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ORIGINAL SCIENTIFIC PAPER

Estimation of Above-Ground Biomass and Carbon Sequestration Potential Using Arboreal Forest Mobile LiDAR Technology in an Azadirachta indica Plantation at Modibbo Adama University, Yola

Procjena nadzemne biomase i potencijala sekvestracije ugljenika korištenjem mobilne LiDAR tehnologije u plantaži Azadirachta indica na Univerzitetu Modibbo Adama, Yola

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ABSTRACT

This study estimates the above-ground biomass and carbon sequestration potential in *Azadirachta indica* plantation at the Modibbo Adama University, Yola, Adamawa State, Nigeria, using Arboreal Forest Mobile LiDAR Technology. The total count method was employed, where 7 sample plots of 40m x 40m were laid. Data were collected using arboreal forest mobile LiDAR software for the diameter and height of each tree from the sample plots. Ground-truthing exercise was conducted using the Traditional method, whereby 3 plots (2, 6, and 7) out of the 7 sample plots laid were randomly selected and measured for diameter and height. Results of the study revealed that the total AGB of the trees was 15.11kg, volume was 21.90m^3, carbon stock was 7.55kg and a CO_2 sequestration of 176.05kg/ha over the years. Results from the computation of the T-test showed P-values greater than the common significant level of 0.05.

Key words: *Arobeal forest mobile LiDAR, Azadirachta indica, above ground biomass, Ground-truth, Carbon sequestration.*

INTRODUCTION - *Uvod*

Forest trees and their biomass play a crucial role in mitigating the effects of global warming and climate change through the carbon sequestration process. Indeed, biomass is the weight of the living tissue of trees which stores carbon, and it is generally expressed in metric tons, as was highlighted by Zell *et al.* (2014). According to Adams (2012), planted forest covers 264 million ha, almost 7 percent (%) of the total global forest cover, the two global developments that biomass plays towards climate change were first, the changes in biomass of forest corresponds directly to the changes in carbon absorption or release to the atmosphere and, secondly, the increasing demand for forest fuel wood energy. Biomass studies also provide details of forest production for individual tree species, par-

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ticularly in plantation forestry. It requires accurate quantification of biomass for tree species using a site-specific allometric model.

Biomass can be assessed by various methods, viz., harvest, field inventory, and integration of field inventory and remote sensing data (Kushwaha *et al.,* 2014). The assessment of Above-Ground Biomass (AGB) requires extensive field inventory. It is laborious and inapt for inaccessible areas and hence, practicable only in relatively smaller and accessible areas. Conversely, integrating field inventory with RS data offers a competent and reliable method of AGB estimation and mapping. Remote Sensing has played a vital role in quantifying carbon stocks during the last five decades. The availability of Earth observation data has made it feasible to quantify forest carbon stocks from local to global scales. A variety of passive optical multispectral and hyperspectral images and active sensors like Radio Detection and Ranging (RADAR) and Light Detection and Ranging (LiDAR) data are nowadays available for AGB studies. However, due to the availability of optical satellite data for the past five decades, it has been widely used for forest biomass studies (Kushwaha *et al.,* 2014).

Carbon sequestration involves the need to accurately quantify and assess the amount of carbon dioxide that is being captured and stored in various natural and artificial reservoirs such as forests, soils, and geological formations (Schlesinger, 2013) One of the key challenges in estimating carbon sequestration is the complexity and variability of the natural system, which makes it difficult to obtain precise measurements. Additionally, there are different methods and approaches for estimating carbon sequestration, each has its strengths and limitations. These may include field measurement, remote sensing techniques and modeling approaches, Intergovernmental Panel for Climate Change (IPCC, 2019). As a vital part of the global carbon cycle, forests are an important consideration in climate change, because scientists have linked the increase in atmospheric carbon with the increase in the global average temperature. Forests are the largest organic carbon pool in terrestrial ecosystems (Zaninovich *et al.,* 2020). Although forests cover only one-third of the total land area, the carbon stock in forested areas accounts for 56% of the total terrestrial carbon pool (Dalmonech *et al.,* 2020).

In recent years, the sustainable management of forests has become an important tool to combat climate change, and changes in forest resources related to climate change and anthropogenic disturbances also affect global climate change (Dulamasuren *et al.,* 2021). Therefore, the estimation of forest carbon stocks is of critical importance for understanding the global carbon cycle and climate change.

Forests offer great potential for the sequestration of atmospheric carbon, and thus, there has been an urgent need to accurately and efficiently quantify forest carbon stocks in recent years (Romanov *et al.,* 2022). However, it is difficult to conduct field-based surveys of forest biomass and carbon stocks, and frequent field visits can further damage forest ecosystems. Therefore, it is challenging to estimate forest carbon sequestration potential or assess its spatial and temporal variability (Xu C *et al.,* 2022). The emergence of remote sensing technology has provided additional possibilities for monitoring changes in forest resources, and its advantages, including rapid, real-time and large-scale monitoring, have made remote sensing a popular technique that is widely used in the fields of ecology and environment monitoring (Fremont *et al.,* 2022). Therefore, estimating the amount of carbon that trees absorb, store and release is key to understanding climate change and exploring how forests might help to address it. The measurement of carbon sequestration in trees is important for carbon offsetting initiatives. It allows organizations and individuals to quantify the amount of carbon dioxide that can be offset by investing in tree planting or forest conservation projects. (Smith *et al.,* 2010)

Although LiDAR can be used for a variety of study areas this research will focus more closely on its use in biomass estimation and measuring carbon storage in forest area. The system of LiDAR including the three different types of platforms: space-borne, airborne, and terrestrial are discussed. It will also discuss how data is acquired using liDAR technology in first and last returns, multiple returns, and full waveform (Parker and Evans 2004).

Government and environmental agencies use baseline data on carbon sequestration in trees to develop policies related to climate change mitigation, land use planning and environmental conservation. Measurements of tree carbon sequestration are aimed at setting targets and monitoring projects towards reducing greenhouse gas emissions (IPCC, 2020). Understanding the carbon sequestration potentials of trees is essential for scientific research and education, It provides valuable baseline data for studying ecosystem dynamics, understating the impact of deforestation and educating the public about the role of trees in mitigating climate change, Provision for baseline research data by quantifying the amount of carbon stored in trees, we can evaluate their contribution to reducing GHG levels in the atmosphere (EPA, 2010).

There are many techniques and equipment that are used in the measurement of dendrometric data, such as the diameter and height of trees; currently, the technology already allows the execution of such tasks with the use of applications on smartphones as an alternative to traditional methods. However, because they are relatively recent technologies, it is necessary to assess their reliability compared to the conventional methods that are already fully mastered by their users. Inventory applications for smartphones have the potential to revolutionize forest in- ventory practices and can benefit all those involved in the forestry sector. By reducing costs and increasing efficiency, these apps add significant value. However, their effectiveness depends on providing accurate results that reflect the reality of the studied forest (André *et al.,* 2023).

Arboreal is a Swedish app that only works on iOS devices. With this app, users can select a specific center within a predetermined area and create a digital boundary. The app requires the user to gather images of every tree inside the boundary. The user is prompted by the app to input the height of a specified tree. Once the data are collected, the app processes them and generates a report with all the relevant information (Arboreal, 2023)

Carbon sequestration estimation requires accurate, reliable, and standardized methods for quantifying carbon storage in ecosystems and environments. Addressing this problem is crucial for advancing our understanding of carbon sequestration processes and for developing effective strategies to mitigate climate change.

Research Question:

Is there a significant difference between data obtained using Arboreal application and the Traditional method?

Hypothesis:

i. *Null hypothesis (Ho):* There is no significant difference between data obtained using Arboreal application and the Traditional method.
ii. *Alternative hypothesis (Ha):* There is a significant difference between data obtained using Arboreal application and the Traditional method..

MATERIALS AND METHODS – *Materijal i metode*

Study Area

The study was carried out in the Neem (*Azadirachta indica*) Plantation located at Modibbo Adama University, Yola, Adamawa State which is situated between latitude 9^0 21' 10" N and 9^0 21'30" N and longitude 12^0 30' 0" E and 12^0 30, 20" E. The dominant tribe is the Fulbe or Fulani; however, a substantial number of Bwatiye also dwell in villages such as Greng, Ntado, and Labondo within the Girei local government area. The local government shares boundaries with Song local government in the north, Fufore local government in the east while River Basin acts as a physical boundary between the local government, Yola North and Yola South local government in the south and Demsa local government areas in the west (Adebayo and Tukur, 1999).

Vegetation

Modibbo Adama University, Yola is in Girei local government area of Adamawa State which falls under Sudan savannah type of vegetation which is characterized by thick vegetation around hills and mountain ranges. The vegetation has a wide variety of savannah tree species among which are; *Acacia Spp*, *Adansonia spp*. The local government has a population of 129,855 people (NPC, 2006) and with total land mass of about 2186 km^2 (Adebayo, 1999).

Climate

It has a tropical climate with distinct dry and wet seasons, the rainfall begins in April and ends in October while the dry season commences in November and ends in March. It is characterized by a single maxima in August. During this season, seventy percent of the total rainfall in the area occurred within four months from May to August. The area has an average of 62 rainy days, while the average amount of rainfall recorded in the area is 972mm. The dry season which is the harmattan period characterized by dry, dusty and hazy northern trade wind that blows over the area from the Sahara desert.

Temperature

Temperatures within the area vary with season. Although the temperatures are relatively high almost all year round. It has a minimum average temperature of 20 - 35^{0}C and a maximum temperature of up to 45^{0}C (Adebayo and Zemba, 2020).

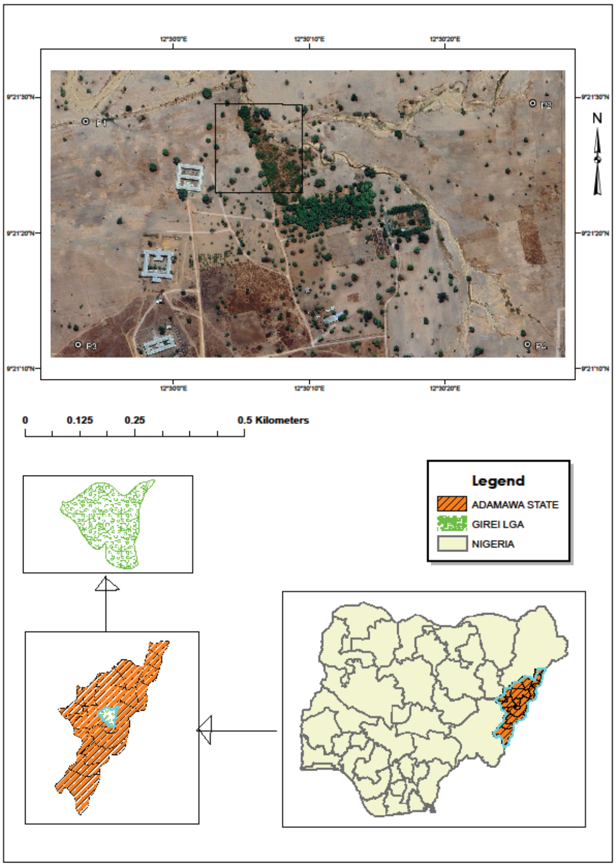

Figure 1: Study Area Map showing *Azadirachta indica* Plantation at the Modibbo Adama University, Yola.

Slika 1: Karta područja istraživanja koja prikazuje plantažu Azadirachta indica na Univerzitetu Modibbo Adama u Yoli.

Source: (Google-earth Pro engine, 2023)

Materials

i. Global Positioning System
ii. Arboreal Forest Mobile LiDAR
iii. Measuring Tape
iv. Surveying Pin
v. Record book
vi. Arc Map 10.6.1
vii. Clinometer

Sampling Technique and Data Collection with Arboreal App

The total count method was adopted to facilitate a more efficient sampling scheme, where 7 plots of 40m x 40m sample plots were laid, covering areas where the tree species were located. Trees in each of the laid sample plots were counted. Data collection was done using the Arboreal Forest mobile LiDAR software. The data collection procedure with the Arboreal application took place according to the protocol presented by the developer, and the device used was an iPhone 12 Pro. The first step was to link up the cell phone device with the camera facing the ground; then, the center of the screen was made to match the center of the plot and the application button was pressed. After completing this, the application defined a virtual limit, one that was also visible on the screen. At the bottom of the screen, the application indicated the distance from the center of the plot, which decreases as the operator approaches it. After delimiting the plot, the measurements were carried out. The measurement of each tree diameter was obtained by pointing the camera to the target tree, two red bars and a black cross will appear on interface of the software, aim and ensure that the two bars aligned to both end of the tree girth, capture and record the value that will pop up at breast height (1.3 meters above the ground).

Whereas, for tree height, the measurement was obtained by pointing and marking the target tree at first, then tilting the camera downward to capture the base of the tree, and then stepping backward in order to clearly see the apex of the tree to capture. Record the value that will pop up as the tree height. This software was employed to ensure precise and consistent measurements, facilitating accurate data collection for further analysis and computation of tree Basal Area, Volume, Biomass and Carbon Stock within each plot.

Data Analysis

Among the 7 plots laid in the study area, 3 plots were randomly selected (plot 2, 6 and 7) for the overall statistical analysis throughout the study. However, secondary parameters such as Carbon stock and biomass were strictly derived from data obtained using a traditional method which was used only for carbon sequestration computations.

I. Basal Area Estimation

Tree stem diameter measurements are often converted to cross-sectional areas. The cross-sectional area at breast height is called the basal area (Avery *et al.,* 2002). To compute basal area, thus, the formula for calculating basal area is as detailed below in equation 1.

Basal Area $BA = \pi * (DBH/2)^2$ .... *Equation 1*

Where:

BA=Basal Area (m^2);

π=Pi is constant (3.143)

D 2 =Dbh (cm)

II. Tree Volume Estimation

To estimate the total volume of trees on the plantation, Huber's formula (Husch, 2002) was employed as shown below in Equation 2.

Volume V = Dm x H ………………………….. Equation 2
Where V = Volume
Dm = Basal Area
H = Height

III. Biomass estimation

To estimate the biomass of woody plants (*Azadirachta indica*), using the allometric growth equation developed by IPCC (2019), the *Azadirachta indica* wood density constant of 0.69g/m-3 (Gisel *et al*., 1992) was multiplied by estimated tree volume as detailed in equation 3.

Biomass BM = WD x TV ……………..…… Equation 3
Where BM = Biomass
WD = Wood density
TV = Tree volume

IV. Carbon Stock

A tree's average carbon content is 50% of its total dry weight. Therefore, to determine carbon stock in this study, aboveground biomass was converted to carbon stock using the default value of 0.5 provided by IPCC (2019) as detailed in equation 4.

Carbon Stock CS = BM x 0.5 …….……… Equation 4
Where CS = Carbon Stock
BM = Biomass
0.5 = Carbon Coefficient

V. Weight of Carbon dioxide

The molecular weight of CO_2 is 44g/m, while the atomic weight of Carbon (C) is 12g/m, this means that for every unit of carbon sequestrated, approximately 3.67 units of carbon dioxide are removed from the atmosphere. Therefore, to determine the amount of carbon dioxide sequestered in a tree, multiply the weight of carbon in the tree by 3.67 (Archer D, 2010) as shown in equation 5

Weight of Carbon dioxide ***WCO_2*** *= WCS x 3.67........ Equation 5*
Where WCO_2 = weight of carbon dioxide sequestered
CS = Caron Stock
3.67 = carbon Unit

Hence, to determine the average annual weight of CO_2 sequestered by the trees in a year, divide the weight of carbon dioxide sequestrated by the tree by the age of the tree as shown in Equation 6 below.

WCO_2 yr-1 = WCO_2 / Age ……………..…… Equation 6
Where WCO_2 yr. -1 = weight of carbon dioxide sequestered by a tree per year
WCO_2 = weight of carbon dioxide sequestered by a tree
Age = Age of the tree

Ground-Truthing

A ground-truthing exercise was conducted in the plantation using the Traditional method, measuring tape was used to obtain measurements for the diameter of each tree by wrapping the tape around the tree stem at 1.3m above ground (breast height). While for height, the tangent formula was used to determine height (Tree Height = (tan θ x D) + H_e) Husch *et al*., (2002). Height of the observer was noted as H_e, horizontal distance to the tree was measured as D, and a clinometer was used to determine the angle of elevation as θ. This was done to evaluate the accuracy and reliability of the data collected using the Arboreal Forest mobile LiDAR.

Statistical Analysis

Statistical analysis was performed to estimate trees' total biomass and carbon stock, with the results presented in tabular form using Microsoft Excel 2016. The analysis involved calculating values and organizing data to clearly represent the findings.

Comparative Analysis

This study further evaluates the accuracy of the data obtained using Arboreal application and the Traditional method. Descriptive statistics such as mean and standard deviation were used to measure the central tendency and quantify the variation and dispersion of the data, Student T-test was used to compare the means of two paired groups to determine if there is a significant difference between them or not.

$$t = \frac{\bar{d}}{s_d \sqrt{n}}$$

Where:

i. *$\bar{d}$: Mean difference*
ii. *S.d: Standard deviatoin*
iii. *n: Sample size*

RESULTS - *Rezultati*

Descriptive and Statistical Summary of Measurable Variables of the Study Area

The results from this study revealed that the study area has a total number of 381 Neem trees that varies by plots, with plot 1 having a total number of 86 trees, followed by plot 2 with 72 trees. In comparison, plot 7 has the lowest number of trees by plot with only 19 trees, as shown in Table 1. Results for the sum of diameter by plots range from 916.6cm to 163.1cm and for height, it varies from 597.3m to 269.2m, with a total of 3730.9cm and 2475m respectively as detailed in Table 1.

Results also showed a range of mean diameters by plots. It ranges from 11.2cm to 8.3cm and the mean height ranges from 7.0 to 6.0m, with a total mean diameter of 66.5cm and total mean height of 45.6m, respectively as detailed in Table 1. Moreover, the results from this study also uncovered a range of minimum diameter by plots with a minimum of 6.0cm to 4.0cm and a maximum of 21.0cm to 15.0cm, whereas for height, it showed a minimum range of 2.86m to 5.0m and a maximum of 12.01m to 10.0m respectively as shown in Table 2.

Estimation of Basal Area in the Study Area

For basal area, the result revealed in Table 1 showed that the total basal area of the trees in plot 1 has the highest sum of basal area to be 3.2m^2. Trees in plot 1 have the highest sum of basal area of 0.82m^2, followed by plot 2 with a total of 0.78m^2, then plot 7 which has the lowest of basal area of only 0.12m^2.

Table 1: Descriptive Summary of Measurable Variables of the Study Area

Tabela 1: Deskriptivni sažetak mjerljivih varijabli područja istraživanja

Plot Number	Number of Trees	Diameter (cm)	Height (m)	Mean Diameter (cm)	Mean Height (m)	Basal Area (m^2)	Volume (m^3)
1	86	916.6	597.3	10.7	6.9	0.819512	5.59
2	72	805.8	456.5	11.2	6.3	0.781067	5.66
3	65	652.1	392.9	10.0	6.0	0.572109	4.00
4	57	497.2	367.6	8.7	6.5	0.379240	2.42
5	42	352.1	269.2	8.3	6.4	0.252129	1.60
6	40	344.0	259.2	8.6	6.5	0.253728	1.71
7	19	163.1	132.3	9.0	7.0	0.120853	0.92
Total	**381**	**3730.9**	**2475**	**66.5**	**45.6**	**3.178638**	**21.90**

Source: field survey, 2024

Table 2: Statistical Summary of Measurable Variables of the Study Area

Tabela 2: Statistički sažetak mjerljivih varijabli područja istraživanja

Plot Number	Minimum Diameter (cm)	Maximum Diameter (cm)	Minimum Height (m)	Maximum Height (m)
1	5.0	17.0	2.86	12.01
2	6.0	21.0	3.00	10.60
3	5.0	16.0	3.00	10.40
4	4.0	15.8	4.00	10.50
5	4.3	15.2	4.00	10.40
6	5.0	15.0	4.00	11.00
7	4.5	15.3	5.00	10.00

Source: field survey, 2024

Estimation of Tree Volume in the Study Area

Results in Table 1 showed that the total volume of trees in the study area was estimated to be around 21.9m^3 in the sampled plots. The trees in plot 2 have the highest average volume of 5.59m^3 compared to the rest of the plots, where plot 7 has the lowest average volume of 0.9m^3.

Estimation of Tree Biomass in the Study Area

For biomass, the result as indicated in Tables 3 showed that the average biomass of trees in the study area was estimated to be 15.1kg in the entire sampled plots. Trees in plot 2 tend to be the highest with 3.9kg followed by plot 1 having 3.8kg whereas plot 7 has the lowest biomass of only 0.6kg, with a total of 15.10786kg.

Carbon Stock Estimation in the Study Area

The carbon stock estimation in the study area showed that plot 2 also tends to have the highest carbon stock with about 1.95kg/m^3, slightly above plot 1 with 1.92kg/m^3. The lowest of carbon stock amongst the sampled plot is 7 with only 0.31kg/m^3, with a total of carbon stock of 7.553951 (Table 3).

Weight of Carbon Dioxide Sequestered in the Study Area

For the weight of CO_2 sequestered, as shown in Table 3, plot 2 also showed the highest amount of CO_2 sequestered, with about 7.2kg, followed by 7.1kg for plot 1, whereas plot 7 showed a relatively low CO_2 sequestration of only around 1.2kg. The carbon dioxide sequestered in the entire plantation amounts to 27.7229kg. Therefore, in summary, this plantation has sequestrated 176.0508kg/ha of CO_2 over the years.

Comparison of the Average Diameter and Height Measurement between the Selected Plots of Azadirachta Indica in the Study Area.

Results obtained showed that the average diameter by the traditional and Arboreal methods are very close, the arboreal application showed a slightly lower mean with similar standard deviation than the traditional method in plot 3. However, it shows the same mean value with a slightly lower standard deviation in plot 6 and a slightly higher mean value in plot 7 with the same standard deviation as shown in Table 4. Results obtained for average height between traditional and arboreal datasets are slightly not common, the arboreal application showed a slightly lower mean value with higher standard deviation in plot 2, also showing a slightly lower mean value with higher standard deviation value in plot 6, while in plot 7 it shows lower value for both mean and standard deviation as shown in Table 4.

Table 3: Biomass Carbon Stock and Weight of Carbon Dioxide (CO_2) Sequestration Equivalent in the Study Area.

Tabela 3: Zalihe ugljika u biomasi i ekvivalentna težina sekvestriranog ugljičnog dioksida (CO_2) u području istraživanja

Plot Number	Biomass (kg)	Carbon Stock (kg)	WCO_2 Sequestrated (kg)	WCO_2 Sequestrated (kg/ha)
1	3.85457	1.927289	7.0731	44.2072
2	3.90392	1.951964	7.1637	44.7731
3	2.76027	1.380136	5.0651	31.6568
4	1.67200	0.836003	3.0681	19.1758
5	1.10289	0.551447	2.0238	12.6488
6	1.18175	0.590879	2.1685	13.5533
7	0.63246	0.316233	1.1606	10.0358
Total	**15.10786**	**7.553951**	**27.7229**	**176.0508**

Source: field survey, 2024

Key: WCO_2 = Weight of Carbon-dioxide

Table 4: Summary of Average Diameter and Height Measurement using the Traditional and Arboreal Method within the Selected Plots of Azadirachta Indica in the Study Area

Tabela 4: Sažetak prosječnih mjerenja prečnika i visine pomoću tradicionalne i arborealne metode unutar odabranih parcela Azadirachta indica u području istraživanja

	Traditional Method				**Arboreal Method**			
	Diameter		**Height**		**Diameter**		**Height**	
Plot	Mean	Std	Mean	Std	Mean	Std	Mean	Std
2	11.29	3.57	6.4	2.04	11.2	3.57	6.3	2.05
6	8.6	2.66	6.5	1.92	8.6	2.64	6.43	1.94
7	8.5	2.75	7	1.81	8.58	2.78	6.9	1.79

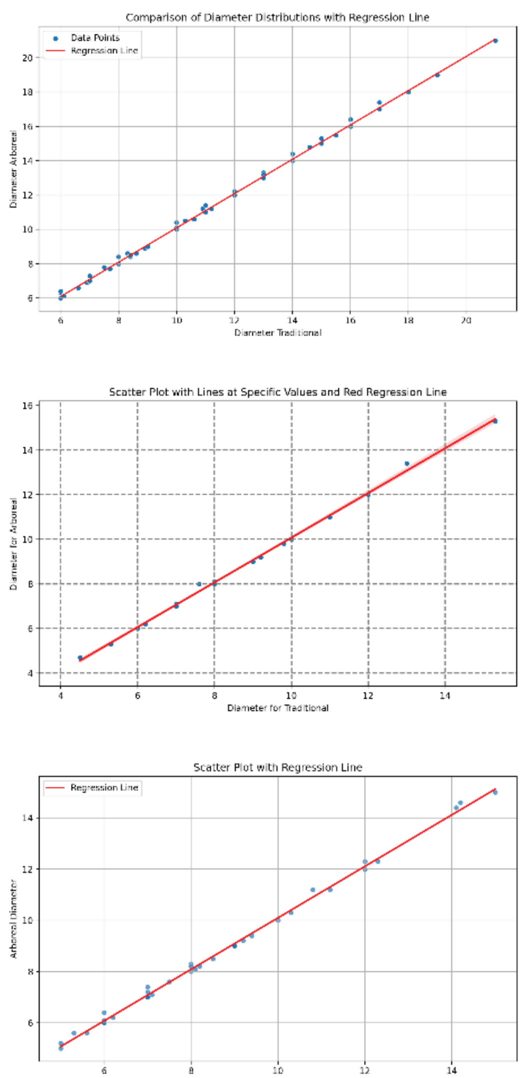

Figure 2: Scatter Plot showing Diameter Distribution values evaluated by Traditional and Arboreal Method for the selected Plots of A. indica in the Study Area.

Slika 2: Raspršeni dijagram koji prikazuje raspodjelu vrijednosti prečnika procijenjenih tradicionalnom i arborealnom metodom za odabrane parcele A. indica u području istraživanja

Comparative Analysis by Paired Sample T-test Between Manual and LiDAR Measurement for Diameter and Height

Results obtained from a paired T-test by plots showed that plot 2 has a t-statistic of 1.91 with a p-value of 0.06 for diameter measurement and a t-statistic of -1.49 and a p-value of about 0.14 for height measurement, with a degree of freedom of 71. For Plot 6, results showed a t-statistic of 1.14 and a p-value of 0.26 for diameter measurement and a t-statistic of 1.84 and a p-value of 0.07 for height measurement, with a degree of freedom of 39. And for plot 7, results unveil a t-statistic of 1.37 and a p-value of 0.18 for diameter measurement and a t-statistic of 1.84 and a p-value of 0.08 for height measurement, with a degree of freedom of 18, all at the 0.05 level as detailed in Table 5.

Carbon Pricing and Monetary Value of CO_2 Sequestered in the Study Area

From the 381 *Azadirachta indica* trees involved in this study, the result revealed that the total amount of CO_2 that was sequestered is 176.0508kg/ha, as shown in Table 6. The total price per unit weight of the CO_2 sequestered by the trees in the plantation amounts to $19.2, which is equivalent to N33,670 over the years. Amongst the plots, Plot 2 has exhibited the highest monetary value for carbon sequestration, which amounts to $4.8, equivalent to N8,549, unlike Plot 7 which has exhibited the lowest with just a dollar amount of monetary value, which is equivalent to N1,909.

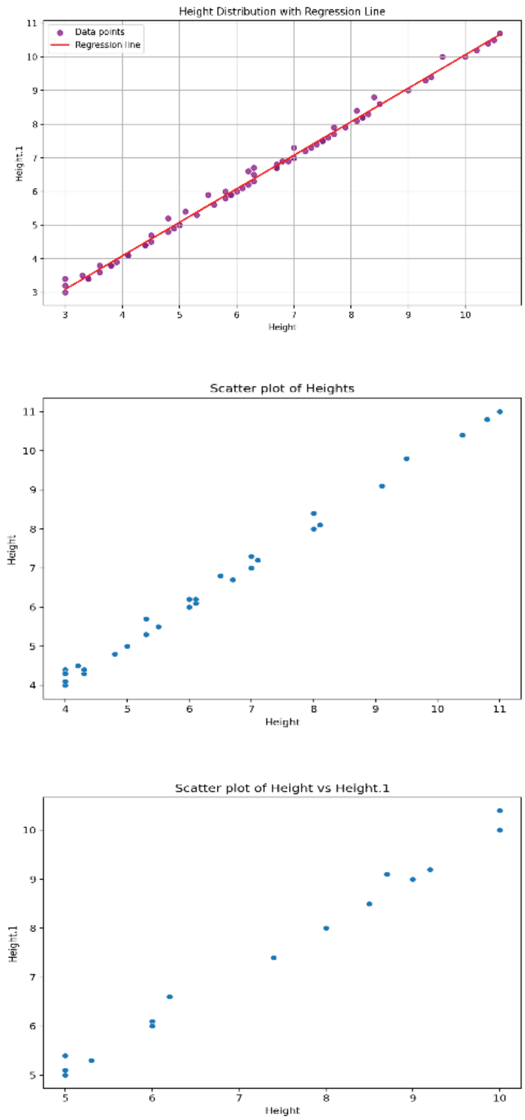

Figure 3: Scatter Plot showing Height Distribution values evaluated by Traditional and Arboreal Method for the selected Plots of A. indica in the Study Area.

Slika 3: Raspršeni dijagram koji prikazuje raspodjelu vrijednosti visine procijenjenih tradicionalnom i arborealnom metodom za odabrane parcele A. indica u području istraživanja

DISCUSSION - *Diskusija*

Descriptive and Statistical Summary of Measurable Variables of the Study Area

The results from this study revealed that the study area has a total number of 381 Neem trees that vary by plot. This is comparatively lower than the number of trees obtained (395) by Saka *et al.*, (2020); this is due to illegal cutting of trees in the study area, which has been reducing the number of standing trees in the plantation. From this study, plot 1 has a total number of 86 trees, followed by plot 2 with 72 trees, while plot 7 has the lowest number of trees by plot with only 19 trees, as shown in Table 1, suggesting a relatively variable young small plantation stand. Results for total diameter by plots range from 916.6cm to 163.1cm, while for height it ranges from 597.3m to 269.2m, with a total of 3730.9cm and 2475m respectively, as detailed in Table 1 as well. The result also uncovered that the trees are yet to reach 30cm, which is the standard diameter threshold for timber purposes. However, they can be used for other purposes, such as in construction, as pillar stands or electrical poles.

Results also showed a range of mean diameter by plots that ranges from 11.2cm to 8.3cm and mean height ranging from 7.0 to 6.0m with a total of mean diameter of 66.5cm and a total mean height of 45.6m respectively as detailed in table 1, indicating a moderate variation in tree size in the study area. Moreover, results from this study also uncovered a range of minimum diameter by plots with a minimum of 6.0cm to 4.0cm and a maximum of 21.0cm to 15.0cm, whereas for height, it showed a minimum range of 2.86m to 5.0m and a maximum of 12.01m to 10.0m respectively.

Basal Area Estimation of the Trees in the Study Area

Basal Area is a fundamental forestry metric representing the cross-sectional area of trees at breast height (1.3m above ground) per unit area (e.g. m^2/ha). It is widely used as a proxy for estimating forest biomass

Table 5: Summary of Paired Sample T-test Between Manual and LiDAR Measurement for Diameter and Height

Tabela 5: Sažetak t-testa uparenih uzoraka između ručnog i LiDAR mjerenja prečnika i visine

S/N	Paired Methods	Plot	Variables	T-Statistic	P-Value	df	CI
1	Manual - LiDAR	2	Diameter Height	1.91 -1.49	0.06 0.14	71 71	0.05 0.05
2	Manual - LiDAR	6	Diameter Height	1.14 1.84	0.26 0.07	39 39	0.05 0.05
3	Manual - LiDAR	7	Diameter Height	1.37 1.84	0.18 0.08	18 18	0.05 0.05

Table 6: Carbon Pricing and Monetary Value of CO_2 Sequestered in the Study Area

Tabela 6: Cijena ugljika i novčana vrijednost sekvestriranog CO2 u području istraživanja

Plot Number	WCO_2 Sequestrated (kg)	WCO_2 Sequestrated (kg/ha)	WCO_2 Sequestrated (tons/ha)	Price of CO_2 (U.S $)	Price of CO_2 (N)
1	7.0731	44.2072	0.0442	4.82	8,444
2	7.1637	44.7731	0.0448	4.88	8,549
3	5.0651	31.6568	0.0317	3.46	6,061
4	3.0681	19.1758	0.0192	2.1	3,679
5	2.0238	12.6488	0.0126	1.37	2,400
6	2.1685	13.5533	0.0136	1.48	2,628
7	1.1606	10.0358	0.01	1.09	1,909
Total	**27.7**	**176.0508**	**0.1761**	**19.2**	**33,670**

**Note: The EU Price of CO_2 forecasted for approximately €100 which is equivalent to $109 in 1st quarter of 2025.*

***Note: The Central Bank of Nigeria Exchange Rate as at 09/01/2025 is 1$ = N 1,752*

and carbon sequestration potentials since tree size and density strongly correlate with biomass accumulation and carbon storage (Sitoe *et al.,* 2014). The result in this study, revealed in Table 1, showed that the total basal area of the trees in plot 1 has the highest sum of basal area to be 3.2m^2. Trees in plot 1 have the highest sum of basal area of 0.82m^2, followed by plot 2 with a total of 0.78m^2, then plot 7, which has the lowest basal area of only 0.12m^2. Sitoe *et al.,* (2014): reported that 1m^2 increase in basal area led to an increase in biomass by 10mg/ha, confirming its reliability in carbon stock estimation.

Volume Estimation of Trees in the Study Area

The volume of trees in a forest is one of the most important statistics in forest management. The individual tree volume is usually considered a function of tree DBH and height (Clutter *et al.,* 1983). In this study, volume was estimated at the plot level where in each plot, volume was computed using Huber's formulae. Developing forest inventory estimates often involves predicting tree volumes from only diameter and height (Meng, 1986), Plot 2 had the highest amount of volume of about 5.657868097m^3, followed by plot 1 having around 5.586347038m^3. Volume estimation showed a declining trend from plot to plot, with plot 7 having the lowest volume of about 0.916616205m^3, whereas the total volume of the entire study area amounts to 21.89552035m^3. Standard volume tables are often used to estimate tree volume as a function of tree diameter and height for both routine forest measurement and forest research purposes (Evert, 1968). The volume trend follows the trend of diameter and height in the various plots because volume was derived from diameter and height.

Comparatively, a study by Thompson *et al.* (2021) reported an average tree volume of 25.50m^3 in a similar forest type, with individual plots ranging from 1.50m^3 to 30.00m^3. Their findings highlighted that environmental factors, such as soil quality and moisture levels, significantly influenced tree growth and volume. A similar study also conducted by Martinez and Chen (2020) found that the average tree volume in a mixed-species plantation was 18.75m^3, with the highest volume recorded in Plot 3 at 22.00m^3. This suggests that tree species composition and management practices can lead to variations in tree volume across different plots.

Biomass Estimation of Trees in the Study Area

Biomass is a key indicator of a forest's ability to sequester carbon, making it essential for studies on climate change mitigation, forest degradation and carbon offset programs (Avitable et al., 2016). As shown in this study, biomass estimated from measurement was obtained using DBH and the wood density of each tree at a plot level; the plots were then summed to obtain the total biomass of the trees in the study area. The total biomass of the trees in the study area amounts to 15.10790904kg. Results indicated that plot 2 has the highest amount of biomass of about 3.903928982kg followed by plot 1 with about 3.854579457kg, with a relatively stable trend across the rest of the plots.

In comparison, a study by Anderson *et al.* (2022) reported an average tree biomass of 18.50kg in a similar forest ecosystem, with individual plots ranging from 1.20kg to 4.50kg. Their findings emphasized the impact of species diversity and soil fertility on biomass accumulation. Additionally, research conducted by Patel and Kumar (2021) found that the average biomass in a mixed-species plantation was 16.75kg, with the highest biomass recorded in Plot 4 at 4.00kg. This suggests that management practices and environmental conditions play a significant role in determining tree biomass across different plots.

Carbon Stock Estimation ofTrees in the Study Area

Carbon stock results revealed that the amount of carbon stored in the plantation by plots was higher at the beginning of the plantation, with plot 2 having 72 tree stands and plot 1 having 86 tree stands, with carbon stocks of about 1.951964493kg and 1.927289728kg, respectively. The other edge of the plantation is covered mostly by fewer trees with plots 6 and 7 having only 40 and 19 tree stands with about 0.590879883kg and 0.316232591kg, respectively. The result also showed that the total carbon stock in the entire study site amounted to 7.55395452kg.

Kumar *et al.,* (2014) similarly found that carbon stock is significantly influenced by tree species composition and stand density, highlighting the variability in carbon storage across different forest types. Pan *et al.,* (2011) reported that forest carbon stocks can vary widely based on management practices and environmental conditions, underscoring the need for localized studies to accurately assess carbon storage. The results from this research were lower than those of Saka *et al.,* (2020), which can be attributed to several factors, including the exclusion of tree felling, measuring below-ground biomass, processing entire tree mass to study the chemical composition, assessing the stock density and so on. Calculating BGB carbon socks requires extracting tree roots and studying tree litter and soil minerals (Beet *et al.,* 2012). lack of this data for inclusion in the calculation implies that carbon and CO_2 sequestration levels estimated for the *Azadirachta indica* plantation of the Modibbo Adama University, Yola, may be lower than the true amount.

Estimation of the Weight of CO_2 in the Study Area

This research further estimated the weight of CO_2 sequestrated in the plantation. According to the results shown, plot 2, as expected, has the highest CO_2 sequestration with about 7.163709691kg. Plot 1 was closing the gap with plot 2 by having around 7.073153308kg. The trend is similar to that of carbon stock, with declining figures throughout the entire plantation, with plots 6 and 7 having around 2.16852917kg and 1.160573608kg, respectively. However, the plantation has a total weight of CO_2 sequestration of around 27.72301309kg, which is equivalent to 176.0508kg/ha over the years.

In comparison, a study by Carter *et al.,* (2020) reported an average CO_2 sequestration of 8.50kg in a similar forest ecosystem, with individual plots ranging from 2.00kg to 9.00kg. Their findings emphasized the role of tree age and species diversity in enhancing carbon sequestration rates. Additionally, research conducted by Nguyen and Tran (2021) found that the average CO2 sequestration in a mixed-species plantation was 6.50kg, with the highest sequestration recorded in Plot 4 at 8.00kg. This indicates that environmental conditions and management practices significantly influence CO2 storage across different plots. Smith *et al.* (2020) found that variability in CO2 sequestration can be influenced by factors such as soil type, vegetation cover, and climatic conditions. Their study indicated that certain plots exhibited higher sequestration rates during specific seasons, aligning with the observed sporadic peaks in the study.

Comparison of the Average Diameter and Height Measured between the Selected Plots of Azadirachta Indica in the Study Area.

Results obtained showed that the average diameter by the traditional and Arboreal are very close, the arboreal application showed a slightly lower mean with similar standard deviation than the traditional method in plot 3. However, it shows the same mean value with a slightly lower standard deviation in plot 6 and a slightly higher mean value in plot 7 with the same standard deviation. Results obtained for average height between traditional and arboreal datasets are slightly uncommon, the arboreal application showed a slightly lower mean value with higher standard deviation in plot 2, also showing a slightly lower mean value with higher standard deviation value in plot 6, while in plot 7 it shows lower value for both mean and standard deviation.

The analysis reveals that the average diameters for the traditional and arboreal datasets are very close, exhibiting similar distribution and characteristics indicating no significant difference in the central tendency or spread. The outlier analysis confirms that there are no extreme values in either of the datasets, further supporting the consistency of the arboreal application data. The analysis also revealed that data obtained for height measured using both methods is relatively uncommon. This may be attributed to the fact that the determination of this exact tree apex was challenging, especially in areas with entangled tree crowns. Thus, influencing the accuracy of the data obtained by the application. Tests performed with the Arboreal application in Sweden also used the RMSE parameter for comparison with the traditional measurement methodology. Those results corroborated those verified in this study, which indica-te accuracy in the measurements of N, G, and d, thus indicating a reduction in the measurement time (Lindberg, L. 2020)

Comparative Analysis

In this study, to evaluate the efficiency of Arboreal Forest mobile LiDAR as compared to manual field measurements, results from the paired t–test for Manual and LiDAR measurements for diameter and Height showed a close relationship. The result from Table 3 revealed a T-statistic of 1.91 with a P-value of 0.06 for diameter measurement and a T-statistic of -1.49 with a P-value of 0.14 for height measurement, both for plot 2, with a degree of freedom of 71. For plot 6, a t-statistic of 1.14 with a P-value of 0.26 for diameter measurement and a T-statistic of 1.84 and a P-value of 0.07 for height measurement, with a degree of freedom of 39. For plot 7, results uncovered a t-statistic of 1.37 and a P-value of 0.18 for diameter measurements and a t-statistic of 1.84 and a p-p-value of 0.08 for height measurement, with a degree of freedom of 18. Therefore, since all the P-values were observed to be greater than the common significant level of 0.05, Hence, this study fails to reject the Null hypothesis, which says that there is no significant difference between data obtained using Arboreal Forest Mobile LiDAR and Manual field measurement.

Keightley *et al.,* (2010) raised the issue of selection of the true measurement and mentioned direct field measurement of felled trees being an important factor affecting the accuracy of field and remote sensing surveys. This gives a valid reason to think about the importance of LiDAR implications in diameter and tree height measurements in comparison to conventional field measurements. Lovell *et al.,* (2011) presented a method for automatic tree location detection and provided stand statistics up to 50m in range within a forest. As shown in the paper, the data also provided stem diameters with accuracy dependent on the tree size and range. Many studies utilized non-destructive recording to provide observations of tree measurements (Keightley *et al.,* 2010).

A case somewhat similar to this research is a study that compared Digital Aerial Photogrammetry (DAP) and Aerial Laser Scanning (ALS) on similar species (Scot pines, Norway spruce and silver birch; Mielcarek *et al.,* (2020). The paired t-test result presented strong evidence that differences between the combinations of field, LiDAR and DAP height measurement are statistically significant and that LiDAR/DAP height measurement tends to underestimate height compared to field data. However, the authors further emphasized the role of the biophysical characteristics of each tree species and the complex and dense forest stands studied, which prevented the tree tops from being visible during field measurements. Whereas, in some cases, it might be hardly fair to blame temporal differences alone for the significant t–test in comparison between the methods.

Carbon Pricing and Monetary Valuation of CO_2 Sequestered in the Study Area

The total monetary value of the carbon sequestration service within the *Azadirachta indica* plantation of the Modibbo Adama University, Yola, was estimated at $19.2 (N33,670) over the years. This value was calculated based on the global price of the voluntary carbon market. The monetary value of the first carbon sequestration depends on carbon pricing mechanisms and the amount of CO_2 stored in forests, typically measured in USD per ton of CO_2 (USD/tCO_2) (Friedhugstein *et al.,* 2022). However, this study estimated a monetary value of carbon sequestration of $19.2, which is comparatively lower than that of Bohre *et al* (2016) who estimated biomass accumulation and carbon sequestration of *Azadirachta indica* in coal mined lands overburden in Singrauli, Madhya Pradesh, India, with a maximum value of CO_2 0.1650 tons ($289).

Additionally, Dongs *et al.,* (2024) also estimated a substantially higher economic value of carbon sequestration of trees in Jos Wildlife Park, Nigeria, the value amounts to $72,550.26 (N56,252,569.59), which by record is comparatively higher than the value obtained in this study. The monetary value estimated in Retezat National Park was $1,706,070 per 10 years. The result was twenty times higher than that resulting from using the price of the voluntary market. Showing an immense gap between the actual market and the needed one.

The monetary value of carbon sequestration varies based on factors such as the characteristics of the ecosystem involved, regional economic conditions, prevailing carbon market prices and the methodologies employed in valuation (Nowak *et al.,* 2002). The payment for ecosystem services related to carbon and sustainable financing mechanisms, such as REDD+ or woodland carbon code, need to be considered seriously and supported by the policymakers and the beneficiaries of this service. The payments need to support the management of the ecosystems to provide the services at a level that will be enable the climate targets adopted lately at EU level to be reached.

Conclusion

This research estimates biomass and carbon dioxide sequestration using Arboreal Forest Mobile LiDAR in an *Azadirachta indica* plantation. The results of the current study show that LiDAR data could be used to estimate forest biophysical parameters of interest by focusing on the individual tree level. LiDAR offers the possibility to automatically derive biophysical parameters over a large area. Therefore, seeing the trees in the forest and, more importantly, measuring them with LiDAR brings an important contribution to concepts such as precision forest inventory and automated data processing for forest applications. It is, therefore, expected that the transition from research to practical applications and operational use of LiDAR in forestry will accelerate. The focus of this research on the individual tree level demonstrated that mobile LiDAR provides the ability to reliably measure tree height, diameter and in the future time other variables such as crown dimensions could also be measured. Thus, improving estimates of forest volume and biomass. However, the study was limited by its exclusion of below-ground biomass (BGB) and soil carbon pool to give a more accurate representation of the *Azadirctha indica* plantation's total contribution in offsetting Modibbo Adama University's CO_2 emission.

The findings of this research show the correlation coefficient between carbon stock and height to be 0.6, indicating a moderate positive relationship, i.e., as height increases, carbon stock also increases. Diameter has a correlation of 0.90, which indicates a strong positive correlation. This suggests that diameter is a more important factor in carbon sequestration than height, which is contrary to the study of Dongs (2024), who suggested tree height as a more important factor than diameter in carbon sequestration. By quantifying biomass and carbon dioxide sequestration of forests, it is critical to assess the role of the trees in reducing the concentration of CO_2 and moderating temperature in the area. More in-depth research could be explored to assess BGB and soil components to further estimate carbon and CO_2 sequestration. LiDAR remote sensing has proven to be a useful tool in the estimation of forest biomass, receiving substantial attention in the literature in recent years, with a rising concern over the global carbon budget. Further development of LiDAR systems, particularly space-born, will be crucial in mapping and monitoring the role of the world's forests in carbon storage.

The results of this study can be scaled up to the national level and will provide insights into the carbon balance of urban ecosystems and the information can be used by urban planners, non-governmental organizations and programs such as REDD+ to gain a better understanding of global carbon budget, practically in adverse tropical region and to better manage vegetation in the urban environments, to establish low carbon cities and subsequently to reduce global carbon emissions while increasing carbon storage.

REFERENCES - *Literatura*

Adams, E.E. (2012). Eco-Economy Indicators. Earth Policy Institute: Washington D.C, United States. http://www.earth-policy.org/indicators/C56

Adebayo A. A., and Tukur A L. (1999). Climate 1(sunshine, temperature, evaporation and Relative humidity), Adamawa state in Maps, Adebayo, A.A and Tukur, A.L. (Eds).pp.20-26.

Adebayo, A. A. and Zemba, A. A. 2020 Climate: Sunshine, Temperature, Evaporation and Relative Humidity, Climate II: In Adebayo,A.A,Tukur,A. L.And Zemba,A.A.A. (2nd Edition) Adamawa State in Maps. Paraclete Publishers. 31 – 35

Anderson, J.K., Newlove-Delgado, T., & Ford, T.J. (2022). Annual Research Review: A systematic review of mental health services for emerging adults – moulding a precipice into a smooth passage. *Journal of Child Psychology and Psychiatry*, 63(4), 447–462. https://doi.org/10.1111/jcpp.1356

Atwell, B.J., Kriedemann, P.E. and Turnbull, C.G.N. (Eds) (1999). Plants in Action. ASPPI MacMillan, South Yarra. 664 pp.

Avery, T.E., & Burkhart, H.E. (2002). *Forest Measurements* (5th ed.). McGraw-Hill.

Avitable, V., Herold, M., Heuveluik, G.B.M., and Lewis, S.L. (2016). An intergrated pen–tropical biomass map using multiple reference datasets, Global change biology 22(4), 1406-1420.

Beets et al., 2012. Schwendenmann & Mitchell, 2014; Wulder et al., 2008, Beets, P. N., Kimberley, M. O., Oliver, G., R., Pearce, S. H., Graham, J. D., & Brandon, A. (2012).

Bohre, Priyanka, Chaubey, O.P. 2016/04/30, 111 - 120. Biomass Production and Carbon Sequestration by Azadirachta indica in Coal Mined Lands, 8 - 10.14257/ijbsbt.2016.8.2.10, International Journal of Bio-Science and Bio-Technology.

Brown, S. (1997). *Estimating biomass and biomass change of tropical forests: a primer.* FAO Forestry Paper 134. Rome: Food and Agriculture Organization.

Carter, S.K., et al. (2020). *Adaptation Strategies and Approaches for California Forest Ecosystems*. U.S. Department of Agriculture, Forest Service. This document outlines various strategies for adapting California's forest ecosystems to climate change, emphasizing the importance of engaging managers in research development to ensure applicability to decision-making processes.

Chave, J., Réjou Méchain, M., Búrquez, A., et al. (2014). Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, 20(10), 3177–3190.

Chen, Q. (2010). Assessment of terrain elevation derived from satellite laser altimetry over mountainous forest areas using airborne lidar data, ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 65, pp. 111-122

Clutter, J.L., Fortson, J.C., Pienaar, L.V., Brister, G.H., and Bailey, R.L. 1983.

Dalmonech, D.; Marano, G.; Amthor, J.S.; Cescatti, A.; Lindner, M.; Trotta, C.; Collalti, A. Feasibility of Enhancing Carbon Sequestration and Stock Capacity in Temperate and Boreal European Forests via Changes to Management Regimes. Agric. For. Meteorol. 2022, 327, 109203.

David Archer Princeton University Press, 2010 - Science - 205 pages A must-have introduction to this fundamental driver of the climate system

Dongs, Y. D (2024). Carbon sequestration potential of some tree species in Jos Wildlife Park, Plateau State Nigeria. *Modibbo Adama University, Unpublished Master's Thesis, 86p*.

Dulamsuren, C. Organic Carbon Stock Losses by Disturbance: Comparing Broadleaved Pioneer and Late-Successional Conifer Forests in Mongolia's Boreal Forest. For. Ecol. Manag. 2021. 499, 119636.

Dunne D. The Carbon Brief Profile: Nigeria. Carbon Brief. 2020. Accessed January 18, 2022. https://www.carbonbrief.org/the-carbon-brief-profile-Nigeria.

Evert, F. Form height and volume per square foot of basal area. *Journal of Forestry*. 66:358-359; 1968.

Feldpausch, T. R., et al. (2012). Tree height integrated into pantropical forest biomass estimates. *Biogeosciences*, 9(8), 3381–3403.

Fremout, T.; Cobián-De Vinatea, J.; Thomas, E.; Huaman-Zambrano, W.; Salazar-Villegas, M.; Limache-de la Fuente, D.; Bernardino, P.N.; Atkinson, R.; Csaplovics, E.; Muys, B. Site-Specific Scaling of Remote Sensing-Based Estimates of Woody Cover and Aboveground Biomass for Mapping Long-Term Tropical Dry Forest Degradation Status. Remote Sens. Environ. 2022, 276, 113040.

Friedhugstein, P., et al. (2022). Global carbon budget 2022. Earth system science data, 14(4) 1917-2005

Gisel Reyes, Sandra Brown, Jonathan Chapman and Ariel E.Lugo 1992, wood densities of tropical species. New Orleans, Louisiana.

Henry M. Wood density, phytomass variations within and among trees, and allometric equations in a tropical rainforest of Africa. Forest Ecol. Manag. 2011; 260(8):1375–1388.

Husch, B, Beers, T.W., & Kershaw Jr., J.A (2002). Forest mensuration (4th Ed). John Wiley and Sons.

IEA.International Energy Agency Website: www.iea.org. https://www.usaid.gov/climate/country-profiles/nigeria

IPCC Special report on climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security and GHG fluxes in terrestrial ecosystems, IPCC (2019).

Keightley KE, Barden GW, (2010). 3D volumetric modelling of grapevine biomass using tripod LiDAR compute electron Agric 74:305-12

Ketterings, Q. M., et al. (2001). Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. *Forest Ecology and Management*, 146(1-3), 199–209

Kumar, L., Mutanga, O., & Sinha, P. (2014). *Remote sensing of aboveground biomass in tropical forests: A review*. Tropical Ecology, 55(3), 239–252.)

Kushwaha, S.P.S., Nandy, S. and Gupta, M. (2014). Growing stock and woody biomass assessment in Asola-Bhatti Wildlife Sanctuary, Delhi, India. *Environmental Monitoring and Assessment* 186:5911-5920.

Lashof D A and Ahuja D R 1990. *Nature* 344 529-31

Lindberg, L. Insamling av Skogliga Data Med Applikationen Arboreal Skog—En Studie om Mätprecision, Noggrannhet och Effektivitet, Umeå. 2020. *Available online: https://stud.epsilon.slu.se* (accessed on 23 March 2023).

Meng, C.H. and Tsai, W.Y. 1986. Selection of weights for a weighted regression of tree volume. Can. J. For. Res., 16:671-673.

Mielcarek, M., Kaminsaka, A., Sterenczak. K. Digital Aerial Photogrammetry (DAP) and Airborne Laser Scanning as sources of information about tree height: comparison of the accuracy of remote sensing methods for tree height estimation. *Remote sensing 2020,* 12, 1808

National Population Commission (NPC). (2006). *Population and Housing Census of the Federal Republic of Nigeria: National and State Population and Housing Tables: Priority Tables (Vol. 1).* Abuja: National Population Commission.

Pan, P, Birdsey, R.A., Fang J., Houghton, R., Kauppi, P. E., Kurzw. A., and Hayes, D. (2011). A large and persistent carbon sink in the world's forest. Science, 333 (6045) 988 – 993.

Parker, R.C. and D.L. Evans. (2004). An application of LiDAR in a double-sample forest inventory. Western Journal of Applied Forestry 19(2): 95–101

Patel and Kumar (2021)

Pham, T.T., Nguyen, T. D., Dao, C.T. L., Hoang, L.T., Pham, L. H., Nguyen, L.T., & Tran, B. K. (2021). Impacts of Payment for Forest Environmental Services in Cat Tien National Park. *Forests, 12*(7), 921. https://doi.org/10.3390/f12070921Nowak, D.J., & Crane, D.E, (2002), " *carbon storage and sequestration by urban trees in the USA. Environmental pollution,* 116(3), 381-389.

Romanov, A.A.; Tamarovskaya, A.N.; Gloor, E.; Brienen, R.; Gusev, B.A.; Leonenko, E.V.; Vasiliev, A.S.; Krikunov, E.E. Reassessment of Carbon Emissions from Fires and a New Estimate of Net Carbon Uptake in Russian Forests in 2001–2021. Sci. Total Environ. 2022. 846, 157322.

Saka M.G, Oho, J.S.A, and Isa, H. D (2020). Assesmsnet of biomass content and carbon stock of plantation-grown Neem specie(Azadirachta indica) in Yola Nigeria. *Journal of research in forestry, wildlife and environment,* Vol 12 (1) March 2020.

Schlesinger, William H. Biochemistry: An analysis of global change. Academic Press, (2013).

Sitoe, A., et al., (2014). Tree biomass and carbon stock estimation in miombo woodlands in Mozambique. Forest, 5(7), 1717-1733.

Smith, Pete et al. The role of trees in carbon sequestration. Forest ecology and management. (Academic Journal).2010.

Thakur TK, Patel DK, Thakur A, Kumar A, Bijalwan A, Bhat JA, Kumar A, Dobriyal MJ, Kumar M, Kumar Biomass Production Assessment in a Protected Area of Dry Tropical Forest Ecosystem of India: A Field to Satellite Observation Approach A Published in *Frontiers in Environmental Science,* Volume 9, DOI: 10.3389/fenvs.2021.757976

The Influence of Land Use and Climate Change on Forest Biomass and Composition Jonathan R. Thompson, David R. Foster, et al. Published in *Environmental Sciences and Management*, Portland State University United Nations Environment Programme/GRID-Arendal 2007 National carbon dioxide (CO2) emissions per capita homepage http://maps.grida.no/go/graphic/national_carbon_dioxide_co2_ emissions per capita, Accessed 25/01/2012)

U.S. Environmental Protection Agency (EPA). (2010). *Annual Report 2010*. Retrieved from https://www.epa.gov/sites/default/files/2013-12/documents/annual-report-2010.pdf

Xu, C.; Wang, B. and Chen, J. (2022). Forest Carbon Sink in China: Linked Drivers and Long Short-Term Memory Network-Based Prediction. *J. Clean. Prod.* 359, 132085.

Zaninovich, S.C.; Gatti, M.G. Carbon Stock Densities of Semi-Deciduous Atlantic Forest and Pine Plantations in Argentina. Sci. Total Environ. 2020, 747, 141085.

Zell, J.; Bösch, B.; Kändler, G. (2014). Estimating aboveground biomass of trees: Comparing Bayesian calibration with regression technique. *European Journal of Forest Research* 133(4): 649-660. http://dx.doi.org/10.1007/s10342-014-0793-7

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SAŽETAK

Ova studija procjenjuje biomasu i potencijal sekvestracije ugljenika korištenjem LiDAR tehnologije u plantaži Azadirachta indica na Univerzitetu Modibbo Adama u Yoli. Primijenjena je metoda totalnog premjera, pri čemu je postavljeno sedam uzoraka dimenzija 40x40 metara. Na svakom uzorku mjerene su dimenzije stabala (prečnik i visina) koristeći softver Arboreal Forest Mobile LiDAR.

Rezultati pokazuju da područje istraživanja sadrži ukupno 381 stablo neem-a, s razlikama među parcelama: parcela 1 broji 86 stabala, parcela 2 ima 72, dok parcela 7 bilježi najmanji broj – svega 19 stabala (tabela 1). Ukupna suma svih prečnika po plohama varira od 163,1 cm do 916,6 cm, dok suma visina stabala se kreće od 269,2 m do 597,3 m.

Temeljnica stabala u plantaži iznosi ukupno 3,2 m^2. Parcela 1 ima najveću temeljnicu od 0,82 m^2, slijedi parcela 2 sa 0,78 m^2, dok parcela 7 ima najmanju – samo 0,12 m^2. Ukupna zapremina stabala je 21,9 m^3. Parcela 2 prednjači s zapreminom od 5,59 m^3, dok parcela 7 ima najmanju zapreminu od 0,9 m^3.

Biomasa stabala u cijelom području procijenjena je na 15,1 kg. Najveću biomasu imaju stabla na parceli 2 (3,9 kg), slijedi parcela 1 sa 3,8 kg, dok parcela 7 ima najmanju biomasu od 0,6 kg. Procjena zaliha ugljika pokazuje da parcela 2 ima najveću zalihu ugljika sa 1,95 kg/m^3, nešto više od parcele 1 (1,92 kg/m^3). Najmanja zaliha ugljika evidentirana je na parceli 7, sa samo 0,31 kg/m^3, dok ukupna zaliha ugljika u uzorcima iznosi 7,55 kg/m^3.

Količina sekvestriranog ugljičnog dioksida (CO_2) pokazuje da parcela 2 ima najveću vrijednost, oko 7,2 kg, parcela 1 slijedi sa 7,1 kg, dok parcela 7 ima relativno malu sekvestraciju od oko 1,2 kg. Ukupno je u plantaži sekvestrirano 27,72 kg CO_2.

Analiza prosječnog prečnika dobivenog tradicionalnom i arborealnom metodom pokazuje vrlo slične rezultate. Arborealna metoda pokazala je blago nižu srednju vrijednost uz sličnu standardnu devijaciju u parceli 3, identičnu srednju vrijednost s nešto manjom devijacijom u parceli 6, te nešto višu srednju vrijednost s istom devijacijom u parceli 7.

Kod prosječne visine, razlike između metoda su izraženije. Arborealna metoda pokazuje blago nižu srednju vrijednost s većom standardnom devijacijom u parcelama 2 i 6, dok u parceli 7 bilježi niže vrijednosti i za srednju vrijednost i za devijaciju.

Ukupna novčana vrijednost sekvestriranog CO_2 u plantaži iznosi 19,2 USD, što je ekvivalentno 33.670 Naira. Najvišu novčanu vrijednost ima parcela 2 – 4,8 USD (8.549 Naira), dok parcela 7 bilježi najnižu vrijednost od 1 USD (1.909 Naira).

Ovi nalazi sugerišu da se osnovni podaci dobijeni ovom studijom mogu redovno ažurirati. Primjena daljinskog istraživanja i GIS tehnologija omogućava vizualizaciju preciznih prostorno-vremenskih obrazaca, što može pomoći u povećanju efikasnosti programa pošumljavanja i obnove šuma. Također, studija ističe potrebu za dodatnim istraživanjima procjene biomase i sekvestracije ugljika pomoću LiDAR tehnologije radi efikasnijeg ublažavanja klimatskih promjena i globalnog zagrijavanja.

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