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EUCALYPTUS TREE HEIGHT IN AN INTEGRATED CROP LIVESTOCK FOREST SYSTEM: COMPARISON BETWEEN MOBILE LASER SCANNING AND DIRECT MEASUREMENT

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Abstract: This study evaluated the accuracy of the Mobile Laser Scanning (MLS) point cloud in estimating the height of *Eucalyptus urograndis* (clone GG100) trees in an Integrated Crop Livestock Forest (ICLF) system. A total of 90 trees distributed across 1 paddock in a 3-hectare area were analyzed. Tree heights were extracted from the 3D point clouds and compared with direct measurements obtained by a measuring tape after thinning the trees. The statistical analysis included the Pearson correlation coefficient (r), root mean square error (RMSE), and mean bias (Bias), calculated in absolute and percentage terms. The results showed a strong and positive correlation of r = 0.86, a RMSE of 2.03 m (5.65%), and a low Bias of -0.36 m (- 1%), indicating good agreement between estimated and observed values. Extracting tree heights from MLS point clouds proved effective in the ICLF system. Minor discrepancies were observed, particularly in smaller trees, but without compromising the applicability of the technology. Therefore, it is concluded that MLS represents a viable and accurate alternative for forest monitoring in integrated production environments.

Keywords: LiDAR, ICLF, point cloud, remote sensing, dendrometry.

ALTURA DE EUCALIPTOS EM UM SISTEMA DE INTEGRAÇÃO LAVOURA PECUÁRIA FLORESTA: COMPARAÇÃO ENTRE VARREDURA A LASER MÓVEL E MEDIÇÃO DIRETA

Resumo: Este estudo avaliou a acurácia da nuvem de pontos do Mobile Laser Scanning (MLS) na estimativa da altura de árvores de *Eucalyptus urograndis* (clone GG100) em um sistema de Integração Lavoura Pecuária Floresta (ILPF). Foram analisadas 90 árvores distribuídas em um piquete em uma área de 3 hectares. As alturas foram extraídas a partir da nuvem de pontos 3D e comparadas com medições diretas obtidas por fita métrica após o desbaste das árvores. A análise estatística incluiu o coeficiente de correlação de Pearson (r), a raiz quadrada do erro médio (RMSE) e o viés médio (Bias), calculados em valores absolutos e percentuais. Os resultados demonstraram forte e positiva correlação de r = 0,86, RMSE de 2,03 m (5,65%) e baixo Bias de -0,36 m (-1%), indicando boa correspondência entre as medidas. Extrair as alturas das nuvens de pontos do MLS mostrou-se eficaz em sistema ILPF. Pequenas discrepâncias foram observadas, principalmente em árvores menores, mas sem comprometer a aplicabilidade da

tecnologia. Portanto, conclui-se que o MLS representa uma alternativa viável e precisa para o monitoramento florestal em ambientes integrados.

Palavras-chave: LiDAR, ILPF, nuvem de pontos, sensoriamento remoto, dendrometria.

1. Introduction

The ICLF system has become established as a sustainable strategy, as it contributes to the conservation of natural resources (Junior et al., 2022), improves animal thermal comfort (Pezzopane et al., 2019), and enhances the physical and chemical properties of the soil (Lemaire et al., 2014). Within this system, the forestry component plays a strategic role by contributing to income diversification and carbon sequestration (Udawatta & Jose, 2012).

Efficient monitoring of tree height in the forestry component is essential for assessing and managing forest resources, as this variable is directly related to estimating wood volume, biomass, and carbon stocks (Wang et al., 2019). Traditionally, dendrometric variables are obtained through classical forest inventory techniques, which provide relevant quantitative and qualitative information for forest management but require greater operational effort and time (Latifi & Heurich, 2019). In this context, the use of remote sensing technologies has proven to be a valuable alternative, enabling the acquisition of reliable estimates more quickly and at a lower cost.

Among these technologies, systems based on Light Detection and Ranging (LiDAR) stand out, including Terrestrial Laser Scanning (TLS), Mobile Laser Scanning (MLS), and photogrammetry. MLS operates using a laser scanner that emits light pulses and measures the distance between the sensor and reflective surfaces. In this study, an individual tree-level analysis approach was adopted, which is crucial for accurately understanding the structure and functioning of forest ecosystems. Therefore, this study aimed to evaluate the accuracy of MLS in estimating the height of eucalyptus trees in an ICLF system by comparing the results with values obtained after tree felling.

2. Materials and Methods

2.1. Study Area

The study was conducted within an ICLF system at Embrapa Southeastern Livestock, located in the municipality of São Carlos, São Paulo State, Brazil (21°58'12"S 47°51'11"W, 860 m alt). The area covers 3-hectares, planted with eucalyptus (*Eucalyptus urograndis* "GG100") in single rows. The spacing between rows is 30 meters, and the spacing between trees within each row is 4 meters. The understory consists of pasture with piatã grass (*Urochloa (*syn*. Brachiaria) brizantha* (Hochst. ex A. Rich.) Stapf "BRS Piatã") (Bueno, 2021).

2.2. Data Collection

The study was conducted with a sample of 90 trees. Tree scanning was performed using an MLS system, specifically the GeoSLAM ZEB Horizon. The equipment was manually operated along the planting rows, following a trajectory parallel to the trees of interest, which enabled the continuous collection of three-dimensional data. At each turning point during scanning, geographic coordinates were recorded to enable accurate georeferencing of the point clouds.

2.3. MLS Data Processing

The point clouds were processed in a computational environment using the R software, version 4.4.1 (R Core Team, 2024), with functions available in the lidR package (Roussel & Auty, 2022). The point cloud was normalized using a digital terrain model generated by the Cloth Simulation Filter (CSF) algorithm (Zhang et al., 2016). Tree height was then extracted from the normalized 3D point cloud, where the height corresponds to the distance between the highest point of the tree crown and the ground. The extraction was based on a spatial mask generated from the geographic coordinates of each tree.

2.4. Statistical Analysis

The accuracy of tree height estimates obtained via MLS was assessed by comparison with reference values measured following tree harvesting. For this purpose, statistical metrics were used. The first was the Pearson correlation coefficient (r), which measures the degree of linear association between observed and estimated tree heights.

In addition to correlation, the root mean square error (RMSE) and mean bias (Bias) were calculated, both in absolute values (in meters) and percentage terms. This dual approach allows for a relative error assessment based on the magnitude of the observed tree heights. The formulas used were as follows:

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2 / n} \quad (1)$$

$$\text{RMSE}(\%) = (RMSE/\hat{y}) * 100 \quad (2)$$

$$\text{BIAS} = \sum_{i=1}^{n} Y_i - \sum_{i=1}^{n} \hat{Y}_i / n \quad (3)$$

$$\text{BIAS}(\%) = (BIAS/\bar{Y}) * 100 \quad (4)$$

Where Y_i is the total height of the i-th tree obtained after felling (observed height), $\hat{Y}_i$ is the total height of the i-th tree estimated using MLS, $\bar{Y}$ is the mean total height of all trees obtained after harvesting (observed heights), and n is the total number of trees analyzed. All height values are expressed in meters (m).

3. Results and Discussion

Tree height estimates derived from the MLS point cloud showed good agreement with observed values, with a Pearson correlation coefficient of 0.86, which indicates a strong positive association between estimated and observed heights. The close proximity between mean values also reflects the method’s good performance, with a mean observed height of 35.90 m and a mean estimated height of 36.26 m. The bias was just -0.36 m (-1%), which is considered low. The RMSE was 2.03 m, equivalent to 5.65%, suggesting that while overall accuracy is satisfactory, there are some notable pointwise discrepancies between estimates and field measurements, justifying a deeper analysis of the distribution of individual errors.

Figure 1 shows individual errors as a function of observed tree heights. The dashed line indicates zero error, while the blue trend line reflects the average variation in error along the height axis. A negative slope indicates that errors tend to increase as observed height decreases. Figure 2 shows the error distribution, with most errors concentrated around zero and few large deviations.

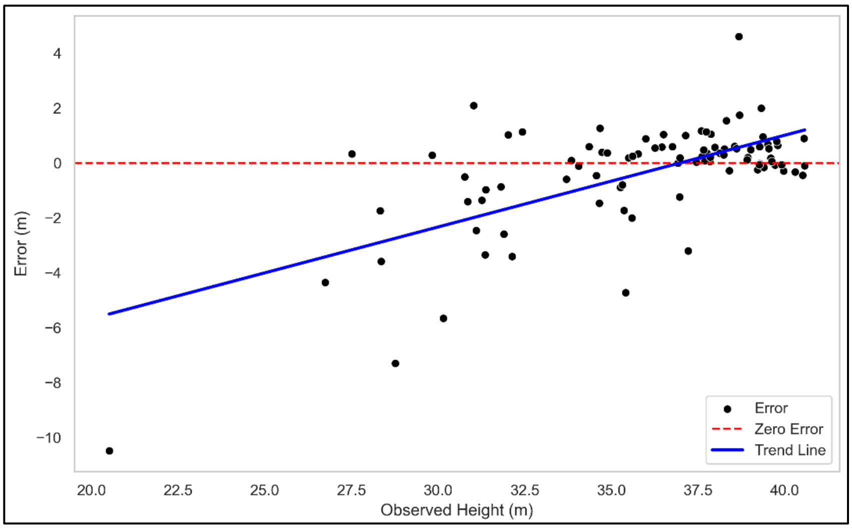

Figure 1. Tree Height Residuals: MLS vs. Observed.

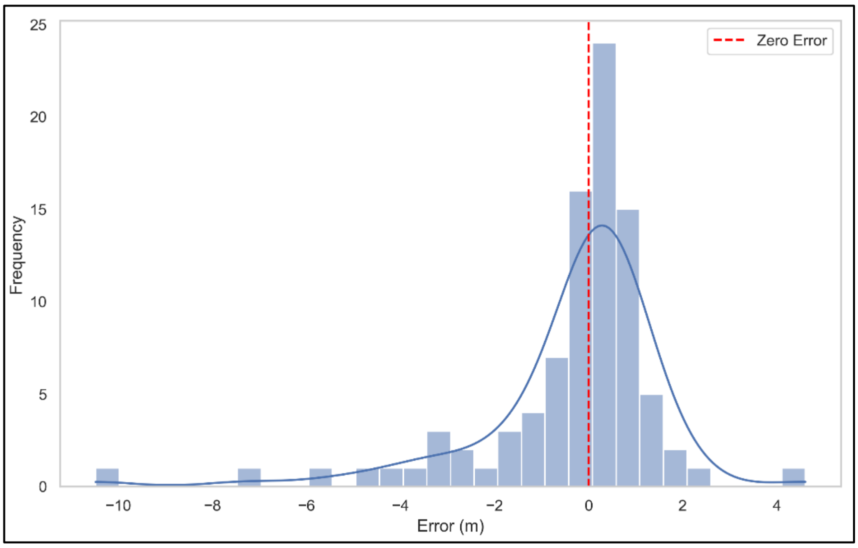

Figure 2. Distribution of Tree Height Estimation Errors.

This behavior can be explained by geometric occlusion caused by surrounding vegetation (Baur et al., 2024). In ICLF systems, trees are spaced widely between rows, but within rows, the smaller spacing between individuals allows for the formation of a closed canopy in some sections—especially among taller trees. As a result, during scanning, smaller trees may be partially or completely occluded by adjacent taller trees. It is important to note that although most errors remain within acceptable limits, extreme negative errors in smaller trees increase the RMSE and, therefore, deserve attention in applications requiring high individual precision, such as tree-level volume or carbon stock estimation.

4. Conclusions

This study assessed the accuracy of a MLS system in estimating the height of eucalyptus trees in an ICLF system by comparing MLS-derived values with reference measurements obtained after tree harvesting. The results demonstrated good performance of height estimates derived from the MLS point cloud; however, a consistent tendency toward overestimation was observed, particularly for smaller trees located near taller individuals. Despite these limitations, the findings support the viability of MLS as a modern, rapid, and accurate alternative for forest inventory in ICLF systems, particularly when the goal is to reduce fieldwork time and operational costs.

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