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TREE HEIGHT ESTIMATION USING DIGITAL AERIAL PHOTOGRAMMETRY IN AN INTEGRATED CROP LIVESTOCK FOREST SYSTEM

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Abstract: Accurate tree height estimation is essential for calculating volume, biomass, and carbon stock in forest inventories. This study evaluated the accuracy of digital aerial photogrammetry using nadir and oblique RGB images captured by an Unmanned Aerial Vehicle (UAV) in estimating the height of *Eucalyptus urograndis* (clone GG100) trees in an Integrated Crop Livestock Forest (ICLF) system. A total of 90 georeferenced trees were analyzed. Images were captured using a DJI Matrice 210 equipped with a Sentera AGX 710 camera. The estimated values were compared with ground-truth measurements obtained after thinning the trees. Results showed strong agreement between predictions and ground truth, with mean heights of 35.90 m (observed) and 35.90 m (estimated), RMSE of 1.92 m (5.34%), and Bias of -0.01 m (-0.01%). The coefficient of determination (R^2) was 0.75. Although a slight overestimation was observed in smaller trees, the technique demonstrated consistent and reliable performance for operational applications. The integration of nadir and oblique images contributed to the accuracy of the 3D model, highlighting photogrammetry as an efficient and cost-effective tool for forest monitoring in ICLF systems.

Keywords: Nadir image, 3D cloud, drone, forest inventory, oblique photogrammetry.

ESTIMATIVA DE ALTURA DE ÁRVORES UTILIZANDO FOTOGRAMETRIA AÉREA DIGITAL EM UM SISTEMA DE INTEGRAÇÃO LAVOURA PECUÁRIA FLORESTA

Resumo: A estimativa precisa da altura de árvores é essencial para o cálculo de volume, biomassa e carbono em inventários florestais. Este estudo avaliou a acurácia da fotogrametria aérea digital, utilizando imagens RGB nadir e oblíquas obtidas por Veículo Aéreo não Tripulado (UAV), na estimativa da altura de *Eucalyptus urograndis* (clone GG100) em um sistema de Integração Lavoura Pecuária Floresta (ILPF). Foram analisadas 90 árvores previamente georreferenciadas. As imagens foram capturadas com DJI Matrice 210 equipada com câmera Sentera AGX 710. Os valores estimados foram comparados com medidas obtidas após o desbaste das árvores. Os resultados indicaram forte concordância entre os dados, com média de 35,90 m (observada) e 35,90 m (estimada), RMSE de 1,92 m (5,34%) e viés de -0,01 m (-0,01%). O coeficiente de determinação (R^2) foi de 0,75. Apesar de uma leve superestimativa em árvores menores, a técnica demonstrou desempenho consistente e adequado para aplicações operacionais. A integração de imagens nadir e oblíquas contribuiu para a acurácia do modelo, evidenciando a viabilidade da fotogrametria como ferramenta eficiente e acessível para o monitoramento florestal em sistemas ILPF.

Palavras-chave: Imagem nadir, nuvem 3D, drone, inventário florestal, fotogrametria oblíqua.

1. Introduction

Tree height estimation is a fundamental variable in forest inventories, as it directly influences the calculation of volume, biomass, and carbon stock in ecosystems. However, accurately obtaining this variable through traditional field methods is challenging (Wang et al., 2019). Given its importance, precise and efficient methods for obtaining this metric have been continuously sought by forestry professionals in order to optimize data collection without compromising information quality (Moreira et al., 2025).

In this context, remote sensing has stood out in recent decades as an effective alternative for acquiring this variable. Its application enables the generation of standardized information with a high level of repeatability, contributing to faster and more efficient inventory processes (Ganz et al., 2019; Waser et al., 2017). Among the tools gaining prominence is the use of UAV, which have proven capable of significantly reducing operational costs, labor demand, and data acquisition time (Tsouros et al., 2019).

Among UAV-based approaches, photogrammetry stands out as an accessible and efficient solution for mapping forest structure. For optimal results, images with high overlap and captured from multiple angles are required, reducing errors in 3D reconstruction (Iglhaut et al., 2019). The combination of nadir and oblique images expands visual coverage and improves tree crown identification, enhancing the quality of the generated models (Nesbit & Hugenholtz, 2019).

Therefore, this study aimed to evaluate the accuracy of digital aerial photogrammetry - using nadir and oblique images acquired by UAV - in estimating the height of eucalyptus trees in an ICLF system. The estimates were compared with measurements obtained using a measuring tape following tree harvesting, in order to assess the performance of the technique for forest monitoring applications in integrated systems.

2. Materials and Methods

2.1. Study Area

The study area is located at Embrapa Southeastern Livestock, in São Carlos – SP, Brazil (21°58'12"S 47°51'11"W, 860 m altitude). The study was conducted a 3-hectare area within an ICLF system. The forestry component consists of single rows of *Eucalyptus urograndis* “GG100” — spaced 30 meters between rows and 4 meters between trees — intercropped with pastures of piatã grass (*Urochloa (*syn*. Brachiaria) brizantha* (Hochst. ex A. Rich.) Stapf “BRS Piatã”) (Bernardi et al., 2019; Bueno, 2021; Pezzopane et al., 2019).

2.2. Data Collection and Statistical Analysis

A total of 90 georeferenced trees were selected for analysis. Tree height estimation was performed using a 3D point cloud generated through aerial photogrammetry using the software Pix4D, based on RGB images captured by a DJI Matrice 210 equipped with a Sentera AGX 710 multispectral camera. The flight was carried out at an altitude of 120 meters, with 70% frontal and lateral overlap. The mission was planned with two image sets: nadir and oblique. Nadir images were captured perpendicularly to the ground, while oblique images were taken with the camera tilted at 45°, covering all four sides of the experimental area in standard flight paths. The combination of these viewing angles enhanced the three-dimensional modeling of the canopy structure.

The processing of the dense point cloud was carried out in a computational environment using R software, version 4.4.1 (R Core Team, 2024), employing tools provided by the lidR package (Roussel & Auty, 2022). For normalization, a digital terrain model was created through the application of the Cloth Simulation Filter (CSF) algorithm, as proposed by Zhang et al. (2016).

After reconstructing the geometry of the area, tree heights were extracted based on a geospatial mask created from the coordinates of each tree. Height was defined as the difference between the highest point of the canopy and the ground surface. The estimated values were compared with tree heights measured directly using a measuring tape following tree harvesting. Statistical analysis included the Pearson correlation coefficient (r), root mean square error (RMSE), and bias (Bias), expressed in both absolute and relative terms. The error was calculated as the difference between observed and estimated heights (observed - estimated).

3. Results and Discussion

Height estimates derived from the 3D point cloud generated via digital aerial photogrammetry showed strong agreement with field measurements. The mean tree heights were the same: 35.90 m for tape-measured values and 35.90 m for the photogrammetric estimates, a difference of just 0.01 m. This suggests that the model effectively represents the overall structure of the stand.

The distribution of estimated heights was also coherent with the statistical structure of the field measurements, with the first quartile (25%) at 34.13 m (observed) and 34.56 m (estimated), the median (50%) at 37.06 m (observed) and 36.56 m (estimated), and the third quartile (75%) at 38.87 m (observed) and 37.92 m (estimated). The bias analysis (Bias = -0.01 m) and the root mean square error (RMSE = 1.92 m, equivalent to 5.34%) support this evaluation. The negative Bias indicates a slight tendency toward overestimation, meaning that the method produced slightly higher values than those measured in the field. However, this difference is considered negligible, particularly for large-scale forest inventories.

The scatterplot (Figure 1), which compares observed and estimated heights, complements the numerical analysis. The blue equality line represents the ideal condition. The concentration of points near this line reveals substantial agreement between datasets, further supported by a coefficient of determination (R^2) of 0.75. Despite the linear trend, a slight asymmetry is noticeable, with points predominantly above the equality line, confirming the overestimation previously mentioned. This overestimation is more pronounced in smaller trees, likely due to the upper portions of their crowns being partially or completely obscured by branches from taller adjacent trees as note by Baur et al. (2024). Nevertheless, the high density of points near the ideal line demonstrates the method's reliability in capturing the vertical structure of the stand.

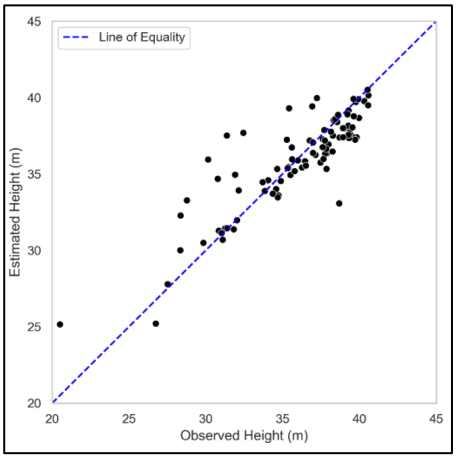

Figure 1. Scatterplot of tree heights measured by a measuring tape versus those estimated using digital aerial photogrammetry.

Most errors remained within acceptable limits, supporting the applicability of the technique at broader scales. Integrating nadir and oblique imagery improved vertical tree representation by increasing point density at canopy edges and crown tops, a critical advantage in structurally complex systems such as silvopastoral stands. While nadir views alone yield low density and high omission rates, oblique angles - particularly at −45° vertical and 0° horizontal -enhance canopy representation, reduce errors, and ensure more consistent structural characterization (Li et al., 2021).

4. Conclusions

RGB photogrammetry proved to be a reliable approach for estimating the height of eucalyptus trees in ICLF systems using UAV-acquired imagery. The approach exhibited strong alignment with field-based measurements and effectively captured the vertical structure of the stand. Although minor overestimations were observed in smaller individuals, the overall performance supports its applicability in operational settings. Furthermore, the integration of nadir and oblique images enhances the quality of 3D reconstruction and improves canopy characterization, establishing this approach a practical and efficient tool for forest inventory and monitoring in integrated agricultural systems.

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