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CARBON ESTIMATION USING AERIAL PHOTOGRAMMETRY IN INTEGRATED CROP LIVESTOCK FOREST SYSTEMS

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Abstract: Integrated Crop Livestock Forest (ICLF) systems combine agricultural productivity with environmental sustainability, promoting pasture recovery, soil improvement, and carbon sequestration. This study aimed to compare the carbon stocks of *Eucalyptus urograndis* (clone GG100) individuals estimated using data collected in the field after thinning the trees and through aerial photogrammetry. Both carbon stocks were calculated using an allometric equation. The study was conducted in a 3-hectare ICLF area. The height and DBH estimates obtained through photogrammetry and applied to the equation showed a coefficient of determination (R^2 = 0.92) compared to observed data, with an RMSE of 0.11 Mg and a bias of -0.06 Mg. The average observed carbon stock was 0.72 Mg per tree (59.76 Mg ha^{-1}), while the photogrammetric estimate was 0.78 Mg per tree (64.74 Mg ha^{-1}). Based on field data, the study area contains approximately 219.32 Mg ha^{-1} of CO_2eq, corresponding to 219 carbon credits per hectare. In comparison, the estimate derived from aerial photogrammetry indicates 237.59 Mg ha^{-1} of CO_2eq, resulting in 237 carbon credits per hectare. The results indicate that photogrammetry is a viable tool for carbon estimation in ICLF systems.

Keywords: Carbon credit, Forest carbon stock, remote sensing, drone, ICLF.

USO DA AEROFOTOGRAMETRIA NA ESTIMATIVA DE CARBONO EM SISTEMAS DE INTEGRAÇÃO LAVOURA PECUÁRIA FLORESTA

Resumo: Sistemas de integração Lavoura-Pecuária-Floresta (ILPF) conciliam produtividade agropecuária com sustentabilidade ambiental, promovendo a recuperação de pastagens, melhoria do solo e sequestro de carbono. Este estudo teve como objetivo comparar os estoques de carbono de indivíduos de *Eucalyptus urograndis* (clone GG100) estimados com base em dados coletados em campo após o corte das árvores e via aerofotogrametria. Ambos os estoques foram calculados aplicando-se uma equação alométrica. O estudo foi conduzido em uma área de ILPF de 3 hectares. As estimativas de altura e DAP, via aerofotogrametria, aplicadas a equação apresentaram coeficiente de determinação de (R^2 = 0,92) em relação aos dados observados, com RMSE de 0,11 Mg e viés de -0,06 Mg. A média do estoque de carbono observado foi de 0,72 Mg por árvore (59,76 Mg ha^{-1}), enquanto a estimativa fotogramétrica resultou em 0,78 Mg por árvore (64,74 Mg ha^{-1}). Com base nos dados de campo, a área de estudo contém aproximadamente 219,32 Mg ha^{-1} de CO_2eq, correspondendo a 219 créditos de carbono por hectare. Em comparação, a estimativa derivada da aerofotogrametria indica 237,59 Mg ha^{-1} de CO_2eq, resultando em 237 créditos de carbono por hectare. Os resultados indicam que a aerofotogrametria é uma ferramenta viável para estimativas de carbono em sistemas ILPF.

Palavras-chave: Crédito de carbono, estoque de carbono florestal, sensoriamento remoto, drone, ILPF.

1. Introduction

Agroforestry systems such as Crop-Livestock-Forestry Integration (ILPF) have been employed as a strategy for restoring degraded pastures and reducing emissions from agricultural activities, contributing to more sustainable land-use practices (Junior et al., 2022; Pezzopane et al., 2021). In the planning of these systems, trees play a key role. In addition to being a potential source of wood for various economic purposes, they also provide important environmental services, such as carbon sequestration and the conservation of natural resources (Wang et al., 2019; Udawatta & Jose, 2012).

In this context, information on forest biomass and carbon stocks is essential for the development of sustainable management programs, especially those focused on climate change mitigation. Estimating the carbon stored in trees, however, depends on collecting essential dendrometric variables, such as Diameter at Breast Height (DBH) - typically measured at 1.3 meters above ground - and total tree height. The accuracy of these estimates is directly related to the quality of the data used, which can be collected through traditional field methods or by using remote sensing technologies (Pulido et al., 2019).

Among these technologies, digital aerial photogrammetry using images captured by Unmanned Aerial Vehicles (UAVs) - equipped with RGB, multispectral, or hyperspectral cameras - has stood out. This approach offers a practical, cost-effective, and non-destructive way to generate three-dimensional models of vegetation, allowing for the extraction of dendrometric variables (Jayathunga et al., 2018).

However, adopting this technology requires validating the generated estimates by comparing them with data collected in the field. In this context, the present study aimed to assess and compare the carbon stocks of *Eucalyptus urograndis* (clone GG100) trees, based on data obtained directly in the field after thinning the trees and on estimates derived from aerial photogrammetry. In both cases, the carbon stocks were calculated using the allometric equation developed by Pezzopane et al. (2021).

2. Materials and Methods

2.1. Study Area

The study was conducted in a 3-hectare area within an ICLF system located at Embrapa Southeastern Livestock, in São Carlos, São Paulo, Brazil (21°58'12"S, 47°51'11"W; 860 m altitude). The *Eucalyptus urograndis* trees (clone GG100) were planted in rows spaced 30 meters apart, with 4 meters between trees in the row, intercropped with palisade 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 Acquisition and Processing

For the observed measurements, after thinning the trees, height was measured using a measuring tape, and DBH (diameter at breast height) was measured using a diameter tape at 1.3 meters above ground level. These directly measured values were considered as ground truth and served as a reference for comparing estimates obtained via aerial photogrammetry.

For the photogrammetric estimates, two UAV (Unmanned Aerial Vehicle) flights were conducted: one at 120 meters altitude with 70% front and side image overlap for estimating tree height, and another at 4 meters altitude flying laterally with the camera facing the trees to capture the trunk and subsequently extract DBH values. The flights were carried out using a Sentera AGX 710 multispectral camera mounted on a DJI Matrice 210 drone. Only the RGB (red, green, and blue) images were used. The point clouds generated were processed in R software, version 4.4.1 (R Core Team, 2024), using routines available in the lidR package (Roussel & Auty, 2022) for extracting tree height and DBH for each individual.

In both approaches, the total biomass of each tree was calculated using the allometric equation developed by Pezzopane et al. (2021): Biomass = EXP (-3.88 + 2.41 * ln(DBH) + 0.62 * ln(Height)). Carbon stock was then estimated by multiplying the biomass by the average carbon content of 0.4549, as reported in the same study. Carbon stock values were expressed in megagrams per tree (Mg tree^{-1}). The planting density was 83 trees per hectare. The conversion factor from carbon stock to carbon dioxide equivalent (CO_2eq) was 3.67, calculated based on the ratio between the molecular weight of CO_2 (44) and the atomic weight of carbon (12), as proposed by Hoen & Solberg (1994).

The comparison between estimated values (from photogrammetry) and observed values (ground truth) was performed by calculating the error between observed and estimated measurements. To assess the accuracy of the estimates, the following statistical metrics were calculated: coefficient of determination (R^2), root mean square error (RMSE), relative RMSE (RMSE%), bias, relative bias (Bias%), and mean absolute error (MAE).

3. Results and Discussion

Figure 1 illustrates the comparison between the carbon stocks estimated by both methods. It can be observed that the lines follow a similar pattern across the 90 trees analyzed, with an overestimation in most cases for the values derived from aerial photogrammetry. This trend aligns with the observed negative bias, given that the errors were calculated based on the difference between observed and estimated values.

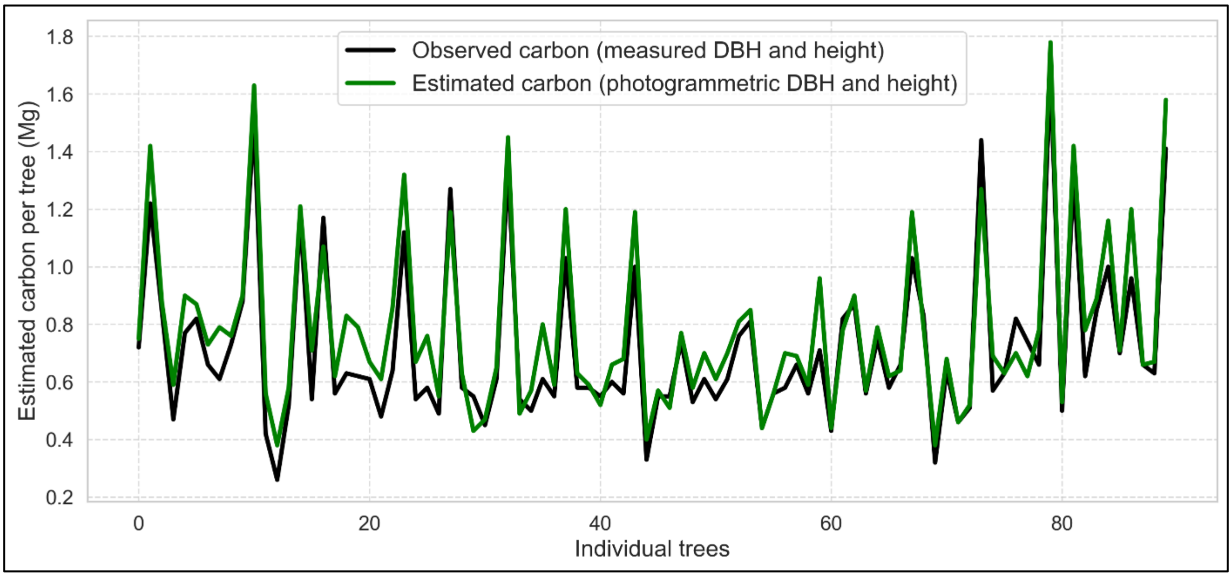

Figure 1. Carbon stock estimated using an allometric equation with field-measured (observed) vs. photogrammetry-derived (estimated) DBH and height.

The average observed carbon stock, based on data collected after thinning the trees, was 0.72 Mg per tree, representing a stock of 59.76 Mg ha^{-1} for the study area. In contrast, the estimated stock based on tree height and DBH data obtained through aerial photogrammetry was 0.78 Mg per tree, equivalent to 64.74 Mg ha^{-1}. The comparative analysis between the two methods showed a high correlation, with a coefficient of determination (R^2) of 0.92. The root mean square error (RMSE) was 0.11 Mg (14.74%), with a negative bias of -0.06 Mg (-8.86%), indicating a tendency toward overestimation in the values derived from aerial photogrammetry. The mean absolute error (MAE) was 0.08 Mg. Given this, according to the data collected in the field, the study area presents approximately 219.32 Mg ha^{-1} of CO_2eq, corresponding to 219 carbon credits per hectare. In comparison, the estimate derived from aerial photogrammetry indicates 237.59 Mg ha^{-1} of CO_2eq, resulting in 237 carbon credits per hectare.

The results indicate that the carbon stock estimates obtained through aerial photogrammetry data, despite showing overestimation, represent a viable alternative in ILPF systems. Its application allows for greater efficiency in data collection, especially in large areas, without significantly compromising the accuracy of the estimates.

4. Conclusions

The comparison between carbon stocks obtained from field measurements and those estimated through aerial photogrammetry showed high correlation and accuracy, despite the overestimation bias. This approach stands out as an efficient and non-destructive alternative for monitoring tree carbon in ILPF systems, demonstrating feasibility for large-scale applications. Future studies may explore the combined use of LiDAR or the application of artificial neural networks to enhance accuracy and reduce errors in automated estimates.

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