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APPLICATION OF PHOTOGRAMMETRY FOR THE ESTIMATION OF TREE HEIGHT IN CLOSED CANOPIED TROPICAL FORESTS OF SOUTHWESTERN NIGERIA

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Abstract

The study estimated tree height from high-resolution Digital Surface Models (DSMs) and Digital Terrain Models (DTMs) products derived from photogrammetric orthomosaics captured with the Sensor Optimized for Drone Applications (S.O.D.A) metric camera mounted on an Ebee *Sensefly* Survey Drone. This was to determine a sustainable approach for the estimation of tree height in dense forests with closed canopies. A 500-meter drone sampling plot was marked for each of the 3 tropical forest reserves that were used for this study, and 10 cm digital aerial photos were captured during the drone survey. The data sets were converted to point clouds and thereafter to Ortho mosaics for DSM and DTM, respectively, using standard processing techniques with the Pix4D software.
Results showed average tree height ranges from 0 - 50 meters for the three forest reserves with photogrammetry, and a correlation of 0.96, R^2 of 97.6, and SE of 0.05 compared with height from field measurements using a laser range finder .The study concluded that Photogrammetry offers a cost-effective, scalable, and spatially continuous approach for estimating tree height over expansive areas in the area of study while enabling integration with GIS and remote sensing workflows, supporting large-scale forest monitoring, inventory, and management with higher efficiency and broader utility.

Keywords: Photogrammetry, Digital Surface Models, Digital Terrain Models, Tree Height

Introduction

Forests, especially tropical rainforests, play a crucial role in global ecological balance by acting as significant carbon sinks, supporting biodiversity, regulating hydrological cycles, and providing livelihood resources to surrounding populations[1]. Among the various structural attributes of forests, tree height serves as a fundamental parameter in forest inventory and monitoring, biomass estimation, canopy structure characterization, and habitat mapping [2, 3]. In tropical ecosystems, where dense canopy closures and high tree diversity are common, the estimation of tree height remains a methodological challenge. Traditional field-based methods, such as clinometers or laser rangefinders, although accurate for point-based observations, are labor-intensive, time-consuming, and impractical for large-scale or inaccessible areas[4, 5] .

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The application of photogrammetry for forest structural analysis has emerged as a viable alternative to conventional approaches. Advances in unmanned aerial systems (UAS), high-resolution sensors, and image processing software have enabled the generation of Digital Surface Models (DSMs) and Digital Terrain Models (DTMs) from overlapping aerial images [6]. These models facilitate the estimation of above-ground vegetation height by subtracting ground elevations (DTMs) from surface elevations (DSMs) [6]. When calibrated and validated against field measurements, photogrammetric methods have shown high accuracy and reliability, making them suitable for ecological and forestry applications [7-9]

In closed-canopy tropical forests, such as those in Southwestern Nigeria, ground-based tree height measurement is complicated by poor visibility, dense understory vegetation, and rugged terrain. Additionally, the logistics and costs associated with accessing these areas frequently hinder continuous and large-scale data collection. Photogrammetry, when mounted on drones with metric sensors like the Sensor Optimized for Drone Applications (S.O.D.A), provides a high-resolution, scalable, and repeatable means of obtaining forest structural metrics across large extents. Moreover, drone-based photogrammetry circumvents some limitations of satellite LiDAR or airborne laser scanning by offering a cost-effective, operationally flexible platform for localized studies.[10-12]

Several studies have demonstrated the efficacy of drone-based photogrammetry for tree height estimation. For instance, [12] found that tree height estimates derived from UAV images correlated strongly with terrestrial LiDAR data in boreal forests. In a tropical context, [6] reported similar success in reconstructing canopy height models using photogrammetric point clouds. These findings point to the growing relevance of structure-from-motion (SfM) photogrammetry as a forest mapping tool. However, most existing research is either concentrated in temperate or semi-arid regions, with limited application in tropical rainforests exhibiting dense canopy closures and high structural complexity.

The present study seeks to bridge this gap by applying photogrammetric methods to estimate tree height in three closed-canopy forest reserves in Southwestern Nigeria. The forests in this region are critical biodiversity hotspots and serve essential ecological functions at both local and national scales. With growing threats from deforestation, logging, and climate change, there is an urgent need for efficient, accurate, and scalable forest monitoring systems.

Despite the growing need for high-quality forest inventory data in tropical ecosystems, the methods predominantly used in Nigeria and similar regions remain largely manual and unsystematic. The conventional use of clinometers or rangefinders for tree height measurement, though accurate on small plots, cannot be reliably scaled across large, remote, or densely vegetated forest landscapes. These traditional methods also present challenges related to observer error, line-of-sight obstructions, and terrain-induced inaccuracies [13-18]. Furthermore, satellite-based remote sensing, while suitable for broader-scale forest monitoring, often lacks the spatial resolution or vertical accuracy needed for fine-scale ecological studies in complex forest environments[19]. There is thus a pressing need for an approach that balances accuracy, spatial coverage, operational efficiency, and cost-effectiveness. Drone-based photogrammetry stands out as a promising solution, yet its application in Nigeria's tropical forest reserves remains underexplored. Moreover, empirical validation of photogrammetrically derived tree height against reliable ground-based methods is essential to ensure the credibility of this approach for forest inventory purposes. The study therefore, estimated tree height from high-resolution photogrammetric datasets (DSMs and DTMs) generated using UAV imagery in three closed-canopied forest reserves in Southwestern Nigeria. Then, compared the photogrammetric tree height measurements were compared with field-based height measurements obtained using a laser rangefinder, after which an evaluation of the accuracy, reliability, and operational efficiency of photogrammetry as an alternative

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approach for forest structural assessment in tropical environments. Furthermore, the study demonstrated the utility of drone-based photogrammetry in supporting scalable and repeatable forest monitoring, inventory, and ecological research.

Methodology

Study Area

The Omo – Shasha – Oluwa forest Complex lies within latitudes 7° 1'7.67"N and 6°44'58.52"N, and longitudes 4°12'31.41"E and, 4°42'55.82"E (Figure 1). It has an estimated land area of 2,223 km ^{2} and a distance of about 25 km as the crow flies to the Atlantic Ocean from its southernmost boundary [20]. The forest reserves were created in 1925 and comprise clusters of contiguous forest reserves spanning parts of Ogun, Ondo and Osun States. These reserves include the Omo, Oluwa, Shasha, Ife and Ago-Owu Forest Reserves which in this study is regarded as the Omo-Oluwa-Shasha Forest complex. Prior to the creation of the state administration in Nigeria, these five forest reserves were all part of the then Shasha Forest Reserve [21-23]. The pristine forest had experienced alteration of structure in some parts as early as 1966 when *Gmelina arborea, Tectona grandis and Pinus caribeae* plantations were established in the forest reserves [24]. Recently, uncontrollable logging and slash and burn farming have further impacted on the forest leaving it in a deplorable state [25]. The topography of the site varies widely from nearly flat to rolling. About 80% of the sites are well drained into the watershed of River Omo the major river traversing the forest complex. The uneven topography is characterized by numerous small hills which are dissected by tributaries of the Omo, Shasha and Oluwa Rivers. The unevenness has been attributed to past geological events. The area was once composed of sedimentary rocks, probably sandstone, of varying coarseness. A period of volcanic activity in the past heated the rocks to an extent that they became viscous and flowed [26, 27].

The sites are made of several soil types but they all belong to the tertiary sediments. Most of the soils are heavily leached. The most commonly occurring series are Alagba, Owode and Oteyyi. The Alagba series are well drained and usually located near slope top and nearly level summit areas of the project site. They are deep soils without stones and concretions. The soil texture is usually sandy loam topsoil and sandy clay subsoil. The soils are derived from ferruginous sandstones [28].

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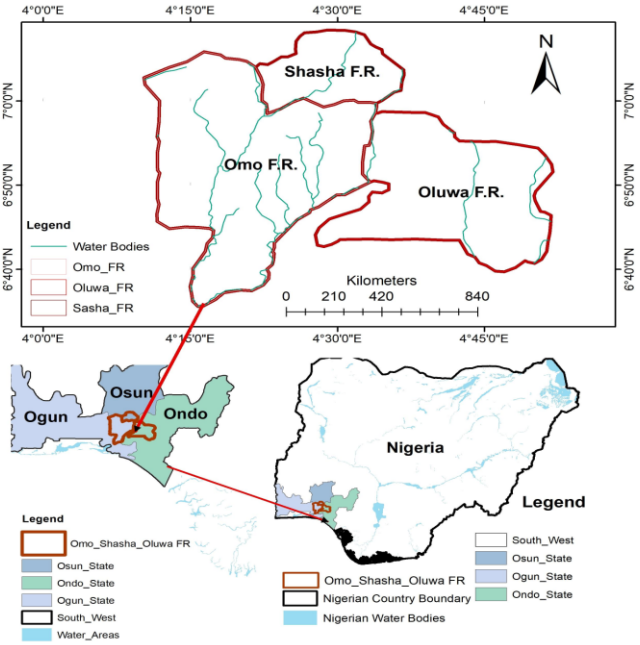


Figure 1: A study area map showing the three conservation forests: OCR, OCR2, and SCR.

Sampling Method

Stratified Random Sampling technique was used to select sampling plots. A sampling grid with 0.5 km by 0.5 km dimensions were overlaid on the land use land cover map derived from World view (Figure 2), and 5 representative plots each for the vegetated land use classes were selected. Garmin 78 Hand Held GPS receiver with an accuracy of 3 meters was used to locate the centre of the selected plots. The concentric plot assessment system (Figure 3) was used to select sub plots (USDA Forest Service, 2004a). Each modified plot was a cluster of four circular 17.95 m radius annular plots with one central 0.1 ha annular plot, three satellite 0.1 ha annular plots, four 7.32m subplots, and one 2.77 m radius micro plot (Figure.3). Each modified plot also contained three 17.95 m long transects from the cluster centre, with the first transect positioned at a random azimuth and the others at 60° and 120° from the first transect.

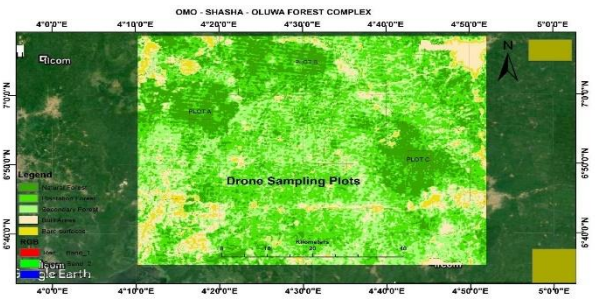


Figure 2: Unsupervised classification of study area with Worldview earth imagery of 2024

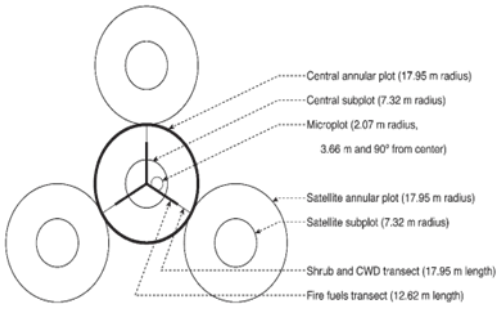


Figure 3 Field plot, adapted from (Gonzalez et al., 2010) and modified from FIA (USDA Forest Service, 2004a)

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Data Types and Sources

The tree height was measured using a Trex Laser Range Finder for trees within the plots that were above 10 cm in diameter. Furthermore, GPS coordinates of sample trees in addition to pre-selected six tree species (Plate 1) were recorded whenever they were observed within the sampling plots. For photogrammetry data, geometrically corrected high quality digital aerial photographs with 7 cm resolution were captured along the flight path with an altitude of 500 m using Sony camera WX 350 Red – Green - Blue (RGB) with a focal length (f = 4.3 – 86 mm), 18.2 Mega Pixel (MP) mounted on Sense fly E-Bee, Unmanned Aerial Vehicle (UAV) drone. (Plate 1)

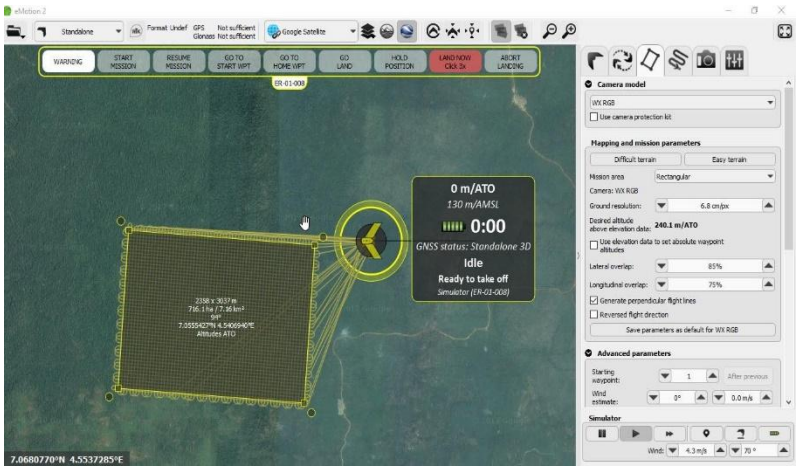


Plate 1: Plot demarcation and calibration in the Sense fly Ebee flight software

The metric camera used was a specialized Canon P3X2 camera optimized for survey called S.O.D.A meaning; (Sensor Optimized for Drone Application), the specifications for the sensor is displayed in Table 1

Table 1: Specifications for Sensor Optimized for Drone Applications

Feature	Value
Sensor Type	APS-C CMOS (23.5 mm × 15.6 mm)
Resolution	20.1 MP (5472 × 3648 pixels)
Pixel Size	3.91 µm
Focal Length	10.6 mm
Image Format	JPEG (RGB)
Weight	76 g
Shutter	Global rolling shutter
Radiometric Correction	Yes

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Processing of Drone Data

The drone data sets acquired were downloaded from the memory card of the S.O.D.A camera in a Dell Latitude Workstation and then processed with the Pix4D software. (Figure 4)

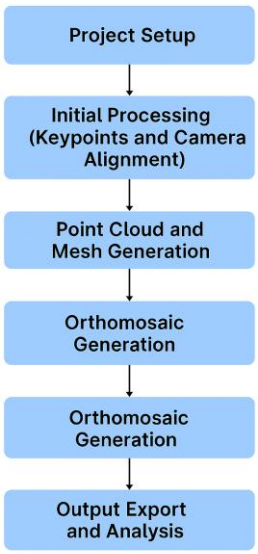


Figure 4: The Workflow for the drone data processing

Canopy Height Model

Study of this nature required a photogrammetric-derived height measurement[6]. This height measurement can also be called Vertical Forest Structure (VFS). VFS for the three sites were derived using the method of [12].

VFS = Digital Surface Model (DSM) – Digital Terrain Model (DTM) ……. (14)

Where: DSM represented the top surface layer of the trees derived from the point clouds of the study area. The DTM was derived from the contour points of the same imagery

Results

The photogrammetrically derived Canopy Height Models (CHMs), generated as the difference between the Digital Surface Models (DSMs) and Digital Terrain Models (DTMs), provided spatially continuous estimates of forest canopy heights across three sampled forest reserves: Omo, Sasha, and Oluwa. (Table 2 and Figures 5 to 8) These CHMs revealed distinct patterns in canopy structure, forest maturity, and vertical complexity.

In Omo Forest Reserve, the CHM values ranged between 0 and 50 meters, with mean tree heights in sampled plots recorded at 61 m, 1.0 m, and 30 m. This range suggests a vertically complex forest with multiple canopy layers, including emergent trees, mid-story vegetation, and undergrowth. The high

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variability also reflects the presence of natural gaps or regenerating forest patches within a generally mature canopy structure.

Sasha Forest Reserve exhibited lower average heights of 56 m, 0.61 m, and 23.48 m, indicating either a less mature canopy or previous anthropogenic disturbance such as selective logging. The lower minimum height values reflect either bare ground or early-stage regrowth, while the reduced average height suggests fragmented canopy conditions with less vertical stratification than observed in Omo.

Oluwa Forest Reserve recorded the tallest canopy height of 65 m, with other sampled values at 1.03 m and 28.26 m. This reserve appears to maintain mature primary forest characteristics, as evidenced by the prevalence of tall emergent trees and a well-structured canopy. The height values point to high vertical continuity and relatively undisturbed vegetation cover.

Table 2: Biophysical variables collected from field survey in Omo Shasha Oluwa Forest Complex,

Biophysical Variables	Omo Forest Reserve	Sasha Forest Reserve	Oluwa Forest Reserve
Tree count	61	56	65
Min height (m)	15	12	15
Max height (m)	50	40	43
Average height (m)	30	23.48	28.26
Standard Dev. height	8	7.43	7.6
Sum height (m)	1819	1315	1837

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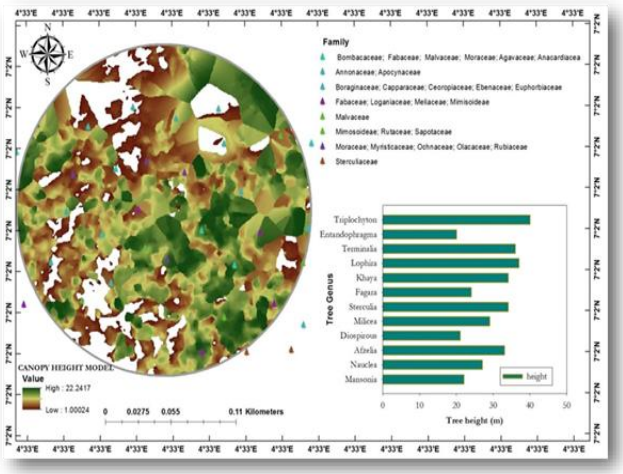


Figure 5: CHM for Sasha FR

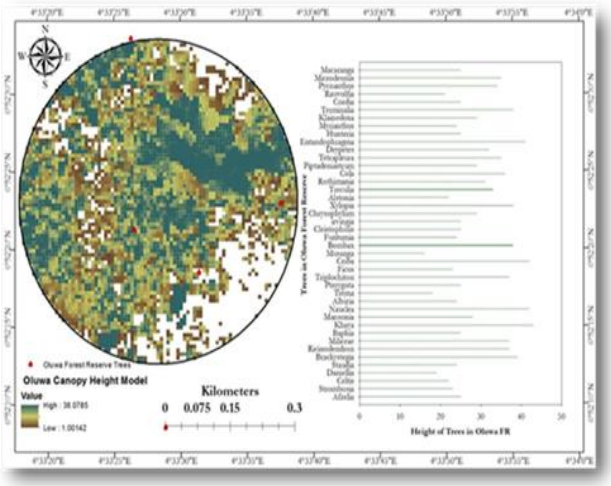


Figure 6 CHM for Oluwa FR

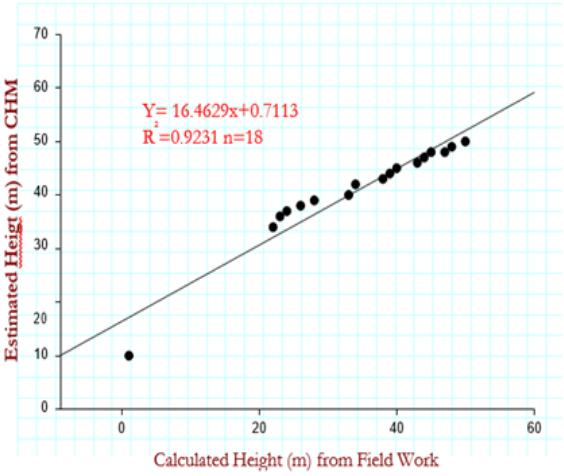


Figure 7: Validation of CHM by correlation.

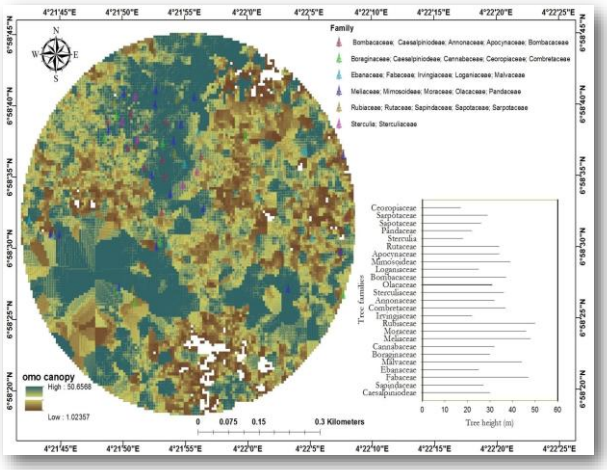


Figure 8: CHM for Sasha FR with calculated height derived from Field work

Discussion

The accuracy of the CHM-derived heights was validated using field-based laser rangefinder measurements, yielding a correlation coefficient (R) of 0.96, a coefficient of determination (R^2) of 97.6%, and a root mean square error (RMSE) of 0.05 m. These statistics confirm the reliability of UAV-based photogrammetric approaches for forest canopy mapping, particularly in regions where traditional methods are hindered by accessibility or labor constraints.

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From a methodological standpoint, this study demonstrates the utility of Pix4D software in deriving DSM and DTM products from drone imagery, which are critical for CHM computation[3, 7]. The approach offers a scalable and cost-effective solution for continuous forest monitoring and biomass estimation, especially in data-sparse regions like Nigeria. Moreover, the results support the integration of CHMs into broader geospatial workflows for forest inventory, REDD+ reporting, and biodiversity assessment The findings from this study have several practical and scientific implications. First, the study provides empirical evidence to support the operational use of photogrammetry in estimating forest structural parameters in complex tropical environments. Second, it contributes to the growing body of knowledge on UAV applications in forestry, particularly in data-sparse regions like Nigeria[6]. Third, the research aligns with national and global priorities related to climate change mitigation, carbon accounting, and forest resource management. Additionally, the integration of photogrammetry with geospatial workflows facilitates long-term monitoring and change detection, offering policy-makers and forest managers a robust decision-support tool. As forests increasingly become focal points in discussions around REDD+ (Reducing Emissions from Deforestation and Forest Degradation) and biodiversity conservation, the ability to obtain accurate, high-resolution forest structural data at scale becomes paramount [2, 3, 9, 29, 30].

Conclusion

In sum, this study addresses a critical gap in forest structural assessment methods within Nigeria's closed-canopy tropical forests. By leveraging drone-based photogrammetry, the research aims to present a cost-effective, scalable, and accurate methodology for tree height estimation, validated against field measurements. The outcomes are expected to inform better forest resource management strategies and provide foundational data for ecological research, forest health assessments, and policy interventions in the region. The significance of this study extends beyond methodological validation; it underscores a transformative shift in how forest structure data can be acquired in developing tropical regions. The affordability, repeatability, and spatial coverage offered by drone-based photogrammetry make it an invaluable tool in countries where logistical, financial, and infrastructural challenges often limit the scope and frequency of field-based forest inventories. In tropical regions of developing nations, forest ecosystems are not only biodiversity hotspots but also critical to local economies, water regulation, and climate resilience. However, these areas are increasingly threatened by deforestation, unsustainable logging, and land-use change. Reliable tree height data derived from CHMs can be leveraged to estimate biomass, monitor carbon stocks, and detect structural changes, providing empirical evidence for conservation planning and sustainable forest management.

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