Deep learning models applied to drone imagery for counting, biometry, and carbon stock estimation in large-scale macaw palm (*Acrocomia aculeata*) plantations

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A paper from the Proceedings of the
17th International Conference on Precision Agriculture and 11th Brazilian Congress on Precision and Digital Agriculture
13-15 July 2026
Porto Alegre, Brazil

Abstract.
Macaúba (Acrocomia aculeata) is a palm tree native to Brazil with high productive, bioenergetic, and environmental potential, especially due to the possibility of its use in vegetable oil chains, sustainable fuels, and carbon credits. However, because it is still a crop under development, technologies capable of monitoring extensive plantations, individualizing plants, and estimating biometric variables and carbon stock on a large scale are required. This study aimed to develop an artificial intelligence model based on YOLOv11-seg, for the segmentation, counting, biometrics, and individualized estimation of carbon stock in macaúba plantations. The model was trained with aerial images obtained by drone and cropped from orthomosaics, using data augmentation. The system showed a precision of 0.972, a recall of 0.964, and an mAP50 of 0.992, indicating a high capacity for plant identification. Application to the total area allowed for the identification of 5,198 individuals and the estimation of 859 Mg of carbon. It is concluded that this approach is promising for automating agricultural and carbon inventories in commercial macaúba crops.

Keywords.
Digital Agriculture; Biofuels; High-throughput phenotyping.

INTRODUCTION

Macaúba (*Acrocomia aculeata*) has gained prominence due to its productive and environmental potential for oil production systems and the generation of carbon credits. However, the crop lacks efficient tools for plant identification and the acquisition of useful biometric data applicable to selection, management, and carbon auditing. Therefore, this study aimed to develop an artificial intelligence model based on YOLO for the segmentation, counting, biometric measurement extraction, and carbon stock estimation of macaúba plants using aerial images obtained by drones, applicable on a large scale and across different spacing scenarios.

METHODOLOGY

The study was conducted in macaúba cultivation areas at the Teaching, Research, and Extension Unit in Genetic Improvement and Production Systems of Palms and Other Oilseeds of the Federal University of Viçosa, located in the municipality of Araponga, in the state of Minas Gerais. Reference measurements were obtained from 88 plants distributed across three spacings: 5 x 5 m, single row (7 x 3.5 meters), and double row (8 meters between rows and 4 x 4 meters in a triangular layout). For carbon estimation in the experimental areas, three zones with 200 plants each were delimited, totaling 600 analyzed plants.

Aerial images were acquired using a DJI Mavic 3M (DJI, China) drone with RTK positioning correction. Flights were conducted at an altitude of 60 m for the 5 x 5 m spacing and 80 m for the single and double rows. The generated orthomosaics were divided into 640 x 640 pixel tiles to construct the dataset. Plant annotation was performed with the assistance of CVAT and SAM 2 (Ravi et al., 2024; Sekachev et al., 2020). Data augmentation involving rotation, blurring, and noise was applied to increase the model's generalization capacity. The final dataset consisted of 434 images: 70% for training, 15% for validation, and 15% for testing. The pre-trained YOLOv11-seg model was used as a baseline, trained over 100 epochs with a batch size of 4. Performance was evaluated using precision, recall, and mAP. The model was integrated with a Python algorithm to automate the georeferenced vectorization of masks, extraction of height, diameter, canopy area, and carbon stock estimation per plant (Fig. 1). Carbon estimation was based on the allometric equation proposed by Moreira et al. (2025), using plant height as the predictor variable.

The evaluation of biometric data was based on the collection of plant height, diameter, and canopy area. For comparison with the reference measurements, the mean absolute error (MAE) and its percentage (MAE%) were calculated. Population estimates based on the reference measurements were performed using simple random sampling with finite population correction (Lohr, 2010).

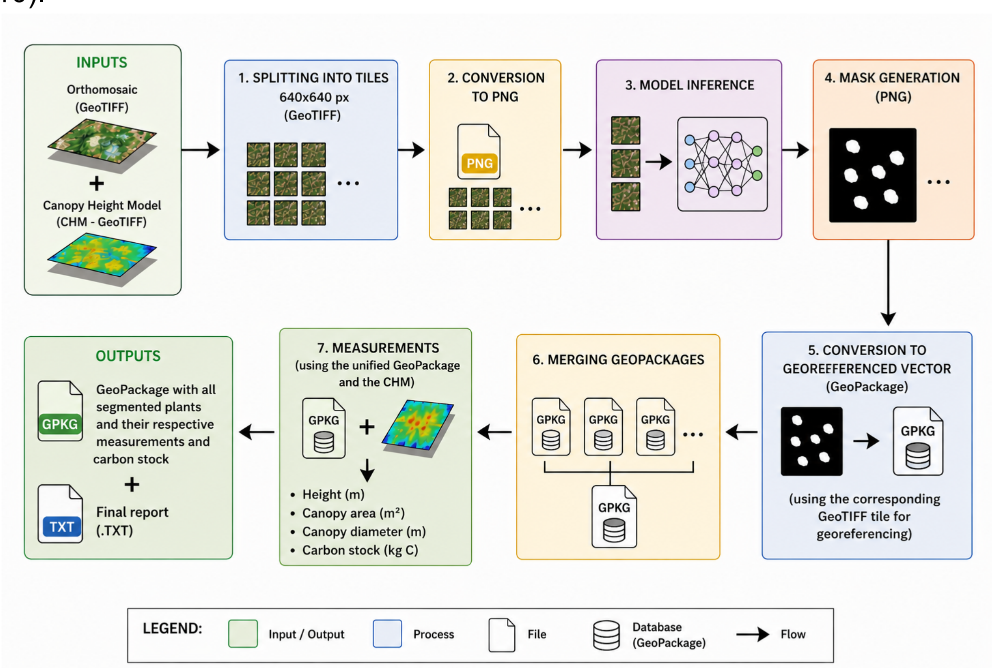

Fig 1. Data processing flowchart

RESULTS:

The model showed high performance in the segmentation of macaúba plants, with a precision of 0.972, a recall of 0.964, and an mAP50 of 0.992, indicating efficiency both in identifying the plants and in distinguishing between individuals and other elements present in the images. However, the obtained mAP50-95 of 0.799 indicates a limitation in the fine segmentation of the canopies (Fig. 2). This indicates that the model adequately recognizes the plants but has greater difficulty in precisely adjusting the mask boundaries, especially in areas with canopy overlap and higher spatial complexity, such as in the double row arrangement.

In the biometric evaluation, plant height obtained an MAE of 0.29 to 0.40 m, with an MAE% between 3.22% and 5.14%. The best percentage result was observed in the 5 x 5 m spacing, while the double row presented the highest error, likely due to the closer proximity between plants and the difficulty in positioning the centroids over the trunks. Canopy diameter obtained an MAE of 0.40 to 0.60 m, with an MAE% between 6.72% and 9.15%. The canopy area, on the other hand, obtained an MAE between 10.59 and 14.47 m² and an MAE% of up to 49.17%. Carbon estimation exhibited an underestimation trend compared to the reference measurements, with percentage differences ranging from 3.83% to 8.26%. Considering the total populations, the differences ranged from 8.32% to 10.13%. The values estimated by the algorithm remained within the confidence intervals of the estimates based on the reference measurements.

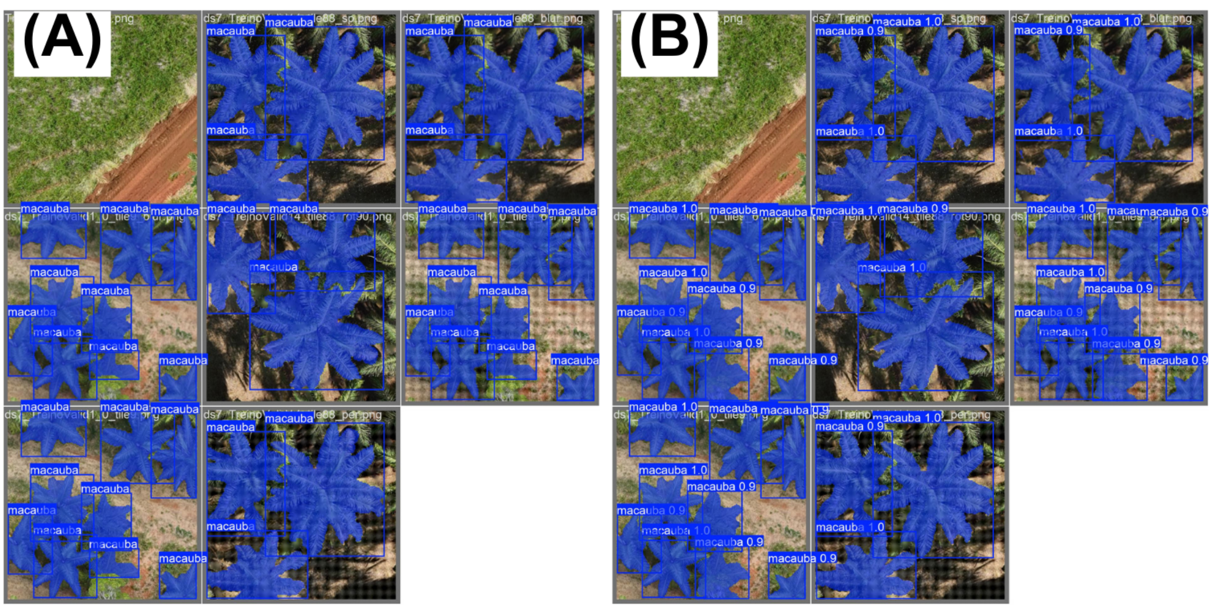

Fig 2. Validation: manual labeling (A) in contrast with model segmentation (B).

In the total area, the algorithm identified and segmented 5,198 plants. The algorithm was also able to extract biometric data individualized for each plant. Based on this data, an average height of 9.56 m, an average canopy diameter of 6.38 m, an average canopy area of 17.65 m², and an average carbon stock of 165.33 kg per plant were obtained. The total estimated carbon stock was 859,365.98 kg. It was not possible to identify all the plants present, as some were located beneath trees and could not be seen. These results highlight the main advantage of the method: the generation of an individualized inventory applicable to large.

CONCLUSION:

The model based on YOLOv11-seg demonstrated high performance, and the developed system showed potential for large-scale applications in agricultural and carbon inventories within commercial macaúba plantations. Future improvements to the dataset, additional training rounds, higher resolution images, and the refinement of fine segmentation are expected to increase the precision of the extracted measurements and carbon estimates.

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