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VOLUMETRIC QUANTIFICATION OF EUCALYPTUS SP. STANDS THROUGH AERIAL PHOTOGRAPHS OBTAINED BY RPAS

Nattan Guylherme Vasconcelos da Silva[1*], Karen Janones da Rocha[2], Laíza Cavalcante de Albuquerque Silva[3], Gustavo Neco da Silva[4]

[1*]Instituto Federal de Educação, Ciência e Tecnologia de Rondônia - IFRO, Departamento de Pesquisa, Inovação e Pós-Graduação em Geoprocessamento, Colorado do Oeste, Rondônia, Brasil - *nattanguylherme.egf@gmail.com
[2]Universidade Federal de Rondônia, Departamento Acadêmico de Engenharia Florestal, Laboratório de Recuperação de Ecossistemas e Produção Florestal (REProFlor), Rolim de Moura, Rondônia, Brasil - karenrocha@unir.br
[3]Instituto Federal de Educação, Ciência e Tecnologia de Rondônia - IFRO, Grupo de Pesquisas Espaciais (GREES), Colorado do Oeste, Rondônia, Brasil - laiza.cavalcante@hotmail.com
[4]Superintendência de Polícia Técnico-Científica de Rondônia, Gerência Regional de Criminalística de Rolim de Moura, Rolim de Moura, Rondônia, Brasil - gustavoneco@politec.ro.gov.br

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Resumo

Quantificação volumétrica de povoamento de Eucalyptus sp. por meio de fotografias aéreas obtidas por RPAS. A obtenção de dados para o manejo das florestas, faz-se necessário a realização do inventário florestal, sendo um procedimento que demanda trabalho de campo, custo elevado e tempo. Portanto, objetivou-se com este trabalho desenvolver equações dendrométricas a partir de imagens aéreas de RPAS (Sistema de aeronaves remotamente pilotadas), associadas manipulação de dados vetoriais, e estimar a produção florestal de *Eucalyptus sp.*, na região sul do estado de Rondônia. A extração das variáveis área de projeção de copa (AC_{RPAS}) e altura total (h_{RPAS}) foram derivadas de imagens de RPAS, as quais foram validadas a partir de dados obtidos em campo por meio de inventário florestal e a cubagem de árvores em pé. Foram ajustadas equações diamétricas e volumétricas em função das variáveis obtidas por RPAS. A altura total das árvores cubadas e h_{RPAS} não apresentaram diferenças significativas (X^2 = 31,013). Ao comparar as estimativas obtidas pela equação de v com seus respectivos valores da cubagem, verifica-se que a equação de v é acurada para estimativas da variável em estudo (X^2 = 0,8077). Os resultados indicaram sucesso na detecção das árvores, mesmo com as dificuldades na delimitação das copas devido à oclusão. Apesar das dificuldades decorrentes de alturas de voo abaixo de 250 m, as estimativas de diâmetro, altura e volume individual utilizando métricas derivadas dos produtos RPAS foram precisas, consistentes com as obtidas no inventário florestal tradicional. O uso de RPAS para quantificação volumétrica de povoamentos florestais em Rondônia é uma abordagem inovadora no setor, apesar dos desafios encontrados.

Palavras-chave: Sistema de Aeronaves Remotamente Pilotadas; Fotogrametria; Morfometria de copa; Cubagem não destrutiva.

Abstract

Volumetric quantification of *Eucalyptus* sp. stands through aerial photographs obtained by RPAS. The data collection for forest management is necessary to carry out the inventory, being a procedure that requires field work, high cost and time. Therefore, the objective of this work was to develop dendrometric equations based on aerial images of RPAS (Remotely Piloted Aircraft System) combined with the manipulation of vector data, and to estimate the forest production of *Eucalyptus sp.*, in the southern region of the state of Rondônia. The extraction of the variables crown projection area (AC_{RPAS}) and total height (h_{RPAS}) were derived from RPAS images, these have been validated from data obtained in the field by means of forest inventory and by standing trees rigorous scaling. Diametric and volumetric equations were adjusted according to the variables obtained by RPAS. The total height (h) of the scaled trees and h_{RPAS} did not show significant differences (X^2 = 31.013). When comparing the estimates obtained by the v equation with their respective values of the scaling, it is verified that the v equation is accurate for estimates of the variable under study (X^2 = 0.8077). The results indicated success in tree detection, even with the difficulties in delimiting the crowns due to occlusion. Despite the challenges arising from flight altitudes below 250 m, the estimates of diameter, height, and individual volume using metrics derived from RPAS products were accurate, consistent with those obtained in the traditional forest inventory. The use of RPAS for volumetric quantification of forest stands in Rondônia represents an innovative approach in the sector, despite the challenges encountered.

Keywords: Remotely Piloted Aircraft System; Aerophotography; Crown morphometry; Non-destructive scaling; Forest Inventory.

INTRODUCTION

In forest management, one of the main sources of information is the existence of solid quantitative relations between growth and other variables, which can be expressed by mathematical models. These models are essential for more accurate estimates of forest production, as well as supporting decision-making on forest stand management.

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As a basis for the sustainable management of forest stands, the use of volumetric equations is one of the main tools for quantifying the production of forest stands. The volume of trees is estimated with a certain ease and accuracy, with volume equations adjusted according to the variables diameter at 1.3 m (D) and total height (h). In order to obtain these data, it is necessary to perform the forest inventory, however, this procedure may present a high operational cost, complexity and delay to produce production estimates and other dendrometric variables, such as the trees rigorous scaling (MIRANDA *et al*., 2015).

In view of this scenario, alternative methods for obtaining forest data are highlighted for providing a reduction in costs and delays in field work when compared to traditional forest inventories, among these are the aerial imaging by Remotely Piloted Aircraft System (RAPS) (GUERRA-HERNÁNDEZ, 2019; ZARCO-TEJADA, 2014). Aerial photographs are an alternative to complement the information collected in the field, due to the high spatial resolution obtained, which allows the counting and measurement of the crown areas (PANAGIOTIDIS *et al*., 2017). Stolle *et al.* (2021) estimated the volume of forest stock of pine and eucalyptus stands by multiplying the number of trees detected remotely by the estimated average individual population volume (individual approach).

In Puliti *et al.* (2019), a comparative analysis of various data sources, including RPAS (visible images, laser scanner), and Airborne Laser Scanner (ALS), was conducted to assess accuracy in a survey of 30 points, covering height, basal area, and trunk volume compared to field data. Different methodologies were compared, such as the combination of RPAS data, visible and Digital Terrain Model (DTM) correction, UAV and laser scanner, and ALS, aiming to determine if the integration of these sources would result in similar volume estimates, noting an efficiency gain of 2.1 times in the volume estimate using true-color (RGB) image data, which would only be achieved with a sample of 60 points.

Due to this, the perspectives of air monitoring and imaging carried out by RAPS are increasingly being used in studies and applications in the forestry area (LIANG *et al.*, 2019; REIS *et al.*, 2019), however it is necessary to evaluate the real applicability of this technique to forest inventories. Beyond the advantages of time reduction in surveys, and consequent cost reduction, coupled with the acquisition of a consistent database for the adjustment of mathematical models (CORTE *et al.*, 2022), the more affordable costs of electronic components make RPAS an innovative tool for obtaining data more easily, optimizing processes, reducing costs, and shortening the time required for traditional forest inventories and the extraction of metrics (GUERRA-HERNÁNDEZ *et al.*, 2019).

Therefore, the objective of this work is to evaluate the hypothesis of the existence of a statistically significant difference between volumetric equations and the estimate of forest production of a *Eucalyptus* sp stand from data obtained from RPAS by-products and the traditional forest inventory of H13 clones, in the southern region of the state of Rondônia.

MATERIAL AND METHODS

Study area

The study was carried out with clones H13 (*Eucalyptus grandis* x *E. urophylla*) of the total stand, located in Londrina farm, margins of BR-364, southern region of Rondônia, in the municipality of Vilhena (12°39'45,54" S, 60°18'33,19" O) (Figure 1), with an average inclination of 2.7%. The stand was implanted in March 2008, adopting a spatial arrangement of 3 m x 3 m, in an area of 29.58 ha. The plantation received silvicultural treatments, such as pruning, chemical weeding, and systematic thinning with the removal of one row at each two rows of the plantation.

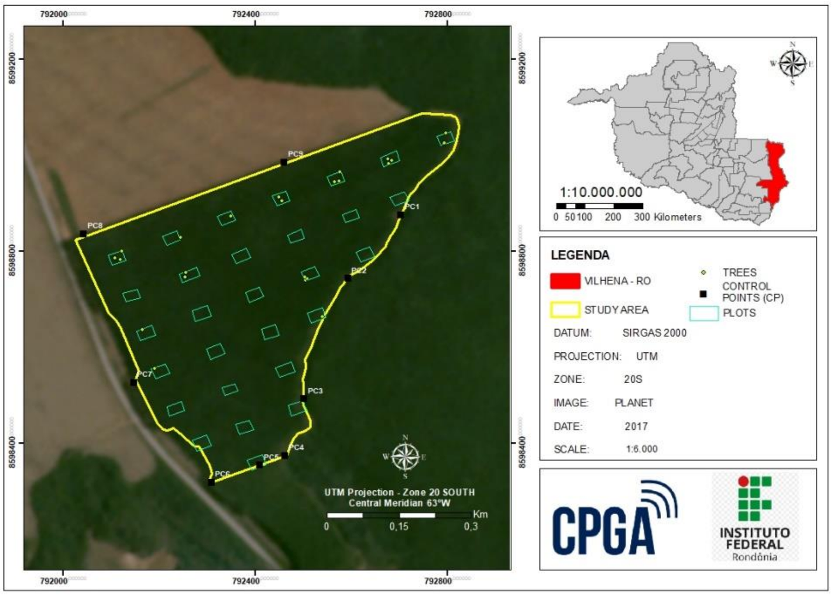

Figure 1. Location of the *Eucalyptus* sp. stand, clone H13 south of Rondônia state, 2020.

Figura 1. Localização do povoamento de *Eucalyptus* sp., clone H13, região sul do estado de Rondônia, 2020.

The climate of the region is Am (monsoon), according to the classification of Köppen-Geiger, that is, humid tropical with dry winter season. The average annual rainfall is 2,200 mm year^{-1}, average annual temperature 24 °C to 26 °C, mean relative air humidity 74% and altitude 600 m (ALVARES *et al.*, 2014). In general, the natural vegetation is characterized by cerrado fragments (IBGE, 2012), and the soils of the region are predominantly Orthic Quartzarenic Neosol and Dystrophic Red-Yellow Latosols - LVAd (SANTOS *et al.*, 2018).

Data Acquisition

The data acquisition was divided into three steps: A) Traditional forest inventory, carried out in January 2017 – at this step, the acronyms of the variables follow the IF subscription; B) Standing tree scaling, held in February 2017 – subscribed scaling; C) Inventory carried out with RAPS, executed in March 2020 – subscribed RAPS (Figure 2).

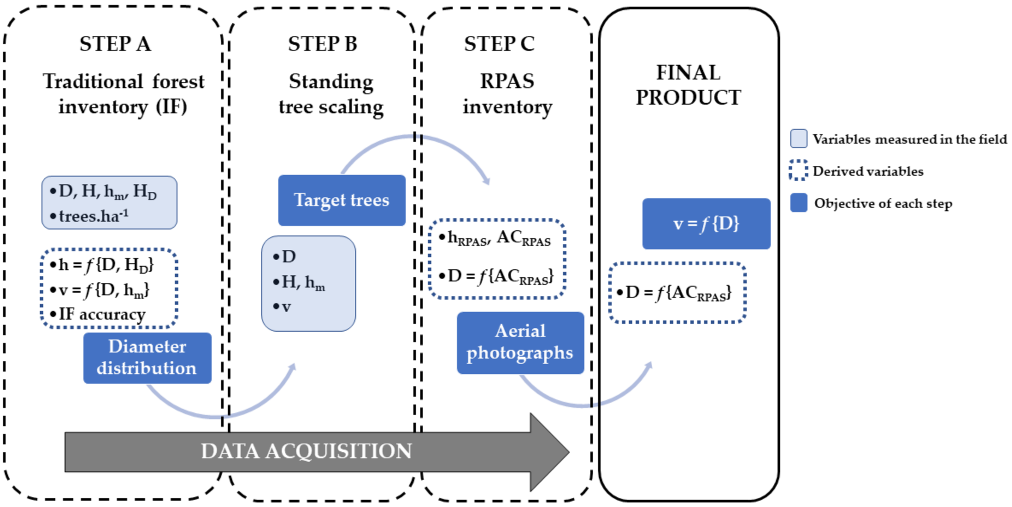

Figure 2. Flowchart to obtain data for volumetric quantification of *Eucalyptus* sp. stands, clone H13, using RPAS, where: D = diameter at 1.3 m, in cm; H = total height, in m; h_m = commercial height, in m; H_D = Assman's dominant height, in m; v = individual tree volume, in m^3; IF = traditional forest inventory; AC = canopy projection area, m²; RPAS = variables obtained by remotely piloted aircraft system (RPAs).

Figura 2. Fluxograma das etapas para obtenção de dados para a quantificação volumétrica de povoamento de *Eucalyptus* sp., clone H13, através de fotografias áreas de RPAS, em que: D = diâmetro a 1,3 m, em cm; H = altura total, em m; h_m = altura comercial, em m; H_D = altura dominante de Assman, em m; v = volume individual da árvore, em m^3; IF = inventário florestal tradicional; AC = área de projeção de copa, m²; RPAS (variáveis obtidas por Sistema de Aeronaves Remotamente Pilotadas).

Step A: Traditional forest inventory

The first step consisted of the installation of 29 sample units of 21 m x 30 m (630 m²) per plot according to the fixed area method, which were systematically sampled in a single selection stage. The data measured to field were: the diameter measured at 1.30 m of ground height (D) of all trees contained in the sample units using a diameter tape; total height (H) of the first fifteen trees of the plot and of the six dominant trees, according to the concept of Assmann's dominant height (1970), using the digital equipment Criterion® RD 1000. The other heights were obtained by the hypsometric equation (Equation 1).

$$\hat{H} = 66{,}8340 - 2722{,}9766 D_{IF}^{-2} - 906{,}1397 * H_D^{-2} \quad (S_{yx}\% = 4{,}6\% \text{ e } R^2_{aj.} = 0{,}72) \qquad \text{(Eq. 1)}$$

where: $\hat{H}$ = total tree height (mm); D_{IF} = diameter at 1.3 m (cm), retrieved from traditional field inventory; H_D = Assman's dominant height (m); $R^2_{aj.}$ = adjusted coefficient of determination; $S_{yx}\%$ = standard estimation error.
em que: $\hat{H}$ = altura total da árvore, em m; D_{IF} = diâmetro a 1,3 m, em cm, obtido no inventário florestal tradicional; H_D = altura dominante de Assman, em m; $R^2_{aj.}$ = coeficiente de determinação ajustado; $S_{yx}\%$ = erro padrão da estimativa em porcentagem.

The individual volume of trees (v), variable of interest in the traditional forest inventory, was estimated by Equation 2. This equation considers 10% to be the maximum permissible error and 95% confidence level. In this study, the ideal sample intensity was met (n > 7), in addition to obtaining a relative sampling error of 3.4%. Therefore, the sample can be considered representative of the population.

$$\hat{v} = e^{-9,4510+2,1141*lnD_{IF}+0,6554*lnh_{mIF}} \; (S_{yx}\% = 10,0\% \text{ e } R^2_{aj.} = 0,98) \quad \text{(Eq. 2)}$$

where $\hat{v}$ = individual tree volume (m^3); D_{IF} = diameter at 1.3 m (cm), retrieved from traditional field inventory; $h_{m\,IF}$ = commercial height retrieved from traditional field inventory; $R^2_{aj.}$ = adjusted coefficient of determination; $S_{yx}\%$ = standard estimation error.
em que: $\hat{v}$ = volume individual da árvore, em m^3; D_{IF} = diâmetro a 1,3 m, em cm, obtido no inventário florestal tradicional; H_{mIF} = altura comercial, em m, obtida no inventário florestal tradicional; $R^2_{aj.}$ = coeficiente de determinação ajustado; $S_{yx}\%$ = erro padrão da estimativa em porcentagem.

Both equation 1 and equation 2 were adjusted for the study area. All trees were distributed in eleven diametric classes with 2 cm intervals, and class centers (CC) from 8 to 28 cm.

Step B: Standing trees scaling

At this step, five trees were randomly drawn in each diameter class to ensure the representativeness of all the diameter variation existing in the stand, except for classes with CC 8, 10 and 28 cm that obtained frequency below 5 trees. t this step, the population was considered infinite, and the maximum permissible error was set at 10% with a 95% confidence level, with the ideal sampling intensity being met (n ≥ 1). Procedure which is justified by the coincidence of the mean and center of each class, which implies the disappearance of the rounding error. The standing trees were scaling was performed in a non-destructive manner, using the equipment Criterion® RD 1000, where the variables $D_{scaling}$ and $H_{scaling}$ were obtained. All trees selected for rigorous scaling were georeferenced with GNSS receiver for better localization in the middle of the stands and extraction of the dendrometric variables (Step C) used in the models adjustments.

Step C: Forest inventory using an RAPS

To estimate the analyzed dendrometric variables such as diameter and individual volume quickly and efficiently, the area was flown over using the DJI Phantom 4 PRO UAV (2017). This aircraft is a quadcopter type aircraft, tracking C/A codes of the Global Positioning System (GPS) and Global Navigational Satellite System (GLONASS) constellations, achieving an accuracy of 10 m. It has a 20-megapixel resolution RGB camera, equipped with a CMOS 1/2,8" sensor (4000 x 3000 pixel), with focal length of 35 mm and maximum shutter speed of 1/8000 s.

The flights planning was carried out in the pix4Capture application (2020), adopting a vertical and horizontal overlap of 80%, flight height of 250 meters altitude, obtaining a theoretical Ground Sample Distance (GSD) of 6.82 cm. Once the flight plan configurations have been defined, only one flight was performed, with an area covering 10% more than an area of interest of 29.58 hectares. This overlap was adopted to reduce distortions in the by-products (orthomosaic, DSM, and DTM) common at the edges of the area of interest (OLIVEIRA & BRITO, 2019), because the steps of alignment and point cloud creation at the edges of the imaged area have fewer available images during the image matching process. The flight was carried out on 03/27/2020, at 12:30 a.m., with the aim of reducing the trees crown shading using the best solar angulation. 153 images were obtained, generating a real GSD of 6.48 cm/px.

For the geometric correction of the images obtained, 9 Ground Control Points (PC) were installed in the area, consisting of black and white painted wooden boards with dimensions of 40 x 40 cm. The centers of these targets were marked using a Topcon Hiper+ geodesic GNSS tracking in L1/L2 phases, and then post-processed by Precise Point Positioning (PPP). It is worth noting that the scaled trees were also georeferenced with GNSS receiver.

Flight processing was performed using the Agisoft Metashape Pro *trial* software by following the steps: (1) Import of images and PCs; (2) image quality assessment; (3) image alignment (*tie point* process); (4) PC management on the targets contained in the images; (5) realignment of images; (6) creation and classification of dense cloud of points; (7) Generation of Digital Surface Model (DSM) and Digital Land Model (DTM); (8) orthomosaic of images. The processing by-products were the DSM, DTM and Orthomosaic. Unsupervised classification of the canopies was not used because they were touching and/or overlapping; the trees were vectorized and classified manually.

As a result, the orthomosaics and DTM and DSM were imported into the QGIS software version 2.18.13 (2017) to obtain the variables crown projection area (AC_{RPAS}) and total tree height (h_{RPAS}). The AC_{RPAS} was calculated for each scaled and georeferenced tree, and the h_{RPAS} was obtained at the highest point altitude value within the AC_{RPAS} in the DSM subtracted by the DTM altitude value at the same point (Figure 3).

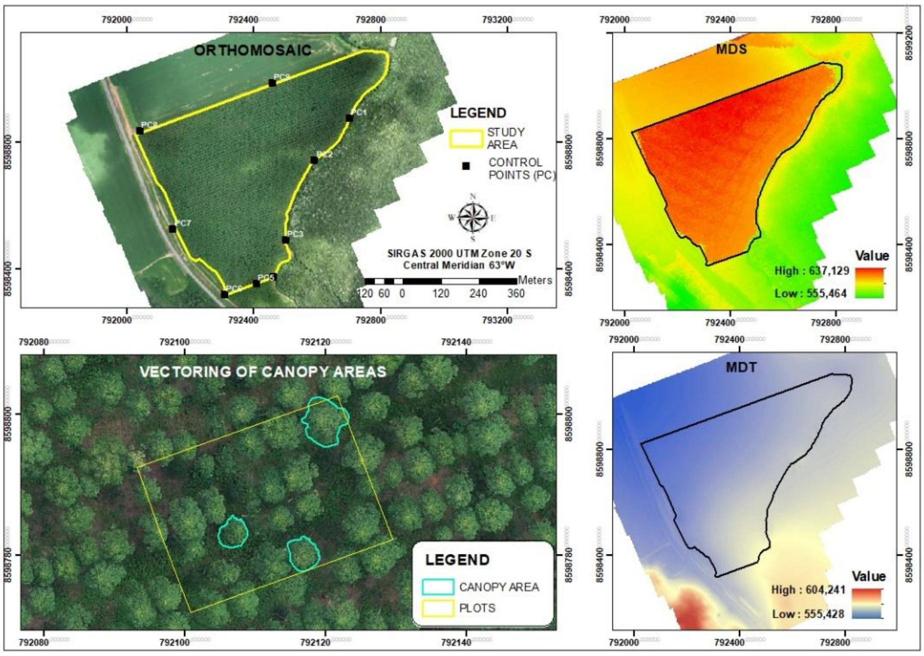

Figure 3. RPAS subproducts: A) Orthomosaic; B) Digital Surface Model (DSM); C) Illustration of vectorization of crown areas by plot; D) Digital Land Model (DTM). Clone H13, southern region of the state of Rondônia, 2020.
Figura 3. Subprodutos derivados de RPAS: A) Ortomosaico; B) Modelo Digital de Superfície (MDS); C) Ilustração da vetorização das áreas de copas por parcelas; e D) Modelo Digital de Terreno (MDT). Clone H13, região sul do estado de Rondônia, 2020.

Data processing and analysis

This study evaluated four models to estimate diameter (Henricksen, Curtis and Stepwise 1 and 2) and three models to estimate volume (Husch, Kopezky & Gehrahardt and Stepwise 3, according to Table 1. In the adjustment of the models for the D and for the individual volume of trees (v), the D collected through the standing tree scaling (Step B) was used, as well as the variables AC_{RPAS} and h_{RPAS} obtained with the RAPS (Step C). The $H_{scaling}$ and the h_{RPAS} did not show significant differences by the chi-square test ($X_{calculated}{}^2{}_{(0.05;24)} = 31.013 < X_{tabulated}{}^2{}_{(0.05;24)} = 36.415$).

For the adjustment of the diametric models, 25 trees were used, and for the volumes, 15 trees were used. Considering the irregularity of the crowns of deciduous trees and that their overlap complicates the reconstruction of these trees in the RPAS point cloud, trees with a height of less than 25 meters were disregarded (NEVALAINEN *et al.*, 2017; HENTZ *et al.*, 2018). For generic models, the selection of variables was performed using the stepwise procedure, with the objective of removing variables that did not influence regression, or highly correlated independent variables that do not express biological realism.

Table 1. Models evaluated for *Eucalyptus* sp. stand, clone H13, southern region of the state of Rondônia, 2020
Tabela 1. Modelos avaliados para povoamento de *Eucalyptus* sp., clone H13, região sul do estado de Rondônia, 2020

Mathematical models	
Diameter at 1.3 m – D	
$Henricksen: \hat{D} = \beta_0 + \beta_1 lnAC_{RPAS}$	$Curtis: \hat{D} = \beta_0 + \beta_1 \frac{1}{AC_{RPAS}}$
$Stepwise\ 1: \hat{D} = \beta_0 + \beta_1 ln^2 AC_{RPAS}$	$Stepwise\ 2: \hat{D} = e^{\beta_0 + \beta_1 ln^2 AC_{RPAS}} * IM$
Volume individual – v	
$Husch: \hat{v} = e^{\beta_0 + \beta_1 ln\hat{D}} * IM$	$Kopezky\ \&\ Gehrahardt: \hat{v} = \beta_0 + \beta_1 \hat{D}^2$
$Stepwise\ 3: \hat{v} = \beta_0 + \beta_1 \hat{D}^3 + \beta_2 \frac{h_{RPAS}}{\hat{D}} + \beta_3 \frac{\hat{D}}{h_{RPAS}}$	

em que: $\hat{D}$ = diâmetro a 1,3 m estimado em função da AC_{RPAS}, em cm; AC_{RPAS} = área de projeção de copa, m²; h_{RPAS} = altura total, em m; $\hat{v}$ = volume individual da árvore, em m³; IM = índice de meyer, utilizado para correção da discrepância logarítmica, $IM = e^{(0,5 * S_{yx}{}^2)}$; S_{yx} = erro padrão da estimativa do ajuste com a variável dependente logaritimizada; β_i = coeficiente de regressão, sendo *i* de 0 a 3.

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where: $\widehat{D}$ = diameter at 1.3 m estimated according to the AC_{RPAS}, in cm; AC_{RPAS} = canopy projection area, m²; h_{RPAS} = total height, in m; $\hat{v}$ = individual tree volume, in m³; IM = Meyer index, used to correct logarithmic discrepancy, $IM = e^{(0{,}5*S_{yx}^2)}$; S_{yx} = standard error of the estimate of fit with the logarithmized dependent variable; β_i = regression coefficient, *i* being from 0 to 3.

The assumptions of homoscedasticity, normality and residue independence were evaluated by the White (W), Shapiro-Wilk and Durbin-Watson (DW) test, respectively. The Student T-test was used to evaluate the significance of the equation coefficients. Adjustment and accuracy statistics, adjusted determination coefficient (R^2_{aj}), standard error of the estimate in percentage ($S_{yx}\%$), as well as the residual scatter chart in percentage, were used as criteria for the selection of equations.

Validation of estimated volume by aerial photographs

The accuracy of the estimates obtained by the individual tree volume equation ($\hat{v}$) were evaluated using the chi-square test (X^2). This process consisted of comparing the values $\hat{v}$ with their respective scaling values, values considered observed. The result was compared with the value tabulated of the 5% error probability level. If *the* $X^2_{calculated}$ $X^2_{tabulated}$, the hypothesis that the volume equation is accurate for estimates of the variable in study is not rejected. The total volume of the stand was estimated with the average total volume of the trees (average $\hat{v}$) from the extrapolated to the estimated density of the stand in the conventional forest inventory (Step A).

RESULTS

The equations that presented non-significant angular coefficients at 5% probability of error were disregarded, both for the adjustment of the diameter at 1.3 m (D) and for the individual volume (v) of the trees. In general, the equations presented good adjustment to clone H13 data (Table 2). The results of the $S_{yx}\%$ statistics, relative to the mean error of the estimates, are lower than ~16% for all equations, with the most accurate mean values obtained in the equations generated by *the stepwise* procedure (Stepwise 1 – $S_{yx}\%$ = 10.9%; stepwise 2 – $S_{yx}\%$ = 11.1%; Stepwise 3 – $S_{yx}\%$ = 5.8%) and Husch ($S_{yx}\%$ = 8.3%). For statistics $R^2_{aj.}$, values greater than 93% were achieved for all equations, indicating appropriate estimates for the variables D and v.

Table 2. Estimated parameters and fit and precision statistics for diametric and volumetric equations with independent variables obtained through by-products of images captured by remotely piloted aircraft system (RPAS) for *Eucalyptus* sp., clone H13, southern region of the state of Rondônia

Tabela 2. Parâmetros estimados e estatísticas de ajuste e precisão para as equações diamétricas e volumétricas com variáveis independentes obtidas por meio de subprodutos de imagens capturadas por sistema de aeronaves remotamente pilotadas (RPAS) para *Eucalyptus* sp., clone H13, região sul do estado de Rondônia

Model	Estimated parameters					Fit and precision statistics			Regression assumptions		
	β_0	β_1	β_2	β_3	*IM*	*SQRes*	$S_{yx}\%$	$R^2_{aj.}$	*W*	*DW*	*SW*
Diameter at 1.3 m - D											
Henriksen	-45,0379^{ns}	18,859*				308,71	16,1	0,98	1,49^{ns}	1,22*	0,96^{ns}
Curtis	41,6555*	-684,9*				301,47	15,9	0,98	1,77^{ns}	1,21*	0,96^{ns}
Stepwise 1	13,6107*	1,4848*				142,65	10,9	0,99	0,54^{ns}	2,07^{ns}	0,94^{ns}
Stepwise 2	2,8847*	0,0013*			1,007	146,21	11,1	0,99	2,10^{ns}	2,17^{ns}	0,97^{ns}
Individual volume - v											
Husch	-7,5408*	2,2506*			1,004	0,0250	8,5	0,94	3,20^{ns}	2,02^{ns}	0,96^{ns}
Kopezky & Gehrhardt	-0,0763*	0,00132*				0,0256	8,6	0,94	3,10*	2,09*	0,96^{ns}
Stepwise 3	3,2362*	0,00007*	-0,739*	-3,4878*		0,0115	5,8	0,97	13,11^{ns}	2.93*	0,96^{ns}

where: β_i = regression coefficient, *i* being from 0 to 3; *IM* = Meyer index, used to correct logarithmic discrepancy, $IM = e^{(0{,}5*S_{yx}^2)}$; S_{yx} = standard error of the estimate of fit with the logarithmized dependent variable; *SQRes* = residual sum of squared; $S_{yx}\%$ = standard error of the estimate in percentage; $R^2_{aj.}$ = adjusted coefficient of determination; *W* = White's homoscedasticity test statistic; *DW* = Durbin-Watson residual independence test statistics; *SW* = statistic of the Shapiro-Wilk residual normality test; ^{ns} = not significant at the level of 5% error probability; * = significant at the level of 5% probability of error.

em que: β_i = coeficiente de regressão, sendo i de 0 a 3; IM = Índice de Meyer, utilizado para correção da discrepância logarítmica, $IM = e^{(0,5*S_{yx}^2)}$; S_{yx} = erro padrão da estimativa do ajuste com a variável dependente logaritimizada; $SQRes$ = soma de quadrado dos resíduos; $S_{yx}\%$ = erro padrão da estimativa em porcentagem; $R^2_{aj.}$ = coeficiente de determinação ajustado; W = estatística do teste de homocedasticidade de White; DW = estatística do teste de independência dos resíduos de Durbin-Watson; SW = estatística do teste de normalidade dos resíduos de Shapiro-Wilk; ^{ns} = não significativo ao nível de 5% de probabilidade de erro; * = significativo ao nível de 5% de probabilidade de erro.

Both the diametric equations for stepwise 1 and 2 presented a similar dispersion of residues, with no marked tendency (Figure 4). The greatest errors usually occurred in the intermediate D, where the residues varied, on average, from -3 to 5 cm. The two equations met the assumptions of regression, and based on the results analyzed, the stepwise equation 1 was selected.

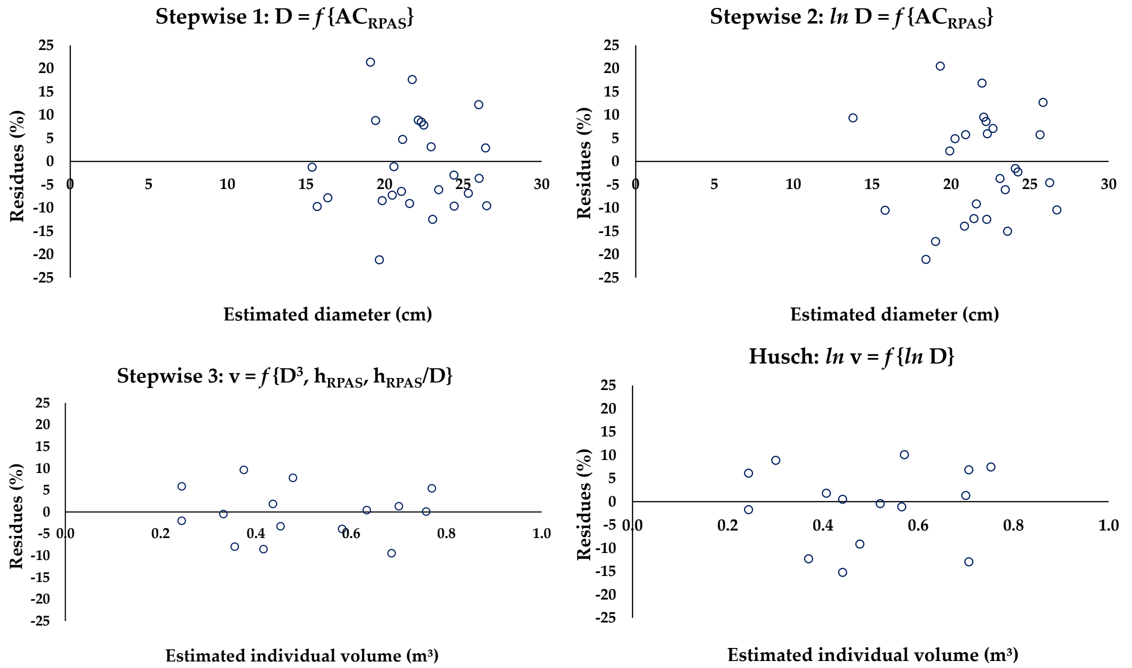

Figure 4. Distribution of residues as a function of the diameters at 1.3 m and the individual volume estimated for *Eucalyptus* sp., clone H13, southern region of the state of Rondônia. where: D = diameter at 1.3 m estimated according to the AC_{RPAS}, in cm; AC_{RPAS} = canopy projection area, m²; h_{RPAS} = total height, in m; v = individual tree volume, in m^3.

Figura 4. Distribuição dos resíduos em função dos diâmetros a 1,3 m e do volume individual estimados para *Eucalyptus* sp., clone H13, região sul do estado de Rondônia. em que: D = diâmetro a 1,3 m estimado em função da AC_{RPAS}, em cm; AC_{RPAS} = área de projeção de copa, m²; h_{RPAS} = altura total, em m; v = volume individual da árvore, em m^3.

For volumetric models, the stepwise equation 3 was the one that presented the best $S_{yx}\%$. However, the residual scatter chart shows a slight tendency, in contrast, the Husch equation has a more uniform dispersion (Figure 3). Nevertheless, the residues varied, on average, from -0.0758 to 0.0529 m³. Additionally, stepwise 3 presented dependence on residues, probably due to the dependent variables H/D and H/D (Table 2). The adjusted model with only one of these relations did not present significant angular coefficients, so it was not considered in this study. Thus, the equation selected to estimate the v of the stands trees was that of Husch.

Upon analyzing the chi-square test statistics, comparing the estimates obtained by the individual tree volume equation ($\hat{v}$) with their respective scaling values, it is verified that the volume equation is accurate for estimates of the variable in study, $X^2_{calculated(0.05;14)} = 0.8077 < X^2_{tabulated\ (0.05;14)} = 26.685$. Based on the traditional forest inventory (Step A), the estimated density for the stands was 692 trees.ha^{-1}. After applying the selected volumetric equation to the trees inventoried by the RAPS, the mean v of 0.5915 m³.tree^{-1} was obtained. Therefore, the estimated total volume for the stand is 409.32 m³.ha^{-1}.

DISCUSSION

Data processing obtained by RAPS

Data acquisition using RPAS (Remotely Piloted Aircraft Systems) faced challenges, especially at flight altitudes below 250 meters. The Agisoft Photoscan Metashape software encountered difficulties in the orthomosaic construction process, where the "recognition of homologous points" stage is crucial for 3D space reconstruction.

In locations with similar targets, this process can fail, affecting reconstruction. Images captured at higher altitudes tend to have more heterogeneity because they cover a larger scene. Therefore, due to the homogeneity of the area, a decision was made to fly at a higher altitude to obtain more heterogeneous images, facilitating recognition and alignment by the software. Moreover, the tree canopies presented problems of overlap, interweaving, and shading, impacting the extraction of information from the obtained by-products.

This difficulty has been reported in various studies, both in planted and natural stands, such as Araújo *et al.* (2020), who used a combination of images collected with a digital camera mounted on RPAS and detailed field mapping of tree canopies to determine the canopy status of individual trees and link this information to traditional forest inventory data in Central Amazonia, Brazil. In any case, in practice, it is expected that estimates of dendrometric variables will be made using data derived from automatically detected trees, and in these situations, it is observed that suppressed trees tend not to be detected (NEVALAINEN *et al.*, 2017). In younger stands, or in less dense conditions, this limitation is likely not to be observed.

Another difficulty found was the use of PC in the middle of the stand. Since it was not possible to perform the tree thinning around the CPs to better visualize the targets in the images geometric correction, these were offset. Therefore, it was decided to remove these CPs (Ground Control Points) to not interfere with the precision and accuracy of the generated by-products, leaving only the CPs around the plot in order to avoid potential obstructions that could hide them.

Regarding the CPs, some studies choose to use groups of CPs, such as Wallace *et al.* (2016), while others, like Ye Seoul *et al.* (2015), opt not to use CPs. Tomaštík *et al.* (2017) conducted tests in three locations with different canopy openness conditions for sloped and complex terrains, evaluating the models accuracy generated in relation to a variable number of CPs. All these cited works, regardless of the use or non-use of CP groups, demonstrated the capability of data collected by RPAS for estimating H, with an error less than 10% – a value usually accepted in the measurement of dendrometric variables in traditional forest inventory. In addition, the results regarding horizontal accuracy in forests with different degrees of forest cover reached sub-decimal values, while vertical errors were less than 20 cm. Therefore, the authors concluded that the use of RAPS provides a high accuracy for determining the height of trees in forest plantations.

For variable D, adequate result was also verified ($S_{yx}\%$ = 10.9%). This result was lower than that of Hentz *et al.* (2018), that obtained $S_{yx}\%$ of 9.0% and 8.4% when estimating the mean d of an *Eucalyptus* sp. plot with dendrometric variables obtained through RAPS. The author used variables extracted from the point cloud from the true-color flight and structural variables – for structural variables, the defined AC (canopy area in m²) and statistics derived from the digital crown height model and DSM were considered. Zandoná *et al.* (2008) upon studying commercial stands of *Pinus* sp, proved the technical feasibility for estimating dendrometric variables working with Laser Scanner Air carried – LSA. The authors proposed a methodology to estimate d according to the h and crown diameter extracted from the LIDAR data and obtained $R^2_{aj.}$ higher than 0.67 and $S_{yx}\%$ lower than 10%.

In view of the above, in addition to vegetation mapping, data acquisition through RAPS has demonstrated great potential for accurate dendrometric parameter estimates. Data collection is fast, consistent and reduces costs, and facilitates the forest inventory process. Another crucial point is that data derived from SSRS can serve as subsidies for relations with D and H and generation of volumetric information from *Eucalyptus* clonal forest stands (TANG & SHAO, 2015).

The volume of trees has been estimated with a certain ease and accuracy, applying volume equations adjusted from data of D and D. Based on the H obtained directly by the images processing and in the D estimated from AC, both H and AC obtained by RAPS, the v of the Clone H13 trees were obtained with good precision ($S_{yx}\%$ = 8.9%). Husch's model was also selected in other studies to estimate the v in stands of *Eucalyptus* clones, being possible to mention Silva *et al.* (2015) in Mineiros-GO and Santana *et al.* (2021) in Tocantins state cerrado, in which they obtained $S_{yx}\%$ of 11.1% and 11.1%, respectively.

Through the images obtained by the RAPS, it is feasible to design the AC in forest stands as well as to obtain the H, which make it possible to reduce the sample effort in the stand, since the data are obtained at the level of individual trees instead of the production unit. It is feasible to adjust mathematical models that correlate with the AC variable obtained by remote sensing with the variables measured to the field: D, H and v, guaranteeing efficiency in obtaining information and results close to those obtained by traditional forest inventories (CORTE *et al.*, 2022).

The total volume estimated for the stand under study– 409.32 m³.ha^{-1} – remained within the range of values verified in the literature. In a comparative study in a five -year-old *Eucalyptus* plot in the state of Paraná with initial density of 2,553 trees.ha^{-1}, Hentz *et al.* (2018) obtained good results by evaluating the total volume of the census with that estimated from data from passive sensors embedded in RAPS, where it received the results of -0.05% (-0.3106 m³) of volume difference (578.2863 m³). While Miranda *et al.* (2019) compared the productivity of seven-year-old commercial plantations in the state of Mato Grosso and initial density of 1,111 trees.ha^{-1}, through traditional inventory, where in Campo Verde, clone H13 obtained a production of 171.7 $m^3.ha^{-1}$ and in Lucas do Rio Verde 188.8 $m^3.ha^{-1}$.

The volumetric growth of the individual tree is subject to silvicultural control, since it depends largely on the diametral growth, which is very sensitive to the stands density; besides also depends on the productive capacity of the site and tree trunk's shape. With a higher population density, the increase is added to a larger number of trees, each with a smaller size. With a lower population density, the same volume increase is concentrated in a smaller number of trees, each of which is larger in size. In this sense, it can be assumed that the stand productivity was adequate, emphasizing that the comparison of the productivity of stands under different management regimes and site conditions should be done with caution.

Estimates of dendrometric variables with RAPS tend to underestimate larger trees and mainly overestimate small trees (HENTZ *et al.*, 2018). The presence of canopies in irregular sizes complicates the definition of detection parameters (AYREY *et al.*, 2017), and the reconstruction of these trees in the RPAS point cloud is hindered by their occlusion in many images (NEVALAINEN *et al.*, 2017), which can directly interfere with the estimation of D.

Due to the great variability in canopy sizes and the overlap among them, smaller canopies - trees with a smaller individual volume - may not be visible in the upper layer of the canopy, and therefore, do not have a significant influence on the production of the stand (HENTZ *et al*., 2018). However, in an attempt to ensure the fulfillment of demands, it is recommended to work with the lower limits of productivity estimates. Although the use of RPAS for data acquisition in various areas is becoming common, in the forestry sector, it is still an innovative tool for the application in volumetric quantification of forest stands in the state of Rondônia.

CONCLUSÃO

- The equation obtained to estimate the individual volume of Clone H13 trees was $\hat{v} = 0{,}000363 * D^{2{,}3753}$. For the application of this equation, the dependent variable is obtained through the equation $\widehat{D} = 13{,}6107 + 1{,}4848 * ln^2 AC_{RPAS}$, where the canopy projection area (AC_{RPAS}) is calculated using aerial photographs and GIS tools;
- There were no problems in detecting the trees, only difficulty in delineating the canopies due to partial occlusion. Even so, it was possible to estimate dendrometric variables, such as diameter at 1.3 m, total height, and individual volume, based on metrics derived from RPAS products. The individual volume estimates were very close to the volumes obtained by cubing the trees, resulting in an adequate estimate of the stand's production, which was 409.32 $m^3.ha^{-1}$;
- Flight altitudes below 250 m hindered the processing of the flight because the adopted software failed to generate good results during the image matching process. It is necessary for other studies to evaluate the influence of flight and processing parameters for locations with a structure similar to the surveyed stand.

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