving from plot-based to hillslope-scale assessments of savanna vegetation structure with long-range terrestrial laser scanning (LR-TLS). International Journal of Applied Earth Observation and Geoinformation. 2020;90(102070). doi: 10.1016/j.jag.2020.102070.

Soares CPB, Neto FP, Souza ALS. Dendrometria e inventário florestal. 2 ed. Viçosa, Brasil; 2011. 272 p.

Spurr S. Forestry inventory. 1952. 476 p.

Srinivasan S, Popescu SC, Eriksson M, Sheridan RD, Ku N. Terrestrial Laser Scanning as an Effective Tool to Retrieve Tree Level Height, Crown Width, and Stem Diameter. 2015;1877–96.

Takoudjou SM, Ploton P, Sonke B, Hackenberg J, Griffon S, Coligny F, et al. Using terrestrial laser scanning data to estimate large tropical trees biomass and calibrate allometric models: A comparison with traditional destructive approach. Methods Ecol. Evol. 2018;9:905–916.

Torresan C, Chiavetta U, Hackenberg J. Applying quantitative structure models to plot-based terrestrial laser data to assess dendrometric parameters in dense mixed forests. For Syst. 2018;27(1):1–15.

Trochta J, Kr M. 3D Forest: An application for descriptions of three-dimensional forest structures using terrestrial LiDAR. 2017;1–17.

UFV. Boletim Meteorológico 2017 [Internet]. Universidade Federal de Viçosa. 2018:170–81.

Available from: http://www.posmet.ufv.br/wp-content/uploads/2015/04/Boletim-meteorologico-2018.pdf

Vaglio Laurin G, Ding J, Disney M, Bartholomeus H, Herold M, Papale D, et al. Tree height in tropical forest as measured by different ground, proximal, and remote sensing instruments, and impacts on above ground biomass estimates. Int J Appl Earth Obs Geoinf [Internet]. 2019;82(January):101899. doi: 10.1016/j.jag.2019.101899 .

Vastaranta M, Holopainen M, Haapanen R, Melkas T, Hyyppä J, Hyyppä H. Comparison between an area-based and individual tree detection method for low-pulse density ALS-based forest inventory. Int Arch Photogramm Remote Sens Spat Inf Sci. 2009;XXXVIII(Part 3/W8):147–51.

Xu C, Manley B, Morgenroth J. Evaluation of modelling approaches in predicting forest volume and stand age for small-scale plantation forests in New Zealand with RapidEye and LiDAR. International Journal of Applied Earth Observation and Geoinformation. 2018;73:386-396. doi: 10.1016/j.jag.2018.06.021.

Xu, D.; Wang, H.; Xu, W.; Luan, Z.; Xu, X. LiDAR Applications to Estimate Forest Biomass at Individual Tree Scale: Opportunities, Challenges and Future Perspectives. Forests 2021,12,550. doi: 10.3390/f12050550.

Wang Y, Lehtomäki M, Liang X, Pyörälä J, Kukko A, Jaakkola A, Liu J, Feng Z, Chen R, Hyyppä J. Is field-measured tree height as reliable as believed – A comparison study of tree height estimates from field measurement, airborne laser scanning and terrestrial laser scanning in a boreal forest. ISPRS Journal of Photogrammetry and Remote Sensing. 2019;147:132-145. doi: 10.1016/j.isprsjprs.2018.11.008.

Wilkes P, Lau A, Disney M, Calders K, Burt A, Gonzalez J, et al. Remote Sensing of Environment Data acquisition considerations for Terrestrial Laser Scanning of forest plots. Remote Sens Environ [Internet]. 2017;196:140–53. doi: 10.1016/j.rse.2017.04.030.

Zimbres B, Shimbo J, Bustamante M, Levick S, Miranda S, Roitman I, et al. Forest Ecology and Management Savanna vegetation structure in the Brazilian Cerrado allows for the accurate estimation of aboveground biomass using terrestrial laser scanning. For Ecol Manage [Internet]. 2020;458(December 2019):117798. doi: 10.1016/j.foreco.2019.117798.