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Use of Terrestrial Laser Scanner for Aboveground Biomass Estimation in a Seasonally Dry Tropical Forest

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A B S T R A C T

Structural parameters of vegetation and quantification of aboveground biomass (AGB) are important in forest monitoring to understand the vital cycle of ecosystems. This activity is even more challenging in seasonally dry tropical forests such as the Caatinga biome. The feasibility of using the terrestrial laser scanner (TLS) to measure structural parameters of plants and estimate aboveground biomass was investigated as an alternative to traditional methods. The study was conducted in an area of caatinga vegetation in the municipality of Petrolina, PE, Brazil, where three experimental subareas were selected to obtain measurements, cutting, and weighing of plants with a soil surface level diameter greater than 2.5 cm, totaling 97 plants. Scans were performed with the light detection and ranging (LiDAR) technology using TLS to obtain a three-dimensional point cloud. The correlation coefficient (r^2) for plant height measured in the field and obtained by TLS was 0.80. The measures of trunk diameter at soil surface level and at heights of 40 and 130 cm showed r^2 of 0.79, 0.78, and 0.76, respectively. New exponential allometric equations were generated using input variables obtained in the field and point cloud TLS. These results demonstrate the feasibility and potential of using LiDAR-TLS in dry forests, such as caatinga vegetation. This emphasizes the need to deepen approaches, tools, and techniques using this technology throughout the year to detect variations due to senescence and, therefore, the carbon cycle.

Keywords: caatinga, LiDAR, biomass, allometric equation.

Uso de Laser Scanner Terrestre para Estimativa de Biomassa Acima do Solo em Floresta Tropical Sazonalmente Seca

RESUMO

Parâmetros estruturais da vegetação e quantificação da biomassa acima do solo (AGB) são importantes para o monitoramento florestal e compreensão do ciclo vital dos ecossistemas. Em florestas tropicais sazonalmente secas como a caatinga, essa atividade é ainda mais desafiadora. Como alternativa aos métodos tradicionais, foi investigada a viabilidade do uso do Escâner Laser Terrestre (TLS) na medição de parâmetros estruturais e na estimativa da biomassa acima do solo de plantas da caatinga. O estudo foi conduzido em uma área de caatinga no município de Petrolina, PE, Brasil, onde três subáreas experimentais foram selecionadas para obtenção de medidas, corte e pesagem de plantas, com diâmetro ao nível do solo maior que 2,5 cm,

totalizando 97 plantas. Escaneamentos foram realizados com a tecnologia de Detecção e Alcance de Luz (LiDAR) utilizando o TLS para obtenção de uma nuvem de pontos tridimensional. O coeficiente de correlação (r^2) para altura da planta medida em campo e estimada pelo TLS foi de 0,80. As medidas do diâmetro do tronco ao nível do solo e nas alturas de 40 cm e 130 cm apresentaram r^2 de 0,79; 0,78 e 0,76, respectivamente. Novas equações alométricas exponenciais foram geradas utilizando variáveis de entrada obtidas em campo e na nuvem de pontos do TLS. Esses resultados demonstram a viabilidade e o potencial do uso do LiDAR-TLS em florestas seca, como a vegetação da caatinga, enfatizando a necessidade de aprofundar abordagens, ferramentas e técnicas utilizando essa tecnologia ao longo do ano, a fim de detectar as variações ocorridas em função da senescência, e assim, do ciclo de carbono.
Palavras-chave: caatinga, LiDAR, biomassa, equação alométrica.

Introduction

Seasonally dry tropical forests (SDTF) constitute approximately 42% of the total terrestrial tropical forests (Riggio et al., 2020). The Caatinga biome, in Brazil, is the largest of these areas in Latin America. It is an ecosystem rich in natural resources, which is home to 1,700 plant species, of which 17.5% is estimated to be endemic, with several morphophysiological adaptations that allow their survival and productivity considering the edaphoclimatic extremes to which they are subjected (Castanho et al., 2020).

Building on this understanding, the Caatinga biome, the largest among seasonally dry tropical forests in Latin America, plays a crucial global role due to its remarkable resistance to water deficit and high temperatures, significantly contributing to carbon retention (Souza et al., 2022). The vegetation density in the ecosystem is variable, serving as the main substrate for photosynthesis (Piao et al., 2020). Menezes et al. (2021) found that carbon in the Caatinga is predominantly stored in different compartments: soil organic matter (72.1%), aboveground biomass (15.9%), belowground biomass (7.3%), dead wood (2.9%), litter (1.3%), and herbaceous biomass (0.5%). These percentages underscore the significance of understanding carbon distribution within vegetation compartments for a comprehensive assessment of the biome's carbon dynamics.

Changes in biomass and vegetation physiognomies wield profound implications on climate dynamics, societal structures, and economic facets (Castanho et al., 2020). The assessment of variability in aboveground forest biomass (AGB) stands as an essential pursuit to unravel intricate relationships within forestry, environmental sciences, ecosystem modeling, and applications related to climate change scenarios (Araújo et al., 2023).

Quantifying AGB is accomplished through both direct and indirect methodologies. The former entails the laborious process of cutting and weighing plants, offering unparalleled accuracy but proving unfeasible on a large scale due to resource intensiveness and the inherently destructive nature of the approach. Conversely, the indirect method necessitates the deployment of tools, coupled with the use of active and passive sensors, to estimate plant structural variables such as total plant height (H) and diameter at breast height (DBH).

Dendrometric variables exhibit potential correlations with biomass, as determined through the direct method (Calders et al., 2020) and/or plant volume, serving as foundational elements for the formulation of estimation equations (Sampaio & Silva, 2005; Sampaio et al., 2010; Dalla-Lana et al., 2018; Barreto et al., 2018; Chave et al., 2004, 2005; Abegg et al., 2023). The formulation of such estimation equations presents several advantages when compared to the direct method, including cost-effectiveness, reduce time expenditure, enhanced data quality and automation, and heightened precision (Abegg et al., 2023). Furthermore, these equations afford the additional benefit of non-destructiveness, preserving the integrity of the vegetation under investigation.

Remote sensing methodologies have found widespread application across diverse domains to optimize costs associated with forest inventories, facilitating rapid and precise data acquisition across expansive terrains. In this context, light detection and ranging (LiDAR) technology has emerged as a noteworthy tool, providing three-dimensional insights into vegetation structures. The outcomes obtained through LiDAR not only closely approximate reality but also enable a reliable assessment of forest resources across multiple scales (Popescu et al., 2018; Zimbres et al., 2020; Ruza et al., 2021).

LiDAR data acquisition is facilitated through aerial sensors, specifically airborne laser scanning (LS), and terrestrial sensors, denoted as terrestrial laser scanning (TLS). The latter has garnered escalating attention within the realm forestry, owing to its high precision and expeditious capacity for detailed tree analysis, as well as its efficacy in volumetric and biomass estimation (Muumbe et al., 2021; Brede et al., 2022; Abegg et al., 2023). Consequently, TLS has proven instrumental in furnishing comprehensive plant-specific information, concurrently serving as a crucial resource for the precise estimation of biomass and carbon (Calders et al., 2020).

Several methodologies have been employed globally to estimate aboveground biomass through the assessment of forest structure using LiDAR technology in tropical and subtropical forests (Brede et al., 2022; Abegg et al., 2023). In Brazil, various studies have applied LiDAR techniques in forest ecosystems, with investigations conducted by Gorgens; Silva; Rodrigues (2014), Silva et al. (2017), Rex et al. (2020), Dalagnol et al. (2021), Zimbres et al. (2020), and Ruza et al. (2021). However, few studies in the Northeast region have used the LiDAR technology in both aerial (ALS) or terrestrial (TLS) platforms in the State of Pernambuco (Galvíncio & Popescu, 2016; Oliveira et al., 2021; Nishiwaki et al., 2021; Barmpoutis et al., 2022), evaluating mangroves and the Caatinga.

Consequently, there exist a lack of knowledge regarding the potential utility of TLS for studying Caatinga vegetation, characterized by a diverse array of species with distinctive features, including multi-stems, slender and contorted branches, and leaf senescence, which contribute significantly to water-use efficiency and biomass production. The viability of applying established allometric biomass estimation equations (Sampaio & Silva, 2005; Sampaio et al., 2010; Dalla-Lana et al., 2018; Barreto et al., 2018) within robust tools such as TLS, for extrapolating results from conventional methods, remains unvalidated.

Novel forest equations, founded on the assertion that LiDAR technology facilitates precise measurements of Caatinga trees (Lima et al., 2021; Oliveira et al., 2021), have been developed. These equations hold applicability in forest management for the estimation of biomass and carbon quantification. Moreover, they prove instrumental in calibrating other remote sensing techniques. The feasibility of employing Terrestrial Laser Scanning (TLS) for the measurements of structural parameters in plants and the estimation of aboveground biomass was investigated as an alternative to conventional methodologies.

Materials and Methods

Study area and inventory of plants in the experimental subareas

The preserved Caatinga vegetation under examination in this study is situated within a designated research area for the exploration of natural resources managed by the Brazilian Agricultural Research Corporation (Embrapa Semi-Arid). This area is specifically located in the municipality of Petrolina, Pernambuco, Brazil, as depicted in Figure 1, and is centered at the geographic coordinates 9°2′24.3″ S and 40°19′10.5″ W, with an altitude of 409 m above sea level.

In accordance with the Köppen classification, the prevailing climate in the region is identified as BSwh′, indicative of a tropical semi-arid climate featuring a distinct dry period in winter and a rainy interval spanning from January to April (Álvares et al., 2013).

The mean annual precipitation is recorded at 500 mm. Air temperature exhibits a range of variation from 20.67 to 32.07 °C (minimum and maximum, respectively), accompanied by an average relative humidity of 62%. The region is characterized by a substantial influx of solar radiation, resulting in elevated potential evapotranspiration levels throughout the entirety of the year (Carvalho et al., 2018).

The predominant soil types in the experimental area are Oxisol (Argissolo Vermelho-Amarelo), Alfisol (Planossolo Háplico), and Vertisol (Vertissolo Hidromórfico), with four stages of stoniness (shallow, slightly stony, stony, and deep) and a flat relief with a maximum slope of 4% (Santos et al., 2009).The field experiment was conducted in April 2018 in subareas 1 and 2, with individual dimensions of 10 x 10 m, and in January 2019 in subarea 3, with a dimension of 14 x 14 m, totaling three subareas (Figure 1d) with caatinga vegetation of tree-shrub size.

Plants with a trunk diameter ≥ 2.5 cm at ground level were identified, totaling 97 plants spatially located as shown in Figure 1d. The species present in the subareas were: *Handroanthus spongiosus* (n=12), *Jatropha mollissima* (Pohl) Baill (n=6), *Jatropha mutabilis* (n=2), *Sapium argutum* (Müll. Arg.) Huber (n=12), *Croton conduplicatus* Humb (n=6), *Manihot pseudoglaziovii* (Pax & K. Hoffm) (n=19), *Cnidoscolus quercifolius* (Pohl) (n=3), *Commiphora leptophloeos* (Mart J.B Gillett) (n=8), *Pseudobombax simplicifolium* (n=1), *Bauhinia cheilantha* (Bong) Steud (n=1), *Schinopsis brasiliensis* (Engl) (n=2), *Cenostigma microphylla* (Pohl) (n=14), *Senegalia piauhiensis* (Benth) (n=9), and *Jacaratia corumbensis* (n=2), of which 40.2 and 16.49% correspond to the families Euphorbiaceae and Fabaceae, respectively. According to Kill (2017), these families present the highest occurrence in the study area.

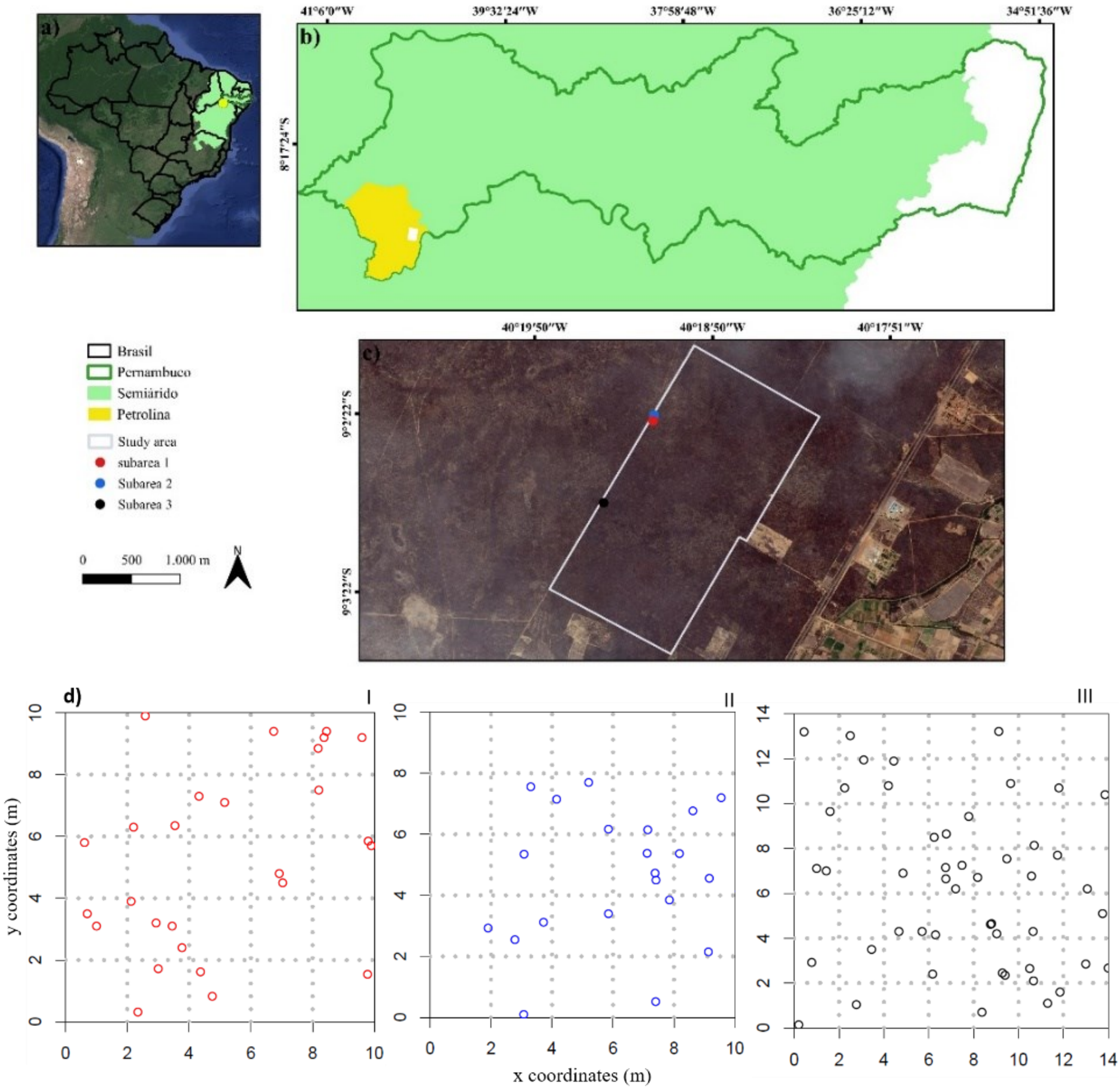

Figure 1 - Geographic Location of the study area: a) Caatinga Biome; b) State of Pernambuco and municipality of Petrolina; c) Experimental subplots; d) Distribution of plants with basal diameter > 2.5 cm, with x and y coordinates (in meters) marked in each subplot, with a 2 m buffer, for dendrometric measurements and biomass estimation, I) subarea 1 (10 x 10 m); II) subarea 2 (10 x 10 m); c) subarea 3 (14 x 14 m), in the municipality of Petrolina-PE.

Structural measurements and plant biomass

The dendrometric measurements of the 97

identified plants were performed according to protocols for the Caatinga vegetation defined by Sampaio et al. (2005) and recommendations from the Brazilian Forest Service (2018) manual. A graduated ruler was used to take the measurements of the total plant height (H), considered from the base to the last photosynthetic point, and crown height (Hc), considering the height of the exit of branches with foliage up to the last photosynthetic point.

Trunk diameter measurements were obtained using a caliper at three heights: DGL – diameter at ground level, D40 – diameter at 40 cm from ground level, and D130 – diameter at a height of 130 cm, also known as diameter at breast height (DBH). All branches in multi-stemmed plants were measured at ground level to calculate the basal area. These diameter measurements allowed calculating the basal area considering a circular shape for the three heights (BA_{GL}, BA40, and BA130).

Biomass was determined by the direct method by cutting the plants in sections and weighing them, taking samples of leaves, thin branches, and thick branches from each plant to determine the fresh and dry matter. The samples of each plant were placed in identified paper bags, weighed, and transferred to a forced-air circulation oven at a temperature of 65 °C for drying until constant weight.

Vegetation scanning – Terrestrial laser scanner – TLS

Subareas 1, 2, and 3 were scanned using the TLS model FARO Focus 3D X130 HDR (Table 1). Four scans were performed with TLS, one in each cardinal direction (Figure 2) to allow a better range of targets. For scanning, TLS was installed on a tripod and set to ½ resolution and 4x quality. Eighteen spherical white polystyrene targets (147 cm in circumference) were placed on tripods distributed within the study area at random distances and free of obstructions to facilitate the recording of the scans in a single point cloud.

The minimum occlusion of the surrounding vegetation was left for better visualization of the plants and their structures in the point cloud. In all cases, surrounding shrubs with DGL < 2.5 cm that surrounded plants within the scan area were excluded to improve the focal view where possible.

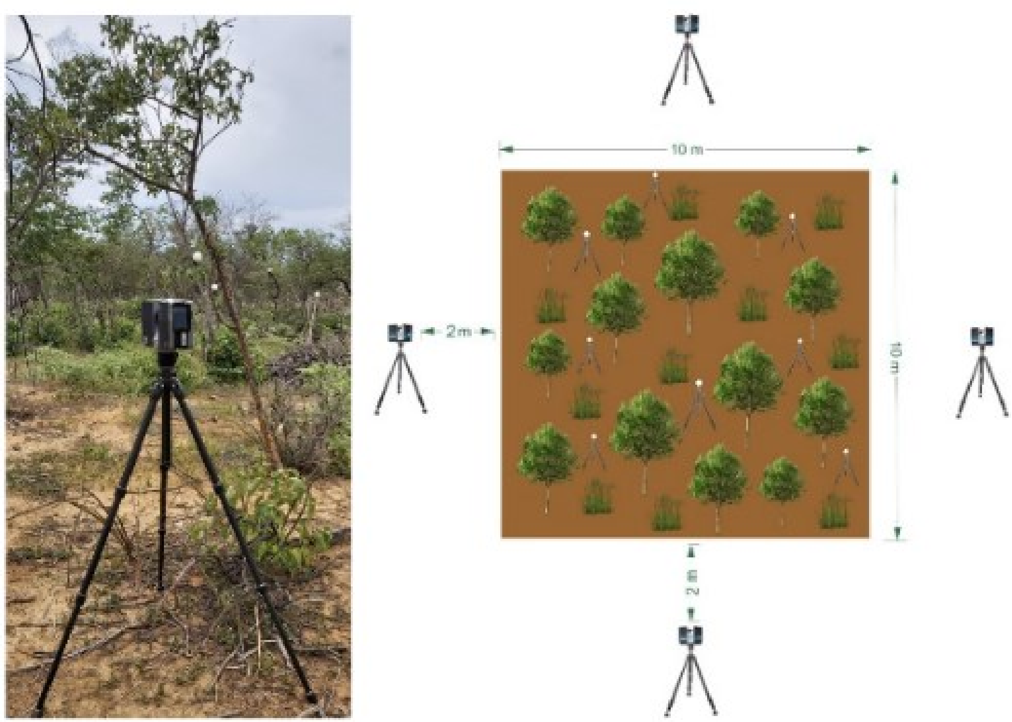

Figure 2 - Terrestrial Laser Scanner (TLS) in operation in one of the experimental subareas and demonstration of the scanning process in the caatinga subareas, Petrolina-PE.

Table 1 - Technical Specifications of the FARO Focus 3D X 130 HDR Terrestrial Laser Scanner.

Laser Measurement Principle	Emission and returno of laser pulses
Speed	976.000 points per second
Camera quality and resolution	170 megapixels
Maximun range	130 m
Vertical/horizontal field of view angle	300° / 360°
wavelength	1550 nm

TLS data processing and estimation of dendrometric variables through the point cloud

The scans acquired with TLS around the vegetation were recorded based on the spherical positions scattered in the subarea, using the FARO SCENE software (FARO Scene, 2018), generating a single three-dimensional point cloud, according to the steps of the flowchart of Figure 3.

Undesirable points were removed from the point cloud through a visual inspection and manual cleaning process performed particularly at the base and top of the plants. After cleaning, the plants were identified and the dendrometric measurements of each plant were extracted using tools of the software Scene (Figure 3).

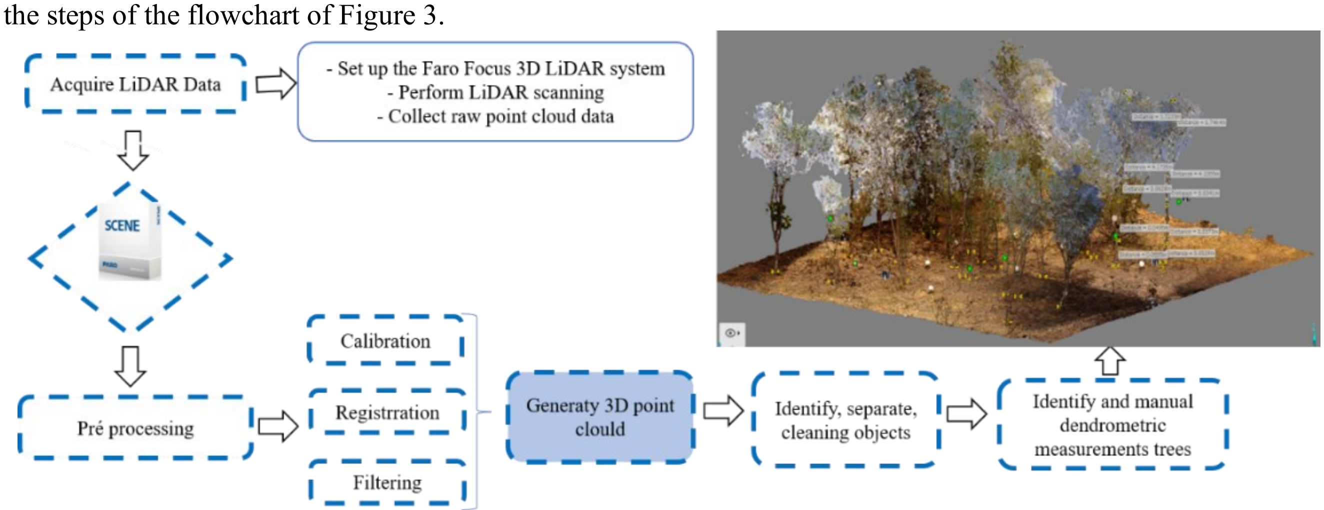

Figure 3 - Flowchart depicting the data processing steps of Faro Focus 3D LiDAR for the generation of 3D point clouds.

Analysis and statistical procedures

Initially, the dendrometric data with the variables measured in the field and extracted from the TLS point cloud were correlation analysis to identify the level of similarity between them through the correlation coefficient (r^2), significance level (p), and root mean square error (RMSE). Subsequently, the dataset was subdivided according to the method adopted by Souza et al. (2022), separating 60% of the data for the development of equations and 40% for their validation. Linear, logarithmic, exponential, and power functions were evaluated. Equations were selected based on the highest correlation coefficient (r^2), standard error of estimate (SEE), and significance level (p).

Equations available in the literature (Table 2), developed for areas of seasonally dry forest such as the Caatinga vegetation, were also tested to estimate the biomass (kg plant^{-1}) based only on dendrometric measurements.

The results were validated according to precision through comparisons of the following statistical indices:

Table 2 - Equations for estimating above-ground biomass (Kg plant^{-1}) based on plant diameter (D, cm) and height (H, m) in the dry tropical forest of Brazil.

Author	**Allometric equation**
Dalla Lana et al. (2018)	AGB = exp (-1.288 + 1.610*log(Db) + 0.434*log(Ht))
Sampaio et al. (2005) 1	AGB= 0.0644*DGL$^{2.395}$
Sampaio et al. (2005) 2	AGB= 0.173*DBH$^{2.295}$
Barreto et al. (2018)	AGB= 0.38*Db$^{1.73}$*Ht$^{0.11}$

*AGB = Above-Ground Biomass; Ht = Total Height plant; DGL = Diameter at Ground Level; Db = Diameter at 30 cm Height; DBH = Diameter at Breast Height.

Root mean square error (RMSE):

$$RMSE = \sqrt{\frac{\sum_i^n = 1\ (AGB_i - \widehat{AGB_i})^2}{n}} \quad (1)$$

Mean absolute error (MAE):

$$MAE = \sum_i^n = 1 \frac{(AGB - \widehat{AGB})}{n} \quad (2)$$

Coefficient of determination (R^2 Adj)

$$R^2{}_{Adj=} R^2 - \frac{[k-1]}{[n-k]} * 1 - R^2 \quad (3)$$

Bias between predicted and reference values:

$$BIAS = \frac{\sum_i^n = 1(AGBi - \underline{AGBi})^2}{n} / \underline{AGB} \quad (4)$$

where AGB_i is the observed aboveground biomass (kg plant^{-1}), $\widehat{AGB_i}$ is an estimate of the biomass (kg plant^{-1}), $\underline{AGBi}$ is the arithmetic mean of the observed biomass (kg plant^{-1}), n is the number of observations, R^2 is the coefficient of determination, and k is the number of parameters in the model.

Results

TLS could identify 100% of the plants with DGL ≥ 2.5, capturing the vegetation structure and allowing dendrometric measurements to be made from the 3D point cloud. The maximum and minimum data for plant height ranged from 7.3 to 1.2 m for data measured in the field and 7.8 to 1.2 m for those estimated by TLS, respectively. A small difference was also observed for crown height, with minimum and maximum values of 0.2 and 5.3 m for the data measured directly in the field, while the estimate made using the 3D point cloud of TLS reached 0.4 and 5.5 m, respectively. Thus, the measurements of plant height and crown height obtained by TLS were very close to those obtained in the field (Table 3).

The measurement values for the variable DGL ranged from 2.7 and 14.7 cm, while TLS estimated values ranged from 2.1 to 18.5 cm. The estimated measures of D40 ranged between 1.5 and 17.3 cm and were also very close to the values observed in the field, which ranged from 1.6 and 14.1 cm. Similarly, the variable D130 showed values varying between 1.1 and 11.2 cm in the field, while TLS showed a variation between 1.0 and 11 cm (Table 3).

All measurements of the variables extracted from the point cloud presented means very close to the data obtained in the field. Figure 4 shows the degree of precision of these data through correlation coefficient (r^2), significance (p), and RMSE. All variables had positive and significant correlation coefficients.

The variable total plant height (H) presented a correlation (r^2) of 0.80 and low RMSE (0.63 m), but this behavior was not observed for crown height (Hc), which presented an $r^2 = 0.39$ and RMSE = 1.78 m, mainly because the highest crown heights are far from linearity; this type of structure consists of mixing them, making identification difficult, overlapping them.

The measurements of the trunk diameter of plants showed a good relationship, standing out the diameter at ground level (DGL), which presented an $r^2 = 0.79$, indicating good performance of TLS in the estimation of this variable (Fig. 4c), which is very present and important in the estimation equations of the biomass of multi-stemmed plants, as can be observed in the Caatinga areas. Only equations obtained with the exponential model showed statistically significant coefficients at the 1% probability level. Equations obtained from linear, logarithmic, and power functions resulted in non-significant parameters, with $R^2 < 0.5$. The equations shown in Table 4 were parameterized from the two-parameter exponential model (a and b), statistically significant ($p < 0.0001$). More than 70% of the variation observed in the equations was explained by H, showing low SEE compared to the overall mean of AGB quantified in the field.

Table 3 - Average values of dendrometric measurements of caatinga plants obtained in the field and estimated from the TLS point cloud.

Method		H (m)	CH (m)	DGL (cm)	D40 (cm)	D130 (cm)
field	min	1.2	0.2	2.7	1.6	1.1
	max	7.3	5.3	14.7	14.1	11.2
	average	3.6	1.8	5.7	3.7	3.2
TLS	min	1.2	0.4	2.1	1.5	1.0
	max	7.8	5.5	18.5	17.3	11.0
	average	3.6	1.8	5.6	3.8	3.7

min = minimum, max = maximum, H= total plant height, CH= canopy heigh, DGL = diameter at ground level, D40 = diameter at 40 cm above ground, D130 = diameter at breast height or at 130 cm above ground surface.

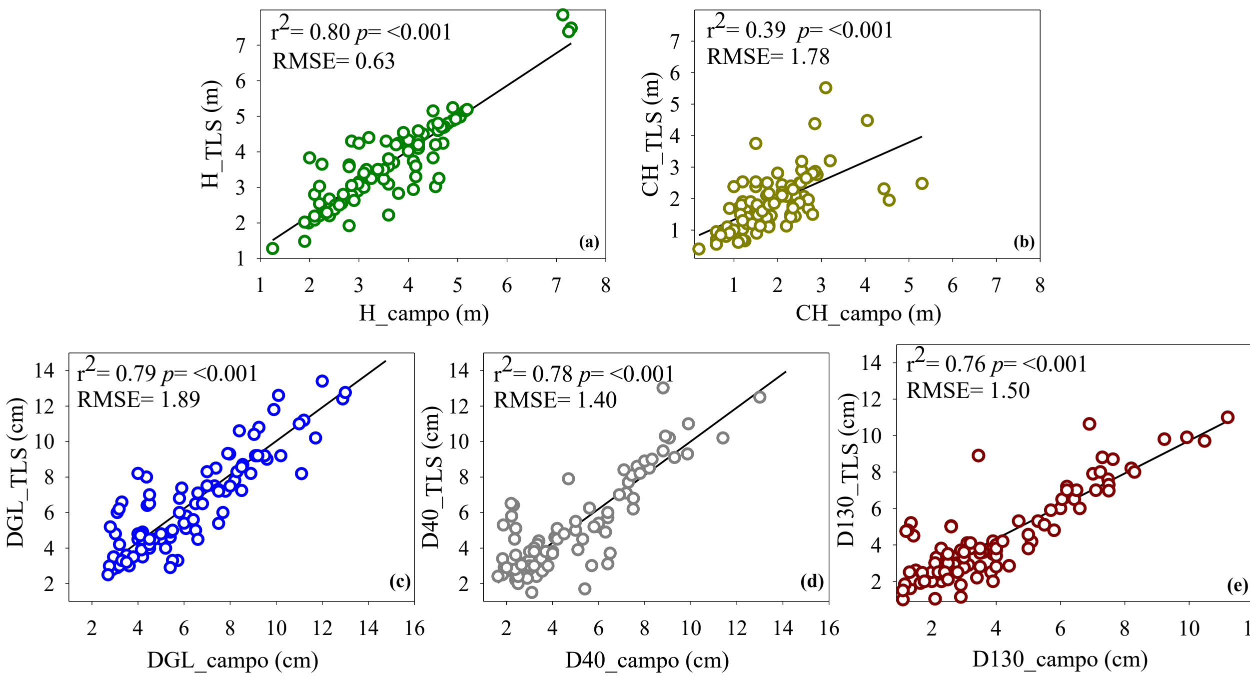

Figure 4 - Linear correlation and mean error between field observed data (x) and estimated TLS (y) for (a) Total plant height (H, m), (b) crown height (Hc, m), (c) trunk diameter at ground level (DGL, cm), (d) trunk diameter at height 40 cm (D40, cm) and (e) trunk diameter at height 130 cm (D130, cm), for caatinga plants in the municipality of Petrolina

Table 4 - Input parameters for biomass estimation using the equation of the form (y) = a. exp (b.x), in Kg per plant, based on field measurements and variables extracted from LIDAR TLS in the municipality of Petrolina, PE, Brazil.

Autor/ number	**method**	**Input variable**	**a**	Std. Error	**b**	Std. Error	$\mathbf{r^2}$	**SEE**	**ρ**
Carvalho 01	Field	DGL	0.15	0.05	0.44	0.02	0.90	4.98	<0.0001
Carvalho 02	Field	BA_{GL}	1.87	0.30	0.02	0.01	0.92	4.46	<0.0001
Carvalho 03	Field	H*DGL	1.86	0.41	3.67	0.22	0.86	5.88	<0.0001
Carvalho 04	TLS	H*DGL	2.81	0.43	2.67	0.12	0.89	5.16	<0.0001
Carvalho 05	TLS	H*D40	3.04	0.50	2.79	0.14	0.86	5.72	<0.0001
Carvalho 06	TLS	$H*BA_{GL}$	4.82	0.68	15.66	0.78	0.85	5.83	<0.0001
Carvalho 07	TLS	H*AB40	4.90	0.76	17.79	0.97	0.83	6.35	<0.0001

Total plant height (H, m), diameter at ground level (DGL, cm), ground-level basal area (BA_{GL}, cm²), diameter at 40 cm height (D40, cm), basal area at 40 cm height (AB40, cm²), standard error of estimate (SEE, Kg per plant).

Three equations (Carvalho 01, 02, and 03) using field data presented DGL, BA_{GL}, and the product H x DGL as explanatory variables, with positive and significant correlation coefficients (r^2) ranging from 0.86 to 0.92 (Table 4). Four equations (Carvalho 04, 05, 06, and 07) were generated with combined variables using data estimated with TLS, all involving the total plant height (H), as this parameter had a good correlation between measured and estimated data. The equations presented r^2 varying between 0.83 and 0.89, generating minimum estimation error (SEE) varying from 5.16 to 6.35 kg plant^{-1} for all equations.

The best-performing equation ($r^2 = 0.89$) with TLS data uses the combination of H x DGL (number 04), while the other equations

showed r^2 around 0.80, also demonstrating a good performance for biomass estimation. Moreover, the biomass estimation with the equation number 03 (field data) and the estimation using the equation number 04 (TLS data) presented the same explanatory variables (Table 4). In other words, these variables showed good correlations with each other individually and, consequently, expressed good relationships with biomass.

The statistical coefficients used to validate the equations generated in this study and those chosen from the literature are shown on Table 5. Data observed in the field and estimated from the point cloud were used according to each equation.

The estimates made using data measured in the field presented coefficients of determination (R^2) varying between 0.46 and 0.72, indicating relative dispersion between the observed and estimated values of biomass, which are considered satisfactory. The estimation equation number 03 obtained the highest R^2 and the other statistical indices were adequate, proving to be a good option for estimating the Caatinga vegetation biomass, considering the maximum diameter range of this study.

Table 5 - Statistical indices and fitness reliability for validating allometric equations for biomass estimation in seasonally dry tropical forest.

author/number	method	variable	R^2	MAE	RMSE	BIAS	$\overline{X}$
Carvalho 01	Field	DGL	0.63	0.19	5.6	1.14	5.11
Carvalho 02	Field	BA_{GL}	0.63	1.15	4.8	0.97	6.06
Carvalho 03	Field	H x DGL	0.72	0.56	3.3	0.67	5.46
Carvalho 04	TLS	H x DGL	0.44	1.09	4.5	0.91	6.01
Carvalho 05	TLS	H x D40	0.48	0.60	4.3	0.87	5.51
Carvalho 06	TLS	H x BA_{GL}	0.36	1.84	5.0	1.03	6.76
Carvalho 07	TLS	H x AB40	0.47	0.97	4.9	1.00	5.88
Dalla-Lana	Field	DGL	0.43	2.91	6.0	1.23	2.01
Sampaio, Silva 1	Field	DGL	0.60	1.56	4.6	0.94	6.47
Sampaio, Silva 2	Field	D130	0.61	9.18	5.0	2.83	5.40
Barreto	Field	DGL	0.59	6.30	8.5	1.73	11.21

Where: R^2 = coefficient of determination; MAE = mean absolute error (kg); RMSE = root mean square error (kg); X = mean biomass; Total plant height (H, m), diameter at ground level (DGL, cm), ground-level basal area (BA_{GL}, cm^2), diameter at 40 cm height (D40, cm), basal area at 40 cm height (AB40, cm^2), diameter at 130 cm height (D130, cm).

Among the equations developed in this research using data estimated through manual measurements extracted from the point cloud, the biomass estimated through the equations numbers 04 to 07 (TLS) showed R^2 ranging from 0.36 to 0.48 when correlating with field data, but MAE and RMSE values were considered low (< 0.60 Kg).

The most prominent equation number 05 using TLS data was AGB = a.exp (b. (H*D40), almost explaining 50% of the biomass variation, showing satisfactory indices and guaranteeing a biomass estimate with a low RMSE (4.3 Kg) and lower bias between observed and measured data (BIAS = 0.87).

Discussion

This research evaluated for the first time the potential use of TLS by multiple scans in a forest with highly heterogeneous structures, called STDF - Seasonally Dry Tropical Forest, in the Brazilian semi-arid region. All individuals were identified in the 3D cutting-off of the evaluated subareas. Beyene et al. (2020) found a similar result in a tropical forest in Malaysia using TLS by manual and automatic detection methods, reaching 99.55% of individual trees using the first method mentioned, detecting a higher number of individuals in the plot. Although 100% of the trees were identified, the adopted field method was based on the exclusion of individuals with DGL < 2.5 cm, that is, shrubs, small trees, and other vegetation were excluded from scanning with the LiDAR TLS and, consequently, from the analyses.

The results of this research showed a satisfactory correlation between field measurements and those estimated from the TLS point cloud. Plant height had an r^2 of 0.80, with standard deviations of 1.09 and 1.12 m for field and TLS data, respectively, and RMSE of 0.68 m. Beyene et al. (2020) used a similar methodology in a tropical forest and reached an $r^2 = 0.86$ and RMSE of 1.74 m. On the other hand, Wang et al. (2019) compared the ability of aerial and terrestrial laser techniques to estimate the height of trees in boreal forests and observed a better correlation when comparing TLS measurements and field data, with an $r^2 = 0.99$, demonstrating the potential of the TLS sensor in obtaining plant height. In this sense, Novotny et al. (2021) found a strong correlation for the same variable between field and TLS measurements ($r^2 = 0.91$), unlike that observed when comparing data automatically extracted from the TLS 3D point cloud and field ($r^2 = 0.78$).

A possible cause for differences in the coefficients that measure precision comparing them with other studies may be related to the number of tall and short trees. In this research, only three plants were taller than 7 m and 94 trees were taller than 5 m. Furthermore, information losses may occur due to overlapping of plants during the scan, leading to underestimations of upper plant structures (Srinivasan et al., 2015). It often happens in the Caatinga when there are several associations of species, with an intertwining of canopies sharing the same space.

The variable crown height showed a low but significant correlation ($p<0.0001$) ($r^2 = 0.39$) and RMSE of 1.78 m. This result is similar to other studies, in which the crown relationships normally show weak correlations, supposedly due to the crown instability induced by the wind action in the field condition at the time of the scan, which may have happened within the time of each scan, which lasted approximately 40 minutes. According to Li et al. (2020), this situation is not favorable for collecting data with high-quality TLS but inevitable when evaluating structural crown information derived from TLS. The effect of wind is reduced in areas with a higher plant density and also when evaluating lower vegetation structures.

In the case of the evaluated Caatinga subareas, the mean plant height of the order of 3.6 m did not require the positioning of the FARO Focus 3D equipment at a height greater than 1.5 m, which is therefore little influenced by the wind. However, the wind can cause a lot of movement in the branches and leaves at the upper canopy height, interfering with the return of the lasers to the sensor and distorting the configuration of the 3D point cloud. Scanning should be performed at times of lower wind speed to avoid these occurrences. Additionally, to accurately analyze the positioning of each scanning point, taking into consideration the area and the number of plants, as discussed by Rocha et al. (2023) when evaluating the capabilities of ALS (Airborne Laser Scanning), TLS (Terrestrial Laser Scanning), and the fusion of ALS + TLS data in detecting finer details of longleaf pine canopies in Florida, USA. These authors concluded that these tools perform well, but TLS is less practical and more costly.

Regarding the measurements acquired from the trunk of the plants at the three heights (ground level and 40 cm and 130 cm in height), the trunk diameter measured at the base (DGL) stood out, showing a higher correlation compared to D40 and D130, demonstrating the potential of TLS in scans close to the surface and possibly where there was less trunk occlusion, unlike the diameter measured at a height of 1.30 m (D130), which also resulted in a good correlation although having a lower r^2, It also resulted in a strong correlation, unlike what was observed in the research by Yrttimaa et al. (2022) using different methodological approaches to extract DBH (Diameter at Breast Height) measurements in boreal forests using TLS, providing accurate measurements when compared to ALS (Airborne Laser Scanning). Terryn et al. (2022) examined individual data from ALS, TLS, and their fusion in Australian tropical forests, concluding that TLS was capable of obtaining structural measurements with detail at the plot level compared to the other methods.

The lowest correlation for the variable D130 may be associated with the trunk thickness at this height, which had a mean diameter of 3.2 cm, with a maximum of 11.2 cm and a minimum of 1.1 cm. These data may be associated with a lower return of laser points, making it difficult to draw up a well-representative 3D point cloud for the conditions of the smaller Caatinga, which grows in more semi-arid areas in the Northeast of Brazil. Most studies have shown an $r^2 > 0.90$ using TLS and employing various algorithms developed to extract information from vegetation, adapting to specific purposes in different forest formations (Srinivasan et al., 2015; Reddy et al. 2018; Novotny et al., 2021; Terryn et al., 2022).

The main reason for evaluating the correlations in this research is related to the need to generate allometric equations with dendrometric input parameters obtained through the three-dimensional point cloud of the TLS scan and make applications and tests in equations already available in the literature for estimation of plant biomass in the

Caatinga using measures of plant structure. Other local and pantropical equations mostly used the variable D130 (DBH) to explain the biomass variation. Most available models for Caatinga use DGL and basal area in addition to D130 (Sampaio, Silva 2005; Dalla-Lana et al. 2018; Barreto et al., 2018). Although these high-resolution analyses can provide valuable information about vegetation dynamics in highly heterogeneous and fragmented landscapes such as the Caatinga, data limitations make analysis for the entire Caatinga domain impossible. For this purpose, remote sensing products that capture biomass information via satellite and/or that use vegetation indices to estimate biomass would be necessary.

The dataset presented here was composed of a combination of shrubs and small trees, with few plants considered robust with measures above average for the Caatinga, which limits the developed equations, requiring further studies expanding the scale of measurements. The lower diameter scale has been improved by adding other variables although there is a non-conformity in the estimates for trees with a larger diameter when there is no variable inclusion, resulting in substantially visible differences (Chave et al., 2005; Oliveira et al., 2021).

Although there are already some models for estimating the biomass of Caatinga plants, this study aims to present new equations developed for applications with TLS and also validate the widely used equations for Caatinga plants proposed by Sampaio and Silva (2005). Therefore, this study aims to propose a reduction of uncertainties with the robustness of non-destructive TLS-derived data when estimating dendrometric measurements for dry forests to quantify biomass.

Importantly, the variation in biomass accumulation may be associated with the forest successional stage, causing variability in the stock and distribution of biomass, number of tillers, or the wide spatial and seasonal variation of plants in the Caatinga, mainly as a result of irregular rainfall distribution (Lima Júnior et al., 2014; Virgens et al., 2017). The study area is considered mature, as it has been without anthropic action for more than 45 years, and completely in balance with the environment, influenced mainly by the environment, with scarce rainfall, low annual precipitations, an extensive dry period, temperatures of the order of 20.67 to 32.07 °C (minimum and maximum, respectively), and high evaporative demand.

The TLS technology was viable to estimate dendrometric measurements at the plot level in a seasonally dry forest of the Caatinga type, being considered of enormous potential to improve results of forest inventories and research in forest ecology in the collection of data quickly and efficiently, improving efforts in tree dendrometry (Calders et al., 2020).

A study in the Southeastern United States conducted by Adhikari et al. (2023) used TLS-derived data in equations to predict AGB (Above-Ground Biomass), achieving an adjusted R-squared (R^2adj) of 0.80, demonstrating the tool's potential.

Few studies have been conducted with TLS in tropical forests in Brazil, such as the research carried out in the Cerrado to evaluate the potential of TLS in identifying the forest structure of savannas, showing good performance of the technique in identifying structures, particularly where vegetation is sparse and allows for better scattering and return of laser pulses (Zimbers et al., 2021). However, it is not the reality of the Caatinga. This biome has smaller trees occurring with high density and often share the same treetop space. In addition, there are many species that develop multi-stems and others that are shrubby, contributing to making it difficult to scan with TLS. Consequently, a lower-quality 3D point cloud and lower correlations with data observed in the field by the traditional method are obtained. Thus, multiple scans at the edges and/or in the center of the plot might be required when using TLS in the Caatinga depending on the vegetation characteristics to obtain a good record and, consequently, a complete and well-representative three-dimensional point cloud.

Among the limitations of using allometric models to estimate biomass, the differences between the number of plants and the vegetation structure where the models were generated and where they will be applied may result in greater uncertainty in the results. There are examples of equations using data measured in the field that explain more than 80% of the biomass variability in the same region, but it was not observed here, demonstrating the ability to adjust and adapt the data, being in accordance with the conditions assumed by the equations and requiring further studies.

Therefore, the evaluation of new geotechnologies in ecosystems such as the Caatinga can improve existing methodologies and develop new equations to reach results closer to reality, mainly applied in the quantification of aboveground biomass to boost initiatives for carbon management, conservation, and restoration (Bispo et al., 2020). Still, TLS has enormous potential to be used as terrestrial truth in analyses of biomass products generated by satellites.

Conclusion

The terrestrial laser scanner (TLS) proves to be a viable tool with significant application potential for extracting structural parameters, particularly dendrometric measurements of Caatinga plants. Using three-dimensional point clouds through a manual method facilitated the extraction of crucial information, including plant height and trunk diameter for Caatinga plants.

This study proposed new allometric equations to elucidate biomass variation in seasonally dry forests, employing field measurements based on the product of plant height and diameter measured at the trunk base (ground level). Furthermore, the developed equations in this investigation are particularly well-suited for applications involving information derived from TLS-generated three-dimensional point clouds, with emphasis on plant height and trunk diameter measured at a height of 40 cm.

The streamlined process for obtaining structural information and vegetation biomass through TLS should be more widely adopted, mitigating the necessity for employing destructive, labor-intensive, and time-consuming field methods. Remote sensing techniques, including TLS and sensors embedded in robots, drones, and cell phones utilizing light detection and ranging (LiDAR) technology, can efficiently produce three-dimensional point clouds.

We propose equations for estimating Caatinga biomass based on dendrometric data extracted from the 3D cloud generated by TLS. However, further in-depth studies are warranted to explore the application of this tool and analysis techniques, particularly focusing on Caatinga. Key areas for future investigation include evaluating biomass at different times of the year to account for seasonal variations, expanding the sampled area for large-scale TLS applications, and exploring direct biomass estimation through measuring plant volume. These aspects represent essential avenues for advancing our understanding of TLS applications in the context of Caatinga ecosystem.

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