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Estimating tree volume based on crown mapping by UAV pictures in the Amazon Forest

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Abstract. The use of remote sensing images obtained by unmanned aerial vehicle (UAV) systems enables measuring the morphometry of the tree canopy to estimate the volume stock in the Amazon Forest. In this study, we used RGB images from a low-cost UAV to map tree species and extract volumetric stock estimates in an Amazonian Forest. Individual tree crowns (ITC) were outlined in the UAV images and identified to the species level using forest inventory data. The average diameter and crown area of the trees were measured to estimate the volume, basal area and DBH per diameter class for 260 ha of tropical forest. The RMSE volume adjustment for the separate field inventory dataset was 19.31% with an R2 of 0.967. The UAV system images has the potential to map tree species and estimate tree biometry in the Amazon Forest, providing valuable insights for forest management and conservation.

Keywords: RGB pictures, diameter class,orthomosaic, tropical forest, UAV.

Introduction

The forest volume is essential to determine the biomass, which constitutes an element responsible for reducing the emission of greenhouse gases and has the capacity to fix atmospheric carbon during its formation process. Tropical forests have high diversity and dynamic characteristics, with constant changes in their structure that require complex planning to execute forestry operations (Coops et al., 2022).

The traditional forest inventory is indispensable for monitoring forests19, as it seeks to monitor and portray changes in the quantitative and qualitative attributes of the arboreal environment (Latifi and Heurich, 2019; Fankhauser et al., 2018a; Tompalski et al., 2021) In turn, these attributes are necessary to support accurate diversity, volume and estimates biomass, being an important tool to assess important aspects such as productivity and the economic and ecological viability of interventions to be conducted in a region, thereby encouraging decision-making by environmental managers (Keenan et al., 2015).

The use of geotechnologies applied in forests for identifying species, biomass and carbon, conservation, monitoring, impact assessment and even tree biometrics is being used more and more frequently (Corte et al., 2022; Moura et al., 2021; da Cunha Neto et al., 2021; da Costa et al., 2021; d'Oliveira et al., 2020; Fankhauser et al., 2018b). The Unmanned Aircraft Vehicle (UAV) with RGB sensors images in the red, green and blue bands, are low-cost equipment with great demand and supply in the market due to their various uses and are becoming popular in the forestry sector for use as support in data collection operations, inspection activities and coverage monitoring, among others.

UAV-based data acquisition usually results in hundreds of high spatial resolution RGB images (ground sampling distance, GSD < 10 cm) (Ferreira et al., 2020; Kattenborn et al., 2021; Morales et al., 2018). The combination of remote sensing and forest inventory data provides accurate information about forest characteristics over large areas (tens to hundreds of hectares) and has been shown to be useful in reducing field efforts (de Almeida Papa et al., 2020; Dalla Corte et al., 2020; Veras et al., 2022).

In traditional forest measurement by census or sampling, the measurement of diameter at breast height (DBH) and total height (h) of trees are generally used due to the high correlation of these variables with parameters such as wood volume and carbon stock (Corte et al., 2020). Data collection is time-consuming, has high costs, low productivity, is restricted to small areas and dangerous to the health of the field worker, and may still encounter geographic obstacles and still risk data collection errors (Latifi, 2020).

The measurement and identification of trees using a UAV system significantly reduces the need for a traditional forest inventory, which contributes to optimizing financial resources, time, labor, planning and forest management, enabling identification of tree distribution, tree density, species, individual counts, monitoring forest phenophases, in addition to tree biometrics (Veras et al., 2022).

In view of the above, this study examines the utility of RGB images captured by a UAV system to map and to estimate the volume of tree species in Brazilian Amazonian forests. We tested the following hypothesis: it is possible to estimate the tree volume from aerial mapping using a UAV system. The objective of the study is to estimate diameter, basal area and volume from the canopy morphometry of large arboreal trees present in the Amazon Forest.

Methods

Study area

The study area is an experimental forest of the Brazilian Agricultural Research Company (Embrapa) located in the municipality of Rio Branco, Acre state, Brazil (10º 01' 22" S, 67º 40' 3" W) (Fig 1). It is a highly diverse native rain forest area of 1,600 ha about 200 m above the sea level, more than 239 species. The orthomosaic used in this study comprises 260 ha. The experimental forest area annually receives 1,950 mm of rain, and the annual average temperature is 24.8 (±0.8)◦C (Ramos *et al.*, 2009). The vegetation of the area is classified as open rain forest with the presence of palms and bamboos (Veloso *et al.*, 1991). Trees exceed 30 meters in height, and there is an abundance of bamboo and diversity of palm trees, along with tree individuals in lower density, and the presence of large trees.

UAV photographs

We collected aerial photographs with the UAV DJI Phantom 4 Pro, equipped with an RGB (red, green, blue) CMOS sensor of 20-megapixel resolution, a 24 mm autofocus lens, and a manual shutter with battery autonomy up to 30 min. The UAV flew 120 m above the forest canopy with a cruising speed of 10 m/s, resulting in images with a GSD of 4 cm. We took a total of 1,585 photographs with a forward overlap of 86.0% and side lap of 86.36% in eight consecutive flights. Before the flights, we established three ground control points (GCPs) on the edges of the forest reserve. A dual-frequency GNSS receiver was installed at each GCP and collected GPS and GLONASS data for 241 minutes. After post-processing procedures, the average horizontal and vertical precision of the GCPs were 10 cm and 3 cm, respectively. Finally, we used the PiX4D software program (Pix4D Inc.) to generate orthomosaics of the study area.

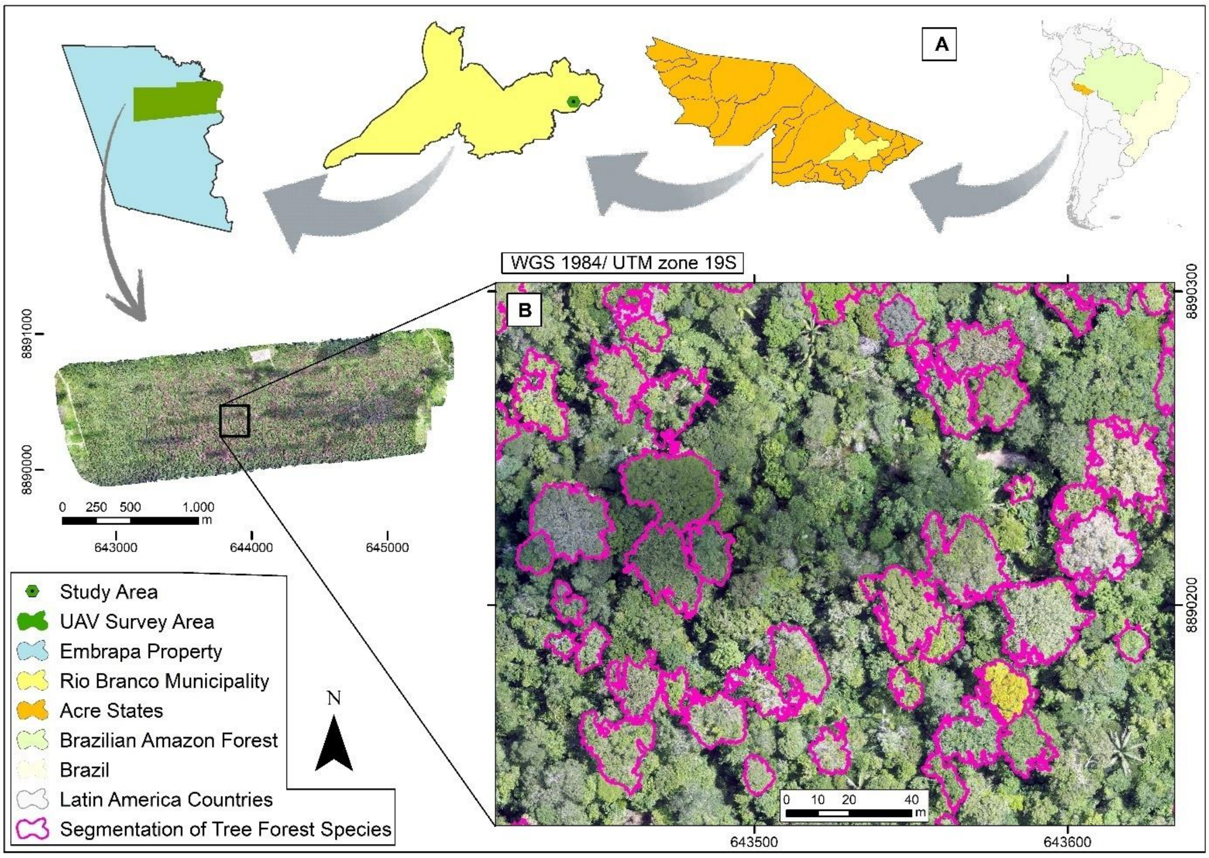

Figure 1. (A) Location of the study area in the Acre state, southwestern Amazon, Brazil. (B) Segmentation of tree forest species in the native forest.

Individual tree crown (ITC) dataset

First, we measured and identified all trees with a diameter at breast height (DBH) greater than 50 cm to the species level in the forest inventory experimental area, the volume (m³) of the trees was derived from the rigorous measurement of 1,500 trunks in a wood storage yard, with input of the DBH and H variables into an equation (1) generated by the Embrapa Acre research institution, as follows:

$$V = -0.225042 + 0.697672(DBH/100)^2 + 0.638055((DBH/100)*2)^H + 1.41241H^{(-1/2)} \quad (1)$$

For this study, we selected the most economically important species for nut and timber production and delineated their ITCs in the UAV images.

We performed the segmentation of each ITC using the Definiens Ecognition software program, then we filtered with the trees from the field forest inventory and excluded the non-whole crowns. ITC delineation was carefully performed so that a single ITC polygon encompasses the same tree. We outlined a total of 388 ITCs, corresponding to 55 species. According to the forest inventory, the DBH of the inventoried trees ranged from 50.0 cm to 190.0 cm, with the total height of some trees reaching 40 m. A greater number of individuals can be seen in the smallest diametric classes (Table 1), constituting similar behavior to a mature forest without anthropic intervention (Meyer, 1952; Assmann, 1970)

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Table 1. Diametric distribution and estimated average height of trees from Lidar and UAV considered to estimate volume through crown morphometry using UAV

Diametric class	Nº Tree	LiDAR (m)	UAV (m)	%
50|- 60	61	30,28	28,02	15,76
60|- 70	57	31,82	29,89	14,73
70 |- 80	49	33,86	30,33	12,66
80 |- 90	47	32,57	30,86	12,14
90 |- 100	43	35,05	32,87	11,11
110 |- 120	37	36,90	33,97	9,56
120 |- 130	28	38,03	35,05	7,24
130 |- 140	20	38,44	35,84	5,17
140 |- 150	16	39,06	35,67	4,13
150 |- 160	12	38,07	35,48	3,10
160 |- 170	10	39,87	36,45	2,58
> 170	7	39,42	36,82	1,81

UAV-derived variables

We derived canopy morphometry metrics, variable area (ca) and diameter (cd) from the UAV images; the crown diameter was obtained from the average between the largest and smallest diameter of each sample (Fig 2). We used the digital terrain model (DTM) and the digital surface model (DSM) from the aerial survey via LiDAR to generate the canopy high model (CHM) obtaining the heights of the trees; then, the CHM model of the UAV was generated through the difference between DTM (LiDAR) and DSM (UAV), seeking to identify a relationship between height and volume.

Predicted dendrometric parameters based on UAV-derived variables

We subdivided the dataset into 70% for fitting and 30% to validate the models. We selected the independent regression variables based on their correlation with the dependent variables (volume - V, basal area - G, and DBH). The Correlation Test (Figure 3) indicates a low relationship between height and all variables, which is not a good parameter to estimate the dendrometric variables, therefore we discarded the use of the canopy height model (CHM). The morphometric diameter and crown area variables obtained a strong correlation with volume, basal area and DBH, which were selected to compose the regression model. Thestatistical analysis was conducted in R language programming with used package metricsand corplot (R Core Team, 2021).

Next, we fitted three linear regression models using volume, basal area, and DBH as dependent variables and the diameter and canopy area as independent variables (Models 2 - 4). We decided to use the tree's diametric class as a categorical variable in order to increase the model accuracy.

$$V = \beta0 + \beta1ca + \beta2cd + \beta iDCi \quad (2)$$

$$G = \beta0 + \beta1ca + \beta iDCi \quad (3)$$

$$DBH = \beta0 + \beta1cd + \beta iDCi \quad (4)$$

In which: βi are the model parameters, ca is the crown area, cd is the crown diameter, DC is the diameter class.

Accuracy assessment

The models' fit was evaluated by the adjusted determination coefficient (R^2), standard estimate error (SEE), and the residual plot, while the model generalization at the validation database was evaluated by the Pearson's correlation coefficient, the root mean square error, paired T-test, and the residual plot.

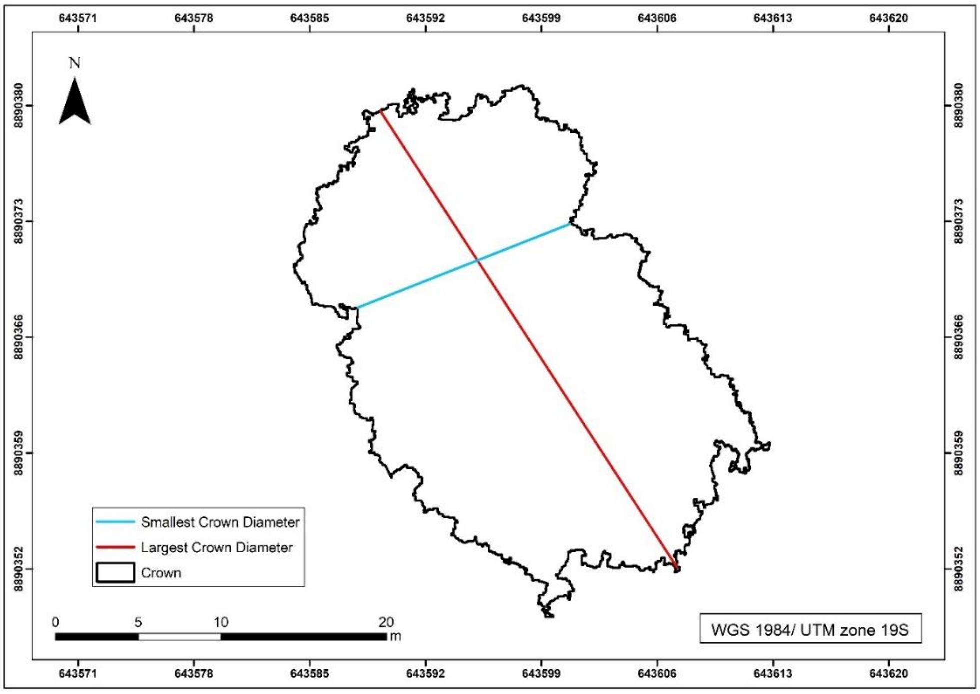

Figure 2. Example of a sample of the average tree crown diameter (cd) obtained by averaging the largest and smallest diameter.

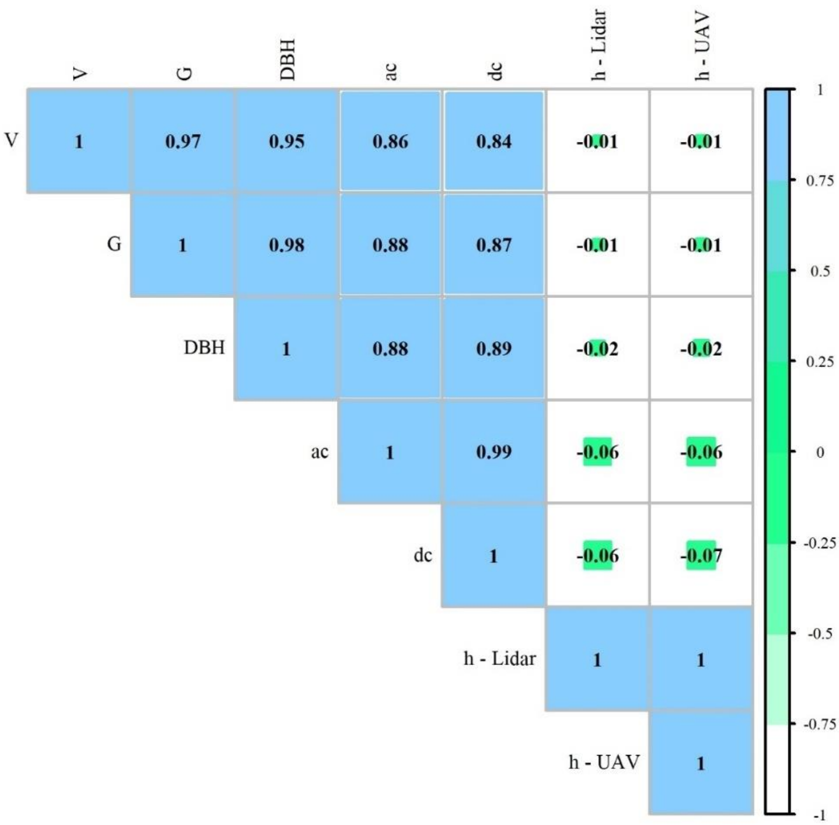

Figure 3. Correlation chart between dendrometric and UAV derived variables.

*Note: h is the Forest inventory tree height, v is the tree volume, G is the tree basal area, DBH is the tree diameter at breast height, ca is crown area, cd is crown diameter, h from UAV height and h from Lidar.

Results and discussion

The volume (v) predictions had metrics on the fit and validation, with SEE of 21.97% for the fit and RMSE 19.13% for the validation, in addition to an R^2 greater than 0.90 in both cases. On the other hand, the basal area (G) and diameter (DBH) estimates had high statistical metrics, with a SEE < 6.5% and $R^2 > 0.99$, denoting the model's accuracy, as well as the potential and the canopy variables' potential for determining these variables (Table 2).

Table 2. Models' statistical metrics.

Variable	Statistical analysis						
	FIT			Test			
	R^2	SEE	SEE (%)	r	RMSE	RMSE (%)	T (p-value)
V	0.916	2.507	21.972	0.967	2.124	19.314	0.04ns
G	0.992	0.045	6.231	0.995	0.052	7.297	0.07ns
DBH	0.993	2.559	2.820	0.995	2.876	3.183	0.02ns

In which: V is volume, G is basal area, DBH is diameter at breast height, R2 is adjusted determination coefficient, SEE is standard estimate error, r is Pearson's linear correlation, RMSE is root mean square error, T is the Paired T-test, ns is nonsignificance.

Only the volume residuals are heteroscedastic, while G and DBH residuals are between -25% and 25%, which demonstrates accuracy (Figure 4). On the fit (Figure 4a). The residual's fit (Figure 4b) obtained a greater variation than the validation. These performances reflected the model's statistical metrics.

The models' accuracy is observed in the correlation plot, in which the volume had a greater variation of observed vs. estimated values, although the regression model's mean line of fit (red line) passes close to the perfect correlation (dashed black line). G and DBH obtained lower variation, with points next to the regression model and the perfect correlation (Figure 5).

Dendrometric variables' accuracy for the fit and validation dataset. The models' coefficients are significant in all the estimated variables, explaining the intercept (β0) variation and the inclinations on the regression curves throughout the diameter classes, indicating there are different inclinations among the diameter classes which explain the tree volume behavior based on the crown variables (Table 3).

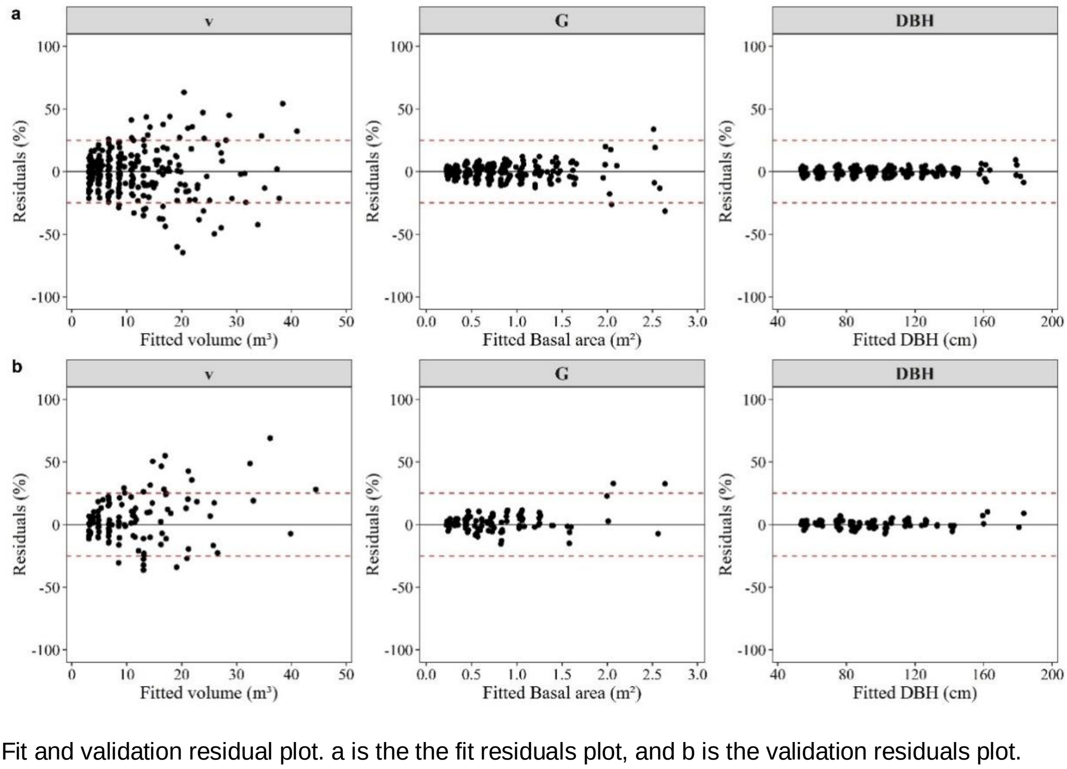

Figure 4. Fit and validation residual plot. a is the the fit residuals plot, and b is the validation residuals plot.

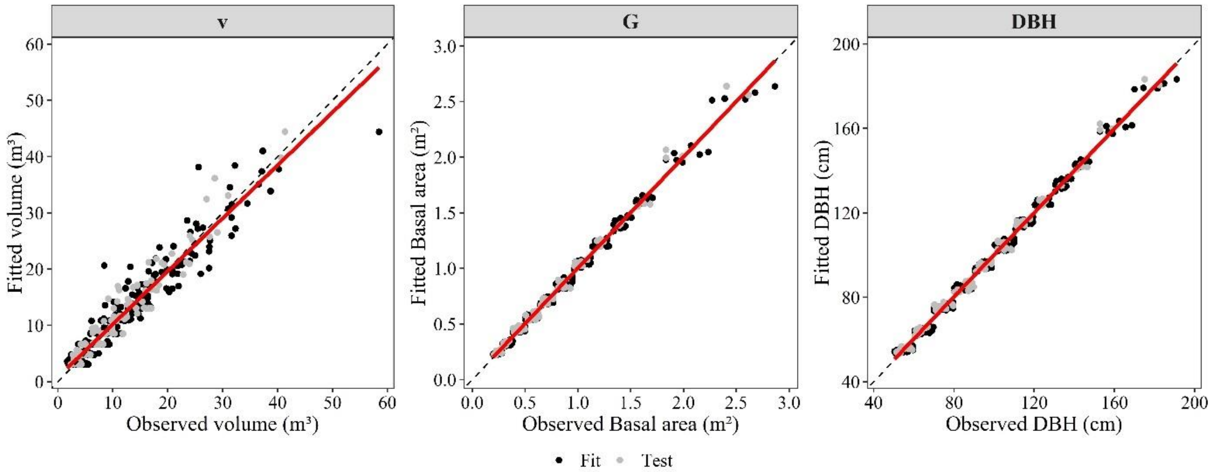

Figure 5. Dendrometric variables' accuracy on fit and validation dataset.

Table 3. Coefficient of the variables used for the model fitting

Parameter	V	G	DBH
β0	12.254*	0.186*	46.390*
β1	0.043*	0.00035*	0.633*
β2	-1.117*	0.073*	8.215*
β3	1.676*	0.181*	18.297*
β4	3.560*	0.291*	27.233*
β5	5.430*	0.418*	36.332*
β6	7.717*	0.561*	45.601*
β7	9.949*	0.729*	55.283*
β8	12.748*	0.867*	62.897*
β9	14.589*	1.057*	72.171*
β10	16.519*	1.251*	80.970*
β11	21.376*	1.619*	96.342*
β12	26.030*	2.133*	115.421*
β13	30.830*	-	-

Note: V is volume, G is basal area, DBH is diameter at breast height, βi is the model parameter, * is significance. Regarding the volume estimates, β1 was associated with crown area and β2 with crown diameter, β3 to β13 were associated the 11 diameter class coefficients. For the G and DBH estimate β2 to β12 were associated the 11 diameter class coefficients. For the G estimates, β1 was associated with crown area, and with crown diameter for DBH. The diameter class 1 was associated to β0 for all variables.

Discussion

Indirect measurement of dendrometric variables has emerged as an efficient and lower-cost alternative, especially in dense coverage such as the Amazon rainforest, where difficult access makes obtaining field data more expensive. The tree crown segmentation using the UAV with RGB sensors proved to be feasible, as it is a low-cost equipment which enables extractingthe variables crown area (ac) and crown diameter (cd) and relate them to variables whichare difficult to measure: DBH, basal area and volume.

In this study, the variables v, G, DBH, ca and cd were strongly correlated with each other (Figure 3), evidencing their importance in the estimates by equations (2-4). The strong correlation is in agreement with the study by Iizuka *et al.* (2018), in which it is mentioned that the variables DBH, area and crown diameter are highly correlated with the individual diameters of the trees.

Obtaining the tree volume is a limiting factor for operational planning in forest management and forest biomass, in which the use of morphometric variables of the crown tend to improve the accuracy of estimates from the UAV (Figueiredo *et al.*, 2014), which confirms the high degree of correlation between canopy variables and volume. DBH is another variable to be considered when estimating volume (Tudoran *et al.*, 2021) due to its high correlation, which is evidenced in this study.

The fitting of the volume model that relates the crown variables and the diametric classproves to be an efficient way for its estimation. The results related to the volume model fit statistics (Table 2) were lower than the studies by Tudoran (2022) (RMSE ≈ 9%) and by Figueiredo *et al.* (2014) (SEE (%) = 16.73). The superiority of the cited studies in addition to the different models used can be explained by being associated with characteristics related to the forest rather than the individual characteristics of the trees, such as DBH, height and crown size, which vary167 in relation to the tree stand structure. The inferiority of the calculated statistics, mainly in relation to the study by Tudoran *et al.* (2021), can be explained by the specificity of the study area, since the Amazon forest has a high degree of complexity which entails a greater variability of the Biometric characteristics of trees.

Therefore, the influence of structure and local conditions in trees should be taken intoaccount when developing models based on biometric variables (Tudoran *et al.*, 2021;Guerra-Hernández *et al.*, 2016). In turn, models that express the relationship between the dendrometric characteristics of trees need to be developed separately for each type of structure.

Figueiredo *et al.* (2014) found that models using variables exclusively from the canopy revealed $R^2_{aj.}$(%), results ranging from 72,68 to 79,44 and percentage standard error Syx(%) between 27,47 to 30,84, which were lower than those models that included the DBH as one of the independent variables, and constituting similar results to the simple entry equations in dendrometric studies in the Amazon. According to the same author, none of the generated models that exclusively use the traditionally employed independent variables (DBH, Ht) obtained better results than models that also apply variables derived from the crown morphometry indices.

The study revealed satisfactory results for the 3 models. The fits of the diameter and basal area models present superior statistics according to the R^2 and SEE values. This can be explained since the DBH and G are variables with a lower degree of uncertainty when measured directly than the volume that is a variable estimated. The fits were satisfactory according to the analyzed statistics when comparing the results obtained with other studies. Tudoran (2022) found an RMSE of 13.7%, which can be explained by the use of the cd variable only as a linear function in estimating the diameter, and the diameter classes in the model in this study were associated in addition to cd. When Tudoran *et al.* (2021) used a third-degree polynomial function using cd as a variable, it resulted in RMSE values which varied between (0.32 – 0.89). This difference in the goodness of fit can be explained by the difference in forest density that influences the DBH-cd relationship.

Despite the results found showing great efficiency in estimating variables resulting from crown morphometry, one of the major limitations in indirect estimations through data capture with passive sensors coupled to UAVs is penetration into dense forests, resulting in partial detection or omission of smaller trees shaded by larger trees, limiting the data collection from the understorey (for example), as pointed out by Iizuka *et al.* (2018) in their tree segmentation study.

Collecting good aerial images with an RGB sensor to accurately define the treetops is still a difficult task. It is necessary to take some precautions: mapping with the UAV in the hours of greatest luminosity, adjusting the camera shutter for fast shooting (>1/500) and the high diaphragm to be more accurate in correctly focusing the target (>209 5.0). The aerial images will be very clear without the rolling shutter effect from following these settings, able to extract more accurate information, even with the existing limitations of the segmentation of the cd and ca variables from the UAV. The inference of hard-to-obtain dendrometric variables such as volume decreases operating costs in forest inventories, in addition to only needing information from larger trees for decision-making, for example in sustainable forest management.

Studies have achieved satisfactory results by segmenting trees from UAV data with spacing between objects (Veras *et al.*, 2022; Tudoran *et al.*, 2021; Torres *et al.*, 2020; Huang *et al.*, 2018; Lin *et al.*, 2015; Torres-Sánchez *et al.*, 2015). The segmentation of trees to obtain dendrometric variables from UAV data in a natural dense forest is complex due to the proximity between tree canopies; data from active sensors, such as Lidar, generally have better performance to segment the tree canopy and characterize the tree stock (Torresan *et al.*, 2020; Figueiredo *et al.*, 2014; Yan *et al.*, 2018).

The use of remote technologies is disruptive and needs to fall into the acceptance of forest managers, which is an essential role of academic research work, since the main dendrometric variable collected remotely (height) did not show good associations with the volume and basal area of trees. On the other hand, the use of crown variables with a high degree of association with volume, basal area and DBH provided accurate estimates, which infers that we should seek alternatives for the use of these variables in order to make the forest inventory less onerous and maintain its precision. Thus, remote RGB sensors can help as complementary tools to the forest inventory, enabling to reduce sampling units in the field and fitting models for the entire area based on morphometric variables of the canopy.

Conclusion

In this work, we have shown that the use of aerial images from a UAV system enables making good indirect dendrometric estimates through tree canopy morphometry for the Amazon Forest. The equation for the variable volume composed by a combination of the area and crown diameter variables by diametric class had an admissible error in the context of inventories in natural tropical forests compatible with the field data of the forest inventory, with R^2 0.967 and RMSE 19.31%. The aerial mapping with UAV to extract information from the biometry of the trees proved to be very useful to obtain a previous estimate of the tree stock of a forest, constituting important data for the environmental manager to plan the management and conservation of forest resources. Future studies will focus on applying this technique to other forest typologies to expand thestudy base and improve the accuracy of the models by using more accurate algorithms and image processing methods.

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