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(Research Article)

Estimation of the structural parameters of an agroforestry system using very high-resolution drone images

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Abstract

Cocoa-based agroforestry systems are designed to improve production and mitigate the adverse effects of climate change. The objective of this study is to enhance our understanding of how to determine the structural parameters of cocoa-based agroforestry systems using drone imagery. To this end, images of ten cocoa plantations were acquired with a Phantom 4 multispectral drone to determine structural parameters such as density, canopy area, and the height of trees associated with the cocoa trees. Visual analysis of the orthophotos identified five land-use types: banana trees, palm trees, other trees, bare soil, and an "other" category encompassing cocoa trees, cashew trees, and shrubs of equal or smaller size than the cocoa trees. Analysis of the results reveals that structural parameters, such as tree density and canopy area obtained from the drone orthophotos, increase with the age of the cocoa plantations. Comparing tree heights measured by drone with those measured on the ground demonstrates the drone's accuracy for this purpose. This tool could therefore be used to assist producers in converting their cocoa plantations to agroforestry systems that comply with current standards, while simultaneously reducing the workload associated with diagnostics.

Keywords: Agroforestry Systems; Cocoa Tree; Multispectral Drone; Structural Parameters; Ortho-Image

1. Introduction

Côte d'Ivoire has been the world's leading producer of cocoa beans since the late 1970s [1]. This achievement is reflected in strong production growth, which increased from 179,200 tonnes in 1970 to 2.2 million tonnes in 2023 (ICCO, 2023). Furthermore, cocoa farming involves approximately 600,000 farmers and supports the livelihoods of nearly 8 million people. However, cocoa cultivation remains largely manual and dependent on natural and environmental constraints, particularly rainfall and the availability of forest resources [2]. In Côte d'Ivoire, agriculture is primarily family-based, relying on a shifting cultivation system [3]. This technique has long been considered a major cause of unsustainable agriculture and is believed to be the root cause of forest degradation. Thus, from 16 million hectares in 1960, the forest area was estimated at less than 3 million hectares in 2020 [4]. The dependence of this crop on forests has led to the shift of the cocoa economy's epicenters from the eastern region of Côte d'Ivoire to the forested areas of the central-west and then the southwest of the country, passing through the pre-forest areas of the central-east [5,6,7]. [8] believe that encouraging effective agroforestry by integrating trees into cocoa plantations could contribute to the sustainability of cocoa production in Côte d'Ivoire. Indeed, agroforestry helps to harmonize the benefits of trees with the livelihoods of communities by promoting sustainable agricultural production [9]. Furthermore, the presence of trees in agroforestry practices helps *to* mitigate the impact of already perceptible climate change [10]. However, the complexity of agroforestry practices leads to the existence of several types of cocoa-based agroforestry systems [11]. The capacity of

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these systems to perform certain functions depends on floristic diversity, density, the age of the farm, and the quality of the associated species [12, 13]. However, floristic inventories of farms are costly in terms of time and money, often incomplete, difficult to control, and cannot be generalized to a national scale [14]. Hence the need for a faster method of data collection. As one of the devices used to acquire aerial images, the drone is equipped with a camera that takes pictures while flying over the study area. Orthomosaics obtained from drone images can achieve a resolution of a few centimeters [15, 16, 17]. These orthomosaics can be used to create land cover maps and enable the identification of environmental components, the calculation of vegetation indices and the determination of stand structure parameters.

It is in this context that this study was initiated to improve knowledge on determining the structural parameters of cocoa-based agroforestry systems using drone imagery. It is based on the premise that the capabilities of scientific drones offer new possibilities for observing cocoa plantation land use units in order to better characterize them. To test this hypothesis, we set ourselves the following specific objectives:

- Identify land use units in cocoa farms,
- Determine structural parameters from ortho-images

2. Materials and methods

2.1. Presentation of the study area

The study area is located in the sub-prefecture of Bonon in the Marahoué region of central-western Côte d'Ivoire. It lies between 6°45'0" and 7°10'0" North latitude and 5°52'0" and 6°14'0" West longitude (Figure 1). This sub-prefecture is characterized by the cessation of cocoa plantation expansion, the aging of the orchards, and declining soil fertility [18]. This area has a Guinean climate with an average monthly rainfall of 97.68 mm and an average monthly temperature of 25.48°C [19]. The soils in this area of Côte d'Ivoire are moderately degraded ferralitic, predominantly clayey-sandy [19].

The sub-prefecture of Bonon is a mosaic of forests and savanna. The savanna in this region resembles an intermediate zone between grassy savanna and wooded and shrubby savanna [20] . The original structure of this vegetation has been severely degraded by human activities, giving way to large expanses of fallow land and perennial crop plantations.

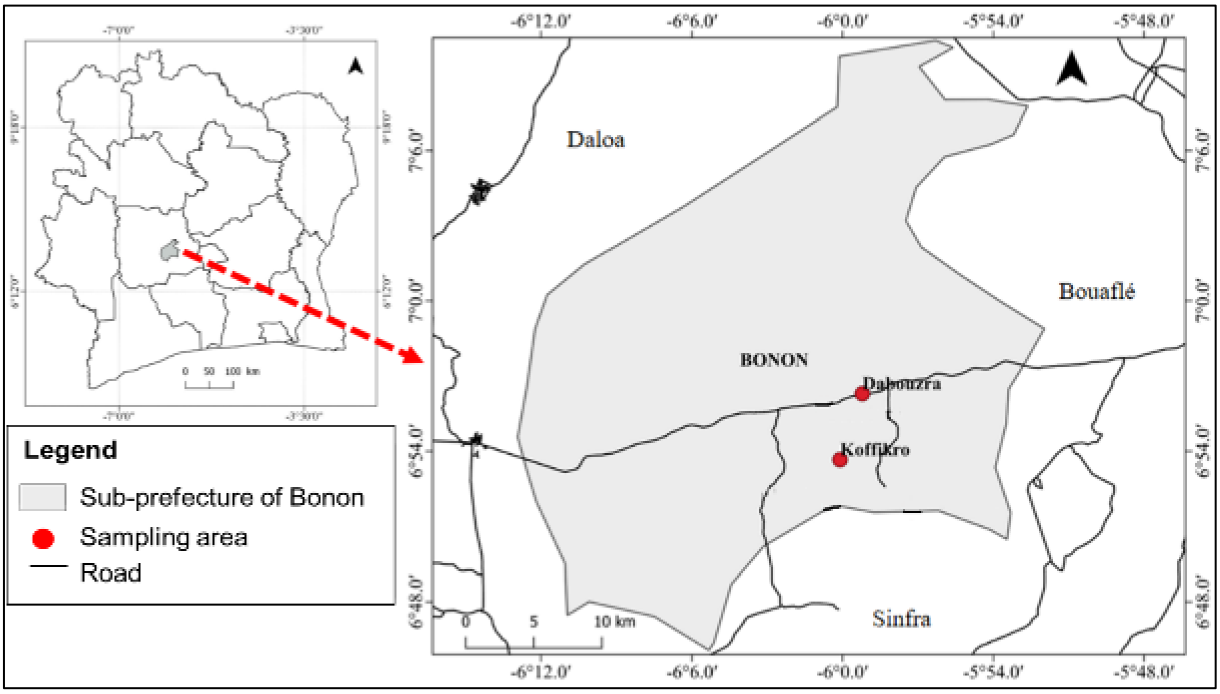


Figure 1 Geographical location of the sub-prefecture of Bonon in the Centre-West of Côte d'Ivoire

2.2. Data Collection

2.2.1. Selection of cocoa plantations

Ten (10) cocoa plantations were selected in the Bonon sub-prefecture based on surveys conducted with cocoa farmers. The plantations were chosen for their accessibility and a surface area of 2 hectares or more. These surveys allowed for the identification and classification of the farms into three age categories: young plantations (between 5 and 15 years old), mature plantations (between 15 and 30 years old), and old plantations (30 years or older).

2.2.2. Ground measurement of tree height

The collection of field data remains necessary to validate the results generated from different remote sensing means [21].

In this study, all trees in the stratum above the cacao trees were considered. The total height (in meters) of each individual was measured using a BUME-LEISS dendrometer at 1.30 m above the ground at "human chest height" for species without buttresses. For individuals with a malformation or a buttress, measurements were taken above the obstacle [22]. Furthermore, the final height used was the average of two measurements on each individual.

2.2.3. Drone Image Acquisition

The images were collected with the drone using the DJI GSPRO app. This app is used for piloting the drone (manually and automatically) and planning flight missions.

The drone used in this study is the DJI Phantom 4 Multispectral (P4 Multispectral), equipped with a camera featuring six sensors: one RGB sensor for visible light imaging and five monochrome sensors for multispectral imaging. The system is powered by lithium batteries, weighing 468 g, while the drone's total weight is 1.5 kg, making it easy to transport for data collection missions. The maximum flight time is 27 minutes, with an operating temperature range of 0 to 40 °C. The P4 Multispectral's shutter speed ranges from 1/100 to 1/20,000 s for visible light imaging and from 1/100 to 1/10,000 s for multispectral imaging.

For all missions, images were acquired at a flight altitude of 80 m (Figure 2), resulting in a ground resolution of 4.2 cm/pixel and a ground area of 1600 m x 1300 m per image. A frame rate of one image every 3 m/sa provided 90% longitudinal overlap. The spacing between flight lines allowed for 70% lateral overlap. These significant overlaps ensured good image stitching during photogrammetric processing [23]. The camera shutter speed was set to 1/20000 seconds, and the ISO sensitivity was set to 400 with a focal length of 6 mm.

Figure 2 Drone flying over a cocoa plantation

2.3. Drone Image Processing

The image processing workflow comprises two main steps: mosaicking the entire overflown scene and extracting the study area. Scene mosaicking was performed using the photogrammetry software Pix4Dmapper, which includes three processing phases : (1) image alignment, (2) construction of a 3D model (dense point cloud), which then allows (3) the generation of a digital surface model (DSM), a digital terrain model (DTM), and an orthophoto. The mosaicking of the study scene is performed automatically after the images are imported into the software. The extraction of the study area was carried out using the mapping software QGIS 2.14.

After image processing, the structural parameters of the different cocoa plantations were determined. These include tree density, canopy area, and tree height.

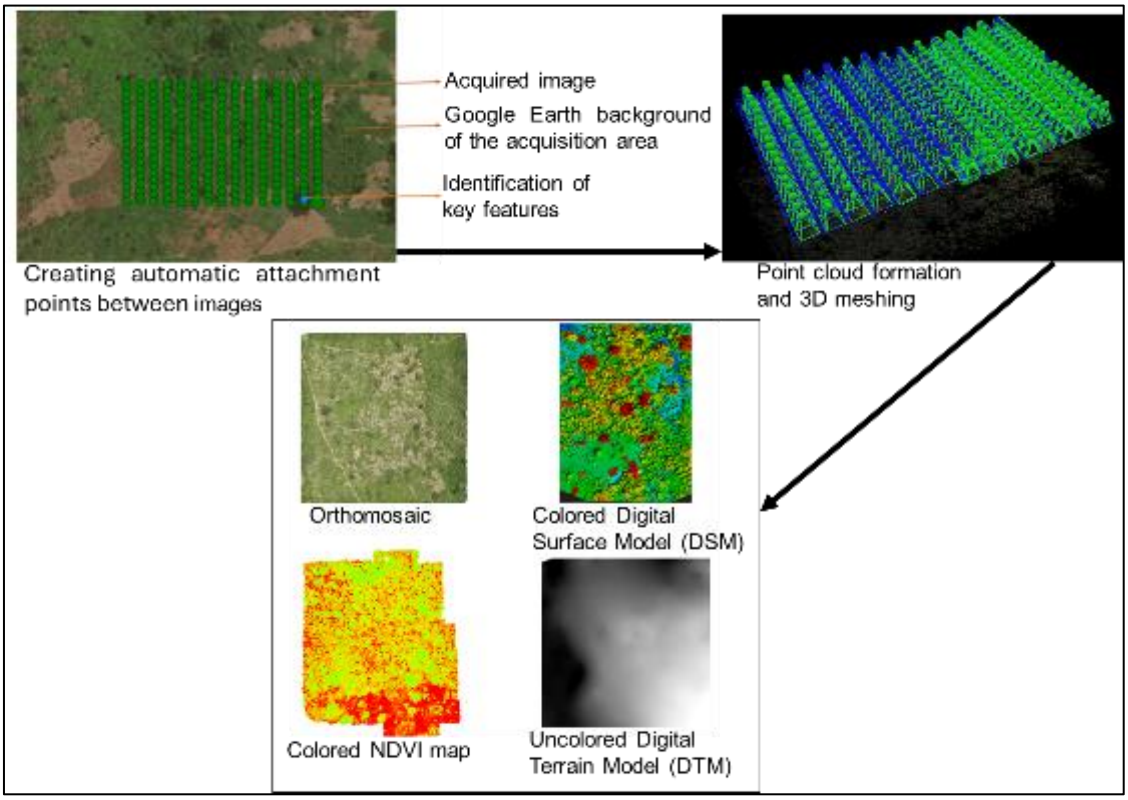


Figure 2 Drone image processing workflow

2.4. Determination of structural parameters from drone images

2.4.1. Determining tree density in cocoa plantations

With an ultra-fine resolution of the drone sensor, it becomes easier to perceive each individual of the plant species on the ortho-images resulting from image processing.

Thus, using the photo-interpretation method, the different individual trees were identified in order to obtain the total number of trees in the area under consideration.

2.4.2. Estimation of tree canopy area

The canopy area of the trees associated with the cocoa trees was estimated based on a photo-interpretation of the orthophoto of each cocoa plantation. First, the canopy of these trees was manually digitized using the QGIS GIS software (Figure 3). Subsequently, the corresponding area was calculated using the same software.

Figure 3 Tree crown delineation on an orthophoto

2.4.3. Estimation the height of the trees

The Digital Height Model (DHM) or Digital Canopy Model (DCM) is defined in the forestry field as the distribution of vegetation or tree heights in a given stand. The DHM was calculated for each plantation using two indicators for the area: the Digital Surface Model (DSM) and the Digital Terrain Model (DTM), obtained from the orthophoto, according to the following equation:

$$MNH = MNS - MNT$$

The principle of creating the MNH from the MS and the MT is illustrated in Figure 4.

The resulting NHM (Natural History Model) is a raster file containing the heights of all individual plant species present on the farm, including herbaceous plants and crops associated with the cocoa trees. This NHM was then imported into QGIS software to determine the individual heights of the trees.

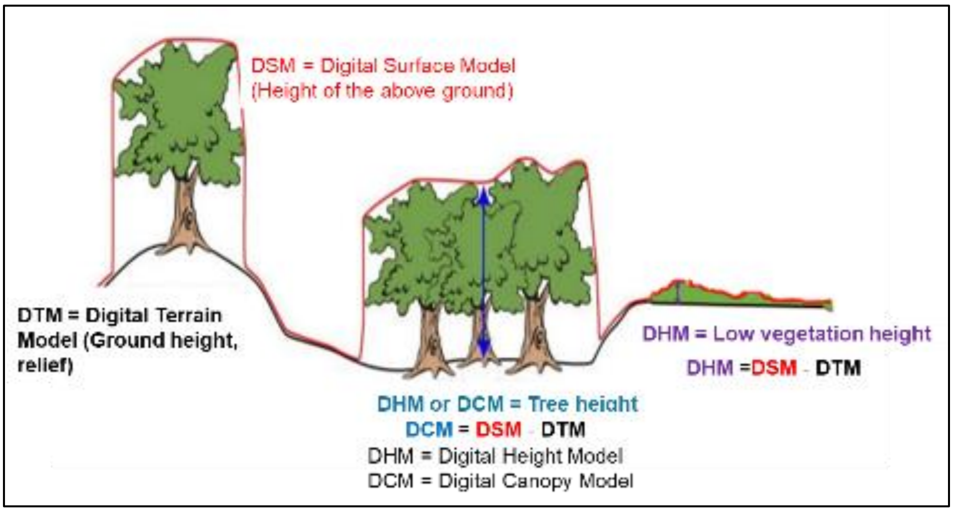


Figure 4 Illustration of the principle of creating the Digital Height Model from the Digital Surface Models and Digital Terrain Model

2.5. Statistical Analysis

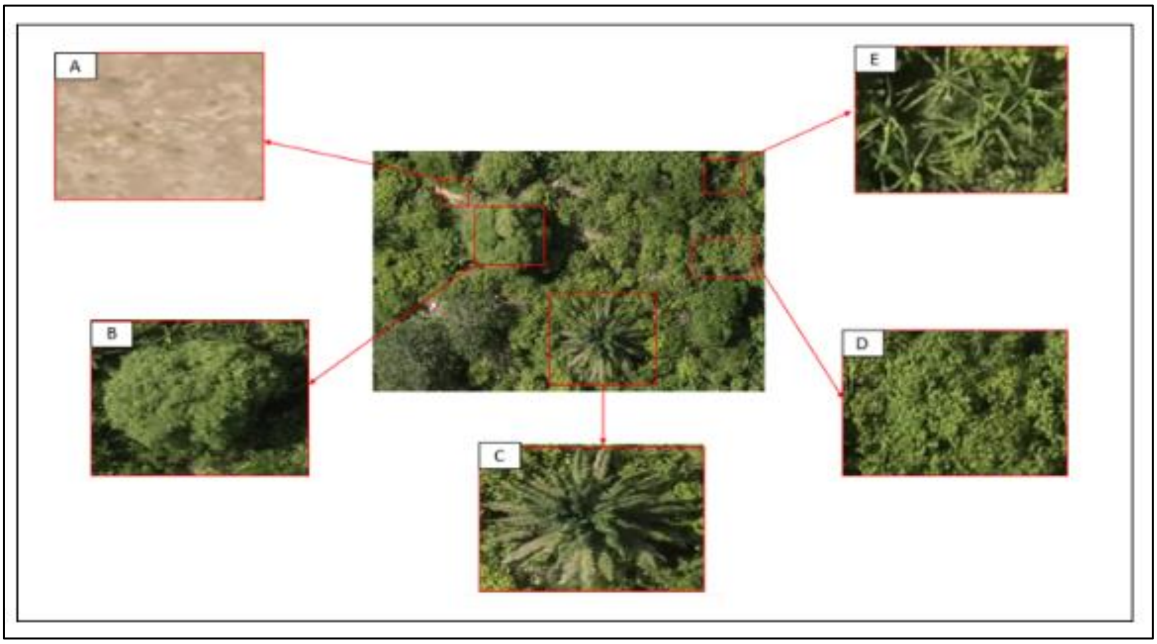
To compare the heights measured by drone with those obtained on the ground, the Wilcoxon test was used. These statistical analyses were performed using the R software.

3. Results

3.1. Cocoa plantation land use units

After assembling the images, five land cover units were identified: banana trees, palm trees, trees, bare soil, and an "other" category including cacao trees, cashew trees, and shrubs of equal or smaller size than cacao trees (Figure 6). The banana type corresponds to land cover with broad leaf blades that take on a cruciform shape in the orthophotos. Palm trees are visible by their characteristic star shape, formed by their broad leaves. The "isolated tree" type is identified by the contiguous, more or less circular shape of its crown. This crown is above the other types of land cover. Bare soils are visible due to the brown color of the earth, indicating the absence of vegetation. The other types of land cover are identified by their higher density within the plantation and do not exhibit the characteristics described above. The cacao tree, the cashew tree, and certain shrubs of similar size found in the cacao-based system could not be distinguished. Indeed, their similar structure, proximity, and especially their identical height prevented their individual separation. They were therefore included in the same type.

The sensor's resolution of 4.2 cm/pixel allowed for easy recognition of land cover units with a height greater than that of cocoa trees.



Bare ground; (B): Tree; (C): Palm tree; (D): Other types of land use; (E): Banana tree

Figure 5 Ortho-images illustrating land cover units in cocoa farms in the Bonon area

3.2. Structural parameters of cocoa plantations

3.2.1. Tree density

The average tree density on farms increases with the age of the farms (Figure 7). Young farms (5 to 15 years old) have an average tree density of 3.60 trees/ha. Mature farms are characterized by an average density of 5.53 trees/ha, and farms older than 30 years (older plantations) have an average density of 6.42 trees/ha. However, the Kruskal -Wallis test found no significant difference between the density classes.

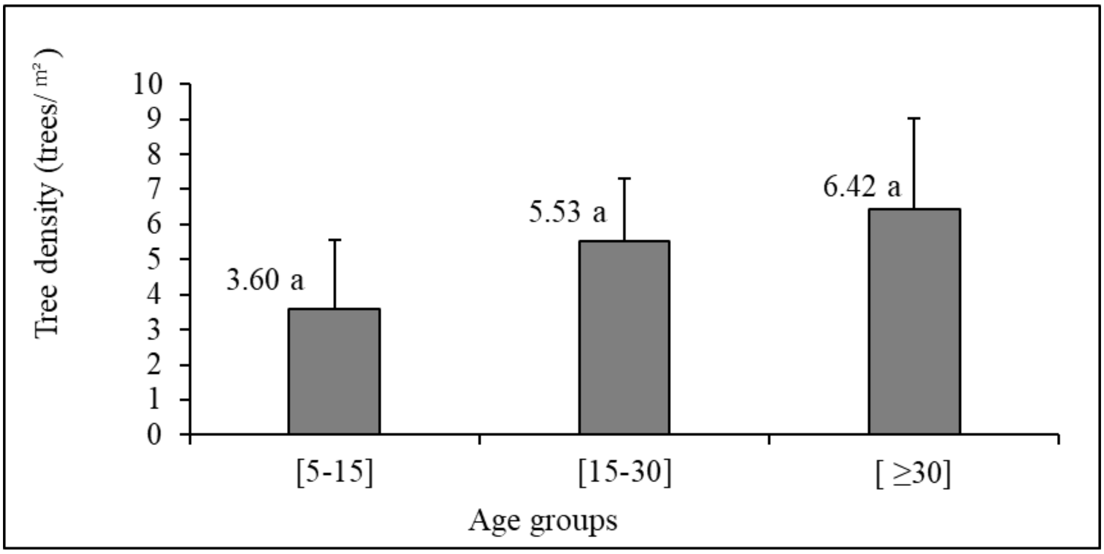


Figure 6 Average tree densities in cocoa farms in the Bonon area according to age class

3.2.2. Tree canopy area

The average canopy area of trees on farms increases with the age of the farms (Figure 8). Thus, plantations aged between 5 and 15 years have a canopy area of 506.70 m^2 / ha, compared to 699.20 m^2 / ha for the 15-30 year age group and 722.91 m^2 / ha for cocoa plantations older than 30 years. However, no significant difference was observed between these age groups.

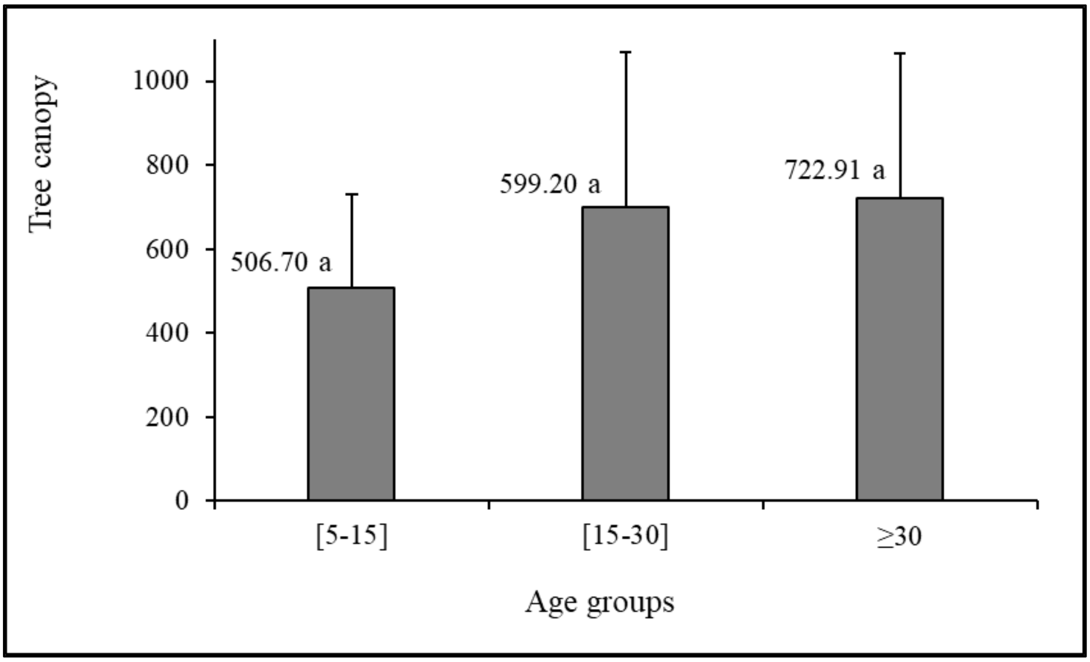


Figure 7 Average canopy area of trees in cocoa farms in the Bonon area according to age class

3.2.3. Tree height measured on the ground and via drone

Table 1 below presents the average tree height, measured using drone imagery, and the height measured on the ground. The results indicate a difference between the measurements obtained from drone imagery (13.96 m) and those taken on the ground (12.43 m). To obtain greater precision, the difference between these two heights was evaluated using the Wilcoxon signed-rank test. The results recorded in the table show a significant difference between the measurements obtained from drone imagery and those taken on the ground. In other words, the measurements from drone imagery are greater than those measured on the ground ($P < 0.005$).

Table 1 Comparison between average drone heights and ground-level heights

Height (m)	Average	P value
Drone	13.96 [a]	2.2e-16
On the ground	12.43 [b]	

The letters next to the numbers indicate a significant difference between the two average heights.

4. Discussion

The use of drone images in cocoa plantations, taken at an altitude of 80 m, allowed for the distinction of certain land cover types through visual or photo-interpretation. These included: bare soil, trees, palm trees, banana trees, and other types of cover. Indeed, according to [16] , processed drone images allow for the identification of different land cover types. However, optimal discrimination on orthophotos was not possible because some species or individuals had similar structures. Thus, discriminating between cashew trees, shrubs, and cocoa trees of similar heights was difficult because they shared the same stratum. Furthermore, the orthophotos did not allow for the precise distinction of individuals located below other individuals. This bias is important to consider in structural analyses using aerospace imagery. An alternative would be to apply photo-interpretation or textural analysis (supervised classification), which could allow for finer differentiation between morphologically similar species. Furthermore, the difficulty in discrimination observed in our study could also be explained by the drone's flight altitude of 80 m. This altitude seems too high. It does not appear suitable for systematic sampling of species present in a system as complex as cocoa plantations in Côte d'Ivoire. Indeed, [24] used a drone equipped with a multispectral camera to monitor agricultural plots infested with the common vole at three flight altitudes: 40 m, 80 m, and 150 m. These authors noted that the best results were obtained for flights at 40 m altitude, and this was true for the different supervised classification methods.

Analysis of the evolution of the average density of trees associated with cocoa crops reveals that older farms have a greater number of trees compared to younger farms. This observation differs from that reported by [18], who showed that a younger farm generally has a higher average tree density.

However, the high tree density (6.42 trees/ha) observed in older farms could be explained by a replanting strategy adopted by the farmers. Indeed, faced with the scarcity of forest for expansion and/or the creation of new plantations, producers in the study area, specifically Bonon, adopted the replanting of cocoa trees as a strategy [25]. Thus, in order to provide shade for the seedlings, producers intercropped trees with young cocoa trees, leading to a progressive increase in tree density as the plantations aged. These results differ from those of [26], which explain that mature plantations do not need shade for good production; on the contrary, yields are high when cocoa trees are exposed to the sun. These authors conducted their research in the sub-prefecture on different agroforestry systems. Furthermore, the work of [27] has shown that in Côte d'Ivoire, three types of previous land use are currently used for cocoa cultivation: old cocoa plantations, old coffee plantations, and fallow land. The latter contains few trees and is therefore less suitable for cocoa cultivation. To increase tree density and make these previous lands more suitable for cocoa, initiatives are being implemented to introduce more and more trees into cocoa plantations.

The increase in average canopy area of trees associated with the age of cocoa plantations, ranging from 506.70 m^2 / ha in young cocoa plantations to 722.91 m^2 / ha, could be explained by the species abandoned or spared during the establishment of the plantations. Indeed, in addition to the fast-growing associated species, the spared trees are very large and belong to the upper canopy. Thus, the growth in height and diameter of the trees leads to an increase in the canopy area.

The Wilcoxon signed-rank test indicates a significant difference between heights measured by drone and those obtained on the ground ($p < 0.05$). This difference could be due to the methodology used on the one hand, and to the accuracy of the drone measurements on the other. Indeed, in the field, the heights obtained with the BUME-LEISS were measured at 1.30 m above the ground, while those obtained by the drone were measured from ground level. Furthermore, the results obtained by [28] showed that applying the existing relationship between digital surface models and digital terrain models to drone images accurately yields heights compared to traditional ground-based measurements. These authors, who conducted their work in forested areas in Spain, stated that canopy height measurements obtained with drones are more accurate compared to traditional ground-based measurements [29, 30]. Indeed, ground-based measuring devices, such as dendrometers, often require adjustment for long-range measurements and precise calibration to compensate for angle variations. This poses a challenge in cocoa plantations, where the terrain and dense canopy limit visual range and field of view. Any variation in calibration can reduce the accuracy of measured heights and thus lead to errors. Furthermore, cocoa plantations have multiple vegetation layers (cocoa trees, shade trees, etc.) and a high density of vegetation, making it difficult to identify individual treetops from the ground, unlike with a drone. This layering of vegetation complicates the determination of each tree's height and can introduce measurement errors.

In contrast, drone images used to estimate heights offer a more objective and standardized approach, minimizing human error and making measurements more reliable overall.

5. Conclusion

This study enabled the identification of land cover types in cocoa-based agroforestry systems using drone imagery. It also determined tree density and canopy area, and compared heights obtained by drone with those measured on the ground. The results demonstrate that drones are a tangible and effective alternative for identifying land cover units. Similar to field forest inventories, drone orthophotos allow for the measurement of structural parameters in cocoa-based agroforestry systems. This study thus highlights the potential of drones in agriculture, specifically for describing and measuring the structural parameters of cocoa-based agroforestry systems. However, certain technical precautions, such as drone flight altitude and the type of post-classification analysis, should be considered to optimize the quality of results obtained through aerospace imagery.-A more detailed study on the ideal flight altitude will help to clarify this issue.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

No conflict of interest to declare.

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