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FORESTRY SCIENCE

Remotely piloted aircraft system (RPAS) applied to the forest Inventory of *Tectona grandis* Linn f.: an RGB-based approach

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ABSTRACT: Advances in the forestry sector are closely linked to scientific research and the implementation of technologies in the areas of sensors, aerial images, GPS, learning algorithms, data processing, as well as the use of computer intelligence systems to obtain and analyze data in forestry plantations, which require tools that provide a higher degree of precision, reduced costs and less time for data collection. This constant evolution of the sector, together with the improvement of Remotely Piloted Aircraft Systems (RPAS), paves the way for the use of this platform in forest data collection. In this article we discussed the use of RPAS to obtain dendrometric and morphometric variables to estimate wood volume in two *Tectona grandis* Linn f. stands, where field measurement and overflight were carried out using the Phantom 4 Pro RPAS. The aerial photos were processed using Pix4Dmapper software to generate the orthomosaic, digital terrain model and surface. Using these products, information was collected on the total height, crown area and crown diameter of the trees, with the aim of estimating volume (v) using the variables collected from the images (indirect method) and with the addition of the variables collected in the field (direct method). The estimates of v showed satisfactory results through the evaluation statistics, and it was possible to estimate forest production from data obtained by RPAS, obtaining an adjusted coefficient of determination of 66% in the indirect method and the estimate together with the field data showed an adjusted coefficient of determination of 94%.
Key words: remotely piloted aircraft system (RPAS), wood volume estimation, forest Inventory, *Tectona grandis* Linn f.

Sistema de aeronave remotamente pilotada aplicada ao inventário florestal de *Tectona grandis* Linn. f.: uma abordagem baseada em RGB

RESUMO: O avanço do setor florestal está intimamente ligado às investigações científicas e a implementação de tecnologias aos segmentos de sensores, imagens aéreas, GPS, algoritmos de aprendizagem, processamento de dados, bem como a utilização de sistemas de inteligência computacional para obtenção e análise de dados em plantios florestais, os quais, prezam por ferramentas que proporcionem maior grau de precisão, redução de custos e menor tempo para coleta de dados. Essa constante evolução do setor, juntamente com o aperfeiçoamento de Sistemas de Aeronaves Remotamente Pilotadas (RPAS), abre caminho para o uso desta plataforma em levantamentos florestais. Neste artigo abordamos o uso de RPAS para obter variáveis dendrométricas e morfométricas para estimar o volume de madeira em dois talhões de *Tectona grandis* Linn f., onde foi realizado a mensuração de campo e sobrevoo com o RPAS Phantom 4 Pro. As fotos aéreas foram processadas no software Pix4Dmapper, para a geração do ortomosaico, modelo digital de terreno e superfície. Por meio destes produtos foram coletadas as informações referentes à altura total, área de copa e diâmetro de copa dos indivíduos, com o objetivo de realizar estimativas de volume (v) com as variáveis coletadas pelas imagens (método indireto) e com a adição das variáveis coletadas em campo (método direto). As estimativas de v apresentaram resultados satisfatórios através das estatísticas de avaliação, sendo possível estimar a produção florestal a partir de dados obtidos por RPAS, obtendo um coeficiente de determinação ajustado de 66% no método indireto e a estimativa juntamente com os dados de campo apresentou coeficiente de determinação ajustado de 94%.
Palavras-chave: sistemas de aeronaves remotamente pilotadas (RPAS), estimativa de volume de madeira, inventário florestal, *Tectona grandis* Linn f.

INTRODUCTION

Forest plantations provide a wide range of inputs used in various sectors of industry. In Brazil, according to the annual report of the Brazilian Tree Industry (IBÁ, 2022; IBÁ, 2023), the planted tree sector has grown by 20.5% in the last decade, in terms of added value. The forestry production chain grew by 7.5% in 2021, reaching gross sector revenue of 244.6 billion BRL, accounting for 1.3% of the

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Brazilian economy. The planted forest area covers 9.94 million hectares, with eucalyptus plantations occupying 7.6 million hectares, followed by pine with 1.9 million hectares and 497,000 hectares distributed among other species (rubber tree, acacia, teak and paricá wood).

Among the other species, *Tectona grandis* Linn f. (Teak) represents 15.29%, with a planting area of 76,000 hectares, being 70,000 hectares only in the state of Mato Grosso, Brazil (IBÁ, 2017). The management of these plantations depends on information about the quality and quantity of available forest resources, in addition to other characteristics of the areas on which the species is being managed. Generally, this information is obtained mainly through the forest inventory (HUSCH et al., 1993); however, due to the high costs of this activity, many companies fail to do so, saving financial resources to keep the activity economically viable. To achieve this goal, alternative methods are sought to reduce costs and increase efficiency in obtaining information about forest plantations (MIRANDA et al., 2015; WANG et al., 2021).

An alternative to obtain this information are the Remotely Piloted Aircraft Systems (RPAS), which prove to be a versatile tool, in addition to assisting in the planning and execution of forest planting. The use of images to obtain information in forest plantations is the subject of study over decades (GOODBODY et al., 2017; RAHLF et al., 2017; WEBSTER et al., 2018; WANG et al., 2021).

The advantages of RPAS compared to manned aerial surveys and orbital sensors are: significant cost reduction for obtaining high spatial and temporal resolution images; the possibility of executing the most diverse flight plans; minimization of potential risk to life; greater versatility of application of the collected data (LONGHITANO 2010; LIMA NETO et al., 2012; SLOMPO, 2013; CARNEIRO, 2015).

The images acquired by the RPAS constitute the basis for the construction of digital surface models (MDS) and orthomosaic models. Due to their high spatial resolution, the derived products inherit these characteristics, and can be used for the most varied purposes, such as: evaluation of the quality of plantings; phytosanitary evaluation; incidence of pests; quantification and location of faults and glades; planning and support for forest management; obtaining dendrometric, morphometric variables and monitoring as described by LIMA NETO (2012); SLOMPO (2013); NUNES et al. (2014); CARNEIRO (2015); BANU et al. (2016) and PANAGIOTIDIS et al. (2016). Among the sensor options for data acquisition mounted on RPAS, this study investigated the feasibility of using RPAS equipped with an RGB sensor to estimate the wood volume of *Tectona grandis* Linn f. through indirect and direct methods. The research evaluated the accuracy of plantation volume estimates using variables obtained from aerial imagery along with field-measured variables (diameter estimation method), and as a second volume estimation approach, using only the variables derived from the images.

MATERIALS AND METHODS

Area of study

The study was conducted on the Panflora farm belonging to the TRC company, located in the municipality of Rosário Oeste, approximately 110 km from Cuiabá, Mato Grosso, Brazil, in two plots of *Tectona grandis* Linn f. of seminal origin, identified as plots 18 and 19 (Figure 1), with 53 hectares and 81 hectares respectively, totaling 134 hectares, planted on January 12, 1998 with initial spacing of 3 m x 3 m. Where throughout its development it was subjected to 4 thinning and 1 phytosanitary thinning.

The climate, according to Köppen-Geiger classification for the planting region is of the AW type (Savanna Tropical with winter dry season), characterized by two well-defined seasons: one dry, corresponding to autumn and winter, going from May to September, and another humid, with torrential rains, corresponding to the period from spring to summer, showing average annual precipitation of 1,335 mm and average temperatures ranging from 22 ºC to 25 ºC (Brazil, 1997). According to CHIARANDA et al. (2015), the study area is located in the Cuiabá River basin, with land between altitudes of 100 to 900 m, predominating the levels of 200 m to 300 m in the *Cuiabana* depression and Casca Plateau, where the study area is located. The soils are classified as Dystrophic Concretionals (SCd) and the original vegetation cover is Open Arboreal Savannah with Gallery Forest (Saf).

Data collection

The data collection of this study was performed in two distinct and independent stages, the first through field measurement and the second through RPAS.

Field measurement

The field measurement was performed through systematic sampling, with 7 (seven) rectangular

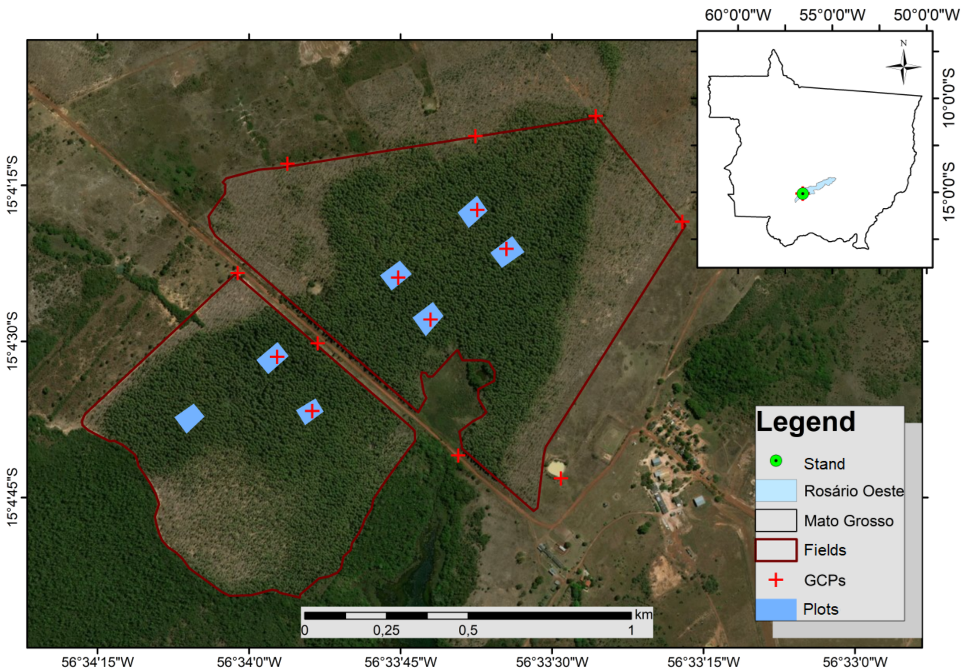

Figure 1 - Location of the study area in the municipality of Rosário Oeste - Mato Grosso, Brazil (Datum SIRGAS 2000).

plots of 4125 m^2 (75 m x 55 m), where the variables diameter at chest height (d) were measured with the use of a tree caliper; Total height (h) with the use of hypsometer and volume (v) with the use of Criterion RD-1000. Non-destructive cubing was performed through the Smalian method in 30 individuals according to the diametric distribution, collecting the diameters at the absolute heights of 0.1 m; 0.3 m; 0.5 m; 0.9 m; and 1.30 m with the tree caliper, and the other measurements were taken with the Criterion RD-1000 at regular intervals of 1 m, up to the maximum observable height. The field measurement data will be used to determine the volume of the measured individuals belonging to the plots and calculate the wood volume of the plantation, to compare with the values estimated from the data collected by RPAS.

Data collection by RPAS

For the execution of data collection, the RPAS Phantom 4 Pro was used, with a 1” 20 megapixel CMOS RGB sensor, with an 8-element lens and a mechanical shutter; Gimbal with 3-axis stabilization; 5870 mAh batteries; Phantom 4 Pro controller, with Hd video transmission system in radio frequency of 5.8 GHz and or 2.4 GHz; GNSS receiver, Accelerometer, IMU (Inertial Measurement Unit) and external card for image storage.

In the plots where the field measurement occurred, manual mowing was performed, due to the natural regeneration exerting a negative influence on the processing of the images to obtain the Digital Terrain Model (MDT), a fact reported by NUNES (2014), where the presence of natural regeneration resulted in displacement of the z axis (elevation) in the MDT in the same ratio as the height of regeneration. Another important aspect of this practice is the greater light permeability inside the plot, providing the collection of information that represents the ground level, corroborating the increase in the accuracy of the MDT; and consequently, the information regarding the total height of the trees, as well as allowing the installation of control points inside the plot.

Aiming to give a greater degree of precision to the MDT and orthomosaic, 14 Ground Control Points (GCPs) were installed, distributed in the study area and inside the plots, using metal targets around the plots, and limestone powder was used inside the plots. The coordinates of the GCPs were collected with the GNSS (Global Navigation Satellite System) Topcom Hiper Lite+ and used for the georeferencing of the images. For the images collection, 6 overflies were carried out, with an average time of approximately 11 minutes, an average distance of displacement of the RPAS of 7.1 km, and the collection of 1,630 photographs for total coverage of the area. The covering used longitudinally was 90%, lateral 80% and flight height of 190 m, flight speed of 14 $m.s^{-1}$ and 2 seconds of interval between capturing photographs obtaining Ground Sample Distance (GSD) calculated of 5 cm.

The camera settings for capturing the images were set manually, using the resolution of 20 megapixels in the 4:3 ratio, to minimize the curvature effect generated by the horizontal aperture that images with 16:9 ratio produce. The exposure time was 1/640 s, ISO-100 and focal length of 9 mm.

Image processing

The image processing was performed using Pix4Dmapper software, utilizing the default parameters of the Structure from Motion (SfM) and Multi-View Stereo (MVS) algorithms, along with the GCPs, to generate the point cloud and orthomosaic (Pix4D, 2017; Jiang, S. et al., 2018). Due to the canopy openness and the presence of GCPs within the plots, it was possible to generate the Digital Terrain Model (DTM), which was manually adjusted to ensure that ground points were correctly identified.

Although, the software offers an automatic point cloud classification option, three tests were performed using standard parameters to distinguish points corresponding to the ground. However, the automated methods were unable to accurately identify the ground, leading to the need for manual filtering to provide greater accuracy to the DTM, which consequently directly impacts the quality of the Digital Height Model (DHM). After obtaining the models, the DTM was subtracted from the Digital Surface Model (DSM), resulting in the DHM, which was used for classification, identification, and collection of information from individuals.

After obtaining the DHM, Geographic Object-Based Image Analysis (GEOBIA) was performed for segmentation and classification of individuals. This process was conducted in e-Cognition software, using RGB bands combined with height information from the DHM. The algorithms applied involved region-growing segmentation techniques, texture analysis, and supervised classification. The intention was to consolidate the pixels corresponding to crowns into a single object representing each tree in the plantation. However, due to the intersection between adjacent crowns, the parameters used returned objects containing the crowns of more than one individual, making automatic separation unfeasible.

To address this challenge, the objects classified as “Crown” were exported to ArcGIS 10.2 software, where manual merging of polygons corresponding to each tree’s crown was performed, allowing their respective identification according to field measurements (Figure 2). From this process, the following variables were extracted: Crown Area by RPAS (ca_R), Crown Diameter by RPAS (cd_R), Total Height by RPAS (h_R), and the Degree of Slenderness (DS) variable of individuals was calculated for use in the equations.

Database

The data collected in the field measurement and through RPAS showed the following descriptive statistics (Table 1).

The possible candidates for outliers were not considered in this way, because they portray the field reality, describing the variation of seminal planting at the end of the cycle. The diametric distribution of the planting is represented in figure 3, using an amplitude of 5 cm. Based on the diametric distribution, 30 trees were selected to perform cubing by the Smalian method, and the other individuals had their volume estimated through the adjusted model proposed by SCHUMACHER & HALL (1933) Equation 1.

$$V = 0.000450 * d^{1.561407} * h^{0.650112} \quad (1)$$

Volume estimation using DAP’s estimated values

From the variables collected through Orthomosaic and MDA, the regression analysis was

Table 1 - Descriptive presentation of the data collected in the forest inventory.

Variables	Min	Median	Average	Max	CV (%)	n
d (cm)	24.85	37	37.31	52.6	12.7914	
h (m)	18	25.6	25.33	29.8	8.6574	
h_R (m)	18.49	23.23	23.28	27.6	6.6565	365
ca_R (m^2)	9.42	44.64	45.40	91.70	29.2058	
cd_R (m)	3.46	7.54	7.52	10.81	15.0591	

Where: ca_R = Crown area by RPAS; d = Diameter at chest height; cd_R = Crown diameter by RPAS; h = Total height; h_R = Total height by RPAS.

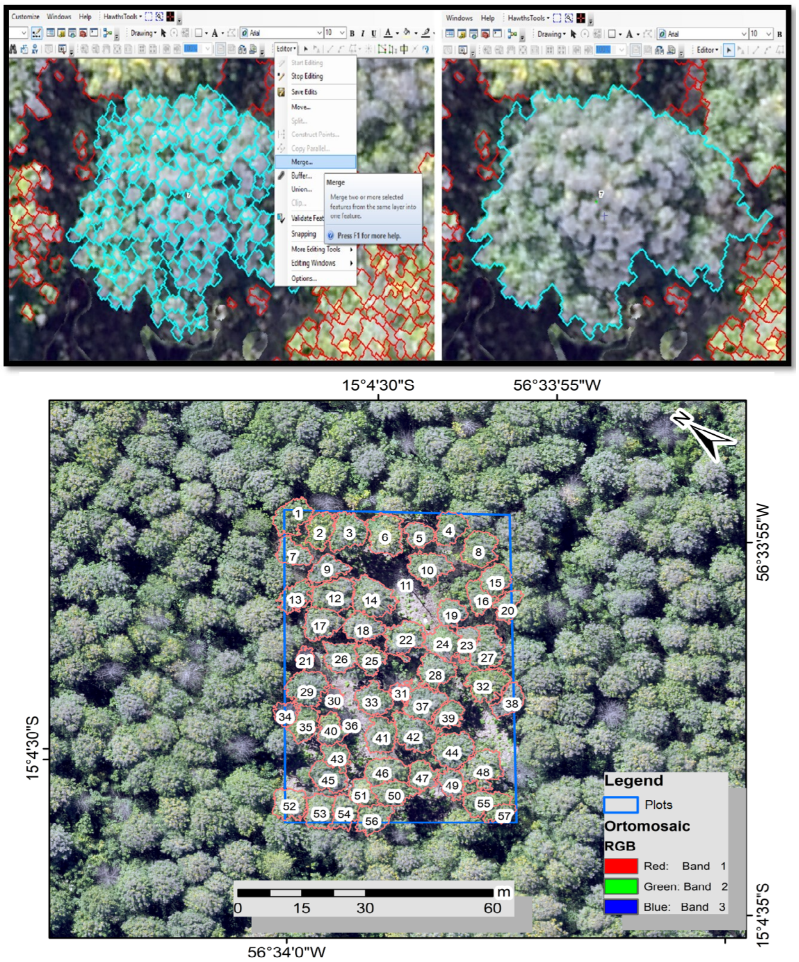

Figure 2 - Merging of crown objects and identification of forest inventory individuals.

performed to estimate the Chest Height Diameter (d_E) and individual basal area (g) from the variables Crown Area obtained by RPAS (ca_R), Crown Diameter obtained by RPAS (cd_R) and Total Height obtained by RPAS (h_R), through the models shown in table 2.

Based on the statistical results of the models presented in table 2, the model for volume prediction will be selected according to the models in table 3. Models 5 and 7 were modified by replacing the Crown Diameter variable with the estimated Degree of Slenderness and DAP with the Crown Area obtained by RPAS. This alteration is based on the existing relationship between crown area and the structural development of the individuals, allowing for an indirect correlation. The inclusion of ca_R as a predictor variable aimed to improve the modeling, facilitating the use of the data collected with the RPAS.

Volume estimation using variables obtained by RPAS

Table 4 shows models used to estimate the volume from the variables ca_R, cd_R and h_R.

Statistical analysis

The selection of models will be based on the following evaluation statistics: graphical analysis of residues E(%) (2); standard estimation error (S_{yx}) (3) and adjusted coefficient of determination (R^2_{aj}) (4).

$$E(\%) = \frac{(Y_i - Y_i')}{Y_i} * 100 \quad (2)$$

$$S_{yx}(\%) = \frac{\sqrt{\frac{\sum(Y_i - Y_i')^2}{n-p}}}{\bar{Y}} * 100 \quad (3)$$

$$R^2_{aj} = 1 - \frac{n-1}{n-(p+1)} - \frac{SQ_{res}}{SQ_{total}} \quad (4)$$

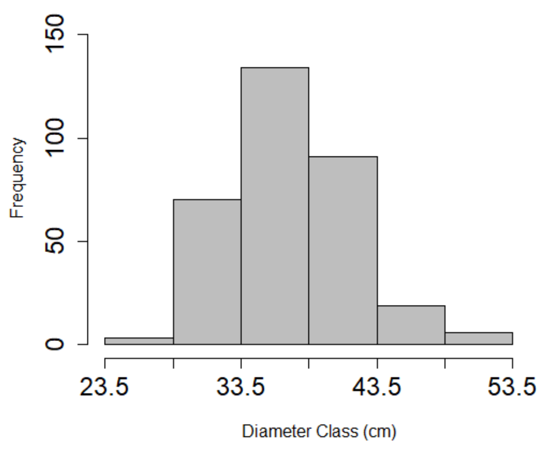

Figure 3 - Diametric distribution of the stand.

The models with the best statistical parameters for the estimation of diameter and volume will be submitted to validation, where 10% of the data were separated to verify the difference between the actual volume and the estimated volume through the methods. All statistical analysis were performed in the R software version 3.3.2 (R CORE TEAM, 2016).

RESULTS AND DISCUSSION

Volume estimation using DAP's estimated values

The models used to estimate the diameter and basal area showed error of the estimate of less than 22%, the highest errors were observed in the models that use ca_R for the prediction of the basal area (g). The other models showed S_{yx}(%) below 11%, where model 8 showed the best result. In general, the adjusted termination coefficient (R^2_{aj}) had low values, the highest value obtained from R^2_{aj} was from model 8, being chosen to perform the volume estimation, show in table 5.

Model 8 has the caveat of not presenting significance in all its coefficients, restricting its application. The models showed low value for R^2_{aj} and E(%), a fact resulting from the high diametric variability of the planting. The graphic analysis of the residues (Figure 4) shows the variability of the cd_R as a function of the d for the trees that are in the initial and final classes of diameter and in the initial and final classes of the diametric distribution of the planting, overestimating the lower diameters and underestimating the upper diameters, with the exception of model nº 3, which, due to its mathematical construction reverses this relationship.

The distribution of the residues of models nº 1, 2, 4, 6 and 8 is similar, showing the tendency of overestimation of the lower diameters and underestimation of the upper diameters, being a

Table 2 - Proposed models for estimation of diameter at chest height and basal area, from the variables obtained by RPAS.

Model Number	------------------------------------Model----------------------------------	---------------------Source--------------------
1	$d_E = \beta_0 \, cd_R$^β_1	SANQUETTA (2014)
2	$d_E = \beta_0 + \beta_1 \, cd_R$	OLIVEIRA (1980)
3	$1/d_E = \beta_0 + \beta_1 \, 1/cd_R$	SANQUETTA (2014)
4	$\ln(d_E) = \beta_0 + \beta_1 \ln(cd_R)$	SANQUETTA (2014)
5**	$\ln(g_E) = \beta_0 + \beta_1 \ln(ca_R)$	SANQUETTA (2014)
6	$d_E = \beta_0 + \beta_1 \, cd_R + \beta_2 \, cd_R^2$	SANQUETTA (2014)
7**	$g_E = \beta_0 + \beta_1 \, ca_R + \beta_2 \, ca_R^2$	SANQUETTA (2014)
8	$d_E = \beta_0 + \beta_1 \, cd_R + \beta_2 \, h_R \, cd_R + \beta_3 \, cd_R^2$	OLIVEIRA (1980)

Where: ca_R = Crown area by RPAS; d_E = Estimated diameter at chest height; cd_R = Crown diameter by RPAS; g_E = estimated individual basal area; h_R = Total height by RPAS; **Modified.

positive slope trend of the residues, while the models nº 5 and 7, which use the variable ca_R as an independent variable to estimate the basal area (g), have a greater amplitude, demonstrating that a small variation in the crown radius (ca_R) exponentially influences the calculation of the basal area. Thus, model nº 8 was selected for use in the volume prediction models arranged in table 3.

The evaluation statistics of the volume prediction models (Table 6) as well as the graphic analysis of residues (Figure 5) indicated the model proposed by FIGUEIREDO et al. (2014) as suitable to perform the volume estimation, in the model of SCHUMACHER & HALL (1933), the effect of positive inclination of the residues is present, while in the residues of the model of FIGUEIREDO et. al. (2014) there was a tendency to underestimate the diameters below 30 cm. The model obtained a satisfactory result, where the separate data for validation demonstrate the success of the model in the volumetric prediction of individuals (Figure 6), presenting an R^2_{aj} of 0.94 (94%) and significance in all coefficients.

Volume estimation with variables obtained by RPAS

The models proposed for volume estimation showed $S_{yx}(\%)$ less than 20% and R^2_{aj} ranging from 0.29 to 0.66 (Table 7). The best result was from model nº 6 proposed by FIGUEIREDO et al. (2014), which was adapted to the variables used in this work. The Model showed the lowest slope trend in its residual distribution (Figure 7), differing from the other models. Validation data prove the R^2_{aj} of 66% (Figure 8), with a tendency to underestimate.

The tendency to underestimate is proven by observing table 8, where forest production is presented, from the volume estimate using the estimated diameter and the volume estimate with the variables obtained by RPAS compared to the traditional forest inventory.

The results of the volume estimate through the estimated diameter demonstrated the possibilities of using the variables obtained by RPAS for the volumetric prediction, but the values of R^2_{aj} and $S_{yx}(\%)$ differ from those obtained in the studies of OLIVEIRA (1980 and 1982), ORELLANA & KOEHLER (2008), COSTA et al. (2014) and SANQUETTA et al. (2014), where the R^2_{aj} are between 57-83.9% and the $S_{yx}(\%)$ less than 28%.

Using aerial photographs to obtain the dendrometric parameters of *Araucaria angustifolia* in natural stands, OLIVEIRA (1980) reported the difficulties encountered in obtaining the crown diameters, due to the existing overlap between the crowns, also verifying a high correlation between the diameter at the height of the chest and the diameter of the crown. ORELLANA & KOEHLER (2008) studied the morphometric relationships of *Ocoteia odorífera*, and using the model proposed by OLIVEIRA (1982) they obtained lower values of R^2_{aj} and $S_{yx}(\%)$. COSTA et al. (2014) evaluated the relationship of the cd_R according to the d for *Araucaria angustifolia* in natural forests using the model proposed by OLIVEIRA (1980) and obtained values of R^2_{aj} and $S_{yx}(\%)$ higher than those of OLIVEIRA (1980). SANQUETTA et al. (2014) in their study of equations to estimate the crown diameter of the species *Acacia decurrens* obtained satisfactory results with R^2_{aj} and $S_{yx}(\%)$ between 50-60% and 13-28% respectively, being the result of the adjustments resulting from the variability of the crown diameter as a function of the diameter at the height of the chest for trees with larger or smaller dimensions.

However, the comparison between the different studies should be made with caution, as many factors, for example, peculiarities of the study area, data quality and data collection technologies can influence the statistical results. The R^2_{aj} in this study is lower than that obtained in other studies, mainly for the estimation of *d* as a function of cd_R and h_R, used in model nº 8. As the main reason, we suspect the amount of thinning to which the planting was subjected, causing the great variability in the *d* in relation to the cd_R, resulting from the improvement of some individuals due to the elimination of competition for thinning, when compared to other individuals, that suffered greater influence by competition, with their growth restricted. Another relevant aspect in this case is the fact that the planting is from seminal origin, collaborating for greater heterogeneity, and in the case of the elimination of competition, individuals can express their crown growth characteristics, corroborating so that the correlation between d and cd_R is modified.

The use of *d* estimates generated by model nº 8 in the model proposed by FIGUEIREDO et al. (2014), obtained very accurate R^2_{aj} and $S_{yx}(\%)$ results, close to those described in their study, where FIGUEIREDO et al. (2014) propose equations to estimate the volumetry of individual trees by the morphometry of the crown obtained with Lidar data. Showing that obtaining morphometric variables and applying these in equations give a greater degree of accuracy to the estimates. In the studies of OLIVEIRA (1980), ORELLANA & KOEHLER (2008), COSTA et al. (2014) and SANQUETTA

Table 3 - Selected models for volume estimation using dE.

Model Number	---------------------------Model-------------------------	--------------------------Source--------------------------
1	$v = \beta_0 * d_E \hat{} \beta_1 * h \hat{} \beta_2$	SCHUMACHER & HALL (1933)
2	$v = \beta_0 + \beta_1 * d_E + \beta_2 * DS + \beta_3 * ca_R + \beta_4 * ca_R^2$	FIGUEIREDO et al. (2014)

Where: ca_R = Crown area by RPAS; d_E = Estimated diameter at chest height; DS = Degree of slenderness (h_R/d); h_R = Total height by RPAS; v = Volume.

Table 4 - Proposed models for volume estimation from the variables obtained by RPAS.

Model Number	------------------------------Model----------------------------	-----------------------------Source-----------------------------
1	$v = \beta_0 + \beta_1 h_R + \beta_2 h_R.cd_R + \beta_3 cd_R$	OLIVEIRA (1980)
2	$v = \beta_0 + \beta 1\ cd_R + \beta_2 cd_R^2 + \beta_3 h_R.cd_R$	OLIVEIRA (1980)
3	$\ln(v) = \beta_0 + \beta_1 \ln(cd_R) + \beta_2 (1/cd_R)$	LENZI et al. (2016)
4**	$\ln(v) = \beta_0 + \beta_1 \ln(ca_R) + \beta_2 (1/ca_R)$	LENZI et al. (2016)
5*	$v = \beta_0\ cd_R \hat{} \beta_1\ h_R \hat{} \beta_2$	SCHUMACHER & HALL (1933)*
6*	$v = \beta_0 + \beta_1 cd_R + \beta_2 DS_R + \beta_3 ca_R + \beta_4 ca_R^2$	FIGUEIREDO et al. (2014)*

Where: ca_R = Crown area by RPAS; d = Diameter at chest height; DS = Degree of slenderness (h_R/d); h_R = Total height by RPAS; v = Volume; *Adapted, **Modified.

Table 5 - Coefficients and adjustment indicators for the diameter estimation models at chest height (d) for *Tectona grandis* Linn f.

Nº	------------------Model-----------------	β_0	β_1	β_2	β_3	R^2_{aj}	S_{yx} (%)
1	$d = \beta_0\ cd_R \hat{} \beta_1$	15.6861*	0.4301*	-	-	0.274	10.65
2	$d = \beta_0 + \beta_1\ cd_R$	20.7315*	2.1970*	-	-	0.281	10.60
3	$1/d = \beta_0 + \beta_1\ 1/cd_R$	0.0170*	0.0752*	-	-	0.278	10.45
4	$\ln(d) = \beta_0 + \beta_1 \ln(cd_R)$	2.7754*	0.4161*	-	-	0.274	10.65
5	$\ln(g) = \beta_0 + \beta_1 \ln(ca_R)$	-3.8004*	0.4161*	-	-	0.263	21.86
6	$d = \beta_0 + \beta_1\ cd_R + \beta_2\ cd_R^2$	30.7698*	-0.5946	0.1895	-	0.285	10.57
7	$g = \beta_0 + \beta_1\ ca_R + \beta_2\ ca_R^2$	0.0772*	0.0003	$-8.7e^{-6}$	-	0.279	21.63
8	$d = \beta_0 + \beta_1\ cd_R + \beta_2\ h_R\ cd_R + \beta_3\ cd_R^2$	29.6137*	-3.0582	0.1470*	0.0835	0.393	9.74

Where: ca_R = Crown Area by RPAS; d = Diameter at chest height; cd_R = Crown Diameter by RPAS; g = individual basal area; h_R = Total Height by RPAS; *= significant coefficients.

Table 6 - Coefficients and adjustment indicators for volume estimation models through estimated diameters for *Tectona grandis* Linn f.

Nº	Model	β_0	β_1	β_2	β_3	β_4	R^2_{aj}	S_{yx} (%)
1	$V = \beta_0 * d_E \hat{}\ \beta_1 * h \hat{}\ \beta_2$	0.0006*	1.5890*	0.5350*	-	-	0.470	16.68
2	$V = \beta_0 + \beta_1 * d_E + \beta_2 * DS + \beta_3 * ca_R + \beta_4 * ca_R^2$	0.3006*	0.0837*	-2.8458*	-0.0138*	$2.6e^{-5}$	0.939	5.65

Where: * = significant coefficients; ca_R = Crown area by RPAS; d_E = Estimated diameter at chest height; DS = Degree of slenderness; h_R = Total height obtained by RPAS.

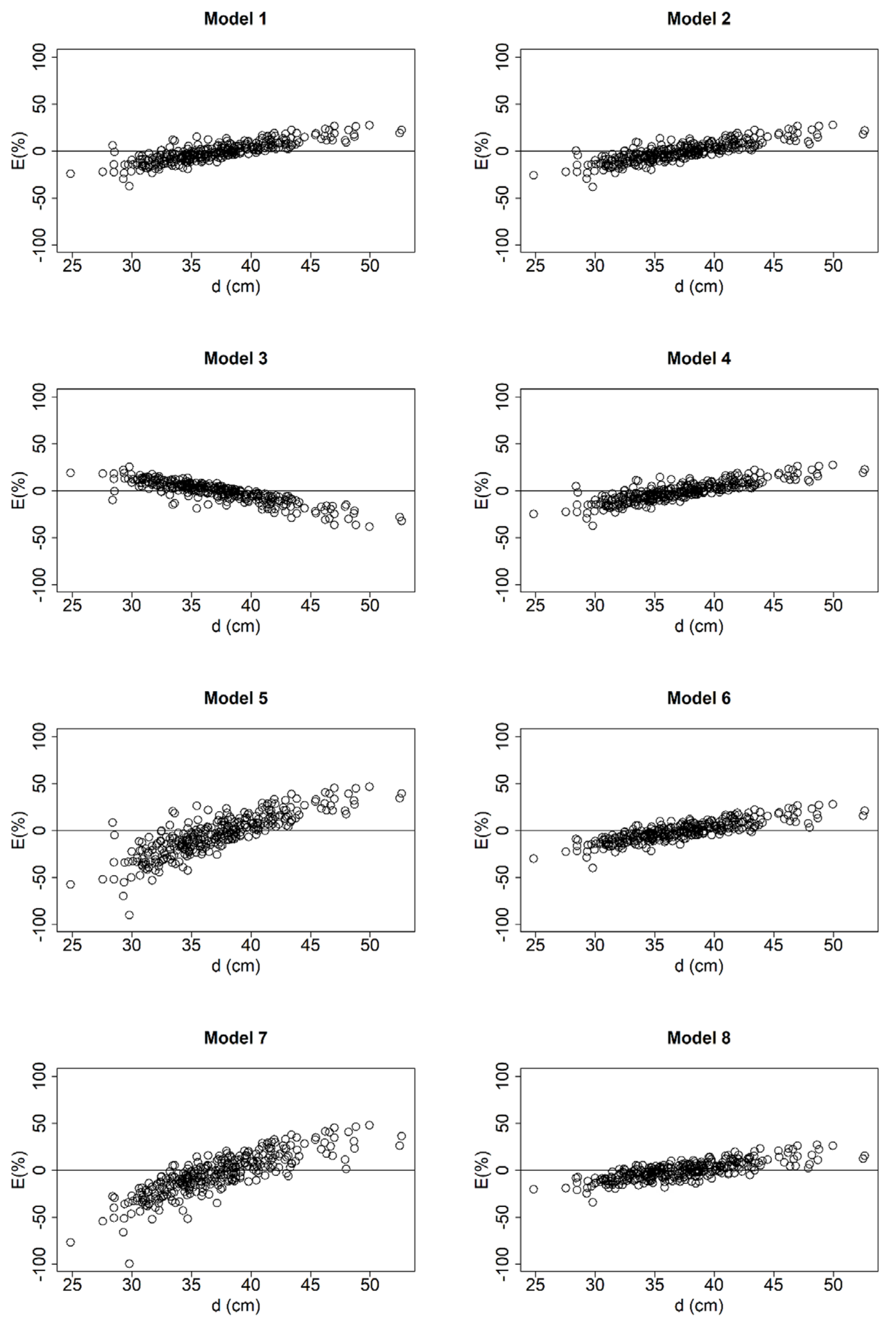

Figure 4 - Distribution of residuals from the diameter estimation models at chest height (d) for *Tectona grandis* Linn f. obtained with RPAS.

et al. (2014) the morphometric variables were not present, decreasing their predictive capacity, or limiting the predictive power to the correlation between the diameter at chest height and the crown diameter of the species studied.

CONCLUSION

From the high-resolution images obtained by RPAS in this study it was possible to obtain images with sufficiently high resolution (GSD of 5 cm) which

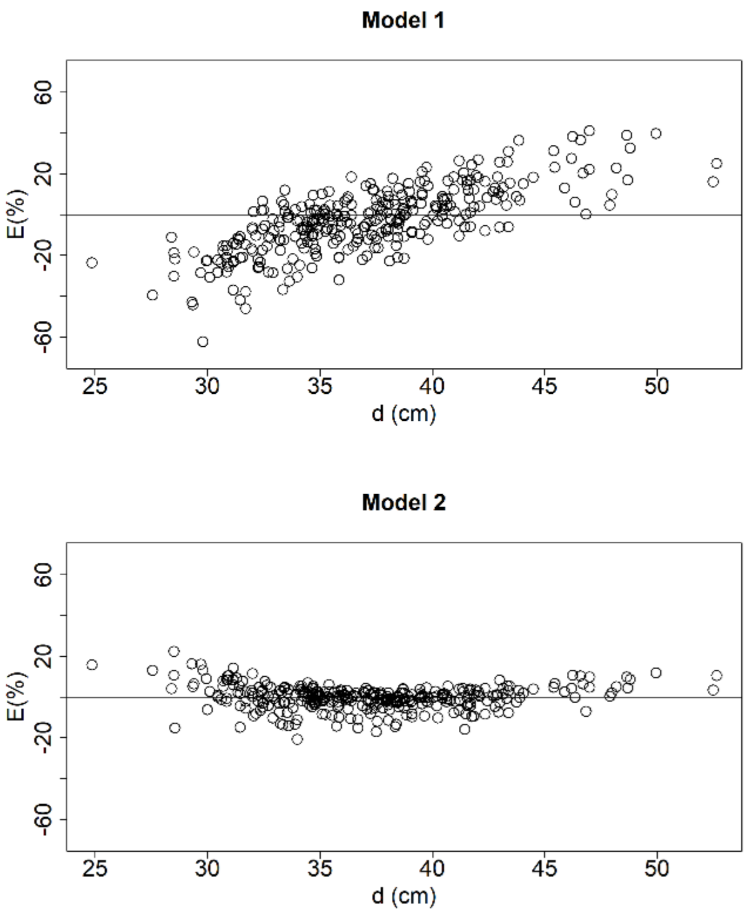

Figure 5 - Distribution of residuals from volume estimation models through the estimated diameters for *Tectona grandis* Linn f. by model 1 (SHUMMACHER & HALL, 1933) and model 2 (FIGUEIREDO et al., 2014).

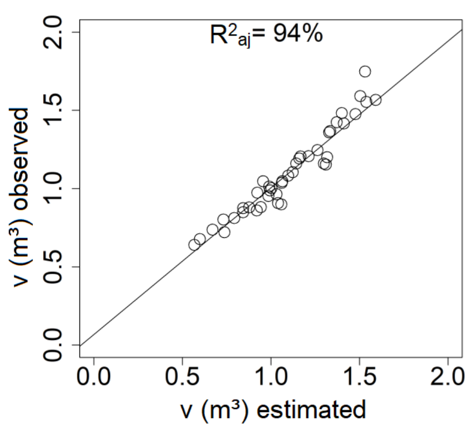

Figure 6 - Volume observed vs. volume estimated by the model of FIGUEIREDO et al. (2014).

Table 7 - Coefficients and adjustment indicators for volume estimation models for *Tectona grandis* Linn f.

Nº	--------------------Model--------------------	β_0	β_1	β_2	β_3	β_4	R^2_{aj}	S_{yx} (%)
1	$v = \beta_0 + \beta_1 h_R + \beta_2 h_R cd_R + \beta_3 cd_R$	-0.4523	0.0408	0.0044	-0.0293	-	0.466	16.74
2	$v = \beta_0 + \beta_1 cd_R + \beta_2 * cd_R^2 + \beta_3 h_R cd_R$	0.7577*	-0.2236*	0.0052	0.0095*	-	0.466	16.74
3	$\ln(v) = \beta_0 + \beta_1 \ln(cd_R) + \beta_2 (1/cd_R)$	-3.9235*	1.5968*	5.5142	-	-	0.291	19.26
4	$\ln(v) = \beta_0 + \beta_1 \ln(ca_R) + \beta_2 (1/ca_R)$	-2.2446*	0.5649*	5.9899	-	-	0.289	19.29
5	$V = \beta_0 cd_R$^ $\beta_1 h_R$^ β_2	0.0020*	0.5151*	1.6601*	-	-	0.466	16.73
6	$V = \beta_0 + \beta_1 cd_R + \beta_2 DS + \beta_3 ca_R + \beta_4 ca_R^2$	1.9935*	0.1811	-2.7026*	-0.0235	0.0001	0.659	13.37

Where: *significant coefficients; ca_R = Crown Area by RPAS; d = Diameter at chest height; cd_R = Crown Diameter by RPAS; DS = Degree of slenderness; h_R = Total Height by RPAS.

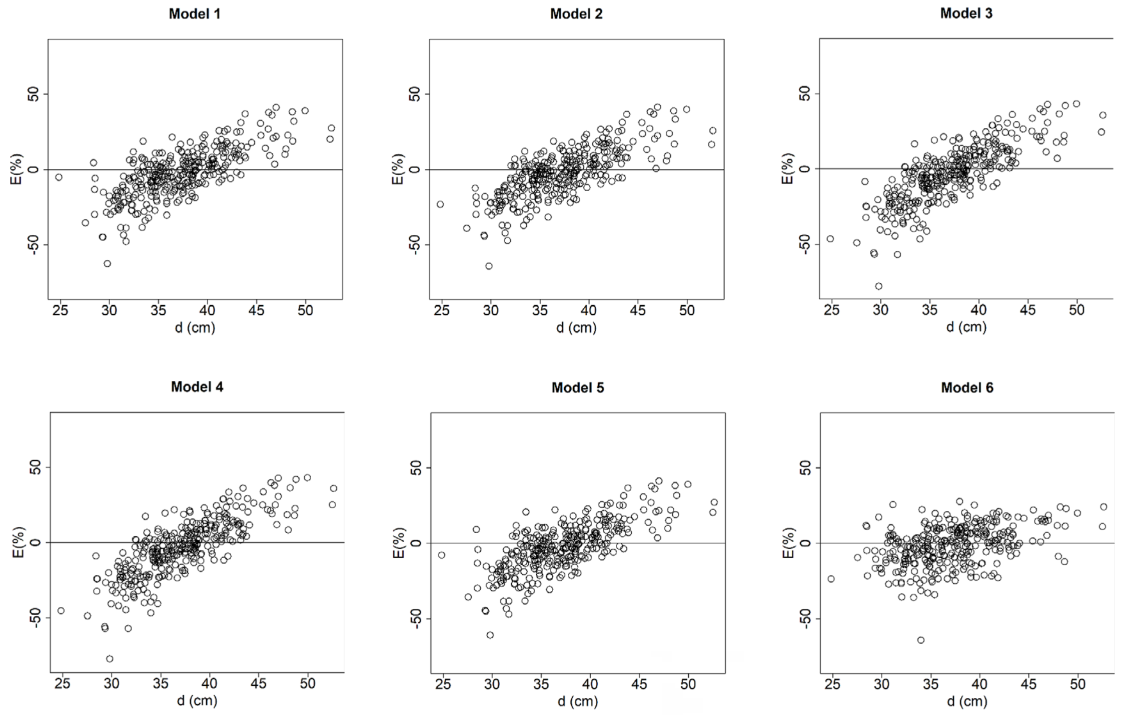

Figure 7 - Residual distribution of volume estimation models for *Tectona grandis* Linn f.

Table 8 - Estimated forest production through forest inventory and inventory through RPAS.

Method	min. by plot.	máx. by plot.	min./ha	avr./ha	máx./ha	min. in 134 ha	máx. in 134 ha
	------------------V (m³)------------------						
Forest Inventory	47.0308	63.3689	114.0142	133.8179	153.6216	15285.0231	20594.8939
Indirect volume estimation with RAPS	40.3841	56.7928	97.9009	117.7902	137.6795	13124.8368	18457.6527
Direct volume estimation with RAPS	42.2366	54.9403	102.3917	117.7902	133.1887	13726.8842	17855.6053

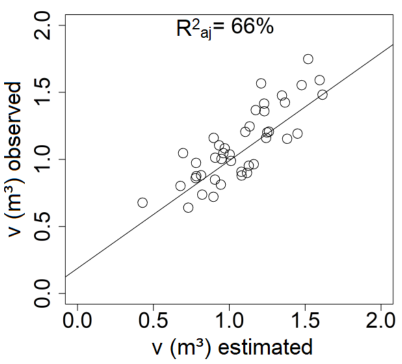

Figure 8 - Values observed vs. estimated by model nº 5 for volume prediction (m³).

allowed to generate Digital Surface and Terrain Model and obtain the Digital Height Model. The estimate of the trees' height had an approximate correspondence with the field data because of the removal of the undergrowth and the use of GSD, allowing the identification of individuals through the orthomosaic. Through the models and methodology tested, it was possible to identify and measure *Tectona grandis* Linn f. trees through images obtained by RPAS, making it possible to carry out the forest inventory without significant losses of precision. Where forest production and dendrometric variables estimated by RPAS showed a standard error of the estimate below 10%. The best model for diameter estimation was the one proposed by OLIVEIRA (1980) and for volume estimation using the estimated DAP values was the model proposed by FIGUEIREDO et al. (2014). Even if the costs for data acquisition and processing by RPAS are not evaluated, the structure presented here can serve as a useful methodology in similar applications. We hope that the development and increase of accuracy since MEYER's initial studies (1961) using aerial photographs, and the most diverse types of data interpolation, analysis, development of equations and use of variables will continue to stimulate research and practical applications for forest science to allow remote inventories.

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DECLARATION OF CONFLICT OF INTEREST

We have no conflict of interest to declare.

AUTHORS' CONTRIBUTIONS

All authors contributed equally for the conception and writing of the manuscript. All authors critically revised the manuscript and approved of the final version.

DATA AVALAIBILITY STATEMENT

The database relating to the forest inventory and the collection of information using RPAS images are available at the link: <https://1drv.ms/x/c/9449905b094cc797/EZfHTAlbkEkggJQhcQAAAAABRuMAydWPDQxkfFLgRj-pgA?e=MGJPAq>.

DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE

No artificial intelligence was used to prepare this article.

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