TREE SPECIES DIVERSITY, BIOMASS PRODUCTION AND CARBON STOCK OF THREE FOREST MANAGEMENT TYPES IN BENUE STATE, NIGERIA

BY

DAU, HENRY JAPHETH
B. For, M. For (Inventory & Mensuration, FUAM)
FWT/18/9425

A THESIS IN THE DEPARTMENT OF FORESTRY AND WOOD TECHNOLOGY, SUBMITTED TO THE SCHOOL OF POST GRADUATE STUDIES, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY (Ph. D.) IN FOREST INVENTORY AND BIOMETRICS, OF THE FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE, NIGERIA

JANUARY 2025

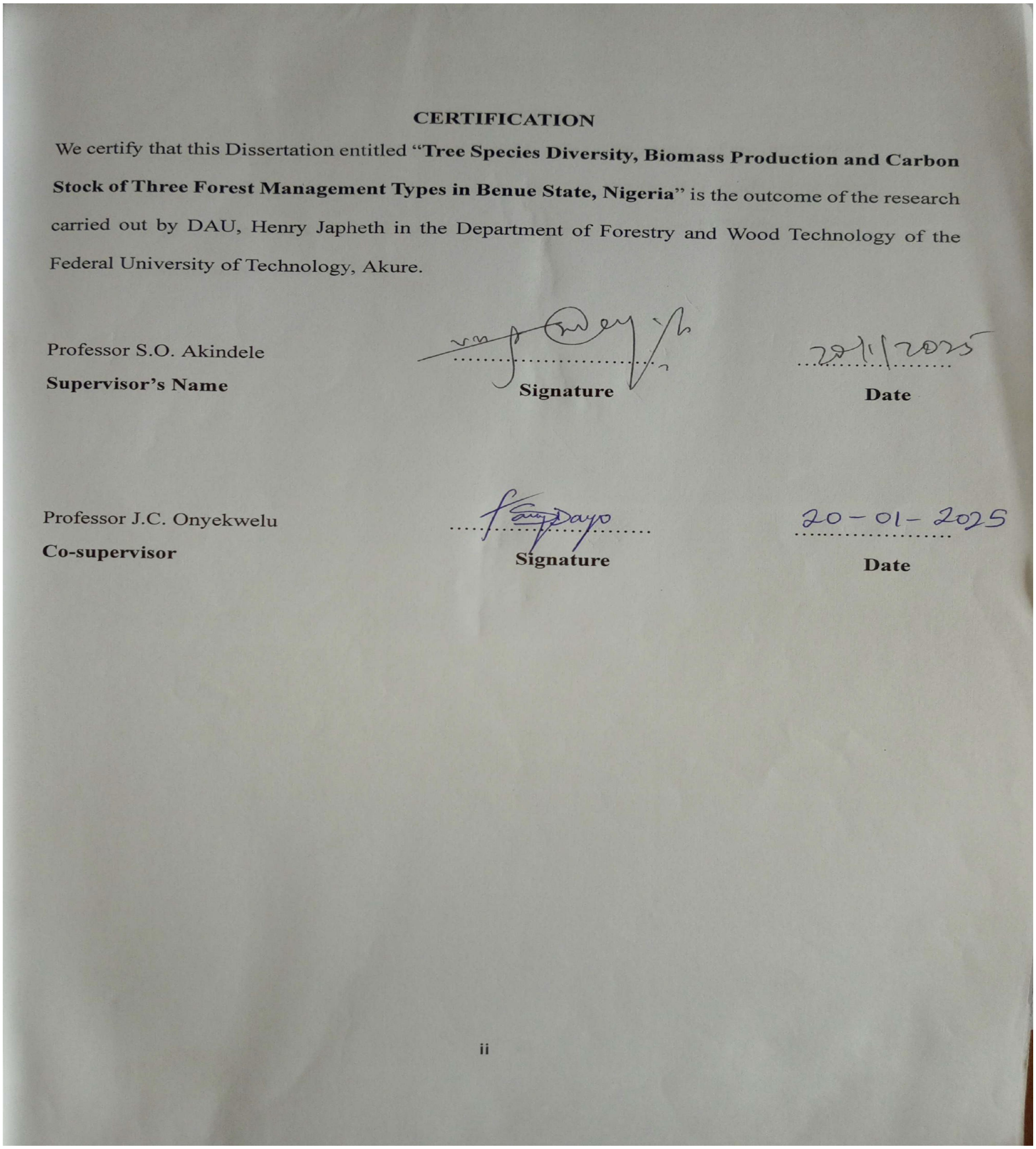
DECLARATION

I hereby declare that this thesis was written by me and is a correct record of my research work. It has not been presented in any previous application for any degree of this University or any other University. All citations and sources of information are acknowledged by means of reference.

Candidate's Name: DAU, Henry Japheth

20th January, 2025

Signature: **Date**



CERTIFICATION

We certify that this Dissertation entitled "**Tree Species Diversity, Biomass Production and Carbon Stock of Three Forest Management Types in Benue State, Nigeria**" is the outcome of the research carried out by DAU, Henry Japheth in the Department of Forestry and Wood Technology of the Federal University of Technology, Akure.

Professor S.O. Akindele		20/1/2025
Supervisor's Name	**Signature**	**Date**
Professor J.C. Onyekwelu		20-01-2025
Co-supervisor	**Signature**	**Date**

DEDICATION

This work is dedicated to the Almighty God, who is the source of my inspiration, strength, and finance and who sustains my life during this study. It is also dedicated to my lovely wife, Loveth Japheth, and my beloved Children, Jotham Shimnom and Jubilee Gyeshimi.

ACKNOWLEDGEMENTS

I thank the Almighty God for His divine protection and strength throughout my years of study and for making me see the successful end of this PhD programme by His grace.

I most heartily express my appreciation to my able supervisors, Prof. S.O Akindele and Prof. J.C. Onyekwelu, whose contributions, corrections, and criticisms made this work worthwhile. My appreciation also goes to the Head of the FWT Department, Prof. A.G. Adedayo, and other academic staff in the Department: Prof. M.B. Oyun, Prof. D.O. Oke, Prof. V.A.J. Adekunle, Prof. (Mrs) O.V. Oyerinde, Dr. (Mrs.) O.O. Sobola, Dr. (Mrs) O.S. Oke, and Dr. A. Lawal, among others.

This acknowledgement would be incomplete without mentioning my beloved friends: Dr F.N. Ogana, Dr. I.A. Zagga, Dr H.I. Aigbe, Dr F.A. Egwumah, Dr. Ubaekwe, R. Mrs A. Usman, Mr I. Duruanyi, Mr Buba Ibrahim, Mr Agada Alhaji and Mr Edwin E. Onyekachi, among others. I extend my gratitude to many other friends, whose names I cannot mention here due to space. I appreciate my late parents (ACP B.Y.E. Dau and Mrs. Florence B. Dau). I appreciate my sisters, Mrs Dorcas Z. Jatau and Mrs Jemimah J. Galadima, for their moral and financial support. I'd like to say a big thank you to my darling wife, Mrs. Loveth Japheth, and my children (Jotham and Jubilees) for creating the enabling environment, love, peace, and perseverance for this work to succeed. I acknowledge with profound gratitude the moral and financial support I received from my wife. Thank you for being there for me.

TABLE OF CONTENTS

CHAPTER ONE

CHAPTER TWO

CHAPTER THREE

CHAPTER FOUR

CHAPTER FIVE

5.0 DISCUSSION ....

CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATIONS ....

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

Table **Page**

ABSTRACT

Carbon stocks can be conserved or increased by the sustainable management of existing forest types. However, anthropogenic activities and poor forest management can adversely affect biomass production and carbon storage. Published information on biomass and carbon storage potentials of different forest management types is scanty, especially in the study area. To this end, this study assessed the tree species diversity, soil properties, volume estimation, biomass and carbon storage of three forest management types (Community Forest Area (CFA), Forest Reserve (FR), and Sacred Grove (SG)) in Benue state, Nigeria. A nested plot design was adopted for data collection. Each nested plot comprises 35 m x 35 m, 25 m x 25 m, 7 m x 7 m, and 1 m x 1 m square plots. The 35 m x 35 m area was the main plot within which all trees with a Dbh of 40 cm and above were measured. The 25 m x 25 m subplot was laid within the main plot, and all trees with Dbh between 20 cm and 40 cm were measured. Within each subplot, a sub-subplot of 7 m x 7 m was laid for the enumeration of trees with a Dbh range of 5 m to 20 cm. A quadrat of 2 m x 2m was laid within the 7 x 7 m plots to assess low vegetation with a diameter <5 cm. A square frame of 1 m x 1m was laid to assess all litter. An experienced forest-type management taxonomist identified all live tree species. Tree growth variables (diameters at the base, breast height, middle, and top of the tree and tree total heights) were measured on all live trees, standing dead and lying dead trees in all plots. An indirect method of biomass estimation was used in this study. Tree core samples were collected at tree breast height (1.3m) using an increment borer. Data were analyzed using descriptive (mean, frequencies, and standard deviations) and inferential (analysis of variance, T-test and Pearson correlation) statistics. A cumulative total of 1,881 individual trees were enumerated in the study area, with 749, 621, and 511 individual trees found under FR, SG, and CFA, respectively. A total of 73 tree species in 35 families were assessed in the study area, out of which CFA had 38 species from 25 families, FR had 28 species from 16 families, and SG had 35 species from 24 families. Most of the tree species were indigenous, with few exotic species (*Gmelina arborea* and *Tectona grandis*). *Khaya senegalensis* and *Gmelina arborea* were present across the three forest management types, with varied frequency of occurrence. The Family Importance Value Index (FIV) in CFA and SG indicated higher family density in these forest management types than in FR. A few families (Caesalpinioideae, Euphorbiaceae, Moraceae, and Fabaceae) were important across the forest management types. Malvaceae, Verbenaceae and Fabaceae were the most important families in CFA, FR and SG, respectively. The Shannon-Wiener index of 3.00, 2.11 and 2.97 were recorded under CFA, SG and FR, respectively and differed significantly. The Margalef richness index was highest (6.01) under CFA and lowest (4.11) under the FR. The highest evenness value of 0.55 was recorded under SG, and the lowest value (0.29) was under FR, indicating a high disparity in tree species richness. G*melina arborea, Sterculia* *setigera, Anogeissus leiocarpa,* and *Daniellia oliverii* were the most dominant species across the study area. *Tectona grandis* and *Monotes kerstingii* were endangered tree species in CFA and SG, respectively. *Hura crepitans* was classified as near threatened under SG. Soils from SG had superior chemical properties, with significantly higher magnesium, nitrogen, phosphorus, and potassium than soils from CFA and FR, indicating richer nutrient availability in SG soils. The Ratkowsky model was the best-fitted model form for volume prediction based on its lowest statistical metrics and highest weight across all sites. There were significant differences in biomass and carbon contents across the forest management types, CFA emerged as the most efficient carbon sink, with an average biomass of 485.39 tons/ha and total carbon of 242.7 tons/ha. In contrast, SG produced the lowest average biomass (230.95 t/ha) and carbon (115.48 tons/ha) contents, while FR had a moderate mean biomass of 301.14 tons/ha and carbon contents of 150.57 tons/ha. Tree species composition, richness, tree size and density influenced biomass accumulation and carbon storage. Preserving forests with high carbon content and encouraging sustainable forest management practices like reforestation and selective logging in CFA is important for combating climate change and building resilience. To promote sustainable forest management, revive damaged forests, and focus on areas with significant carbon sequestration capabilities, it is important to have strong policies and involve the community.

CHAPTER ONE

1.0 INTRODUCTION

1.1 General

Biomass is the net primary productivity of the forest ecosystem in the form of dry matter. Primary productivity is the energy or mass storage rate in the organic matter of plants per unit surface area of the earth (Šímová and Storch, 2016). Carbon makes up around 18 percent of the composition of all living organisms, making it the predominant chemical element. It is the primary source of energy used by all organisms on Earth's land. Carbon can be found widely as carbon dioxide (CO_2) and methane, according to Riebeek (2011). The interaction between carbon and water in oceans, rivers, and streams leads to the creation of carbonic acid (Barker and Ridgwell, 2012). Carbon dioxide and other greenhouse gases in the atmosphere trap heat from the sun, leading to increased temperatures and the phenomenon known as global warming (Kweku *et al.,* 2018). When carbon interacts with the forest ecosystem's energy, it is utilized by the plant during photosynthesis to manufacture its food, and oxygen is released through plant respiration, which is utilized by all animals (higher and lower animals) (El Moll, 2022).

Estimating the amount of carbon sequestered in tropical forests requires an accurate assessment of tree aboveground biomass (TAGB) (Okuda *et al.,* 2004). Reducing Emissions from the Deforestation and Degradation (REDD) program requires the accurate computation of carbon contents stored in tropical forest types, which is vital for climate mitigation. In tropical areas, forest degradation and deforestation are considered factors of global warming (Gunlu *et al.,* 2014), where CO_2 is rapidly released into the atmosphere. This traps the heat generated when sunlight radiates the earth's surface during the day. As a result, the rate of carbon in the atmosphere, currently about 0.04%, is rapidly increasing due to the release of stored carbon into the atmosphere.

Live tree biomass, litter, woody debris and deadwood (standing and lying deadwood), lower vegetation, and soil carbon constitute the main carbon pool in tropical forest ecosystems (Vashum and Jayakumar, 2012). Tree above-ground biomass accounts for the largest proportion out of all carbon pools; forest degradation and deforestation greatly affect tree above-ground biomass (Gibbs *et al.,* 2007).

Carbon stocks can be conserved or increased by the sustainable management of existing forest types, afforestation (tree planting), re-afforestation, and rehabilitation of forests. However, deforestation, forest degradation, and poor forest management limit carbon storage (Elvis *et al.,* 2009). Afforestation (tree planting on previously unforested land) has been identified as a cost-effective and environmentally friendly approach for carbon sequestration (Onyekwelu, 2004; Niu and Duiker, 2006; Onyekwelu, 2007; Ostadhashemi *et al.,* 2014).

The direct (destructive) and indirect (non-destructive) methods of above-ground biomass estimations are used. The direct method requires the harvesting and weighing sample trees or small sample sections in a forest stand, which is harmful and costly (Chenge and Osho, 2018). This method is more accurate than the non-destructive method in determining biomass for a specific area; it is reliable if the samples are typical of the forest stand (Onyekwelu, 2004). The destructive method is strenuous, time and resource-consuming, and impracticable for large-scale biomass estimation due to its destructive nature and the amount of biomass that is usually processed (Verwijst and Telenius, 1999; Vashum and Jayakumar, 2012). This destructive method is not applicable in forests with endangered species (Montès *et al.,* 2000). However, it is helpful in situations of developing biomass models that could be applied in assessing biomass on a larger scale (Navár, 2009).

The indirect technique of biomass estimation is establishing a relationship(s) between biomass and some measurable tree variables (such as diameter at breast height, total height, crown diameter, and wood density) using regression analysis (Araujo *et al.,* 1999). However, this method estimates tree biomass without cutting the trees. The indirect method of biomass estimation is inexpensive and less time-consuming. Its application is preferable for tree species that are threatened or in a reserve area with strict harvesting of tree species (Montes *et al.,* 2000).

1.2 Research Problem Statement

Forest ecosystems sequester about eighty percent above ground, while twenty percent below ground terrestrial organic carbon, make forest ecosystems important to maintain the global carbon balance and mitigate climate change (IPCC, 2001). Most areas with protected reserves are fast changing due to land type systems (ecosystem degradation and deforestation). Deforestation is one of the world's most pressing development concerns and a severe long-term environmental issue in Nigeria.

The forest is frequently viewed as a free, good stock resource, which could be converted to other uses without much consideration of the implications of negative actions toward the forest ecosystems and its role in mitigating climate change; thus, many forest areas have been seriously deforested or degraded as widely observed. With the rising levels of carbon dioxide in the atmosphere because of deforestation, and anthropogenic, among others; there is a compelling need to quantify tree biomass and carbon contents in distinct forest types (Forest Reserves, Sacred Groves and Community Forest Areas) in Benue State, because of the significant contribution in reducing the effects of climate change by storing carbon contents of the area.

There is a dearth of knowledge on the best forest management type and good fit functions (models) to calculate tree biomass and carbon contents in the study area (Community Forest Areas (CFAs), Forest Reserves (FRs) and Sacred Groves (SGs)). There is no updated information on tree species diversity, distribution, and abundance. No studies have investigated the impact of various forest management practices (CFAs, FRs, and SGs) on soil physicochemical characteristics and carbon storage.

Different forest types store certain carbon quantities in their below-ground and above-ground components. Carbon contents in forests vary between geographical locations and stand ages (Onyekwelu *et al.*, 2006), land cover types and land use (Mauya *et al.,* 2019), species (Salas-Macias *et al.,* 2017, Yang *et al.,* 2019), vegetation types (Sapit *et al.,* 2011; Mitra *et al.,* 2011; Sahu *et al.,* 2016). There is hardly any available finding comparing the biomass and carbon contents across the three forest management types in the study area.

There is a need to accurately estimate the quantity of tree biomass and carbon contents emitted into the atmosphere if the forest management types in the study area are destroyed or the amount of carbon stored in the forest management types is appropriately conserved.

1.3 Research Objectives

The general objective of this study is to assess tree species composition and to estimate the total biomass and carbon contents of three forest management types (Community Forest Areas (CFAs), Forest Reserves (FRs) and Sacred Groves (SGs) in Benue State, Nigeria; with the view of understanding their contributions to climate change mitigation and the best management type to recommended. The specific objectives of this study are to:

i. assess the composition and diversity of trees in the three forest types in Benue State, Nigeria.
ii. evaluate soil physicochemical properties and soil carbon storages in the study area
iii. assess tree growth characteristics of the management types (CFAs, FRs and SGs) in Benue State, Nigeria.
iv. fit volume models for the Forest Management Types
v. estimate total biomass and carbon contents of the forest management types in the study area.

1.4 Research Justification

Many research works have been carried out on aboveground biomass and carbon contents, with an overwhelming focus on plantation forests (Drake *et al.,* 2002; Oladoye *et al.,* 2015; Onyekwelu 2004; Onyekwelu *et al.,* 2006; Teobaldelli *et al.,* 2009; Ebuy *et al.,* 2011; Gunlu *et al.,* 2014; Ige 2018; Oladoye *et al.,* 2018); using field data alone (Oladoye *et al.,* 2015; Ige, 2018; Oladoye *et al.,* 2018); and forest reserves (Onyekwelu *et al.,* 2008; Onyekwelu and Olusola 2014; Chenge and Osho 2018). Available data indicates the paucity of published information on the estimation of tree biomass and carbon contents of the forest management types in the study area.

Forest ecosystems typically pool carbon contents in large quantities, this varies between forest types (Wang *et al.,* 2024). Thus, this study provided baseline knowledge on the influence of management types on biomass production and carbon accumulation in Benue State. Biomass and carbon stock equations to predict or estimate forest yield are lacking for the study area. A model developed and validated using data from a specified region is unlikely to work well in a different region.

By quantifying biomass and carbon stocks, this study supports the development of Certified Emission Reduction projects (certificate), generating economic benefits for local communities and promoting climate-resilient forest management. Industrialized countries can trade, sell, or use these credits to satisfy their Kyoto Protocol emission reduction targets (UNFCCC, 2010; Chenge and Osho, 2018). Nigeria is one of the countries that signed the Kyoto Treaty, which requires mandatory reporting on carbon dioxide (CO_2) production and removals in the forestry unit of Federal and State Governments.

Uncertainty in biomass estimation arises from incomplete data, methodological inconsistencies, and ecological complexities, making it impossible to meet the Kyoto Protocol's need for accurate carbon accounting (IPCC, 2003), however, these were considered to ensure accurate estimation of biomass and carbon contents. Other importance of this study includes updated knowledge on plant structure, tree species diversity, the status of forest types, soil physic-chemical properties and soil carbon of the area.

1.5 Research Scope

This research was conducted in six forest locations (two from each of three forest management types (CFAs, FRs and SGs) in Benue State, Nigeria. Data was measured from 9 nested sampled plots under three management types, each containing three nested plots measuring 35 x 35m, 25 x 25m, 7 x 7m, and 1 x 1m using a non-destructive approach. Tree species diversity and distribution were assessed to examine the conservation importance of each forest type. The physicochemical properties of the soils were analyzed to determine the nutrient status of the soils across the forest types. Data were analyzed using descriptive and inferential statistics (ANOVA, Paired T-test, and Ordinal regression) using R. Studio version 1.3.959 (2009-2020).

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Concept of Biomass

2.1.1 Forest Biomass

According to Konstantinavičienė and Vitunskienė (2023), biomass refers to the biodegradable components of biological products, residues, and wastes from forestry, agriculture, and other industries. It encompasses the total mass of all living things, including above- and below-ground living biomass in a specific area or species, and is typically expressed as dry weight (IPCC, 2006a). Tree biomass is the total organic matter in a tree. If the mass is described as a unit of area, such as tons per hectare, it is termed biomass density (Brown 1997). Within forest ecosystems, it is referred to as forest biomass. Forest biomass can be estimated for an individual tree, by using a sample or the whole population of trees in each land area, ecosystem, region, country, etc.

As per Wang *et al.* (2019), the role of biomass is crucial in signifying both the energy-charging mechanisms within forests and the vegetation's capacity in ecosystems to capture carbon. The changes in forest biomass have been a focal point because they are linked to the carbon cycle, which then affects worldwide climate trends and environmental shifts (Santoro *et al*., 2018). Apart from serving as a key indicator of carbon sequestration, forest biomass also holds significance in gauging energy production within natural ecosystems. Estimating the total amount of forest biomass is crucial for a range of reasons, such as evaluating soil nutrients, forecasting fire risks, and promoting sustainable forest management.

Within forest ecosystems, forest biomass can be broadly categorized into two main groups: above-ground biomass (AGB) and below-ground biomass (BGB). The components of AGBs encompass tree stems, foliage, branches, bark, and litter. BGB is made up of tree roots and soil organisms, encompassing plants and animals. The AGB and BGB have a close relationship, gathering resources and interacting with nearby trees and vegetation

(Jianjun *et al*., 2019). The degree of interaction between the two compartments has typically been considered in isolation of one another (González-Megas and Menéndez, 2012).

Above-ground tree biomass is made of organic material produced and accumulated by above-soil tree components (tree branches, leaves, twigs, litter, among others) in the forest ecosystem (Wakawa, 2016). Typically, 70–90% of the biomass in trees and forests is above ground (Chen *et al.,* 2018). Thus, above-ground biomass stands out as a significant carbon sink within forest ecosystems, serving as a crucial indicator of the overall vegetal health of the forest across various seral stages (Deb *et al.,* 2017). Vegetal health is the state of a plant's total health and condition, encompassing its physical, physiological, and ecological characteristics. The seral stage is the growth processes that take place during ecological succession (i.e. change in structure and composition of an ecological community over time due to disturbance).

The Reduced Emission from Degradation and Deforestation (REDD+) processes, which aim to mitigate emissions resulting from deforestation and forest degradation and managing forests sustainably and conserve and improve forest carbon stocks, are supported spatially by explicit measurements of forests' AGB (Kaasalainen *et al.,* 2015). To substantially minimize the uncertainty in carbon storage estimation and guide strategic forest management plans, it is essential to quantify and monitor AGB promptly over various times and space (Saatchi, 2011; Deo *et al.,* 2017a).

Below-ground biomass accounts for between 10 to 30 percent of the total biomass. Estimation of BGB components is difficult, expensive, and destructive (Onyekwelu, 2004; Chenge and Osho, 2018). It is difficult to collect BGB due to the excavation of the soil and the capital involved. This relates to the challenges in characterizing the structural features of tree roots, especially in uneven forests with strict management and different management regimes. Accurate measurements of root components such as lengths, widths, and weights, are laborious and time-consuming.

2.1.2 Methods of Forest Biomass Estimations

Estimating AGB is an essential stage in assessing carbon stocks and fluxes in carbon sequestration research, particularly in tropical forests (Gibbs *et al.,* 2007). The estimation of tree AGB can be carried out through either direct or indirect methods:

i. Direct Methods of Biomass Estimation

The direct method of biomass estimation is also referred to as the destructive method. It involves using destructive procedures such as felling a whole tree, cutting part of the tree as samples, weighing fresh parts sampled and oven-drying and weighing of the dry samples of the trees in the laboratory biomass estimation. The most precise approach for determining biomass and carbon stocks in forest ecosystems is through destructive methods when executed accurately (Gibbs *et al*., 2007; Chenge and Osho, 2018). This method entails harvesting whole trees or tree samples in a known area and weighing the various components of the harvested tree (i.e., fresh weight), such as trunk, leaves, branches, twigs and afterwards obtaining their over-dry weights (Ravindranath and Ostwald, 2008). Thus, this approach of biomass evaluation is best used in a little region or small sample sizes of trees, i.e., the approach is not practical over a large-scale plantation or natural forest areas (Liu and Westman, 2009).

Capital, labour, logistics, and protected sites all limit the feasibility of using the direct method of biomass estimation. Samples are mostly underrepresented in locations with complex terrain, changing climatic conditions, cultural values, or political restrictions (Picard *et al*., 2012). According to Montès*et al*. (2000), this approach can be unsuitable in degraded forests harbouring vulnerable species. The method is typically used to calibrate biomass equation(s) that may measure biomass on a wider scale (Segura and Kanninen, 2005; Navár, 2009). Destructive sampling is required to fit equations (allometric models) for biomass that can be used for indirect biomass estimation. Usually, a sample of trees for destructive sampling is chosen based on the population distribution, such as age class and diameter class.

Onyekwelu (2004) and Olayode *et al*. (2015) described a comprehensive procedure for the direct biomass estimation method. Olayode *et al.* (2015) employed the direct method to assess biomass and carbon stocks of *Tectona grandis* (teak) plantations in selected forests in southwestern Nigeria. Based on their report, the harvested tree was divided into different components (bole, branches, and leaves). The bole was sectioned into billets while the branches and leaves were cut off from the main stem. To determine the bole fresh weight, every billet was weighed on the field, and the leaves and branches were separately weighed to obtain their respective fresh weights. Wood discs approximately 3 cm thick were obtained from the bole, and the initial weights were measured during the process. samples of the fresh leaves (1 kg) and fresh branches (1 kg) were collected and weighed. The wood discs, branches, and leaf samples were subsequently transported to the laboratory and dried in an oven for twenty-eight days.

The discs' initial weights were measured in the laboratory and were subjected to further drying at 105°C in the oven until their weight reached a constant value. The branches and leaves samples underwent oven-drying at 80°C until reaching a steady weight. The ratios of dry weight to fresh weight for the branch sample, leaf sample, and discs were subsequently calculated. Bole biomass was determined by multiplying the dry weight-fresh weight ratio of the disc by the total fresh weight of the corresponding tree bole. Similarly, the dry weight-fresh weight ratios of the branches and leaves were multiplied by the corresponding ratio of total fresh weight to determine their biomass. The total AGB of the fallen tree was estimated by adding the biomasses of the bole, branches, and leaves. The direct method of biomass determination used by Olayode *et al*. (2015) was like the method used by Onyekwelu (2004) for AGB production for *Gmelina arborea* plantations in Southwestern Nigeria.

Sabina *et al.* (2011) used the direct method to estimate AGB and BGB in a Brazilian Cerrado natural forest. The authors then used the biomass from the direct method to calibrate allometric equations for the Brazilian Cerrado natural forest. Similarly, Manyanda *et al*. (2019) and De Oliveira et *al.* (2019) used the direct method to calculate the AGB and carbon stocks in an open Brazilian Savannah. Given the destructive nature of the direct method, there has been limited research conducted in Nigeria utilizing the direct method for biomass estimation.

ii. Indirect Method of Forest Biomass Estimation

The indirect approach to estimating biomass from trees is non-destructive since no trees are felled down to collect data. This method is appropriate for locations with rare or endangered tree species or areas where tree removal is extremely challenging or not feasible. Unlike the direct method, this approach requires less time and work. The allometric/allometry approach and the remote sensing system approach are the two primary categories under the indirect methods for biomass estimation of forest ecosystems.

- ***Allometric equation approach***

Instead of felling a forest or part of it, Equations are employed in the allometric method to estimate tree biomass. The allometric equation approach to biomass estimation utilizes commonly measured tree variables (Ravindranath and Ostwald, 2008; FAO, 2020). This method relies on allometric equations calibrated for biomass estimation, with the dependent variables being the biomass, and the independent variables being tree characteristics. The biomass content of a specific forest ecosystem is estimated using the estimated parameters of the equation. The biological plausibility of the allometric equations is tested using an independent dataset by comparing the observed and predicted biomass using a student t-test procedure and residual analysis.

The age of the forest, the site's characteristics, and the species all affect how reliable allometric equations are at predicting biomass (Vorster *et al.,* 2020). Site-specific allometric equations have proven to be more accurate in predicting forest biomass than generic allometric equations or remote sensing methods since they account for site factors (Kim *et al.,* 2011). Though equations that consider a wide range of environmental factors may be appropriate, such equations should be tested, because they account for the effects of the site.

The incorporation of Dbh, height, derivatives of Dbh, and height, along with wood density as independent variables, is generally effective in achieving accurate biomass estimations (Onyekwelu*,* 2004; Pearson *et al*., 2007; Kuyah *et al.,* 2012). Many researchers have developed allometric equations for biomass estimation in diverse forest ecosystems, both within and beyond the borders of Nigeria (Onyekwelu, 2004; 2007; Wang, 2006; Ounban*et al.,* 2016; Salas-Macias *et al.,* 2017).

The Guinea savanna ecosystem in Nigeria currently lacks species-specific or site-specific allometric biomass equations. There are no established site-specific allometric equations for estimating biomass in the Guinea savanna ecosystem of Nigeria, with a gap in Benue State. An allometric equation is vital as destructive biomass estimation may not be feasible due to the limited resources available in the savanna forests. Oladoye *et al.* (2018) utilized ordinary least square regression to formulate an allometric equation for estimating the AGB and carbon stock of the *Nauclea diderrichii* (De Wild. and T. Durand) Merrill even-forest in the Omo Forest Reserve, Nigeria, were estimated by Oladoye *et al*. (2018) using ordinary least square regression. In a similar study within the Omo Forest Reserve, Nigeria, Ige (2018) assessed the above-ground biomass and carbon stock of Gmelina arborea (Roxb.) stands. The author used Dbh, tree height or wood density to develop allometric equations. However, their models were species-specific and focused on plantation of monoculture. Oke *et al. (*2020) calculated AGB, BGB and carbon stock of Okomu National Park in the tropical rainforest ecosystem of Nigeria. The authors only focused on live trees, tree ring core and litter without accounting for dead woods, twigs, and stumps. Chenge and Osho (2018) estimated biomass and carbon stock for the Omo Forest reserve located in Nigeria, they incorporated field and remotely sensed data. Aghimien (2019) presented the findings of a study on the AGC stock estimation in secondary forests in Ibadan, Nigeria, using Pleiades satellite imagery. In Sokoto state, Nigeria, Ibrahim *et al*. (2018) evaluated the carbon stock in the Majiya fuelwood reserve.

Several researchers have examined carbon stocks and biomass in various parts of the world. Kendie *et al*. (2019), studied the biomass and soil carbon stock potential of eucalyptus plantations, exclosures, and natural forests. To estimate individual tree above-ground biomass as a function of breast height diameter, total height, and wood density in tropical forests, Brown *et al*. (1989) developed allometric regression models. However, there is scanty research conducted to evaluate the total biomass and carbon stock of forests in Benue State, Nigeria, across different management approaches. This necessitated a study to calculate and contrast the overall biomass and carbon stocks of the state of Benue's forests under various management types.

- ***Remote sensing system approach***

The constraints and limitations of field measurements are thought to be addressed by remote sensing technologies. Remote sensing (RS) is the science and art of measuring or gathering data on characteristics or attributes of an object or phenomenon recorded using recording equipment not near the subject of the study (Yanow, 2018). Remote sensing technology enables the capture of location variation in desired characteristics by offering a comprehensive image of the surface area under investigation. Remote sensing technology has the advantage of collecting data on places of interest that are difficult or impossible to reach (Vashum and Jayakumar, 2012).

Monitoring natural resources on a large scale, and even globally, is enabled by remote sensing (RS). As per Roy *et al*. (2014), it is the only way to combine practicality and affordability when collecting data across a wide region. The mapping and studying of vegetation and land changes are done using remote sensing data. Another use of it is measuring carbon stocks in forests (Goetz *et al*., 2009). To map and track the AGB of forests, many researchers combined data from RS with data collected on the ground (Baccini *et al.,* 2004*;* Anaya *et al.,* 2009; Avitabile *et al.,* 2012; Lu *et al*., 2012; Mitchard *et al.,* 2014; Badreldin and Sanchez-Azofeifa, 2015). Information obtained through remote sensing (RS) has gained heightened importance as a valuable resource for approximating forest biomass.

Now, the only way to extensively map the spatial distribution of AGB is by merging estimates acquired through fieldwork with data extracted from RS (Chenge and Osho, 2018). It is anticipated that, in the foreseeable future, there will be an increase in access to satellite-based estimates of carbon stocks (Bordoloi *et al*., 2022). However, it's crucial to note that remote sensing data alone doesn't directly determine the quantity of biomass in a forest. Instead, characteristics related to biomass and various tree characteristics, including tree height, crown size, density, type, volume, and leaf area index, are scrutinized (Georgia *et al*., 2017).

Field measurements are frequently utilized in the formulation of allometric equations and to verify the precision of remotely sensed data. In instances where field measurement data are scarce or lacking, remote sensing data can be employed to estimate forest biomass over larger geographical areas once its accuracy has been validated (Fabio *et al*., 2017). For mapping and monitoring of aboveground biomass, the remote sensing approach consists of distinct sensors, which include Radio Detection and Ranging (RADAR), Light Detection and Ranging (LiDAR), and optical sensors. Each type of sensor comes with its own set of advantages and disadvantages. Optical sensors are often considered the most reliable and popular (Chenge and Osho, 2018). However, in areas characterized by high biomass densities or complex forest stand structures, optical sensors may encounter a challenge known as data saturation (Lu *et al.*, 2014).

2.2 Concept of Forest Carbon

2.2.1 Carbon, Carbon Dioxide, Greenhouse Effect and Carbon Cycle

Carbon is a non-metal with the molecular sixth (6) position that can be found in both pure (graphite and diamond) and almost impure (coal and charcoal) forms; however, it can also mix with other elements to create molecules. Carbon is a common element, accounting for an estimated average of 14% of all dried solid mass in all life forms. This is present in the atmosphere as carbon dioxide (CO_2) at a rate of 0.04%. CO_2 is a neutral, unscented gas that is found in nature. It has a sublimation highest temperature of 70 °C and a vapour density of 1.53. It is water soluble to a degree and is a greenhouse gas responsible for regulating the Earth's temperature (Goel and Agarwal, 2014).

According to Sabine and Feely (2003), CO_2 is a minor constituent of the Earth's atmosphere, with its present atmospheric concentration level of about three hundred and seventy ppm in quantity. It is emitted as a by-product of aerobic respiration (Sabine and Feely, 2003). The process by which plants take in CO_2 and expel oxygen is known as photosynthesis (O_2). A greenhouse gas called carbon dioxide warms the earth by absorbing long-wavelength radiation from the atmosphere and trapping heat there (Melissa, 2019). CO_2 and other greenhouse gases, including water vapour, methane, nitrous oxide, and chlorofluorocarbons, help keep the earth warmer than it would be without their presence in the atmosphere by trapping radiation (Sabine and Feely, 2003).

Over the past 20,000 years, the global mean surface temperature has experienced a rise of 0.8 °C, coinciding with a notable increase in carbon dioxide concentration in the atmosphere. In the last 150 years alone, carbon dioxide levels have surged up to thirty percent, escalating from 280 to 370 parts per million (ppm), an unprecedented level in recorded observations (Sabine and Feely, 2003).

The Earth naturally warms because of the greenhouse effect, driven by gases in the atmosphere. Key greenhouse gases contributing to the Earth's changing climate include CO_2, CH_4, N_2O, and fluorinated gases such as hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, and nitrogen trifluoride. These gases trap solar heat that would otherwise escape to space (Melissa, 2019). CO_2 is the most prevalent greenhouse gas, making up approximately 76% of all greenhouse gas emissions (ECCC, (2019). Methane, the second most crucial greenhouse gas (GHG), nitrous oxides and fluorinated gases are emitted from industrial activities. Ninety percent (90%) of carbon dioxide (CO_2) is produced through the combustion of fossil fuels such as coal, crude oil, and natural gas. This represents a substantial source of greenhouse gas emissions, with CO_2 being a major contributor to climate change (William and Craig, 2020).

Understanding the origins of heat energy, its utilization, carbon dioxide release rate, and carbon circulation knowledge is essential for the success of any measure to mitigate climate change. The carbon cycling process is a biogeochemical cycle involving the movement of carbon among the earth's biosphere, atmosphere, geosphere, pedosphere, and hydrosphere (Riebeek, 2011). The carbon cycle entails the transfer of carbon through interconnected components such as the oceans, atmosphere, terrestrial ecosystems, and Earth's crust, forming an integrated system (IPCC, 2012). The carbon cycle moves in gigatons of carbon annually, and the atmosphere, land, and sea can all store carbon in gaseous, liquid, or solid form (Melieres and Marechal, 2015).

Carbon is transferred from one or multiple carbon storage areas to another in an ongoing cycle known as carbon flux. Carbon pools are the main reservoirs for the exchange of carbon. These pools include the atmosphere, terrestrial biosphere, forests, oceans, soils, and sediments (Plate 2.1). The primary factor behind the observed rising trend in global temperatures is the flux of carbon into the atmosphere, with water (O_2) serving as the primary contributor (Katie and Anne, 2020). Carbon is retained in flora species within the biosphere. During photosynthesis, plants use CO_2 from the atmosphere as the building elements of food (Plate 2.2). Carbon is also present in the soil due to the breakdown of deceased animals and animal waste products (Plate 2.2) (Bot and Benites, 2005; Osman, 2022). Plants store about 560 petagrams of carbon (PgC), with trees storing the largest amount (UNH-report, 2008).

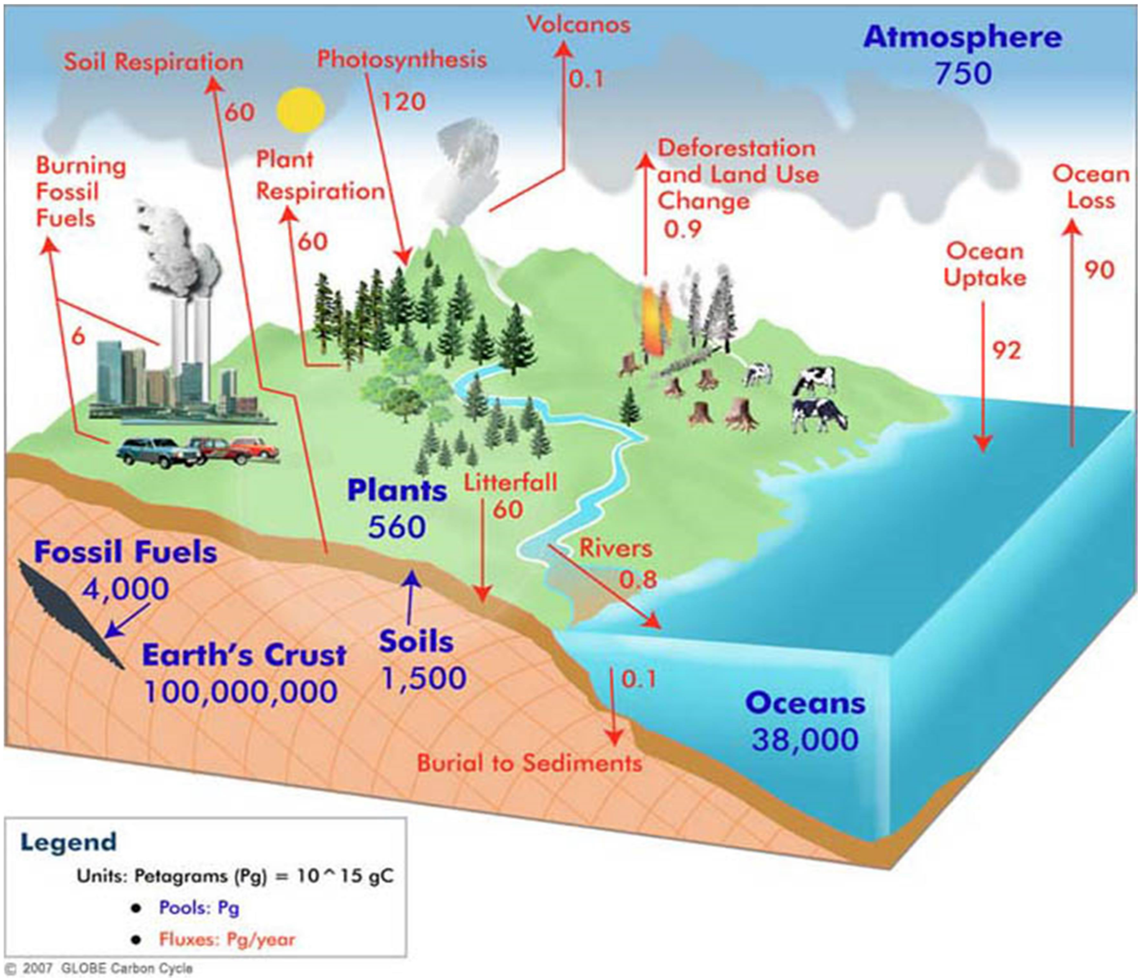


Plate 2.1: Carbon Cycle Process and the Earth Carbon Pools

Source: UNH (2008).

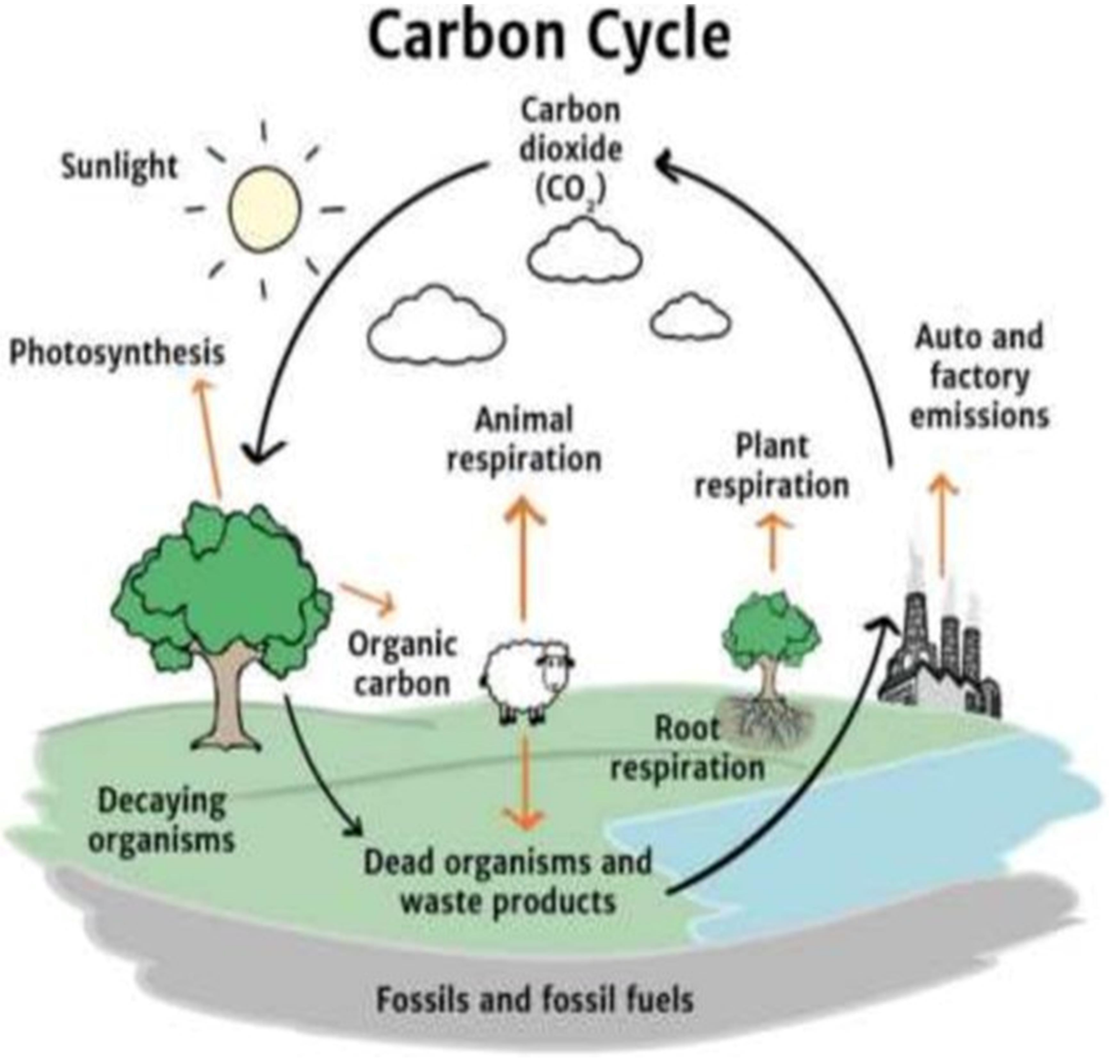
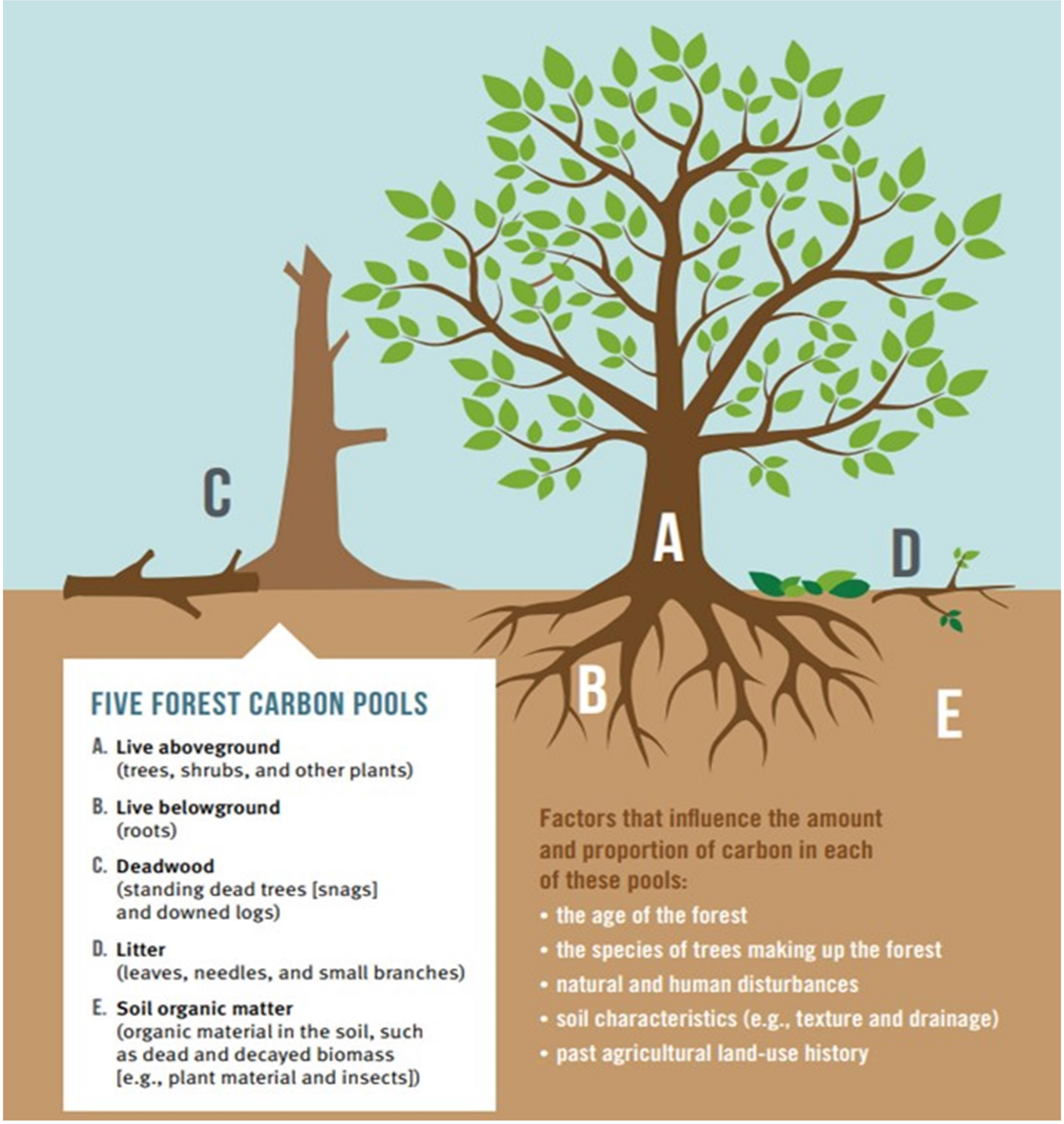


Plate 2.2: Complete Carbon Cycle (Source: UNH, 20180)

2.2.2 Forest Carbon Pools

Forests have vital importance in the global carbon cycle. Carbon transport between the atmosphere and the terrestrial biosphere is the most important aspect of the forest carbon cycle (Gibbs *et al.,* 2007; Thompson, 2023). The CO_2 in the atmosphere is converted into terrestrial organic carbon using the photosynthetic process, which is subsequently stored as biomass by trees and other plants (e.g., vegetation). Carbon pools are carbon reservoirs that can absorb and release carbon (FAO, 2020). Forest carbon is reported in seven distinct pools (Skog *et al.,* 2004) (Plate 2.3), five of which are part of the forest ecosystem (EPA, 2020). The five components are live AGB, BGB, soil carbon, dead wood, and forest litter (Plate 2.3). The largest pool is the carbon kept in the AGB of trees (Gibbs *et al.,* 2007). The other two pools include mineral soils derived from rocks and organic soils originating from decomposed organic matter. The area of the earth covered in organic material generates a reservoir of fresh organic matter, predominantly plants, which consist of aboveground and belowground organic matter. Plants, animals, soils, and microorganisms are all examples of organic matter (UNH report, 2008).



FIVE FOREST CARBON POOLS

A. **Live aboveground**
(trees, shrubs, and other plants)

B. **Live belowground**
(roots)

C. **Deadwood**
(standing dead trees [snags]
and downed logs)

D. **Litter**
(leaves, needles, and small branches)

E. **Soil organic matter**
(organic material in the soil, such
as dead and decayed biomass
[e.g., plant material and insects])

Factors that influence the amount and proportion of carbon in each of these pools:

- the age of the forest
- the species of trees making up the forest
- natural and human disturbances
- soil characteristics (e.g., texture and drainage)
- past agricultural land-use history

Plate 2.3: The Carbon Pool of Forest Ecosystem (Source: Catanzaro and D’Amato, 2019)**.**

i. Above-ground biomass: Above-ground biomass (AGB) refers to the standing dry mass of woody plants, including trees and shrubs (Wilkes *et al.,* 2018). Changes in forest ecosystems and variations in forest biomass have a significant impact on the exchange of carbon between terrestrial forest ecosystems and the atmosphere. Deforestation and forest degradation directly affect the AGB of trees, influencing the carbon pool in terrestrial ecosystems (Houghton, 2005). Ravindranath and Ostwald (2008) reported AGB as a crucial carbon reservoir in terrestrial forests, emphasizing its susceptibility to alterations in land use systems such as deforestation and forest degradation (Plate 2.4).

ii. Below-Ground Biomass (BGB): The living pools of carbon (C) in forests, particularly the above-ground biomass (AGB) and below-ground biomass (BGB), play a substantial role in contributing carbon to the terrestrial ecosystem (Eggleston *et al.,* 2006). The BGB, comprising all live roots, significantly contributes to the carbon cycle by participating in the movement and retention of carbon in the soil (Vashum and Jayakumar, 2012). Temperature, rainfall, terrain, forest structure, and forest composition are impacted by land use, human activities, and species numbers, leading to changes in above-ground and below-ground carbon storage in forests (Arasa-Gisbert *et al.,* 2018; Wei *et al.,* 2013; Hu *et al*., 2015). Calculating the total amount of plant material below ground, including roots, rhizomes, and related mycorrhizal fungi, is known as estimating BGB. BGB is crucial for assessing how well the ecosystem functions, how much carbon is stored, and how nutrients are cycled. Indirect procedures, non-destructive measurements, destructive sampling, and other methods and techniques are used to estimate BGB.

iii. Deadwood biomass: Deadwood constitutes a significant portion of carbon storage and movement, contributing to around 8% (equivalent to 73 petagrams) of the overall carbon reservoir in global forests. This encompasses fallen and upright dead tree trunks, branches, and additional woody materials (Pan *et al*., 2011). The stocks and fluxes of dead wood carbon are highly biogeographic variables. For instance, Pan *et al*. (2011) reported that total dead wood carbon stocks across different vegetational zones in the world accounted for between 2.8 and 11.7% of the sum forest C storage (Plate 2.4). This variability is caused by variations in decomposition rates that are correlated with climate and the wood characteristics of different species (Luyssaert*et al.,* 2017; Adam *et al.,* 2021). Also, harvesting activities, impacts from windstorms, occurrences of wildfires, outbreaks of pests or pathogens, and other small-scale disturbances alter the dynamics of dead wood (McGee, 2000).

iv. Forest litter: Forest litter is also known as litter biomass; it is regarded as a minor pool because it only contributes a small amount of C within the terrestrial pool (Ravindranath and Ostwald 2008). Although litter only makes up about 6% (Plate 2.4) of the entire carbon stored in the forest. It is a vital component of carbon and a key player when transporting substances within the ecosystem (EPA, 2020). Additionally, it connects the soil carbon, and the vegetation carbon pools (Pan *et al.,* 2011). The amount of carbon stored in a litter can be estimated using data on its known carbon content (Domke *et al.,* 2016), by multiplying litter volume and its carbon content. One can estimate the amount of carbon stored in litter by determining the rate of breakdown and the cycle of organic carbon in the litter layer (Wanlong and Xuehua, 2020).

v. Soil carbon: Soil organic matter is the largest contributor to forest carbon stocks following above-ground biomass (Kumar *et al.,* 2006). The soil represents a significant source of carbon emissions post-deforestation (Page *et al.,* 2002). Within a forest ecosystem, soil organic matter encompasses soil organic carbon (SOC), playing a crucial role in nutrient and carbon cycling between the lithosphere and atmosphere (Lal, 2005). Globally, soil contains approximately 1500 PgC of carbon (Zomer *et al.,* 2017), with organic carbon being the predominant form found in soil.

The quantity of organic carbon tends to decrease with increasing soil depth; routine soil measurements typically extend to a depth of 1 meter (UNH-report, 2008). In most cases, this catches most of the carbon in soil; however, this does not apply in areas with very deep soil. Most of the carbon in soil comes from decomposing plant matter, which microbes break down. The degradation process releases carbon into the atmosphere since the bacteria's metabolism eventually breaks down the organic materials to CO_2 (FAO, 2005).

Over time, the dimensions of these pools and the rate at which carbon passes through them undergo significant fluctuations (Green and Byrne, 2004). The quantity of carbon stored in a forest varies based on the carbon released into the atmosphere through processes such as tree growth, mortality, and decomposition, as asserted by Katie and Anne (2020) (Plate 2.4). According to Hoover and Riddle (2023), a forest is considered a net carbon sink when it sequesters more carbon than it releases into the surrounding environment. When the total amount of C released by the forest during a given period exceeds the amount of C trapped in the forest, the forest is considered a net carbon source of emissions.

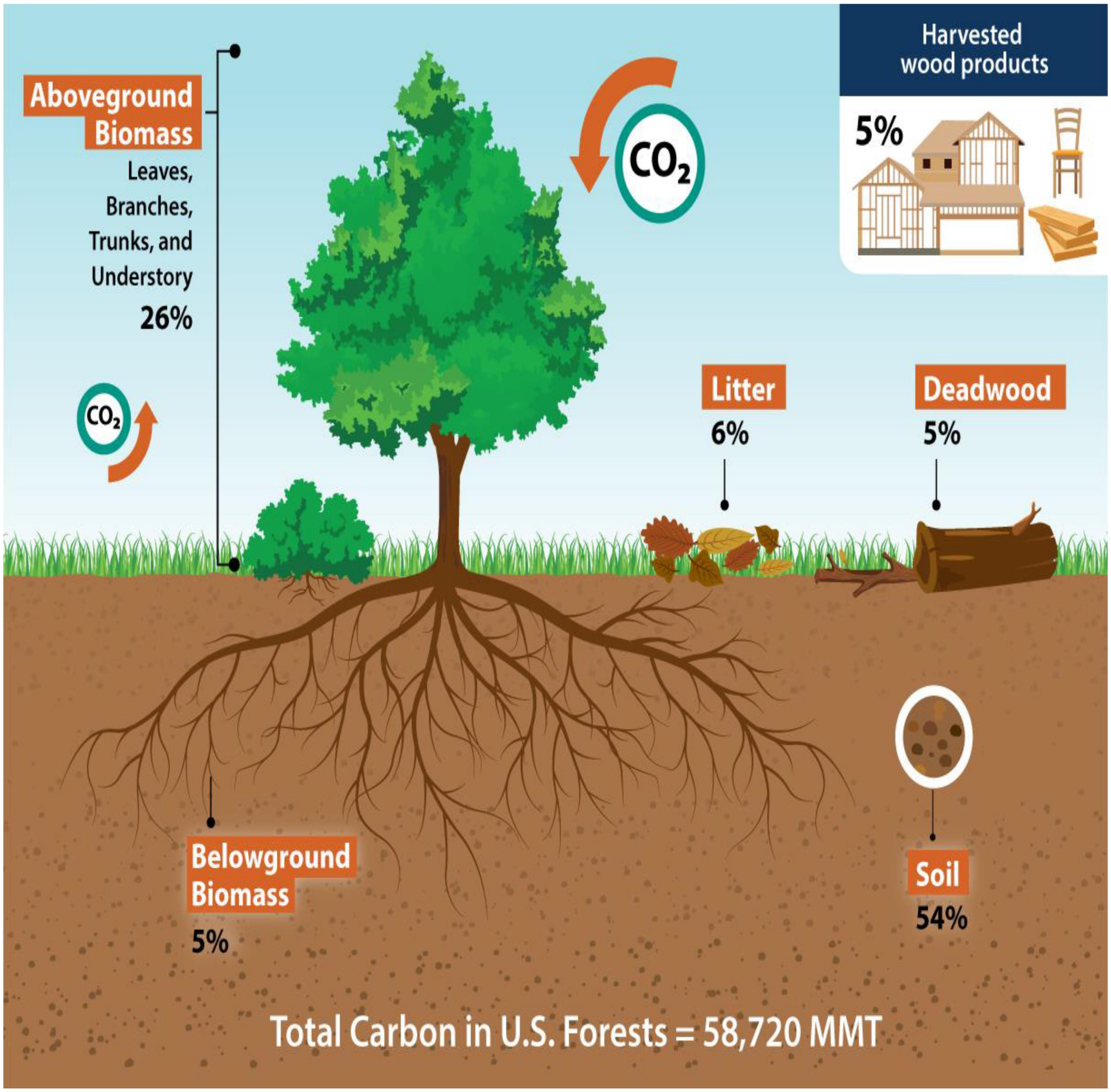


Plate 2.4: Rate of Carbon Flows within Forest Ecosystem (Source: EPA Inventory Report, 2020).

2.3 Biomass and Carbon Sequestration in Forest Management Types

In carbon sequestration, different processes remove CO_2 from the atmosphere and store it in various reservoirs (forests, soils, seas, and geological formations). CO_2 is extracted from the atmosphere via photosynthesis and stored in tree components and other vegetation in forest ecosystems. Forests accumulate a substantial amount of C in AGB and BGB (Pan *et al*., 2013). Carbon accumulates in soils, deadwood, litter (such as fallen leaves and stems), AGB (such as leaves, trunks, and limbs), and BGB (such as roots) in forest ecosystems (EPA, 2018).

Forest ecosystems accumulate organic compounds with an extended carbon residence time, storing more C than other terrestrial ecosystems (Watson *et al.,* 2000; Lorenz and Lal, 2010). Forests are essential to the global carbon cycle because of their ability to remove carbon dioxide from the atmosphere by photosynthesis and store it in various components like wood, leaves, and soil. Encompassing nearly one-third of the Earth's land area, forests contribute significantly to the global carbon pool, holding around 80% of all terrestrial above-ground carbon and 40% of all terrestrial below-ground carbon (Ameray *et al.,* 2021). The global forest ecosystems store over 650 gigatons (Gt) of carbon, with 289 Gt (44%) in AGB and BGB, 72 Gt (11%) in decaying wood and debris, and 292 Gt (45%) accumulated in the soil (FAO, 2020). While planted forest ecosystems currently make a relatively small contribution to the overall terrestrial carbon balance, it is anticipated that in the future, their capacity to absorb and store carbon will have a greater impact on reducing climate change (Canadell *et al.,* 2007).

Since forests store high amounts of carbon (Hurteau, 2020; Agbelade and Onyekwelu, 2020), their management could be crucial in lowering or increasing atmospheric CO_2 levels. For example, while anthropogenic factors inject enormous quantities of CO_2 into the atmosphere leading to world warming, sustainable forest management, forest conservation, afforestation and reforestation either maintain or increase the amount of carbon stored in forests (IPCC, 2001), leading to mitigation of global warming.

2.3.1 Forest Reserves

A forest reserve, as reported by the IUCN, is a safeguarded area that undergoes conservation and effective management for indications of conservation to offer unique opportunities for study or research and is significant for flora, fauna, or features of geological or other special interest (Dacumos, 2006; Burhenne-Guilmin, 2011). A forest reserve is a section of woodland designated and preserved by the government to preserve biodiversity from anthropogenic activities such as poaching, and tree felling is prohibited for commercial purposes in forest reserve centers (Ajibola, 2021). It can also be described as an area of land where commercial wood harvesting is controlled or regulated to protect tree species of cultural, economic, and/or ecological importance. Six National Wildlife Parks and 160 designated forest reserves are in Nigeria (Adekunle *et al.,* 2013) and are administered by governments.

Aside from the established forest reserves, all other woodlands are considered free areas (Adekunle *et al.,* 2013). The significant loss of animal and plant species in West and Central African forests has raised the need to conserve and sustainably manage vulnerable African ecosystems (Adekunle, 2006). Improving the soil's and trees' capacity to absorb carbon on land, protecting biodiversity, sustaining other ecosystem services, and preserving forest reserves help in absorbing and sequestrating CO_2 that has been emitted into the atmosphere through anthropogenic activities (Griscom *et al.,* 2017).

Numerous studies have been conducted on biomass and carbon sequestration in forest reserves. Eneji *et al.* (2014), reported that Nagi-Naka and Agan forest reserves in Benue State sequestered an estimated total area of 26,881.8 kg and 26,146.4 kg of CO_2, respectively. Mensah *et al*. (2020) reported that the above-ground carbon stocks in Gallery forests, woodlands, and savannahs in West Africa were 42.12 Mg C ha^{-1}, 30.8 Mg C ha^{-1}, and 23.5 Mg C ha^{-1}, respectively. Kendie *et al*. (2019) evaluated the biomass and soil carbon stocks in distinct forests (natural forests) in Northwestern Ethiopia; there were distinct patterns in the carbon stocks of the carbon pools between the different forest types. While the litter carbon stock decreased as the area was enclosed, in natural forests, the stores of organic carbon in the soil, above ground, and below ground have all risen. Natural forests can help slow climate change because they typically store large amounts of carbon (Kendie *et al.,* 2019). A study by Olufunke *et al.* (2015) assessed the carbon storage capacity of natural forests in South-west Nigeria. The results showed that Osho Forest had the highest carbon stock, holding 29.36 tons, closely followed by Shasha Forest Reserve with 24.36 tons. In contrast, Gambari Forest Reserve had significantly lower carbon storage, with a value of 14.84 tons.

Many works on biomass and carbon storage have been conducted in natural forests located within and outside Nigeria (Mitra *et al.,* 2011; Eneji*et al*., 2014; Olufunke *et al.,* 2015; Ige, 2018; Ibrahim *et al.,* 2018; Kendie *et al.,* 2019; Aghimien, 2019; Mensah *et al*., 2020). However, fewer, or no published work on biomass and carbon stock is available for the existing forest reserves in Benue State, Nigeria. There is limited research conducted to evaluate below-ground biomass in Nigeria's forest reserves. Thus, this research determined total biomass and C stock to ascertain the contribution of natural ecosystems to climate change adoption and mitigation in the study area.

2.3.2 Sacred Groves

Sacred groves are areas of unaltered forests with abundant biodiversity guarded by native communities based on taboos and societal and religious beliefs (Onyekwelu, 2021). A sacred grove (SG) is a community of trees with religious, social, and cultural significance in society (Manyam and Japheth, 2022). Sacred groves can be found in diverse societies and cultures, taking on various forms like remnants of ancient forests and locations designated for deity worship, celebrations of religion and culture, cemeteries for kings and chiefs, and ancestral worship centers, among others (Adeyanju, 2020). Sacred groves serve as a sanctuary for endangered native flora and fauna species and a significant genetic resource (Khan *et al.,* 2008; Rawat *et al.,* 2011; Onyekwelu, 2021). Sacred groves offer important ecosystem services and sequester C in soil. Quite often, sacred groves are less disturbed than other forest ecosystems and can serve as a model for effective forest management for mitigating climate change and sequestering carbon (Aioub and Naghi, 2021).

According to Dar *et al.* (2019), the C stock varied from 17.5 to 204.9 mg C ha^{-1}. In 41 sacred groves in Central India, the total amount of soil organic carbon ranged from 22.4 to 112.5 megagrams of carbon per hectare, while biomass production varied from 34.9 to 409.8 (Mg C ha^{-1}). According to Devi *et al.* (2021), two urban sacred forests in Sikkim Himalaya have carbon stocks ranging from 76.58 to 156.04 (Mg C ha^{-1}). 15,084.34 tons of carbon and 55.34 tons of carbon dioxide were found to have been sequestered by the sacred groves in the Kathmandu Valley (Shrestha *et al.,* 2016). In the Gedeo Community in Southern Ethiopia, Sacred groves were noted to accumulate between 255 and 637 megagrams of carbon per hectare (Mg C ha^{-1}) of biomass and a carbon stock range of 127.5 and 318.5 megagrams of carbon per hectare (Mg C ha^{-1}) (Maru *et al*., 2022). Sacred groves in southwestern Nigeria produced biomass of 87.8 t ha^{-1} to 231.85 t ha^{-1} and carbon stock of 43.9 t ha^{-1} to 115.9 t ha^{-1} (Onyekwelu *et al.*, 2024).

2.3.3 Community Forest Area Management

Community Forest areas are forest ecosystems existing on communal lands or state lands and managed by local or community people and leaders (Wiersum, 2004). A community forest consists of institutional structures that allow communities to be fully or partially involved in decision-making regarding forest management, and resources, and provide labour and knowledge to ensure both social well-being and the health of the forests (Danks and Fortmann, 2004). Practicing community forestry as a form of forest management system is undertaken by rural people to support their livelihoods (Wiersum, 2004). It involves determining the utilization and preservation of forest resources within a local community, organizing activities based on shared values, and aligning with the community's interests. Community Forest Management (CFM) refers to a set of institutional arrangements whereby communities provide manpower and information to sustain healthy forests and enhance social well-being, and where they either fully or partially participate in decision-making, and reap the benefits (Danks and Fortmann, 2004).

Community forest management encourages rural people to participate in forest management activities because of their livelihood on forest resources. The participation of community inhabitants in forest management activities helps to protect forests from degradation and deforestation; this improves the local community's social and economic well-being by fostering participation, ownership, and decision-making. The effectiveness of CFM is determined by the interaction between communities and resources on the one hand, and government policies and access regulations to forest resources on the other (Client Earth report, 2014).

Forests cover thirty-one percent of the entire expanse of the Earth's surface, local communities and Indigenous people own or manage about 22% of the world's forests (Bhattarai *et al.,* 2012). The main objective of CFM initiatives, which have been put into effect in several developing countries, is to preserve forests and assist community inhabitants in sustaining their livelihood, especially regarding their daily requirements for fuelwood, fodder, timber, income, and specific non-wood forest resources (Bhattarai *et al.,* 2012). Community Forest Areas offer environmental services that are crucial for both ecosystem health and human well-being, through carbon sequestration, soil conservation, air purification, and water management, among others.

The carbon storage of community forests has been the subject of very few studies. Bhattarai *et al.* (2012) investigated the efficiency of CFM in sequestration of carbon across three distinct physiographic zones of central Nepal that CFM led to consistent growth in carbon stock levels, between 1 to 3 metric tons per hectare annually (t/ha/yr), depending on local circumstances. In three Nepalese community forests, Karky (2008) carried out an inventory of carbon in the forest and produced an annual carbon increment of between 1.13 and 3.1 ha^{-1} yr^{-1}. For the mid-hills of Nepal, Rana (2008) recorded an average carbon increment of 1.4 metric tons per hectare per year (t ha-1 yr-1). Annual carbon increment was 3.7 metric tons per hectare per year (t ha-1 yr-1) for community forests in Uttarakhand, India (Banskota *et al.,* 2008). About 163.9 t ha^{-1} of carbon stock was estimated for ten forest communities in the upper highlands of Asia (Gautam *et al*., 2009).

Few works have been done on biomass and carbon sequestration in community forests in Nigeria. Agbelade and Lawal (2019) estimated the biomass and C stock of Otun Ekiti and Ogun Onire community forests to be 6.07 t/ha and 30.02 t/ha, respectively.

2.4 Tree Species Composition and Distributions

Deforestation, forest degradation, and changes in natural ecosystems and their resources have been global issues (Warneck, 2003). Forests in the tropics are being lost at alarming rates due to extensive anthropogenic activity affecting species composition, richness, and diversity (Burivalova *et al.*, 2014) among other factors. For succession processes to be guided to maintain species and habitat diversity, tree species distributions, vegetation status, and pattern must be continuously assessed and managed (Attua and Pabi, 2013). Understanding forest ecosystems' growth dynamics depends on understanding forest stand structure (Ozcelik *et al.*, 2008) and management types.

Details on the composition and state of a forest stand, and its regeneration and diversity, are crucial for conservation. Knowledge of species diversity's relationship with biomass and carbon stocks would increase the efforts of governments and stakeholders in effectively managing the forest ecosystems in Nigeria. Understanding the composition and distribution of forests is crucial for making informed decisions and effectively organizing and implementing conservation strategies for the sustainable management of forested areas.

It is essential to delineate patterns in species composition to effectively oversee both disturbed and undisturbed stands while comprehending the ecosystem's services and goods (Neelo *et al.*, 2015). Implementing conservation measures and sustainable land-use methods is crucial to avoid further degradation of natural resources. Through sustainable land use methods, different diversity indices are used to evaluate the composition and distribution of trees in an ecosystem (Sanders and Rahbek, 2012; Naveed and Erwin, 2015; Sevda and Emire, 2018). Species diversity, richness, and evenness serve as key indices in biodiversity studies within forest ecosystems. Beta diversity indices are rarely utilized to assess species diversity in conservation practices in Nigerian forest ecosystems (Japheth and Meer, 2023). The commonly used alpha diversity indices by researchers encompass the Shannon-Wiener diversity index, Margalef index, species evenness, and Chao index (Sevda and Emire, 2018; Bunde *et al.,* 2018; Meer and Tella, 2018; Amonum *et al.,* 2019b; Chenge *et al.,* 2019). The distribution and composition of tree species related to above-ground biomass at the landscape level have received little attention (Shiva and Chungla, 2020).

There are many studies on diversity and composition of tree species from different forest types (sacred groves, plantations, forest reserves or community forest areas) (Adekunle, 2006; Ikyaagba, 2008; Onyekwelu *et al.*, 2008; Edet *et al.,* 2012; Adekunle *et al.,* 2013; Onyekwelu and Olusola, 2014; Udofia *et al.,* 2014; Nodza *et al.,* 2014; Barau *et al.,* 2015; Amonum *et al.,* 2019a; Japheth and Meer, 2023; Onyekwelu *et al.,* 2024).

2.4.1 Species Diversity

In ecology, the Shannon-Wiener diversity index is frequently employed as a scale. The species diversity is estimated to be using Claude Shannon's entropy formula as a basis for estimation. This index considers the relative abundance (evenness), and the number of species present in a habitat (richness). The Shannon and Weaver (1949) diversity index has been utilized to study species diversity within an ecosystem. The diversity index is a metric that represents the number of species present in a community and considers the individual's distribution across the community (Tucker *et al.,* 2017). The richness and evenness of species within the community are directly correlated with an increased index. The index is a function of species diversity; a higher index indicates greater diversity of more species present and vice versa. The Shannon-Wiener index (H') is estimated as follows (Kent and Coker, 1992; Magurran, 2004) (equation (eqn)1):

$$\mathrm{H} = -\sum_{i=1}^{s} p_i ln p_i \qquad (1)$$

In the formula, "ln" represents the natural logarithm, "s" is the total number of species, and "p_i" denotes the percentage of individuals in the ith species.

Many Nigerian authors (Meer and Tella*,* 2018; Amonum *et al*., 2019a; Chenge *et al.,* 2019; Dar *et al.,* 2019; Onyekwelu *et al.,* 2022) have adopted the Shannon-Wiener index to describe tree species variety in forest ecosystems in Nigeria. Adekunle *et al.* (2013) reported a Shannon-Wiener diversity index of 3.74 in a Nigerian strict nature reserve, while Aigbe and Omokhua (2015) reported a Shannon-Weiner index of 3.80 for Oban Forest Reserve. Chenge *et al*. (2019) reported a Shannon-Weiner index of 3.93 in the Shasha Forest Reserve in Nigeria. Nur *et al.* (2016) recorded Shannon's diversity index of 3.49 for a tropical rainforest ecosystem in Bangladesh. According to Dar *et al.* (2019), the species diversity index for 41 sacred groves in Central India ranged from 0.77 to 2.53.

To effectively conserve biodiversity and lessen the effects of climate change and global warming, it is essential to comprehend the relationship between species diversity and carbon storage in forest ecosystems (Subashree *et al*., 2020). Review and implementation of forest policies require data on the effects of tree species diversity indices on biomass and carbon stock.

Numerous studies have been conducted globally to assess the relationship between biomass (carbon stocks) and tree species diversity. (Gamfeldt *et al.* 2013; Poorter *et al*., 2015; Shirima *et al.,* 2015; Shen *et al.,* 2015; Baul *et al.,* 2021; Subashre *et al.,* 2020). Research indicates that the structure of a forest stand, including parameters like tree height, Dbh, density, and basal area, alongside tree species diversity, significantly influences biomass and carbon stocks (Kamruzzaman *et al.,* 2018; Alamgir and Al-Amin, 2007; Mandal *et al.*, 2016). The diversity of tree species positively influences above-ground biomass and carbon stocks of tropical forests, as suggested by studies in Asia and Africa (Shen *et al.,* 2016; Day *et al.,* 2014; Poorter *et al*., 2015; Shen *et al.,* 2015). These studies propose that higher diversity and richness of tree species in an ecosystem are associated with increased above-ground biomass (AGB) and carbon stock.

Baul *et al*. (2021) documented an estimated mean tree carbon stock of 46 Megagrams of carbon per hectare (Mg C ha-1) and a species diversity index value of 1.24 and then concluded the diversity of tree species and richness have exerted a positive impact on both biomass and carbon stock, a rise in species richness and diversity index by one unit increased to 22 Mg C ha-1 and 30 Mg C ha-1 in biomass and carbon stock, respectively. According to Chen (2006), carbon stock increases slowly as tree diversity rises and saturates at low species diversity. Research on tree carbon stock throughout a tree's life revealed that tree species have varying capacities for storing carbon (Mensah *et al*., 2020). In Northeast China, it was found that *Acer mono, Quercus mongolica, and Betula platyphylla* store more carbon compared to Ulmus japonica, *Tilia amurensis*, and *Pinus koraiensis* (Chen, 2006).

2.4.2 Species Richness

Species richness is a measure of species diversity obtained through a simple count of the number of species in each sample, often expressed more meaningfully as species richness per unit area, ranging from alpha (specific to a site) to gamma (for an entire study area) (Peter and Martina, 2019). The species richness index is calculated using the total number of species and individuals in a sample or site. Margalef's and Menhinick's indices determine the richness of a forest ecosystem. Although both indices offer measurements of species richness, their calculation methods and the aspects of richness they stress are distinct (Death, 2008).

The Margalef's index quantifies species richness by considering the total number of species in a community and their distribution based on abundance. The index gives more weight to rare species in the community. A greater value of Margalef's index signifies increased species richness. This index is commonly used to compare locations (Mulya *et al*., 2021). It is calculated using the following formula:

$$\text{Margalef'}s index = \frac{S-1}{Ln(N)} (2)$$

"S" is the number of species in the community, and "N" denotes the total population of the community.

The Menhinick index is a metric for species richness that centers on the percentage of species to individuals in the community. The index is a measure of species richness, it has no bounded range, and its variation depends on the number of species (Bhandarkar and Bhandarkar, 2013). The potential bias in species richness brought on by community size is taken into consideration by the Menhinick index. Uncommon species are given lower priority, while greater attention is given to how community size impacts diversity. A higher index value denotes greater species richness. Menhinick's index is calculated as the number of species (n) divided by the square root of the total population (N) The following equation is used to determine the index:

$$\text{Menhinic}k's\text{index} = \frac{S}{\sqrt{N}} (3)$$

N is the total number of individuals, S is the total number of species, and D is the species richness index (Margalef index).

High species richness is a characteristic of many tropical forests (Chenge *et al.,* 2019). Many researchers have published results on species richness with biodiversity conservation. Onyekwelu *et al. (*2020) reported Margalef species richness values of 8.05, 5.57, 7.94, and 10.24 for overstory forest layers of Osun-Osogbo, Igbo-Olodumare, Idare Hill, and Ogun-Onire sacred groves, respectively. For the understory layer of Osun-Osogbo, Igbo Olodumare, Idare Hill and Ogun-Onire, Onyekwelu *et al. (*2020) reported tree species richness values of 8.12, 5.65, 9.90, and 11.31, respectively. Adekunle *et al.* (2013) reported a very high Margalef index value of 64.72 for a strict nature reserve in the Akure forest reserve in southwest Nigeria. A study in Shasha Forest reserve, Nigeria recorded a Margalef index value of 13.82 (Chenge *et al.,* 2019) while Salami *et al.* (2021) reported species evenness values for forests in three states of Northern Nigeria: 13.49 for Kogi State; 10.86 for Bauchi State and 8.3 for Katsina State. Low species richness values of 5.14 were reported by Shuaibu and Ogunsola (2018) and 2.12 by Zankan *et al.* (2019).

Species richness plays a crucial role in the functioning of ecosystems, a factor that should not be underestimated (Maestre *et al*., 2007). Studies have noted an increase in the relationship between species richness and biomass, and carbon stocks in forests (Poorter *et al.,* 2015). The Reducing Emissions from Deforestation and Forest Degradation (REDD+) initiative acknowledges the importance of evaluating species richness and carbon stocks in tropical forest management to mitigate carbon emissions and preserve biodiversity. A thorough understanding of the relationship between species richness and carbon stocks is crucial for the effective implementation of REDD+ policies (Subashree *et al.,* 2020).

2.4.3 Species Evenness

The distribution of species abundance within a community is termed "species evenness." Maximum species evenness is achieved when every species in a community has the same level of abundance. The highest species evenness, represented by a value of 1.0, occurs when all species in a sample have equal abundance. As the relative abundances of species vary, evenness approaches zero (Pyron, 2010). An evenness index, such as the Pielou index, is employed to characterize species evenness. The PielouEvenness index value ranges from 0 to 1 (Pielou, 1969). Pielou's evenness value is 0 in the presence of a dominating trend and 1 in the case of a homogeneous individual distribution among species. The Pielouevenness index is mostly used to calculate species evenness using equation 3 (Pielou, 1969):

$$\mathrm{E} = \frac{H}{lnS} (3)$$

In the context of the Pielou Evenness Index, "S" represents the total number of species, "H" is the Shannon-Wiener function, and "E" denotes the evenness index.

In Nigeria, Adekunle *et al*. (2013) reported a Pielou evenness of 0.82 for a strict nature reserve in the Akure Forest Reserve, situated in southwestern Nigeria. Chenge *et al.* (2019) reported a Pielou evenness index of 0.87 for Shasha Forest Reserve, Nigeria. The Pielou evenness value of 0.84 was obtained by Agbelade *et al.* (2017) while the value of 0.97 was reported by Shuaibu and Ogunsola (2018). Low species evenness in an ecosystem could be attributed to a high degree of exploitation for wood fuel, lumber, and deforestation for farming. The Southern and Northern guinea savanna zones of Taraba State, Nigeria had a mean species richness index of 0.57 and 0.56, respectively, while the Montane eco-zone had a mean species richness of 0.52 for trees as reported by Japheth and Meer (2023).

Tree species' evenness could be higher at the overstory layer of the forest than at the understory layer (Onyekwelu *et al.*, 2020). For example, 0.63, 0.36, 0.36, and 0.43 were reported as the species evenness for the understory layers of sacred groves in Osun-Osogbo, Igbo-Olodumare, Idare Hill, and Ogun-Onire, respectively, which are lower than the species evenness values for the overstory layer of the sacred groves, which were 0.84 in Osun-Osogbo, 0.52 in Igbo-Olodumare, 0.86 in Idare Hill, and 0.85 in Ogun-Onire (Onyekwelu *et al.,* 2020). Dar *et al.* (2019) reported species evenness values for trees in 41 sacred groves in Central India to range from 0.28 to 0.90. Species evenness, richness, and diversity influence the local and global carbon cycle (Subashree *et al*., 2020). The high potential for carbon stock, richness, and evenness in tropical forests may be due to their high species diversity (Jhariya, 2017).

Tree species evenness and tree carbon storage showed a positive correlation, although the relationship did not reach statistical significance (Chen, 2006). The natural logarithm of tree carbon storage showed a significant linear relationship with tree species evenness (Chen, 2006). According to the author, carbon storage increases with species richness, though it might first reach saturation at low species densities before continuing to rise. Shirima *et al.* (2015) discovered unimodal connections between above-ground carbon (AGC) and the evenness of tree species, in miombo woodlands montane forests. However, due to the limited presence of large trees that played a significant role in aboveground tree carbon, carbon stocks in miombo woodlands had only a slight and negative relationship with tree species diversity. Shirima *et al.* (2015) found different results from previous studies conducted in subtropical forests in Nepal's Terai region (Mandal *et al*., 2013) and Puerto Rico (Vance-Chalcraft *et al*., 2010). According to Cai *et al*. (2008), variations in forest tree structure in response to growth-limiting elements like light availability may account for this discrepancy.

2.5 Soil Organic Carbon (SOC)

2.5.1 Soil Organic Carbon (SOC) in Forest Management Types

Soil Organic Carbon (SOC), as reported by Senwo (2021), holds significant importance in agriculture, climate change mitigation, and the establishment of sustainable food sources. It functions as a form of organic material within the soil, serving as a natural energy reserve and playing a crucial role among biopolymers (Senwo, 2021). SOC plays a role in enhancing soil stability in biological, chemical, physical, and structural aspects, improving its moisture retention capacity. Additionally, it plays a vital role in the generation of organic acids in the soil, essential for mineral dissolution, making nutrients accessible to plants, and facilitating nutrient leaching. SOC is indispensable for promoting soil quality, thereby supporting the growth of forests. The pace of SOC accumulation and decomposition directly impacts the ability of terrestrial ecosystems to sequester carbon and influences the global carbon balance.

Soil carbon sequestration is the act of taking carbon dioxide (CO_2) from the atmosphere and placing it into the carbon pool in the soil. The process of soil carbon sequestration involves changing carbon dioxide (CO_2) from the soil air into inorganic forms like secondary carbonates, although the production rate of inorganic carbon is not very high (Lal, 2008). The transformation of natural habitats into farmland has resulted in the emission of 50-100 gigatons (GT) of carbon from the soil to the air, leading to a decline in soil organic carbon levels (Lal, 2009).

Carbon release from the soil can be attributed to factors such as reduced plant root and residue input into the soil, intensified soil tillage leading to breakdown, and an escalation in soil erosion (Lemus and Lal, 2005). Due to the decrease in SOC stocks, there is a soil carbon deficit, which prevents the soil from storing carbon in the ground using a variety of land management techniques (Ontl Schulte, 2012). Changes in soil temperature and moisture content, combined with the succession of plant species that return varying amounts and qualities of biomass to the soil, could lead to a SOC loss because of the conversion of the forest ecosystem to other land uses (Offiong and Iwara, 2012).

Forested areas always have a higher amount of Organic Carbon (OC) when compared to other exposed vegetation areas (Bhunia *et al.,* 2019). OC is an effective indicator for determining soil productivity capacity (Shukla *et al.,* 2006). In terms of global climate change, Barrow (2006) and Khresat *et al.* (2008) stated that the destruction of natural ecosystems due to anthropogenic activities contributes to increased CO_2 emissions of the atmosphere.

Soil serves as a valuable sink and pool of carbon (C). However, anthropogenic activities cause the soil to release carbon, such as deforestation, which significantly raises the amount of GHG in the atmospheric region (IPCC, 2001). Rapid restoration of efficient atmospheric C removal vegetation systems can be achieved by utilizing reforestation techniques that repair degraded areas and by encouraging good forestry practices that have no adverse effects on soils or their productivity (Cunningham *et al.,* 2015).

Soil houses the largest active carbon pool on land and is integral to the global carbon cycle; estimating SOC is essential (Scharlemann *et al*., 2014). Around the world, soils are thought to hold more than twice as much carbon as the atmosphere (750 Pg) or living vegetation (560 Pg) combined (Picchio *et al.,* 2022). Soil carbon sequestration decreases soil erosion and enhances surface water quality and soil physical properties (Lal *et al.,* 2007). The decomposition rates of microorganisms largely determine the quantities of soil organic carbon (C) and nitrogen (N), which are directly correlated with the diversity and composition of trees (Simard *et al*. 1997; Van der Heijden *et al.* 1998).

2.5.2 Soil Organic Carbon in Primary Tropical Forest

A vital part of supporting essential ecosystem activities and services for humanity is soil organic carbon (SOC) (Chen *et al.,* 2023). The extensive conversion of primary forests into plantations and secondary forests due to economic development raises uncertainties about how this transformation may impact the composition and distribution of SOC (Margono *et al.,* 2014; Curtis *et al.,* 2018). It is crucial to comprehend how SOC reacts to these forest transformations.

The Soil Organic Carbon (SOC) content of primary forests in a tropical karst region of southwest China was documented by Zhang *et al.* (2023). According to their report, SOC content ranged from 13.00 to 46.19 g kg^{-1}, aligning with the findings of Pang *et al*. (2019) and Hu and Lan (2020) in the subtropical karst region. In subtropical China, primary forests exhibited significantly higher SOC content, with a mean value of 32.8 mg g^{-1} soil (Chen *et al*., 2023).

Chen *et al.* (2023) noted a substantial reduction in Soil Organic Carbon (SOC) content when primary forests were converted to secondary forests or plantations. Primary forests, known for their diverse species composition, have a more significant impact on SOC accumulation through contributions from litter (Yang *et al*., 2004; Wang *et al.,* 2010; Zheng *et al*., 2019). This causes SOC breakdown and erosion to increase with plantation establishment and management (Guillaume *et al.,* 2015). Differences in SOC content between primary and secondary forests suggest that as secondary forests mature into older primary forests, they are more likely to store carbon. It could be explained by the fact that primary forests have a lot of plant biomass and have noticed little disturbance for a long time, both favourable conditions for SOC accumulation (Luyssaert, 2008).

2.5.3 Soil Organic Carbon in Sacred Groves

Sacred Groves play a vital role in the accumulation of SOC and the rejuvenation of soil health (Dar *et al.,* 2019). SOC is a highly dynamic attribute that varies based on temporal, spatial, and depth considerations (Batjes and van Wesemael, 2015). Factors such as forest types, litter quality and quantity, litter input, soil type, soil texture, soil chemistry, precipitation, temperature, altitude, and soil moisture collectively impact SOC in forest ecosystems (Jobbagy and Jackson, 2000; Sundarapandian*et al.,* 2016).

In Sikkim Himalaya's urban sacred grove trees, the upper soil layers contain more soil carbon than the lower soil layers (Devi *et al.,* 2021). This pattern of carbon increase in soil is linked to greater biodiversity, more trees, and an increase in surface soil debris. Soil organic carbon storage in sacred groves (SGs) in central India, reported by Dar *et al.* (2019), ranged from 22.4 to 112.5 Megagrams of carbon per hectare (Mg C ha^{-1}), with an average of 62.3.6 Mg C ha^{-1}. Hangarge *et al.* (2015) reported SOC ranging between 65.8 and 138.6 Mg C ha^{-1} in sacred groves in the Bhor region of the Western Ghats, Maharashtra. Abere *et al.* (2017) reported SOC content in a sacred grove in the Banja district of the Amhara region, Ethiopia, as 230.8 Mg C ha^{-1}. Sundarapandian *et al.* (2013b) documented SOC storage in specific sacred groves in the tropical dry forests of Sivagangai District, Tamil Nadu, India, ranging between 33.36 Mg C/ha and 48.82 Mg C/ha. The clay content's stabilizing effect on SOC contributes to a reduction in carbon output (Jobbágy and Jackson, 2000).

2.5.4 Soil Organic Carbon in Degraded Forests

Sahu *et al.* (2016) reported SOC of 58.13 tons/ha of India's Odisha Forest contains tropical dry deciduous forests. Zhang *et al. (*2023) studied the SOC concentrations of shrublands, young, and mature secondary forests in a tropical karst region of southwest China, result showed that the soil layer was from 0 to 50 cm in the research area, young and mature secondary forests had average SOC contents of 27.85 and 28.44 g/kg, respectively, and their stages grew by 0.38 and 0.41 times, respectively. There was a rise in SOC content with the transition from shrubland to young secondary forest. The SOC content increases substantially as shrubland gives way to young secondary forests (Zhang *et al*., 2023). Young secondary forest, which represents the initial stage of seasonal rainforests, is characterized by substantial biomass. According to Yang *et al*. (2016), restoring vegetation significantly enhances Soil Organic Carbon (SOC) content, with an increase ranging from 35% to 100% observed after reforestation (Johnson, 1992). SOC content at each stage of vegetation regeneration gradually reduced, as soil depth increases (Zhang *et al.,* 2023).

In the PokhareKhola Sub-Watershed located in Nepal's Dhading district, Pradhan *et al.* (2012) reported on SOC contents under various forest types from different soil depths (cm) of 0-20, 20-40, 60-80, and 80-100. The results showed that SOC of 0.58, 0.21, 0.21, 0,20, and 0.16%, respectively, were observed from the degraded forest area. Research by Shapkota and Kafle (2021) found that the concentration of organic soil (SOC) in oak, hardwood, and mixed hardwood forests ranged from 1.9 to 4.8%. However, as soil depth increased, SOC levels decreased across all forest types, likely due to the dense forest canopy and active microbial processes in the soil. Shapkota and Kafle proposed that the higher concentration of Soil Organic Carbon (SOC) in the uppermost layer may be a result of the rapid decomposition of forest litter. Elevated levels of SOC stocks are often associated with high soil fertility (Kafle, 2019).

Soil organic carbon accumulates because of several factors, including high moisture, microorganisms, regular disturbances, a large amount of litterfall, and plant roots in the topsoil (Barreto *et al.,* 2011). Because root residues and secretions dominate the regulation of lower SOC, animal activity and litterfall have minimal effects (Fontaine *et al*., 2007). As a result, lower SOC exhibits little variation. Additionally, the delayed breakdown of conifer species' litter (combined with high soil moisture) causes higher soil C (Moro and Domingo, 2000).

2.6 Threats to Biodiversity

Human population growth represents the main threat to Earth's biodiversity and, consequently, to human well-being. Anthropogenic factors (Mathew, 2019), high population growth rate, poverty, policy and legislation, illegal and indiscriminate logging, climate change, and insecurity, among others, are some of the underlying threats and causes of the degradation of biodiversity. These factors are briefly discussed below.

2.6.1 *Anthropogenic activity*

Anthropogenic activities play significant roles in the decline of tree population within forest areas, coupled with its adverse effects on the regenerative capabilities of the forest, opening the door for degradation and deforestation (Dar *et al.,* 2022). A high percentage of the people in most African nations rely on the forest for their basic energy needs, thus increasing the pressure and threats on the forest.

2.6.2 *High population growth rate*

Nigeria's population could exceed 350 million by 2050, according to the United Nations Department of Economic and Social Affairs (UNDESA), this would make it the third most populous in the world country (UNDESA, 2022). The high population in Nigeria is increasing the demand for food; shifting cultivation remains a common farming method among small-scale farmers providing over 90% of the world's food supply (Rahman and Chima, 2018). The tilling method can cause habitat degradation because of ineffective land management practices.

The loss of vegetation for farming purposes (because of the increase in human population leading to high demand for farmland), and unequal access to farmland are all contributing factors to the loss of biodiversity in forests. Natural ecosystems are being destroyed to make way for agricultural plantations, irrigation systems, the production of food, and livestock, and the utilization of non-timber forest resources because of the rising population and rising demand for biological resources.

2.6.3 *Illegal logging and conversion of forests*

Logging and conversion of forests to agricultural or grazing land are among the primary drivers of biodiversity loss (Emma-Okafor *et al.,* 2010). Illegal logging and exploitation of economic tree species (e.g. *Khaya senegalensis, Naucleadiderrichii (Opepe), Terminalia ivorensis (Odigbo), Terminalia superba (Afara), and Triplochiton sceleroxylon (Obeche)* have been significant threats to biodiversity (Ojo, 2016). Habitat degradation due to high illegal logging and indiscriminate felling of trees are now rampant and common in the Guinea savanna ecosystem. Unlawful and unselective cutting down of trees is conducted for various reasons, such as charcoal and fuelwood production, agriculture, timber production, and others. However, there are hardly any regeneration activities being carried out by the people or government to substitute the trees that are cut down (Omofonmwan and Osa-Edoh, 2008).

2.6.4 Invasive alien species

After habitat loss, the second most significant threat to the diversity of plant species globally is posed by invasive alien species (Chornesky and Randall, 2003). Invasive plants in Nigeria include water hyacinth (*Eichhornia crassipes*), Nipa palm (*Nypafructicans*), wild sunflower (*Tithonia diversifolia*), and Typha grass (*Typha dominguenesi*). These plants pose a threat and have a significant impact on both terrestrial and aquatic biomes (Borokini *et al.,* 2010). Plant diversity is impacted positively and negatively by the varying values of plants for economic and medical purposes. Cultural traditions that encourage the utilization of wildlife during festivities may lead to a decrease in the number of species found in limited geographic areas (Osawaru *et al.,* 2018).

2.6.5 Poverty

The Human Development Index Report (UNDP, 2009) affirms that poverty levels in Nigeria increased from twenty-seven percent in 1980 to sixty-eight percent in 1996, a mean yearly rise of eight-point eighty-three percent over a sixteen-year time. In Nigeria, there are still a lot of impoverished people (World Bank report, 2020). According to World Bank brief report of 2020, Nigeria's 2019 Poverty and Inequality Report, shows that nearly 83 million people or 40% of the entire populace in Nigeria, live below the 137,430 Naira ($381.75) annual poverty threshold. Poverty is an underlying threat to biodiversity management. The rural poor easily obtain food, fiber, and minimal commercial gain from biodiversity, however, biodiversity is constantly on the losing end.

2.6.6 Effect of climate change

Kotir (2011) reported that climate change constitutes the result of natural and man-made disturbances, such as greenhouse gas emissions and ozone layer loss, causing a change in an area's climate. Climate change significantly affects biodiversity by influencing species, ecosystems, and ecological processes (Weiskopf *et al*., 2019). According to Díaz *et al.* (2019), biodiversity and ecosystems face a widespread and increasing global danger due to climate change. Climate change impacts the structure and function of ecosystems, also, the products and services they offer to society, according to Díaz *et al*. (2019).

Nigeria is experiencing the effects of climate change. Individual species are affected as well as their interactions with other creatures and their surroundings (Weiskopf *et al*., 2019). The effects of global warming result in habitat loss, fragmentation, and range shifts, which cause population decreases and local extinctions of some species (Muluneh, 2021). The interactions between species have changed, and the risk of extinction has grown. Additionally, the supply of ecosystem services is in jeopardy due to climate change, which influences human welfare. Efforts at conservation, mitigation, and adaptation must be made to curtail the impacts of global warming on biodiversity (Weiskopf *et al*., 2019).

2.6.7 Policy and Legislation

Effectiveness and enforcement are key factors in determining the effect of policies and legislation on biodiversity loss. As per an IUCN report, an effectively designed and appropriately implemented policy can establish protected areas, regulate harmful activities, and promote sustainable resource management (Dudley, 2008). In this way, ecosystems, species, and genetic diversity can be preserved. Nevertheless, ineffective conservation measures can lead to biodiversity loss due to insufficient governance, inadequate enforcement, and conflicting interests (Muhumuza and Balkwill, 2013). Ineffective or poorly enforced policies can fail to address key drivers of biodiversity loss, allowing destructive practices to flourish. The management of biodiversity in Nigeria is threatened by governance, institutions, and policy changes due to a lack of interest and/or conflict of interest and corruption. For instance, ineffective public forestry agencies' capacity for research, education, training, and extension, as well as poor governance and corruption, could pose challenges to biodiversity management (Mayer *et al.,* 2013).

Sacred groves and forest areas within the community in the research area have remained preserved with little or no exploitation despite the socio-economic issues related to rural livelihoods and forest dependence in recent years. There have been numerous studies (Tee and Ageende, 2005; Dagba *et al.,* 2013; Tee *et al.,* 2014a; Tee *et al*., 2014b; Yager *et al*.,

2018) conducted in the study area, however, these studies only assessed the diversity of tree species in their respective study sites. No online publication has been created to assess the factors contributing to forest conservation based on the management methods used in the specific research area. Comprehensive knowledge of the factors influencing forest conservation and the resources involved are essential to tackle deforestation issues. Nonetheless, there is a lack of up-to-date information on these conservation factors in Benue State.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 The Study Area

3.1.1 Location

Data for this study were collected from three forest management areas (Community Forest Areas (CFAs), Forest Reserves (FRs), and Sacred Groves (SGs) in Benue State, Nigeria. Two forest areas were sampled from each management type, giving a total of six forest areas. Several factors were considered for the selection of the forest areas under study. These include areas with minimal human disturbances (anthropogenic activities), accessibility, logistics, collaboration opportunities with local stakeholders, and security.

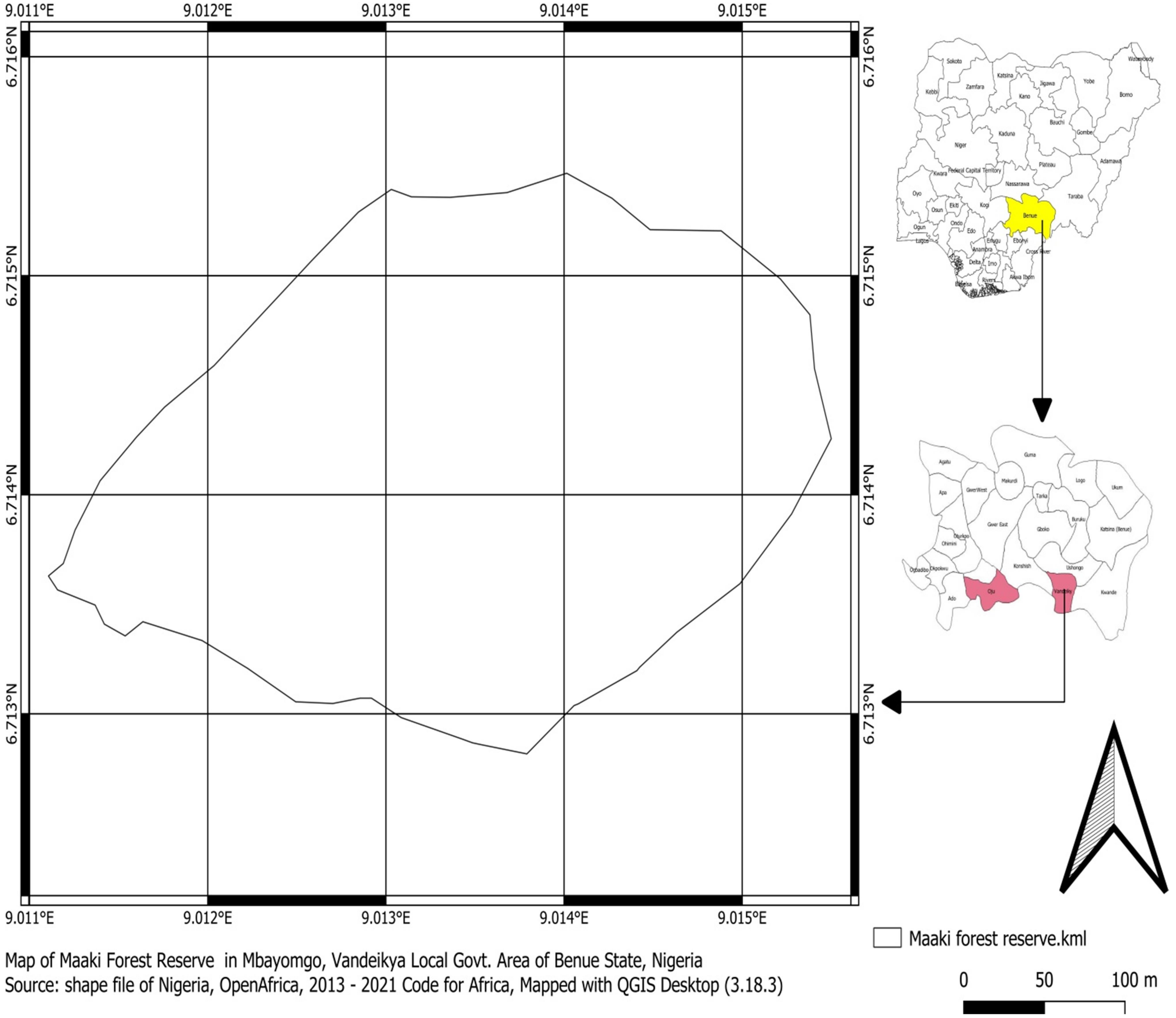
Two Community Forest Areas (CFAs) were selected for this study. The Maaki Community Forest Area (CFA) is in the Mbayongo Vandeikya Local Government Area (L.G.A). The area has landmass coverage of about 9.19 hectares (Figure 3.1a). This lies between Latitude 6.712 °N to 6.716 °N and Longitude 9.011 °E to 9.016 °E. The Tse Mba CFA is located between latitudes 6.850 °N and 6.854 °N and longitudes 9.084 °E and 9.090 °E and covers an area of around 7.82 hectares (Figure 3.1b).

Two sacred groves were selected for enumeration in this study. OhumaIpenu-Igede SG lies between Latitude 6.957 °N to 6.973° N; and Longitude 8.502° E to 8.515° E (Figure 3.2a). The area has a land area of about 109 hectares. Igeche SG has a total land area of about 41.27 hectares. IgecheIpenu-Igede sacred grove lies between Latitude 6.803° N to 6.811° N; and Longitude 8.438° E to 8.448° E (Figure 3.2b).

Two Forest Reserves (FRs) were involved in this study. The Mbaakon Forest Reserve is situated in the Mbaakon area of Vandeikya L.G.A. It has land coverage of about 20.38 hectares. Mbaakon FR lies between Latitude 6.893° N to 6.901° N; and Longitude 9.134°

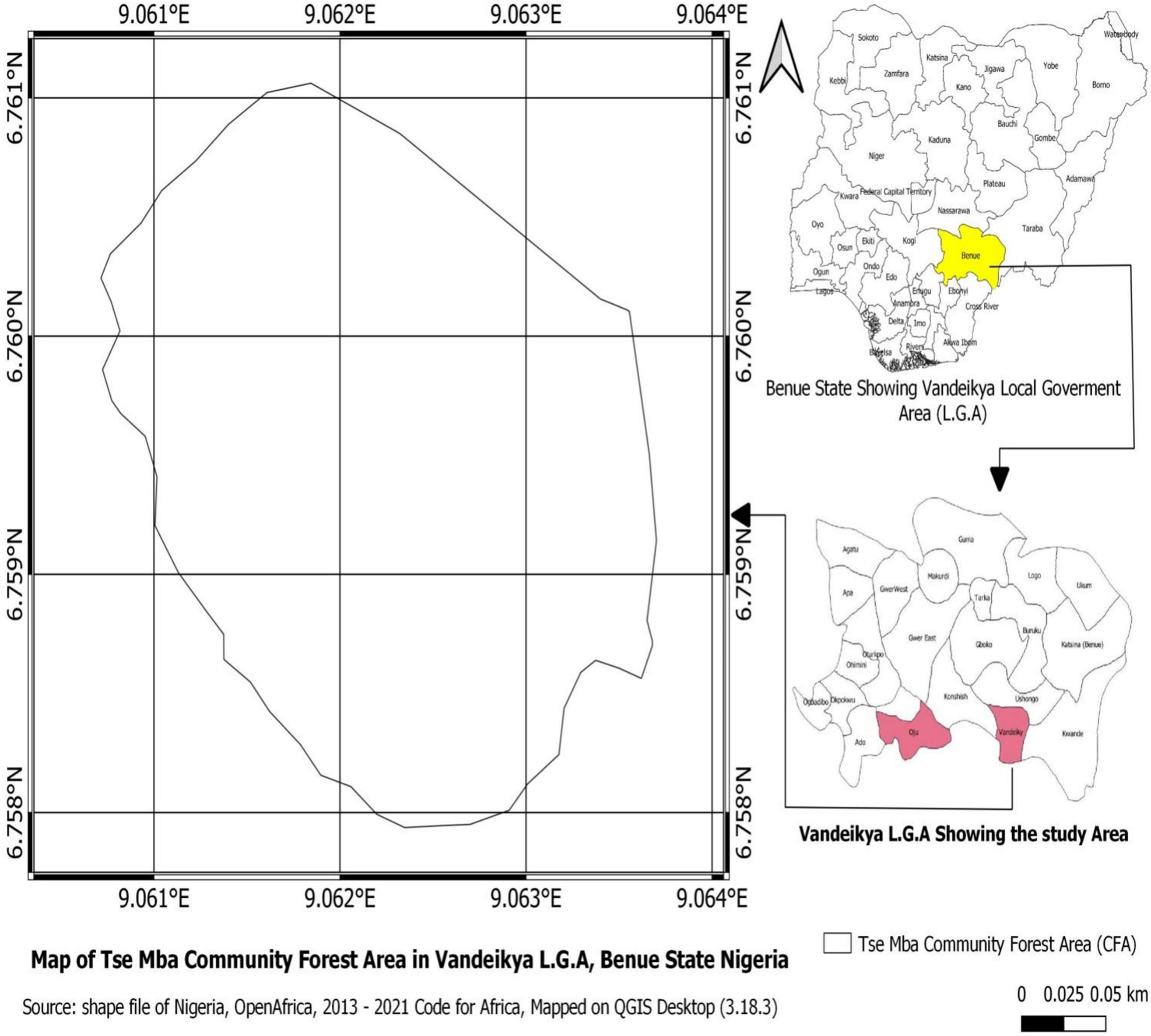
E to 9.139° E (Figure 3a). Yandev F.R is located between 7.3574° N to 7.36353° N; and 9.05112° E to 9.04222° E (Figure 3.3b).

All the forest management types are situated in Benue State, Nigeria. The State is in Nigeria's central belt, within the lower Benue trough. It is located between 6° 25' and 8° 8' north latitude and 7° 47' and 10° 0' east longitude. In the Northern part of the State, it borders Nasarawa State and East Taraba State; in the South and southwest, it borders Cross-River State and Enugu States, respectively (Dau *et al*., 2016). Benue State covers 34,059 square kilometers of land (Dau and Chenge*,* 2016). The Tiv people are the most common tribe in Benue, with the Idoma, Igede, and Etulo tribes also being significant in the region. Oranges, mangoes, sweet potatoes, cassava, soya beans, flax, yams, sesame, rice, ground nuts, and palm fruits are the prominent crops in the area.



Map of Maaki Forest Reserve in Mbayomgo, Vandeikya Local Govt. Area of Benue State, Nigeria
Source: shape file of Nigeria, OpenAfrica, 2013 - 2021 Code for Africa, Mapped with QGIS Desktop (3.18.3)

Figure 3.1a: Map of Maaki Community Forest Area (Inserts: Nigeria showing Benue State; Benue State showing the Location of Vandeikya L.G.A).



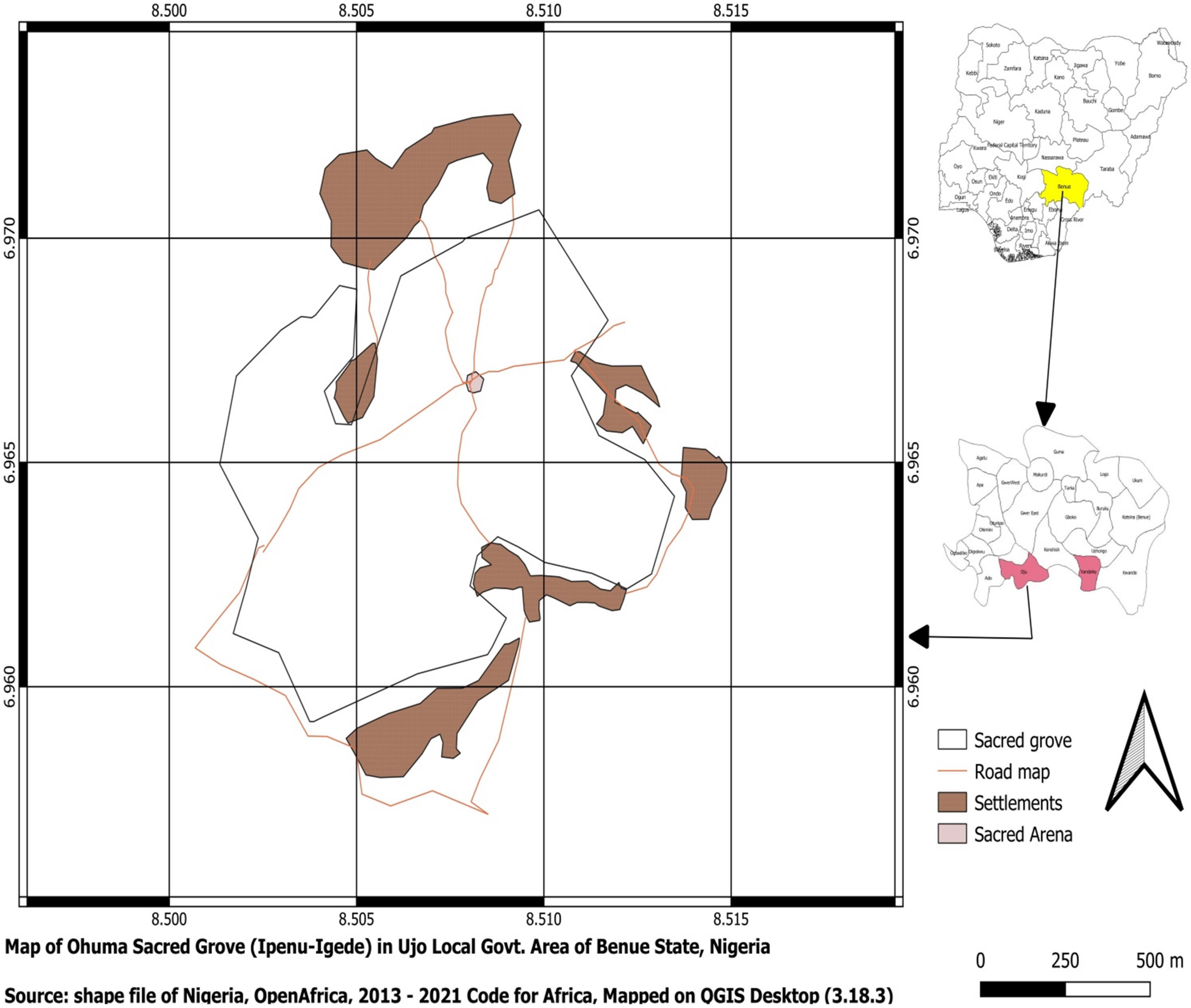
Benue State Showing Vandeikya Local Goverment Area (L.G.A)

Vandeikya L.G.A Showing the study Area

Map of Tse Mba Community Forest Area in Vandeikya L.G.A, Benue State Nigeria

Source: shape file of Nigeria, OpenAfrica, 2013 - 2021 Code for Africa, Mapped on QGIS Desktop (3.18.3)

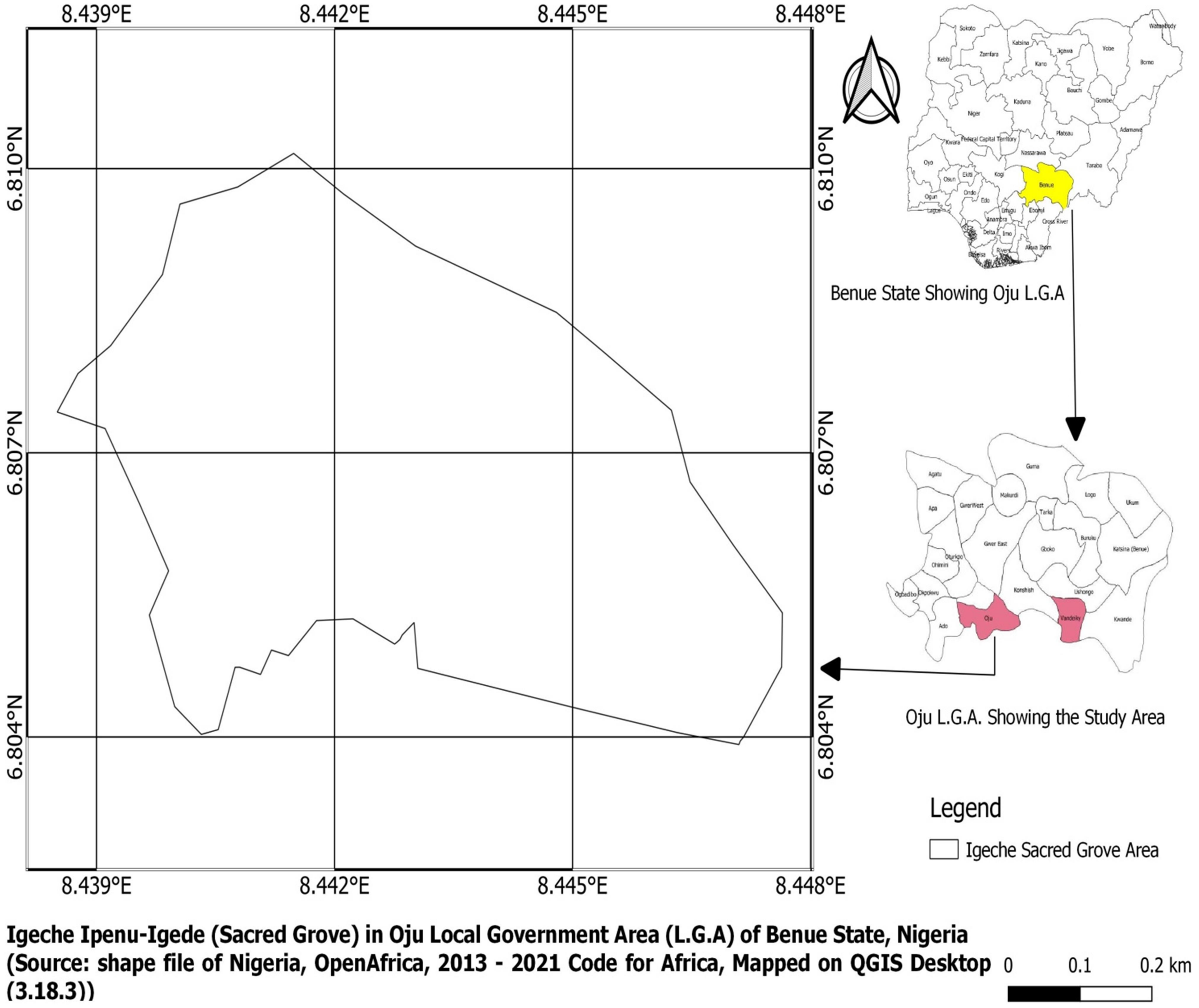
Figure 3.1b: Map of Tse Mba Community Forest Area (Inserts: Nigeria showing Benue State; Benue State showing the location of Vandeikya L.G.A)



Map of Ohuma Sacred Grove (Ipenu-Igede) in Ujo Local Govt. Area of Benue State, Nigeria

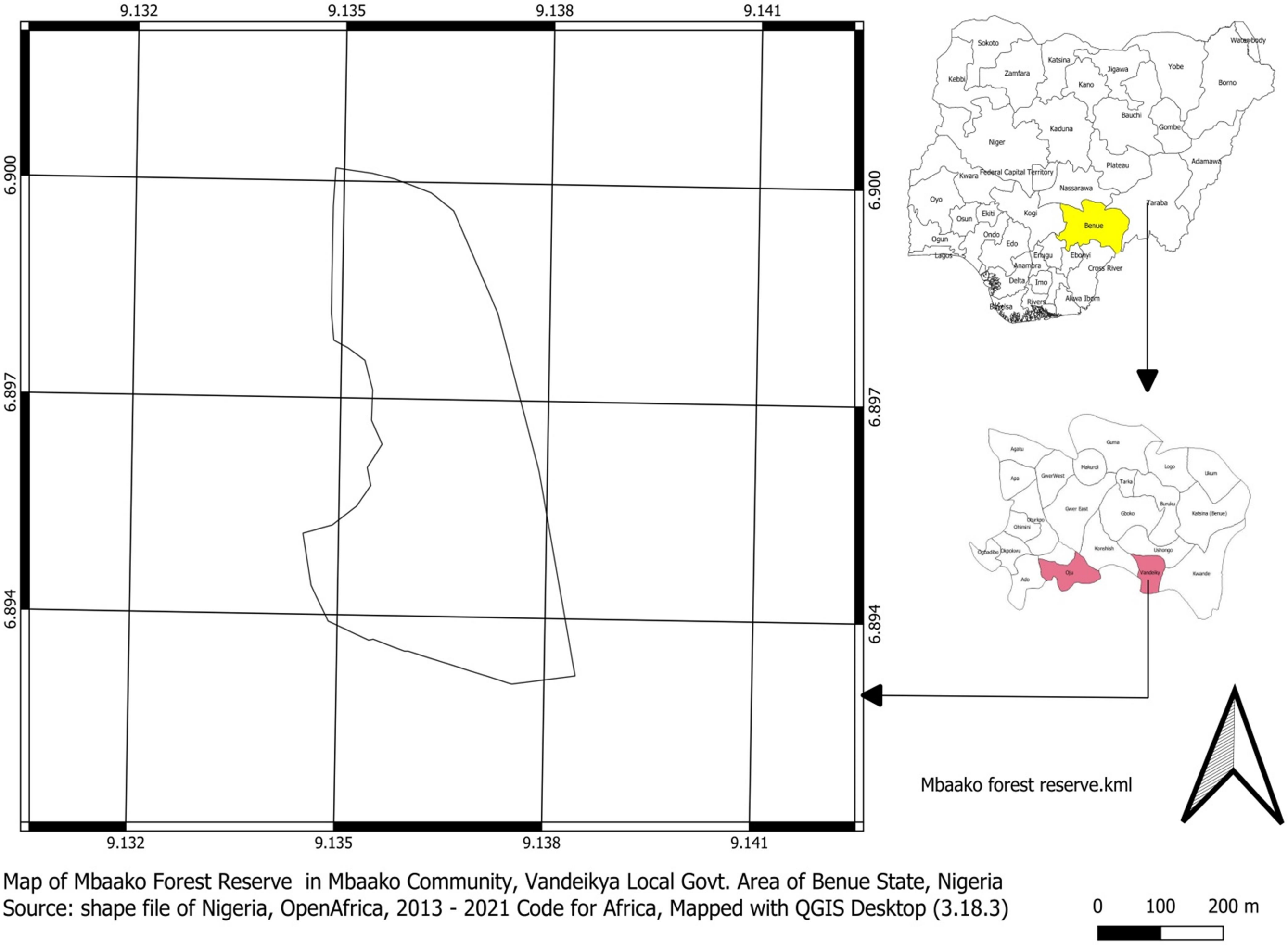
Source: shape file of Nigeria, OpenAfrica, 2013 - 2021 Code for Africa, Mapped on QGIS Desktop (3.18.3)

Figure 3.2a: Map of OhumaIpenu-Igede Sacred Grove (Inserts: Nigeria showing Benue State; and Benue State showing the location of Oju L.G.A).



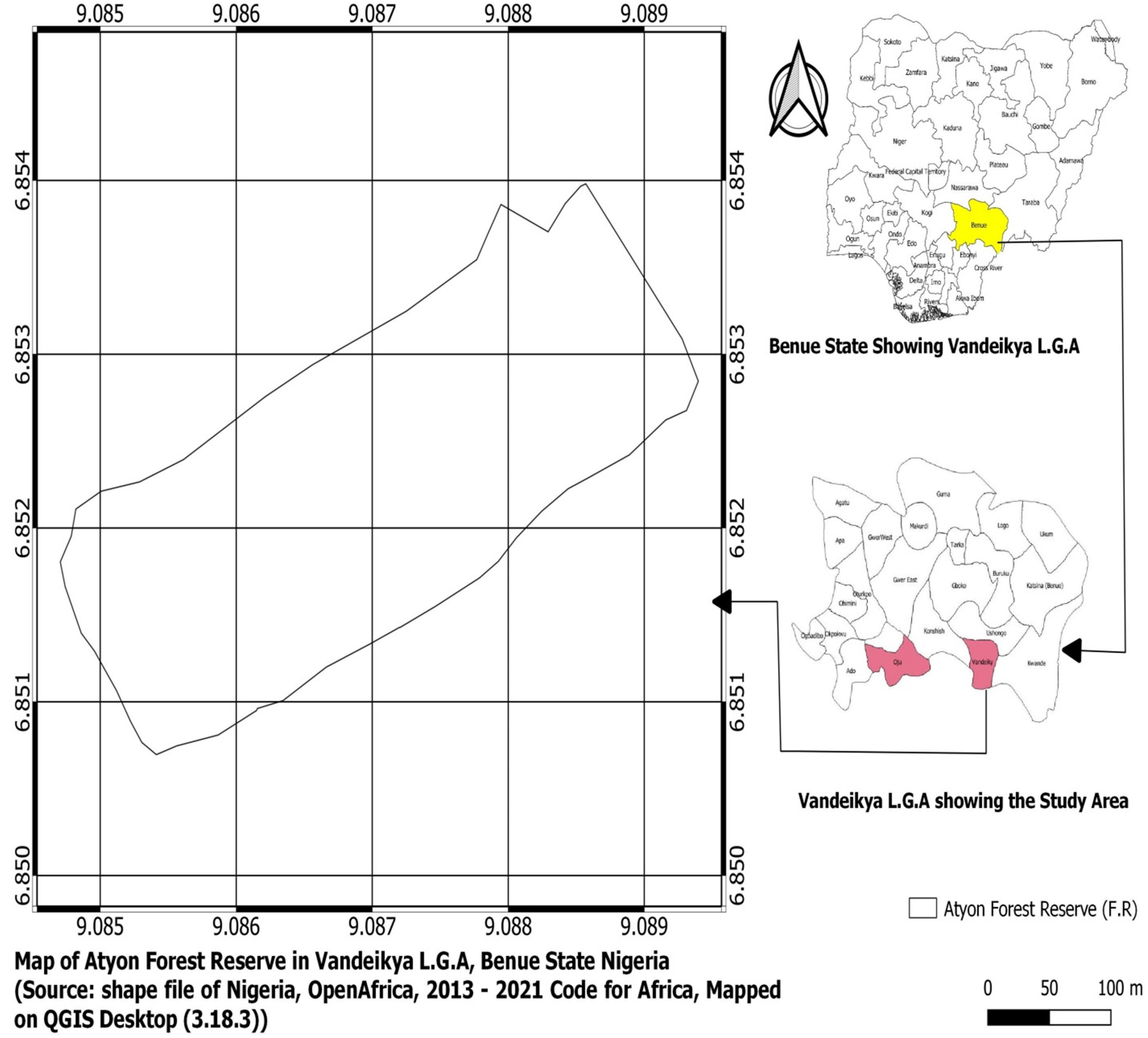
Igeche Ipenu-Igede (Sacred Grove) in Oju Local Government Area (L.G.A) of Benue State, Nigeria (Source: shape file of Nigeria, OpenAfrica, 2013 - 2021 Code for Africa, Mapped on QGIS Desktop (3.18.3))

Figure 3.2b: Map of IgecheIpenu-Igede (Sacred Grove) (Inserts: Nigeria showing Benue State; and Benue State showing the location of Oju L.G.A).



Map of Mbaako Forest Reserve in Mbaako Community, Vandeikya Local Govt. Area of Benue State, Nigeria
Source: shape file of Nigeria, OpenAfrica, 2013 - 2021 Code for Africa, Mapped with QGIS Desktop (3.18.3)

Figure 3.3a: Map of Mbaakon Forest Reserve (Inserts: Nigeria showing Benue State; and Benue State showing the location of Vandeikya L.G.A)



Map of Atyon Forest Reserve in Vandeikya L.G.A, Benue State Nigeria (Source: shape file of Nigeria, OpenAfrica, 2013 - 2021 Code for Africa, Mapped on QGIS Desktop (3.18.3))

Figure 3.3b: Map of Atyon Forest Reserve (Inserts: Nigeria showing Benue State; and Benue State showing the location of Vandeikya L.G.A)

3.1.2 Topography and drainage

The hilly terrain is appreciably found at the border areas of the state and Cameroon country, Cross River, Ebonyi and Taraba States. Steep mountains, deep valleys, and rugged contours are the typical geographic characteristics of the research locations (Benue State, 2021). The primary rivers in the area are the River Benue and the River Katsina-Ala, along with their tributaries, that flow through the region (Akintola, 2013). *Mkomon, Amile, Duru, Loko Konshisha, Kpa, Okpokwu, Mu, Be, Aya, Apa Ogede, and Ombi* are among the smaller rivers (Abah and Petja, 2017). The state has a high drainage density, and many streams are seasonal and flow over impermeable geological environments, indicating low groundwater components and very high runoff (Akpen *et al.,* 2019).

3.1.3 Geology and soils

Benue State is underlain by basement and sedimentary rocks, which vary in character across the State (Grant, 1971); the sedimentary basins, which have Cretaceous to Tertiary sediment, fill (Fatoye and Gideon, 2013). Ancient igneous and metamorphic basement complex rocks are found primarily in *Kwande, Ushongo, Guma, Vandeikya*, and the eastern half of *Oju* LGAs (Akpen *et al.,* 2019).

Different rivers (such as that of *Katsina-Ala, and Buruku,* among others) and alluvial deposits are found on the flood plains of the State; alluvial deposits, which are made up of a variety of clays, sand, gravels, and pebbles, lie on top of meta-sediments and comprise the surface geology (Akpen *et al.,* 2019). Mineral deposits such as Mineral salts and gemstones, coal, lead–zinc, barytes, clay, phosphate, glass sand, fluorspar, salt, ironstone, uranium, sulphur, graphite, cassiterite, manganese, mica, and silver among others are found mostly in the study area (Fatoye and Gideon, 2013).

3.1.4 Climate and vegetation

Benue State is classified as a tropical savanna climate (AW climate), with two seasons, the wet and the dry season, according to the Köppen climatic classification (Krishnamurti, 2021). The wet season runs from April to October, with annual rainfall ranging from 1120 to 1500 mm; the dry season is from November to March, with annual rainfall ranging from 1120 to 1500 mm (Amonum and Japheth, 2019). The climate is characterized by high temperatures fluctuating between 27-38 ^{0}C as the mean annual, and relative humidity is between 60-80% (Dau and Chenge, 2016). The state's southeastern region, which borders the Obudu-Cameroun Mountain range, has a colder temperature than Plateau State.

The vegetation in the research area consists of the Southern Guinea Savanna type, characterized by dense forests, tall grasses, and herbs, along with riparian forests near a stream. *Prosopis africana, Detarium microcarpum, Khaya senegalensis, Danielliaoliveri, Terminalia avicennioides, Lannea acida, African peach (Nauclea latifolia), Parkia biglobosa, vitellaria paradoxa; Pterocarpus erinaceas, Ficus sur, Parinaricuratellifolia* (Amonum *et al.,* 2016).

3.1.5 Forest Management Practices

The study areas are all-natural forests with minimal disturbance in the selected forest type managements managed by the Benue State Government (FRs) and communities. CFAs and SGs have 0% disturbance (i.e. no activities are allowed in areas with occasional fire outbreaks). The forest management practice of the study area emanates from three basic indigenous conservation systems, namely: observance of laws and taboos, application of punitive measures, and Agroforestry (Tee *et al.,* 2014a). Timber exploitation for commercial or domestic purposes is prohibited in the study areas; the dynamics and functioning of the forests continue under minimum disturbance. Harvesting forest products (wood and wildlife) is prohibited in these areas. No, silvicultural practices are carried out in all the selected forest types (CFAs, SGs, and FRs).

3.2 Data Collection

3.2.1 *Sampling technique*

Three nested plot samples (measuring 35 x 35m, 25 x 25m, 7 x 7m, and 1 x 1m) were established using GPS hand-held equipment through systematic line transects in each of the three forest types (Chenge and Osho, 2018). The design of nested plot samples of different sizes accommodated lower vegetation of different sizes (Rabindranath and

Ostwald, 2007). This reduced expenditures while maintaining estimate precision (Tomppo*et al.,* 2010) and is scientifically sound for most plant types with trees (FAO, 2020).

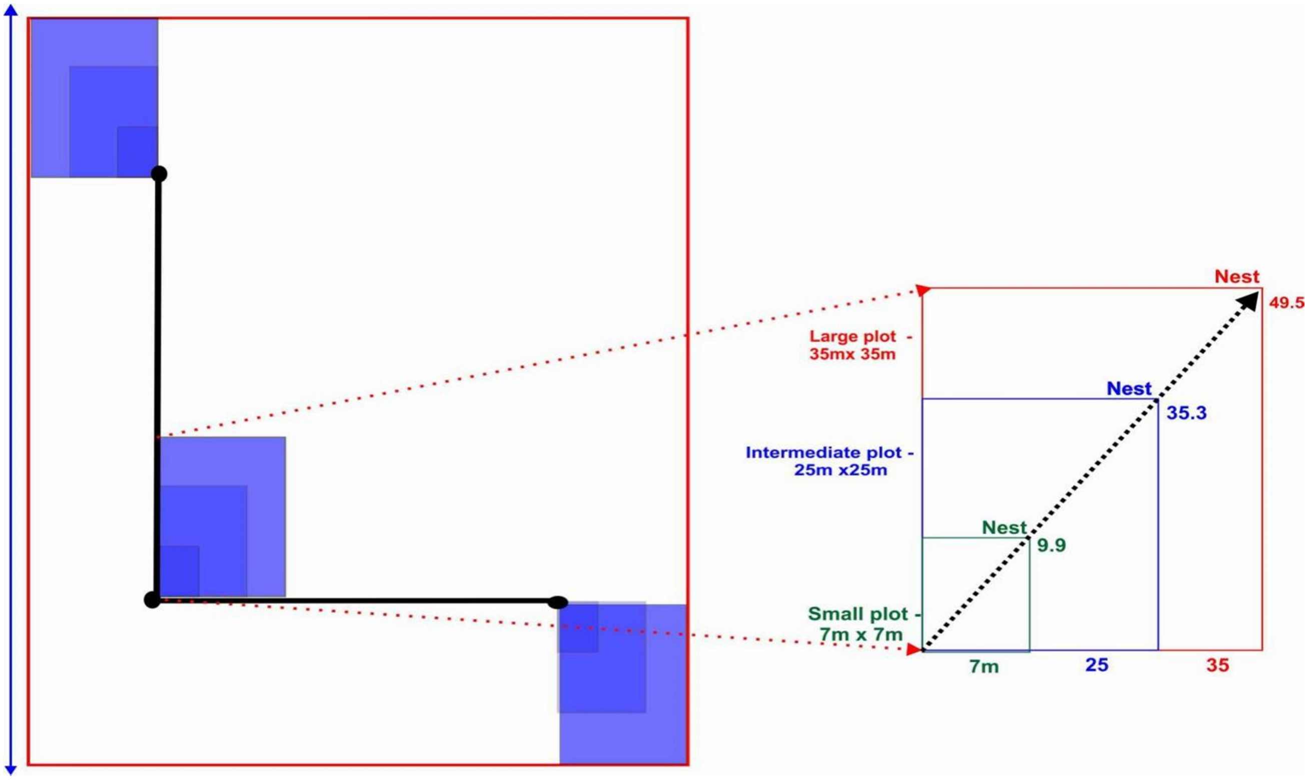


Figure 3.4: Sketch Diagram of a Nested Plot (Source: FAO, 2020).

3.2.2 Location of sample plots layout

Before the field survey, plot locations were delineated for all the sites on high-resolution satellite imagery using the Google Earth Pro application (Desktop 7.1.4 version) to access the sampling plots as simply and quickly as possible in the study area (Japheth *et al.,* 2023). A Microsoft Excel spreadsheet was used to produce random values, which were used to select nine coordinates on the Google Earth Pro Map (version 7.3.6.9796, 2022), to avoid bias during the laying of plots. On the Google Earth Pro interface, three points in each forest type were marked as the starting points of plots within each forest type, along with their relative coordinates using the (World Geodetic System 1984) with Universal Transverse Mercator projection method typically employed in Nigeria because it has minimal distortion among other reason, with Longitude and Latitude (X, Y). The points were transferred to Garmin e-Trex 10 GPS for tracking on the field (Chenge and Osho 2018).

On the point for each coordinate in the area, three nested sample plots were laid as shown in Figure 4. The elbow plot was on the point of the coordinate, the north nested plot was laid 100 m away toward the North part of the coordinate and the east plot was laid 100 m away toward the East part of each coordinate. This gave an L-shaped structure. Each nested sampling comprised 35 × 35 m, 25 x 25 m, 7 x 7 m, and 1 x 1 m square nested plots. Three (3) nested plots were laid in each forest management type, given a sum of nine nested plots (made 36 sample plots i.e. 9 nested plots x 4 plots in each nested plot) for this study. Strata for collecting debris and litter for biomass mapping were used.

The 35 x 35 m sample plot was the main plot (Figure 4) and all trees with Dbh ranging from 40 cm and above were selected for measurement within these plots' sizes. A sub-plot measuring 25 m x 25 m was placed within the larger plots, and all trees with a diameter at breast height (Dbh) between 20 and 40 cm were surveyed. Within each sub-plot (25 x 25 m) a sub-sub-plot of 7 x 7 m in size was laid for enumeration of trees with a Dbh range of 5 m to 20 cm. A quadrat 2 x 2m size was laid within the 7 x 7 m plots to assess low vegetation with a diameter <5 cm that could not be measured, a square frame of 1 m x 1m was laid to assess all litter.

3.2.3 Tree enumeration and soil sample collection

All live tree species in each nested plot were identified; and all live trees, standing dead and lying dead trees within the sample plots were measured. Low vegetation (such as herbaceous and shrub species with Dbh <5 cm) within 2 x 2m were also measured. A 1 x 1 m^2 frame was established at a relatively undisturbed part of each sample plot. Litter (which is referred to as a layer of decaying leaves, twigs, and wood components that form a layer on the ground above the mineral soil) were all gathered within the square frame (pieces of litter that fell on the frame border were cut using a sharp knife). The collected litter was weighed within 24 hours of collection to obtain fresh weight. After being weighed, the litter was divided into four equal portions, while one of the parts was transported to the laboratory for oven-drying at 70°C until it reached a constant weight (Ribeiro *et al.,* 2011).

Tree variables measured on all live trees include diameters at breast height (Dbh), base (Db), middle (Dm), top (Dt), and tree total heights (Th). The measurement was done with a Mirror (spiegel) relascope (Oladoye*et al.,* 2018). Because height measurement is difficult and expensive, the standard practice during inventory is to take a few height measurements as precisely as possible on sample trees with clear boles, and then establish height-diameter relationships that can be used to compute the heights of trees for which height measurement was impracticable (for example, any thick undergrowth or inaccessible clear bole due to climbers or obstruction by other trees) (Ebeniro, 2018).

Borderline trees were included, wherever half of the diameter of the stem base was inside the plot, trees positioned on the plot's edge were regarded inside. Half of the base of the tree's stem inside the plot before it fell, was inside the plot. Stem quality (straight, bend or croaked), tree condition (hollow, diseased, damaged (damage severity and causative agent)) and crown condition (healthy or unhealthy) were all determined by observing (examining the physical attributes (bole, bark, and crown) each tree in the study area.

The non-living woody biomass too large to be included in the litter pool was considered dead wood. Standing and laying dead wood with a diameter of less than 5 cm (commonly referred to as coarse woody debris) were included in the dead wood pool, while those with a diameter of 2 to 5 cm were referred to as fine woody debris (FAO, 2020). Standing dead trees were measured parallel with living tree measurements, within each nest. Measurements of variables (Dbh, Db, Dm, Dt, and Th) were taken on standing dead woods and the status. Tree variables (Dbh, Db, Dm, Dt and Th) were measured on lying dead wood. The part of a lying dead wood outside sample plot boundaries was not measured. This was to minimize errors and mix-ups (FAO, 2020).

The tree decomposition (decay) class was determined as follows: Class 1 – branches and twigs still on the standing dead trees that resemble live trees (except for the absence of leaves). Class 2 - signs of decomposition were observed or exist, with loss of twigs, branches and crown. A "machete" test was used to assign deadwood (standing or lying) to one of three decay categories: (i) sound (S), (ii) intermediate (I) or (iii) rotten (R), by striking the wood with a machete (IPCC, 2003; FAO, 2020). The decay status of the dead wood was classified as category 1- sound produced when the machete bounced back when it was used to strike the dead wood; category 2 - intermediate: if the machete slightly enters the dead wood; category 3 - rotten: if the dead wood turns into pieces and crumbles when hit by the machete, showing that the tree had rotten (IPCC, 2003). For lying dead wood, measurements were obtained for the diameter at the base (Dbase), the diameter at the top (Dtop), and the deadwood length (L). The *Smalian* formula was used to calculate deadwood volumes based on these observations and converted to biomass using the decay class values obtained.

$$\mathrm{V} = (\pi/4) \times (D^2 + d^2) \times L \qquad [1a]$$

Where: V = volume of the tree or log, D = diameter of the large end, d = diameter of the small end, L = length of the tree or log, π = mathematical constant approximately equal to 3.14159

Core samples (of live trees) at diameter breast height for each tree species were extracted (from bark to pith) as reported by Martin and Thomas (2011). An increment borer was used to extract the core samples. Within 24 hours of removing the bark from the cores, for each core sample, lengths were measured, and the weights were weighed (as fresh weight) on a digital electronic weighing balance before being tagged and placed in a transparent nylon bag for further examination at the laboratory.

Soil samples were systematically collected using a soil auger at random depths of 0-20 cm within a nested plot (large, intermediate, and small plots, all mixed to form a composite sample) and replicated thrice. The 20 cm depth for soil accommodates mobile nutrients (Amonum *et al.,* 2020). The soil samples were appropriately labelled and placed in polythene bags for easy identification. Before laboratory analysis, samples were air-dried, crushed (with a mortar and pestle), and sieved at a size of 2 mm.

3.2.4 Laboratory procedure

The litter collected was oven-dried at 70 °C until a constant weight was attained, while the dead wood samples were oven-dried at 105°C until a constant weight was attained. Core samples were oven-dried to constant weight (final weight) at 70 °C (Williamson and Wiemann 2010) and weighed with an electronic balance. The final weight (a constant weight) divided by the initial weight (fresh mass) for each core sample of species will give the wood density (Chave *et al.,* 2005; Navarro *et al.,* 2013).

The Soil Science laboratory at the Nasarawa State University, Lafia campus, Nigeria, was utilized to analyze soil physicochemical properties and soil carbon. During the soil routine analysis, standard laboratory procedures were followed. The Boyoucos hydrometric method was used to determine particle size fractions for soil texture (Bouyoucos, 1962; Day, 1965; Gee and Bauder, 1986). The pH of the soil was evaluated using a glass electrode and a 1:1 (soil solution ratio) suspension of water (H2O) and potassium chloride (1M KCl) (Van Reeuwijk, 1992). Soil organic carbon was determined using the wet-oxidation method described by Walkley and Black (1934). The Kjeldahl digestion was used to determine the total nitrogen.

3.3 Data processing and analyses

Data that were collected from the study area were used to compute the following:

3.3.1 Tree species composition and distribution

Diversity indices of tree species were determined, the indices computed include (I) Family richness, (ii) Family relative density, (iii) species relative density, (iv) species relative dominance, (v) species richness, (vi) Shannon-Wiener diversity index, (vi) species evenness (vii) Importance Value Index with soft-wares (PAST version 2.14 and MS Excel 2010) (Turyahabwe and Tweheyo, 2010; Adekunle *et al.,* 2013; Spellerberg, 1991; Magurran, 2004).

3.3.2 Basal area

Equation [1] was used to compute the basal area of all trees. Total plot BA was calculated by summing the basal areas of all trees in the plot. The mean basal area was calculated by adding all the plots' basal areas and dividing the result by the number of sample plots. The mean plot basal area was multiplied by the number of sample plots in one hectare to get the basal area per hectare.

$$\mathrm{BA} = \frac{\pi D^2}{4} \qquad \text{Equation} \qquad [1]$$

Where: BA is the basal area (m2); D is the diameter at breast height (cm); π is 3.142.

3.3.3 Volume Estimations

i. Volume over bark (VOB) of individual trees was computed with Newton formula [Equation 2], this relates tree volume to the tree's measurable attributes such as Dbh, diameter at the base, middle top and total height (Husch *et al.,* 2003).

$$V=\frac{\pi Th}{24}\mathrm{Db}^2+4\mathrm{Dm}^2+\mathrm{Dt}^2) \qquad \text{Equation} \qquad [2]$$

Where: V= volume; Db, Dm and Dt = diameters at base, middle and top, respectively; h = total height; π =3.142.

Summing up the volumes of all trees in the plot gave the total plot volume. Summing up the volumes of all plots and dividing the result by the number of sample plots yields the mean plot volume. By multiplying the mean plot volume by the actual number of sample plots in one hectare, volume per hectare was computed.

ii. The volume of tree core samples was calculated by the dimension method using the equation by Chave *et al.* (2005), thus:

$$\text{corevolume}\,\frac{\pi D^2}{4}\mathrm{l} \qquad \text{Equation} \qquad [3]$$

Where: π =3.142; D= diameters of the borer, l =core length (m).

3.3.4 Wood density

i. The density of the core samples was calculated using Equation 4.

Wood specific gravity (Wood density)

$$\rho\left(\frac{\mathrm{g}}{\mathrm{cm3}}\right)=\frac{\mathrm{DW(g)}}{\mathrm{VFW(cm3)}} \qquad \text{Equation} \qquad [4]$$

Where: *p* is wood-specific gravity*;* DW is dry weight; VFW is the volume of core samples.

ii. Decayed wood density: If there is a sign of decay (including loss of twigs, branches and crowns), the density of decayed stems was determined using an intact level (known as

Percentage Weight Lost). To account for the lost or decayed branches, leaves and twigs, a correction factor of 0.9 (for a dead tree without leaves), 0.8 (for a dead tree without leaves and twigs) and 0.7 (for a dead tree without leaves, twigs and branches) for biomass estimation were used (Jae Soo *et al.,* 2014; FAO, 2020).

3.3.5 Biomass Estimation

i. Tree biomass: computing biomass for each tree (live trees, standing dead trees, and lying dead trees) in the study area was calculated using equation [5] (IPCC, 2006b):

$$\mathrm{B} = \mathrm{VOB} \times \mathrm{WD} \qquad \text{Equation} \qquad [5]$$

Where: B is biomass (kg/ha); VOB is volume over bark (m^3/ha); WD is wood density (kg/m^3).

This method excludes non-merchantable components (tree branches, twigs, and leaves). To make up for this shortcoming, the Biomass Expansion Factor (BEF) was used to account for the non-merchantable components of the live trees. This was done by multiplying the estimated biomass with a constant of 1.74 if the biomass volume is greater than 190 t/ha as reported by IPCC (2006a). However, BEF was computed if biomass is less than 190 t/ha using the equation proposed by IPCC (2006a) and stated in equation 6:

$$\mathrm{BEF} = \mathrm{Exp}\{(3.213 - 0.506 * \mathrm{Ln}(\mathrm{BV})\} \qquad Equation \qquad [6]$$

Where: BEF is Biomass Expansion Factor; Ln is natural log; BV is biomass volume

ii. Above-ground biomass (AGB): The AGB of trees (live trees, standing dead trees, and lying dead trees), litter, stumps, and low vegetation from the study area were computed using the fitted modified allometric function. Thus, plot AGB was calculated as the summation of the AGB of all individual trees within each sample plot, and AGB per hectare will then be obtained by multiplying the mean AGB per plot by the number of sample plots in a hectare. The estimated AGB per hectare was multiplied by the total number of hectares per forest type.

iii. Below-ground biomass (BGB): The below-ground biomass was estimated by multiplying AGB with a constant ratio (0.26) using the root-shoot ratio developed by IPCC (2006b).

iv. Total Biomass (TB): Total biomass was estimated by summing the below-ground and Above-ground biomass as demonstrated by equation 7.

$$\mathrm{TB} = \mathrm{AGB} + \mathrm{BGB} \qquad \text{Equation} \qquad [7]$$

v. Carbon Stock (CS): Tree carbon stock was computed as 50% of the biomass (Brown *et al.,* 1989; Bhat and Ravindranath, 2011; Timilsina *et al.,* 2014). Thus, the coefficient of 0.5 for the conversion of tree biomass to carbon, as recommended by Meragiaw *et al.* (2021) and Fonseca *et al.* (2012) was used for conversions of biomass to carbon stock:

$$\mathrm{Carbonstock} = \mathrm{TB\ X\ 0.5\ or} \left(\frac{\mathrm{TB}}{2}\right) \qquad \text{Equation} \qquad [8]$$

The dry biomass of low vegetation in the area was converted to carbon concentration by considering the proportion of 47% (IPPCC, 2006a); for litter and grasses, the carbon stock was considered as 44.36% (de Oliveira *et al.,* 2019). Carbon stock (CS) per plot was estimated as the summation of the CS of all individual trees within each sample plot, and CS per hectare will then be obtained by multiplying the mean CS per plot by the number of sample plots in a hectare. To get the carbon contents for each forest type, the estimated carbon contents per hectare were multiplied by the total number of hectares.

3.4 Model calibration and validation

A greater percentage of the data (70-75%) was utilized to calibrate the volume model, while a smaller fraction (25-30%) was saved for validation (Muchoney and Strahler, 2002; Zeng *et al.,* 2014). Different volume model forms were fitted into the data to compute species-generic volume for trees with missing total height in the study area. Even though tropical forests often have 300 or more species, research has proven that species-specific relationships (models) are not required to generate credible estimations of forest biomass or carbon stocks (Daba and Soromessa, 2019). The diameter at breast height alone might explain more than 95% of the diversity in tropical forests (Gibbs *et al.,* 2007). The generic-species volume model was utilized due to its ability to simplify estimating wood volume, eliminating the need for complex species-specific models. This approach allows for generalization across different species in mixed-species forests.

3.4.1 Model calibration

Regressing a dependent variable (i.e., volume) against one independent variable (Dbh) was used to calibrate the volume model. The volume and Dbh data were fitted to the different model forms (Table 3.1) to select the best-performing form.

Table 3.1: Calibrated Model for Tree Volume across the Forest Management Types in Benue, State Nigeria

Model type	Model Form	References
Logistic power [1]	$V = \frac{b_0}{\left(1 + \left(\frac{Dbh}{b_1}\right)^{b_2}\right)}$	Mehtätalo *et al.* (2015)
Weibull [M2]	$V = b_0 - b_1 * \exp(Dbh^{b_2})$	Bailey (1979)
Gompertz relation model [M3]	$V = b_0 * \exp(-\exp(b_1 - b_2 * Dbh))$	Gompertz (1825)
Ratkowsky [M4]	$V = \frac{b_0}{(1 + \exp(b_1 - b_2 * Dbh))}$	Ratkowsky (1990)
Simple linear regression [5]	$V = b_0 + b_1 * D\text{bh}$	Lockhart *et al.* (2005)

Polynomial [M6]	$\mathrm{V} = b_0 + b_1 * D\mathrm{bh} + b_2 * Dbh^2 + b_3 Dbh^3$	-
Power [M7]	$= b_0 * Dbh^{b_1}$	Batista *et al*. (2001); Fang and Bailey (1998
Single logarithm [8]	$\mathrm{V} = b_0 \,\mathrm{Ln}(b_1 * Dbh)$ equation	-
Reciprocal [9]	$\mathrm{V} = \frac{b_0 + b_1}{Dbh}$	-

3.4.2 Criteria for model selection

The models that were fitted were evaluated and the ones suitable for estimation were chosen according to specific criteria to determine their suitability for future use. The performance of each model was ranked, and the best-performed model in the overall rank was selected. The assessment was based on all the following criteria:

i. The significance of the regression equation (F-ratio) indicates whether the models can be accepted for biomass estimation. The model should be significant ($p < 0.05$) to be accepted and valid for estimation. If the computed F is less than F-tabulated, the model was significant.

ii. The coefficient of determination (R^2) indicates how well the regression line fits the data (Foli *et al.,* 2003). It calculates the percentage of variance in dependent variables that can be explained by changes in the independent variable (s). R^2 always has a value between 0 and 1. To express it in percentage, it is commonly multiplied by 100.

iii. The Root Mean Square Error (RMSE) is also known as the error variance standard deviation or the total standard error of estimate; the lower the RMSE, the better the model.

It is a measure of the data spread and hence an indication of the precision of the projected response; the lower the RMSE, the better the model. This model selection criterion is acceptable. The RMSE of the model with log-transformed dependent variables is lower than that of the model with untransformed dependent variables. Thus, to be able to compare the RMSEs of log-transformed and untransformed models, the Furnival index (Furnival index, 1961) was computed and used (Vanclay, 1994; Phillip, 1994); the Furnival index adjusts the standard error of the regression to facilitate the comparison.

The following is how the Furnival Index was calculated; for each model under consideration, analysis of variance was used to calculate the value of the square root of the error mean square. For each model, the geometric mean of the derivative of the dependent variable for y was calculated using the observations. The nth root of the product of the observations is used to get the geometric mean of a set of n observations. The Furnival index for each model is then calculated by multiplying the square root of mean square error values with the inverse of the geometric mean. as thus:

$$\text{Furnivalindex} = \sqrt{MSE}\left(\frac{1}{Geometricmean(y^{-1})}\right)\text{Equation}[10]$$

iv. Akaike's Information Criteria (AIC) The AIC can be termed as a measure of the goodness of fit of any estimated statistical model. It tries to select the model that most adequately describes an unknown, high-dimensional reality. This means that reality is never in the set of candidate models that are being considered (Prabhat, 2010).

v. Bayesian Information Criteria (BIC) is widely used in model selection criteria, it tries to find the true model among the set of candidates. The BIC is a type of model selection among a class of parametric models with different numbers of parameters. BIC measures the extent of shrinkage, which involves data values moving closer to a central point like the mean. BIC measure shrinkage results in simple, sparse models which are easier to analyze than high-dimensional models with many parameters. BIC penalizes free parameters more strongly. A free parameter is a variable in a mathematical model which cannot be predicted precisely or constrained by the model and must be estimated experimentally or theoretically (Prabhat, 2010). It can also be said that BIC is consistent whereas AIC is not so. BIC is more tolerant when compared to AIC, it shows less tolerance at higher numbers (Prabhat, 2010).

3.4.3 Model validation

Validation is the construction of an acceptable level of confidence that a conclusion about a modelled process is valid about the actual process (Ajayi and Odey, 2012). Thus, 25-30 % of data from the study area was used (independent of those used to develop the model) for model validation. Model validation would be done by determining the difference between the volume observed and estimated (by the chosen models), then subjected to analysis using a paired t-test ($\alpha = 0.05$); this will check the plausibility, accuracy, and performance of the model's basis. Careful inspection of the model output and behaviour was examined based on normal probability plots.

3.5 Statistical Analyses

Analysis of Variance (ANOVA) was used to test significant differences in the biomass accumulation and carbon contents of three forest management types (CFAs, FRs, and SGs) under investigation. Biomass and carbon contents of the different forest types made up the treatment. The Tukey post hoc test was used for the follow-up test when treatment means were significantly different at 0.05 levels. Pearson matrix correlation was used to determine the relationship between biomass and forest types and between the physic-chemical properties of soil and forest types. Descriptive statistics were used to describe the data structure of the forest types in the area.

CHAPTER FOUR

4.0 RESULTS

4.1 Biological Diversity of the Different Forest Management Types

4.1.1 Family Importance Value Index (FIV)

The results of the Family Importance Value Index (FIV) for dominant families in the different forest types (Table 4.1) show a total of 25, 16 and 24 tree families were enumerated in the Community Forest Area (CFA), Forest Reserve (FR) and Sacred Groves (SG), respectively (Table 4.1), revealing that CFA and SG had similar family density, both of which were higher than the number of families found in FR. Only a few tree families were recorded to be important across the three forest management types investigated in this study, these are Caesalpinioideae, Euphorbiaceae, Moraceae, and Fabaceae (Table 4.1). Other families were found to be important in only one or two of the three forest management types.

The Malvaceae family was the most important in the CFA forest management type, with an FIV of 13.97 % and had the highest basal area of 13.96 m² ha^{-1}, indicating that the tree species belonging to this family contributed substantially to total basal area production in this forest management type. Other tree families that are very important in the floristic composition of the CFA include Anacardiaceae, Caesalpinioideae and Moraceae (Table 4.1). Within the FR forest management type, the Verbenaceae family had the highest FIV value of 29.96 %, thus, making it the most important family in this forest type. The family with the highest FIV contributed the highest total basal area in the FR forest management type. Table 4.1 reveals that the Verbenaceae family had the highest basal area of 14.81 m² ha^{-1} in FR. Other important families in the FR were Caesalpinioideae, Fabaceae and

Rubiaceae. Similarly, the family with the highest FIV in SG had the highest total basal area production. While the Fabaceae family had the highest FIV of 11.98 % under SG management type, the highest basal area of 9.64 m^2ha^{-1} was recorded by members of the Fabaceae family (Table 4.1). In addition, the Annonaceae, Sterculiaceae and Caesalpinioideae families were recorded to be very important in the floristic composition of SG forest management type.

Except in CFA, the most important families (i.e. families with the highest FIV in each forest type) in the three forest types did not make the highest contribution to total stand volume production. For example, in FR and SG, the most important families were Verbenaceae and Fabaceae, respectively, but the highest contributors to total stand volume production were Meliaceae (8.49 m^3 ha^{-1}) and Bignoniaceae (7.60 m^3 ha^{-1}), respectively (Table 4.1). With the volume production of 13.64 m^3 ha^{-1}, the Anacardiaceae family was the highest contributor to total stand volume production in the three forest management types, which had recorded 4 tree species investigated in this study. The results of family RDo in the three forest management types indicated that families with the highest FIV also doubled as those with the highest relative dominance (RDo), except in the CFA where the Anacardiaceae family had the highest FIV of 13.94%, however, the Malvaceae had the highest RDo of 22.68% (Table 4.1). Under the FR and SG forest types, the most important families of Verbenaceae and Fabaceae, had the highest relative dominance of 53.24 % and 15.85%, respectively.

Table 4.1: Family Importance Value Index (FIV) of Dominant Families in the Study Area

Family	No. of species	BA (m^2/ha)	Vol. m^3/ha	R.D (%)	R. Do (%)	FIV (%)
			CFA			
Anacardiaceae	4	10.43	13.64	10.53	16.95	13.74
Caesalpinioideae	4	3.46	5.09	10.53	5.62	8.08
Euphorbiaceae	3	1.91	7.21	7.89	3.10	5.50
Fabaceae	3	1.18	9.38	7.89	1.92	4.91
Loganiaceae	2	0.26	9.14	5.26	0.42	2.84
Malvaceae	2	13.96	8.36	5.26	22.68	13.97
Moraceae	3	4.15	9.45	7.89	6.74	7.32
Verbenaceae	2	3.27	8.64	5.26	5.31	5.29
Total	23	38.62	70.91	60.5	62.74	61.63
			FR			
Acanthaceae	2	0.09	8.25	6.67	2.52	4.60
Caesalpinioideae	4	4.31	8.24	13.33	15.49	14.41
Fabaceae	5	1.08	7.56	16.67	3.88	10.28
Loganiaceae	2	1.92	7.63	6.67	6.90	6.79
Meliaceae	2	0.43	8.49	6.67	1.55	4.11
Moraceae	2	0.08	7.03	6.67	0.29	3.48
Rubiaceae	3	0.65	3.27	10.00	2.34	6.17
Verbenaceae	2	14.81	8.24	6.67	53.24	29.96
Total	22	23.37	58.71	73.35	86.21	79.78
			SG			
Anacardiaceae	2	2.61	5.32	5.41	4.29	4.85
Annonaceae	3	3.33	4.76	8.11	5.47	6.79
Bignoniaceae	3	1.73	7.6	8.11	2.84	5.48

Caesalpinioideae	2	5.11	5.07	5.41	8.40	6.91
Combretaceae	2	3.44	6.45	5.41	5.66	5.54
Euphorbiaceae	3	1.5	4.88	8.11	2.47	5.29
Fabaceae	3	9.64	6.04	8.11	15.85	11.98
Moraceae	3	1.42	6.02	8.11	2.33	5.22
Total	21	28.78	46.14	56.78	47.31	52.05

Where: BA is basal area per hectare, R.D is species relative density, R.Do is species relative dominance, FVI is family importance value index.

4.1.2 Tree Species Composition and Abundance

A total of 1,881 individual trees from 73 tree species belonging to 35 families were identified in the three forest management types (CFA, FR and SG) in Benue State of Nigeria (Table 4.2). Most tree species were Indigenous species, and a few exotic tree species such as *Gmelina arborea, Tectona grandis,* and *Albizia lebbeck* were found in the study forests. While *Gmelina arborea* occurred at all three forest management types, *Tectona grandis* was only found at the CFA and *Albizia lebbeck* was only found in FR (Table 4.2). Results in Table 4.2 reveal that a few tree species (e.g. *Khaya senegalensis, Gmelina arborea, Dialiumguineense, Daniellia oliverii,* and *Afzelia africana)* were present in all three management types, however, their frequency and distribution percentages varied. For example, *Khaya senegalensis* occurred 3 times in CFA, accounting for 0.64% of all the trees identified in that area. It occurred 10 times in FR, with a total of 1.41% of all the trees surveyed, and 84 times in SG, making up 14.7% of all the trees surveyed in SG.

For *Gmelina arborea,* there were 46, 296 and 63 individuals in CFA, FR and SG, respectively, accounting for 9.79%, 41.75% and 11.0% of all trees in the respective forest types. There were 16 occurrences of *Dialiumguineense* in CFA (3.40%), 24 in FR (3.39%), and 88 in SG (15.4%). There were 7 observations of *Daniellia oliverii* in CFA (1.49%), 114 observations in FR (16.08%), and 24 observations in SG (4.2%). For *Afzelia africana,* 29 individuals (5.1%), 9 (1.27%) and 1 (0.21%) were enumerated in SG, FR and CFA, respectively (Table 4.2).

Some tree species were identified in two forest types. For example, 2 individuals of *Strychonos spinosa*was were observed in CFA, which represented 0.43% of the total number of trees in that forest type, while it was enumerated 49 times in FR, accounting for 6.91% of all trees surveyed, but was not identified in SG (Table 4.2). Only SG and FR were found to have *Afrormosia laxiflora* and *Albizia lebbeck,* respectively. Other tree species that were found to occur in two of the tree forest management types were *Ceiba pentandra, Bombax buonopozense, Erythrophleum suaveolens, Ficus sur, Isoberlinia doka,* and *Spondias mombin,* among others (Table 4.2).

Most of the tree species (about 66%) identified in the three forest management types were enumerated in only one of the three forest types (Table 4.2). For example, although *Burkea africana* was found to occur 46 times in FR (accounting for 6.59% of the total observations in that forest type), the species was neither enumerated in CFA nor SG (Table 4.2). Some of the tree species with a relatively high frequency of observations in only one of the three forest management types are: *Sterculia setigera* (CFA: 64)*, Cola gigantea* (SG: 45)*, Anogeissus leiocarpa* (CFA: 33)*, Tectona grandis* (CFA: 32), *Spondias mombin* (CFA: 28) and *Prunus Africana* (CFA: 27). *Acanthus montanus, Aleurites moluccanus, Allophylus africanus*, *Anogeissusleiocarpa*, *Bobgunnia madagascariensis, Eugenia uniflora* among others were only identified in CFA (Table 4.2).

Table 4.2: Tree Species Occurrence and Percent Frequency across Forest Management Types in the Study Area

S/N	Species	Families	CFA		FR		SG	
			Freq. (Count)	Freq. (%)	Freq. (Count)	Freq. (%)	Freq. (Count)	Freq. (%)
1	*Acanthus montanus*	Acanthaceae	6	1.28	-	-	-	-
2	*Afzelia Africana*	Caesalpiniodea	1	0.21	9	1.27	29	5.1
3	*Afrormosia laxiflora*	Papilionoideae	-	-	-	-	1	0.2
4	*Albiziak, lebbeck*	Caesalpiniodeae	-	-	18	2.54	-	-
5	*Aleurites moluccanus*	Euphorbiaceae	2	0.43	-	-	-	-
6	*Annona senegalensis*	Annonaceae	-	-	1	0.14	16	2.8
7	*Alchornea cordifolia*	Euphorbiaceae	-	-	-	-	8	1.4
8	*Allophylus africanus*	Sapindaceae	6	1.28	-	-	-	-
9	*Anthocleista djalonensis*	Loganiaceae	-	-	11	1.55	-	-
10	*Anogeissusleiocarpa*	Combretaceae	33	7.02	-	-	-	-
11	*Annona squamosa*	Annonaceae	-	-	-	-	10	1.7
12	*Anthocleista djalonensis*	Loganiaceae	1	0.21	-	-	-	-
13	*Anthocleista nobilis*	Loganiaceae	-	-	-	-	8	1.4
14	*Antidesma venosum*	Phyllanthaceae	2	0.43	-	-	-	-
15	*Artocarpus altilis*	Moraceae	-	-	-	-	14	2.4
16	*Bobgunnia madagascariensis*	Fabaceae	1	0.21	-	-	-	-
17	*Bombax buonopozense*	Bombacaceae	4	0.85	1	0.14	-	-
18	*Burkea Africana*	Caesalpinioideae	-	-	46	6.49	-	-
19	*Canarium schweinfurthii*	Burseraceae	-	-	-	-	8	1.4
20	*Ceiba pentandra*	Malvaceae	4	0.85	-	-	9	1.6
21	*Cola gigantea*	Sterculiaceae	-	-	-	-	45	7.9
22	*Combretum nigricans*	Combretaceae	-	-	-	-	4	0.7

Where CFA is Community Forest area, FR is Forest Reserve, SG is Sacred Grove, - is not present.

Table 4.2: Continued

S/N	Species	Families	CFA		FR		SG	
			Freq. (Count)	Freq. (%)	Freq. (Count)	Freq. (%)	Freq. (Count)	Freq. (%)
23	*Crescentia cujete*	Bignoniaceae	2	0.43	-	-	-	-
24	*Crossopteryxfebrifuga*	Rubiaceae	-	-	-	-	8	1.4
25	*Daniellia oliverii*	Caesalpinioideae	7	1.49	114	16.08	24	4.2
26	*Detarium microcarpum*	Fabaceae	1	0.21	2	0.28	-	-
27	*Dialiumguineense*	Fabaceae	16	3.40	24	3.39	88	15.4
28	*Elaeis guineensis*	Palmaceae	64	13.62	-	-	34	5.9
29	*Erythrophleum suaveolens*	Euphorbiaceae	8	1.70	49	6.91	-	-
30	*Eugenia uniflora*	Myrtaceae	23	4.89	-	-	-	-
31	*Ferruginous bridelia*	Euphorbiaceae	-	-	-	-	4	0.7
32	*Ficus exasperate*	Moraceae	-	-	-	-	1	0.2
33	*Ficus platyphylla*	Moraceae	4	0.85	-	-	-	-
34	*Ficus sur*	Moraceae	7	1.49	2	0.28	-	-
35	*Ficus sycomorus*	Moraceae	-	-	2	0.28	-	-
36	*Fluggea virosa*	Euphorbiaceae	1	0.21	-	-	-	-
37	*Gmelina arborea*	Verbenaceae	46	9.79	296	41.75	63	11.0
38	*Hannoa undulata*	Simarcubaceae	11	2.34	-	-	-	-
39	*Hura crepitans*	Euphorbiaceae	-	-	-	-	6	1.0
40	*Hymenocardiaacida*	Hymenocardiaceae	-	-	-	-	8	1.4
41	*Irvingia gabonensis*	Irvingiaceae	-	-	-	-	2	0.3
42	*Isoberlinia doka*	Caesalpiniodeae	7	1.49	1	0.14	-	-
43	*Khaya grandiflora*	Meliaceae	-	-	4	0.56	-	-
44	*Khaya senegalensis*	Meliaceae	3	0.64	10	1.41	84	14.7
45	*Kigelia africana*	Bignoniaceae	2	0.43	-	-	4	0.7

Where CFA is Community Forest area, FR is Forest Reserve, SG is Sacred Grove, - is not present.

Table 4.2: Continued

S/N	Species	Families	CFA		FR		SG	
			Freq. (Count)	Freq. (%)	Freq. (Count)	Freq. (%)	Freq (Count)	Freq. (%)
46	*Landolphia owariensis*	Apocynaceae	4	0.85	-	-	-	-
47	*Lannea spp*	Anacardiaceae	3	0.64	1	0.14	-	-
48	*Lophira lanceolata*	Rubiaceae	-	-	7	0.99	-	-
49	*Maranthes polyandra*	Chrysobalanaceae	-	-	9	1.27	-	-
50	*Markhamia tomentosa*	Bignoniaceae	-	-	-	-	12	2.1
51	*Milicia excelsa*	Moraceae	10	2.13	-	-	5	0.9
52	*Mitragyna inermis*	Rubiaceae	3	0.64	1	0.14	-	-
53	*Monotes kerstingii*	Dipterocarpaceae	-	-	-	-	9	1.6
54	*Newbouldia laevis*	Bignoniaceae	-	-	-	-	18	3.1
55	*Parkia biglobosa*	Mimosaideae	-	-	-	-	5	0.9
56	*Prosopis africana*	Fabaceae	-	-	-	-	10	1.7
57	*Prunus africana*	Rosaceae	27	5.74	-	-	-	-
58	*Pterocarpus erinaceus*	Fabaceae	-	-	7	0.99	-	-
59	*Sarcocephalus latifolius*	Rubiaceae	-	-	6	0.85	-	-
60	*Senna siamea*	Fabaceae	-	-	4	0.56	-	-
61	*Spondias mombin*	Anacardiaceae	28	5.96	-	-	12	2.1
62	*Sterculia setigera*	Malvaceae	64	13.62	-	-	-	-
63	*Stereospermum kunthianum*	Apocynaceae	-	-	1	0.14	-	-
64	*Strophanthus hispidus*	Apocynaceae	-	-	2	0.28	-	-
65	*Strychonos spinosa*	Loganiaceae	2	0.43	49	6.91	-	-
66	*Tectona grandis*	Lamiaceae	32	6.81	-	-	-	-
67	*Terminalia macroptera*	Combretaceae	-	-	-	-	21	3.7

Where CFA is Community Forest area, FR is Forest Reserve, SG is Sacred Grove, - is not present.

Table 4.2: Continued

S/N	Species	Families	CFA		FR		SG	
			Freq. (Count)	**Freq. (%)**	**Freq. (Count)**	**Freq. (%)**	**Freq (Count)**	**Freq. (%)**
68	*Tetrapleura tetraptera*	Fabaceae	5	1.06	-	-	-	-
69	*Trema orientale*	Ulmaceae	14	2.98	-	-	-	-
70	*Uapaca heudelotii*	Phyllanthaceae	-	-	-	-	1	0.2
71	*Uvariachamae*	Annonaceae	10	2.13	-	-	1	0.2
72	*Vitellaria paradoxa*	Sapotaceae	-	-	1	0.14	-	-
73	*Vitex doniana*	verbenaceae	6	1.28	31	4.37	1	0.2
		Total	**470**	**100.00**	**709**	**100.00**	**573**	**100.00**

Where CFA is Community Forest area, FR is Forest Reserve, SG is Sacred Grove, - is not present.

4.1.3 Tree Species Richness

The Margalef index quantifies species richness based on the number of species and individuals sampled, based on species abundance. The Margalef index estimated for the various forest management types in this study ranged from 4.11 to 6.01, with the CFA having the highest richness index, Sacred grove having a Margalef index of 5.34, FR area having the lowest Margalef index value of 4.11 (Table 4.3). The FR management type exhibited the lowest Margalef index value, thus indicating lower species richness. Compared to the Margalef indices of CFA and FR, the SG had an intermediate level of species richness.

The trend of Margalef index of tree species richness (i.e. CFA > SG > FR) aligned with the trend of number of species in the three forest types (38, 35 and 28 in CFA, SG and FR, respectively) (Table 4.3), thus confirming the trend in tree species richness in the three forest management types. The result of the analysis of variance (Table 4.3) indicated a significant difference between the Margalef index of the three forest management types in this study. The Margalef indices of CFA (6.01) and SG (5.34) were statistically similar ($p>0.05$) (Table 4.3). However, the Margalef index of CFA and SG were significantly higher than the value of the index recorded for FR (4.11).

Table 4.3: Tree Species Diversity Indices for the Different Forest Management Types

Indices	Community Forest Area	Forest Reserve	Sacred Groove
No. of sampled trees	470^{c}	709^{a}	573^{b}
Taxa_S	38^{a}	28^{c}	35^{b}
Family	24^{a}	16^{b}	24^{a}
Dominance_D	0.07^{c}	0.22^{a}	0.08^{b}
Simpson_1-D	0.93^{a}	0.78^{b}	0.92^{a}
Shannon_H	3.00^{a}	2.11^{b}	2.97^{a}
Evenness_e^H/S	0.53^{a}	0.29^{b}	0.55^{a}
Menhinick	1.75^{a}	1.05^{c}	1.45^{b}
Margalef	6.01^{a}	4.11^{c}	5.34^{b}
Equitability_J	0.83^{a}	0.63^{b}	0.85^{a}
Fisher_alpha	9.76^{a}	5.82^{b}	8.17^{a}

Ecology Indices across the forest management types with different superscripts are significantly different ($p \leq 0.05$)

4.1.4 Tree Species Evenness

The pattern of evenness of tree species in the three forest management types was found to vary widely, with a range of 0.29 to 0.55 (Table 4.3). The highest evenness value of 0.55 was recorded in SG, slightly higher than for species within the CFA (0.53) (Table 4.3), indicating a similarity in species distribution under the two forest management types. The lowest species evenness value of 0.29 was obtained for the Forest Reserve, indicating a high disparity of tree species distribution in FR compared to the SG and CFA. Thus, there is a less balanced distribution of individual tree species in FR, an indication of the dominance of this forest type by a few tree species. Similarly, SG and CFA had the highest equitability index of 0.85, indicating a more equitable species distribution within the ecosystem.

The Community Forest Area had an equitability index of 0.83, indicating an equitable distribution of tree species as was recorded in SG. The lowest equitability index of 0.63 was obtained in FR, suggesting a lower equitable species distribution within this forest type (Table 4.4). The species evenness index of SG (0.55) and CFA (0.53) were not statistically different. The species evenness index of CFA and SG were significantly higher than the value of the index recorded for FR (0.29) (Table 4.3). The equitability index significantly differed across the three forest types, CFA and SG having no significantly different equitability index (0.83 each), and FR had an equitability index significantly lower than those of the other forest types (i.e. CFA and SG).

4.1.5 Tree Species Diversity and Density

Based on the total individual trees, 749 were sampled from FR, 621 from SG, and 511 from the CFA (Table 4.3). Twenty-eight (28) tree species were recorded in the FR, and 35 species were found in SG. while 38 different species were identified in the CFA in this study (Table 4.3). Thus, the CFA had the highest number of identified tree species, closely followed by that found in the SG while the lowest number of tree species was recorded in the FR forest management type (Table 4.3). The Shannon-Wiener species diversity index (H') for CFA (3.00) and SG (2.97) was not statistically different ($p>0.05$). The H' for CFA and SG were significantly higher ($p<0.05$) than the value recorded for FR (2.11) (Table 4.3). Tree species density was statistically different ($p<0.05$) across the forest types. FR had a significantly higher ($p<0.05$) tree density of 709, compared to the

densities of 573 and 470 for SG and CFA, respectively, while SG had a significantly higher tree density than CFA (Table 4.3).

Tree species diversity in the three forest management types was investigated using Shannon-Wiener and Simpson diversity indices. Generally, tree species diversity was highest within the CFA, followed by SG and FR, which had the lowest species diversity. While the Shannon-Wiener diversity index ranged from 2.11 to 3.00, the Simpson diversity index ranged from 0.78 to 0.93 (Table 4.3). The results indicated that the diversity of species found within CFA and SG were similar, judging from their similar Shannon-Wiener and Simpson diversity indices (Table 4.3). Tree species in the FR were less diverse than species in the CFA and SG.

Statistical analysis showed variances in Simpson and Shannon-Wiener diversity among the three forestry management types (Table 4.3). The tree species diversity in both CFA and SG was not significantly different. However, the diversity of species in the two forest types was significantly higher than the diversity indices of the FR (Table 4.3), indicating that CFA and SG supported richer and more diverse tree communities than FR.

The degree of variation in species composition was measured using the similarity index. The results indicated that the similarity in species compositions between any two of the forest management types ranged from 58% to 73% (Table 4.4). The species composition of CFA and FR were the least similar, with a similar index value of 58%. This indicates that about 42% of the species compositions in the CFA and FR were specific to each forest management type, while the others (58%) were common to both. There was a similarity index of 64% between CFA and SG, which indicated a marginally higher species composition similarity between these two forest types (i.e. CFA and SG) compared to the species similarity between CFA and FR (Table 4.4). The results indicated that the highest species diversity value of 73% was obtained between FR and SG (Table 4.4), suggesting that the similarity of tree species compositions between FR and SG was higher than between any other pair of forest management types investigated in this study.

Table 4.4: Similarity Index (%) for the different Forest Management Types

Forest Management type	**Species Similarity Index (%)**		
	Community Forest Area	**Forest Reserve**	**Sacred Groove**
Community Forest Area (CFA)	-	-	-
Forest Reserve (FR)	58	-	-
Sacred Groove (SG)	64	73	-

4.1.6 Tree Species Relative Dominance and Relative Density

The relative dominance (RDo%) values indicate the degree with which each tree species dominates the ecosystem being investigated. *Anogeissusleiocarpa, Gmelina arborea, Milicia excelsa, Spondias mombin, Sterculia setigera, Tectona grandis and Uvariachamae* were identified as tree species with high RDo values of ≥ 5.0 in the CFA (Table 4.5). *Daniellia oliverii, Erythrophleum suaveolens, Gmelina arborea, Strychonos spinosa,* and *Vitex doniana* dominated the FR. In the SG, *Afzelia africana, Ceiba pentandra, Cola gigantea, Daniellia oliverii, Dialium guineense*, *Gmelina arborea, Khaya senegalensis,* and *Terminalia macroptera* were the tree species with high RDo. *Gmelina arborea* stood out with the highest relative dominance at 49.5 % in FR; however, in comparison, the species had a much lower RDo of 7.12 and 5.02% at SG and CFA, respectively.

The presence of *G. arborea* across the three forest types indicated its importance and influence in the study area. Tree species with low RDo values simultaneously in two forest types include *Detarium microcarpum* and *Mitragyna inermis* in CFA and FR; *Kigelia africana* was the only tree species with a low RDo value in CFA and SG. There was no tree species with low RDo values across the three forest types (Table 4.5). *Detarium microcarpum* was estimated to have an RDo of 0.04 and 0.20 in CFA and FR, respectively. *Mitragyna inermis* showed a low RDo of 0.08% in CFA and 0.05% in FR. *Kigelia africana* had RDo of 0.16 and 0.9% in CFA and SG, respectively.

In CFA, *Sterculia setigera* had the highest relative dominance at 20.83%, indicating its significant dominance in this forest type. *Anogeissusleiocarpa* followed closely with an

RDo of 14.02%, indicating its substantial presence. *Spondias mombin* and *Uvariachamae* showed moderate relative dominance with RDo values of 10.02 and 5.30, respectively, indicating their moderate influence. *Milicia excelsa and Tectona grandis* had relative dominance values of 5.43 and 5.08%, respectively, showing a comparatively lesser degree of dominance in the CFA ecosystem compared with the species mentioned above. Among the tree species with the low RDo in CFA are *Strychonos spinosa* with RDo of 0.42%, followed by *Fluggea virosa* with RDo of 0.39. *Acanthus montanus, Aleurites moluccanus* and *Afzelia africana* had low RDo values of 0.10, 0.18, and 0.01%, respectively, in the CFA.

The results of the relative dominance of species in FR (Table 4.5) showed *Erythrophleum suaveolens* had an estimated R. Do value of 12.17% as the second highest after *Gmelina arborea* with an RDo value of 49.5%, indicating substantial dominance of these species in this forest type. *Daniellia oliverii* (7.43%), *Strychonos spinosa* (5.57%) and *Vitex doniana* (5.15%) exhibited lower relative dominance values, which indicated their lower dominance of this forest type compared to *Gmelina arborea and Erythrophleum suaveolens*. A few species (*Annona senegalensis, Strophanthus hispidus, Detarium microcarpum, Senna siamea*, *Ficus sur, Ficus sycomorus, Isoberlinia doka*, *Lannea spp*, *Stereospermum kunthianum*, and *Vitellaria paradoxa)* identified with low RDo in FR. Tree species with low RDo in the FR were *Annona senegalensis* (0.43%), *Strophanthus hispidus* (0.27%), *Senna siamea* (0.24%) and *Detarium microcarpum* (0.20%). Other species include *Ficus sur* (0.08%), *Ficus sycomorus* (0.22%), *Isoberlinia doka* (0.12%), *Lannea spp* (0.08%), *Stereospermum kunthianum* (0.01%), and *Vitellaria paradoxa* (0.03%).

The relative dominance (RDo) values of tree species in SG showed that *Cola gigantea* exhibited the highest relative dominance at 14.63 %, indicating significant dominance of the species in the frest type. *Khaya senegalensis* had a relative dominance of 11.25%, indicating substantial influence as well. Other species with high RDo in SG were: *Afzelia africana* with an RDo value of 7.26%, *Ceiba pentandra* (7.10%)*, Daniellia oliverii* (8.54%), and *Dialium guineense* (6.78%), while *Terminalia macroptera* had 5.52% relative dominance among the listed species. Tree species in the SG area with low RDo values were identified as *Artocarpus altilis* (1.97%), *Parkia biglobosa* (1.81%), *Markhamia tomentosa* (1.15%) and*Alchornea cordifolia* (0.97%), while *Anthocleista nobilis* and *Ferruginous bridelia* had RDo of 0.60 and 1.38%, respectively. Other species with low RDo values include *Newbouldia laevis* (0.83%), *Irvingia gabonensis* (0.43%), *Crossopteryx febrifuga* (0.29%), *Milicia excelsa* (0.26%) and *Combretum nigricans* (0.22%).

Gmelina arborea was identified among the tree species with the highest RD across the three forest types. Results in Table 4.5 revealed that *Gmelina arborea had* high RD values of 41.7% in FR, 11.0% and 9.8% in FR and CFA. The FR's high RD value for G. arborea indicates that this forest type is predominantly dominated by a single tree species: *Gmelina arborea* (Table 4.5). The tree species with low relative density (RD) values across the forest types in the study area were: *Mitragyna inermis,* with low RD values of 0.6 and 0.1% in the CFA and FR, respectively, *Vitex doniana* with low RD values of 1.3% (CFA) and 0.2% (SG), while the species was not identified in FR.

In CFA, *Sterculia setigera* stood out as the species with the highest relative density of 13.6%, followed by *Gmelina arborea* with RD of 9.8%, *Tectona grandis* with RD of 6.8%, while *Anogeissusleiocarpa*, *Prunus africana, and Spondias mombin* had relative densities of 7.0, 5.7, and 6.0%, respectively (Table 4.5). However, *Ficus platyphylla* and *Landolphia owariensis* each had a low RD value of 0.9 %, indicating equal but low abundance in CFA forest type. *Tetrapleura tetraptera* and *Vitex doniana* had RD values of 1.1 and 1.3%, respectively. *Fluggea virosa* exhibited the lowest RD value of 0.2% in CFA, indicating a relatively low abundance of the species in the CFA compared to other species mentioned above.

In FR*, Daniellia oliverii* had the highest relative density of 16.1%, was next to the RD of G. *arborea* (41.7%), indicating its significant presence in this forest type. Other species, like *Erythrophleum suaveolens, Burkea africana*, and *Strychonos spinosa,* had relative densities of 6.9%, 6.5, and 6.9, respectively. Tree species identified in FR with the low RD included *Maranthes polyandra*, having a relative density of 1.3%, *Lophira lanceolata* and *Pterocarpus erinaceus with* RDs of 1.0% and *Sarcocephalus latifolius* with RD of 0.8%. The lowest RD of 0.1 in FR was estimated by *Lannea spp.* and *Stereospermum kunthianum, Senna siamea, Strophanthus hispidus*, and *Vitellaria paradoxa,* indicating a lower presence of these species in the study area.

*Dialium guineense*in in the SG forest area was identified as the species with the highest relative density of 15.4% among the species in this forest type, indicating its significant presence in the SG. *Khaya senegalensis* recorded an RD of 14.7%, its considerable presence. *Cola gigantea* had an RD value of 7.9%, indicating its moderate presence, while *Afzelia africana* exhibited a relative density of 5.1% in the SG. *Uapaca heudelotii* and *Uvariachamae* each had a very low RD of 0.2%, indicating their low level of presence in the SG forest type (Table 4.5).

4.1.6 Tree Species Importance Value Index

The Importance Value Index (IVI) provides the significance of various species within a community by taking factors such as relative dominance, frequency, and relative dominance of the species into consideration. *Gmelina arborea* was present across the three forest types with high IVI values of 45.1% in FR, 7.4% (CFA) and 9.1% in SG, indicating that the species is very important in the floristic compositions of the three forest types, particularly forest reserve. *Daniellia oliverii* was present in FR and SG and among the dominant species with high IVI values (11.8% in FR and 6.4% in sacred grove), indicating their considerable ecological importance within the two forest types. However, the species was among tree species with low IVI values in the CFA.

In the Community Forest Area (CFA), *Gmelina arborea, Sterculia setigera, Anogeissus leiocarpa* and *Spondias mombin* were a few species with higher IVI values. The IVI of 17.2% for *Sterculia setigera*was the highest estimate for all the tree species in the CFA. This indicates that *Sterculia setigera* is very important in the flora within the community forest ecosystem. *Anogeissus leiocarpa,* with an IVI of 10.5%, was also a prominent and important species within the CFA. Similarly. *Spondias mombin*, with an IVI of 8%, is also important in the flora of the CFA, accounting for 8% of all species identified within this forest type. *Tectona grandis* is another tree species of commensurate importance in the floristic compositions of the CFA with an IVI value of 5.9%. Tree species such as *Daniellia oliverii* (1.8%), Ficus sur (1.3%), *Hannoa undulata* (1.6%), *Isoberlinia doka* (1.9%), and *Tetrapleura tetraptera* (1.5%) were identified among the species with low IVI values, indicating their comparatively less importance within the CFA. Tree species with very low IVI values in CFA include *Afzelia africana*, *Anthocleista djalonensis*, *Bobgunnia madagascariensis*, and *Detarium microcarpum,* with each having an IVI value of 0.1%. *Kigelia africana* had an IVI value of 0.3%.

In the Forest Reserve (FR), the Importance Value Index (IVI) varies among different species. *Erythrophleum suaveolens* showed a noticeable IVI of 9.5%, signifying its significant contribution to the dynamics and the floristic compositions of the FR. *Strychnos spinosa and Burkea africana* exhibited comparably lower but considerable IVI values of 6.2% and 5.5%, respectively, indicating their moderate importance in this forest type. With an IVI of 4.8%, *Vitex doniana* is also an important species in the flora of the FR. Among the identified species in the FR area, those with relatively low IVI values were *Afzelia africana* (1.6%), *Anthocleista djalonensis* (1.5%), *Khaya senegalensis* (1.1%), *Pterocarpus erinaceus* (1%), and *Sarcocephalus latifolius* (1.1%). Conversely, species such as *Detarium microcarpum* (0.2%), *Ficus sur* (0.2%), *Isoberlinia doka* (0.1%), *Lannea spp* (0.1%), and *Mitragyna inermis* (0.1%), among others, exhibited very low IVI values, indicating their low importance within FR.

Khaya senegalensis emerged as the most important tree species, with the highest IVI of 13% in the Sacred Grove, indicating its substantial presence and ecological importance within the SG. Cola gigantea and *Dialiumguineense* were important species within SG with high IVI values of 11.2% and 11.1%, respectively. *Terminalia macroptera* had a moderate IVI value of 4.6%. *Alchornea cordifolia, Anthocleista nobilis, Canarium* *schweinfurthii, Prosopis africana, Parkia biglobosa, Afrormosia laxiflora, Ficus exasperate, Uvariachamae, and Vitex doniana*were among the species with low IVI values in SG. The IVI of *Prosopis africana* was estimated at 1.9%, *Parkia biglobos*a at 1.3%, Alc*hornea cordifolia* had an estimated value of 1.2% and *Anthocleista nobilis, Canarium schweinfurthii,* and *Ferruginous bridelia* had IVI values of 1.0% each. Species like *Afrormosia laxiflora, Ficus exasperata, Uvaria chamae, and Vitex doniana* had very low IVI values of 0.2% each, indicating their low importance within the SG ecosystem.

4.1.7 Tree Species Status in the IUCN List

For conservation status, the International Union for Conservation of Nature (IUCN) classified tree species into the following categories: Least Concern (LC), Vulnerable (VU), Endangered (EN), Near Threatened (NT), Threatened (T) or Not Available (NA). Following the IUCN tree species categorization, the three forest management types in this study were designated as: Least Concern (LC), Vulnerable (VU), Endangered (EN), Near Threatened (NT), or Not Available (NA), the results are presented on Table 4.5.

The distribution of species according to their IUCN status across three forest types (Table 4.5), showed a total of 20 species (*Acanthus montanus,Daniellia oliverii, Detarium microcarpum, Ferruginous bridelia, Ficus platyphylla, Hura crepitans, Irvingia gabonensis, Sterculia setigera, and Strychonos spinosa, Khaya senegalensis, Kigelia africana, Landolphia owariensis, Parkia biglobosa, Sterculia kunthianum, and Tetrapleura tetraptera,* among others) were identified across the forest types as 'not available' on the database of IUCN.

CFA accounts for 9 of the 'not available' species (*Acanthus montanus, Daniellia oliverii, Detarium microcarpum, Ficus platyphylla, Khaya senegalensis, Kigelia africana, Landolphia owariensis, Sterculia setigera, Strychonos spinosa*), FR accounted for 4 species (*Daniellia oliverii, Detarium microcarpum, Khaya senegalensis, Strychonos spinosa*) while the SG accounted for 7 species (*Daniellia oliverii, Detarium microcarpum, Ferruginous bridelia, Khaya senegalensis, Kigelia africana,* and *Parkia biglobosa*). For the ’Vulnerable’ species category, there were 3 vulnerable species (*Afzelia africana, Prunus africana,* and *Tetrapleura tetraptera*) in CFA, while *Afzelia africana*was the only vulnerable tree species in FR and SG. For the ’Endangered’ species category, CFA had only one species: *Tectona grandis*, FR had no endangered species within its community while SG had *Monotes kerstingii* as the only endangered species. A total of 25 species in CFA were categorized under the ‘Least Concern’ category while 27 and 24 tree species in FR and SG, respectively, were categorized under the ‘Least Concern’ category (Table 4.5). The ‘Near Threatened’ species were absent in CFA and FR, however, SG had one tree species (*Hura crepitans*) under this category.

Table 4.5: Relative Density, Dominance, and Important Value Index of Tree Species across the Forest Types

S/N	Species	Families	Frequency			Relative Density (RD%)			Relative Dominance (RDo%)			Importance Value Index (IVI%)			IUCN Status
			CFA	FR	SG	CFA	FR	SG	CFA	FR	SG	CFA	FR	SG	
1	*Acanthus montanus*	Acanthaceae	6	-	-	1.3	-	-	0.1	-	-	0.7	-	-	NA
2	*Afzelia africana*	Caesalpiniodea	1	9	29	0.2	1.3	5.1	0.0	1.9	7.3	0.1	1.6	6.2	VU
3	*Afrormosia laxiflora*	Papilionoideae	-	-	1	-	-	0.2	-	-	0.2	-	-	0.2	LC
4	*Albizia lebbeck*	Caesalpiniodeae	-	18	-	-	2.5	-	-	2.4	-	-	2.4	-	LC
5	*Aleurites moluccanus*	Euphorbiaceae	2	-	-	0.4	-	-	0.2	-	-	0.3	-	-	LC
6	*Annona senegalensis*	Annonaceae	-	1	16	-	0.1	2.8	-	0.4	2.7	-	0.3	2.7	LC
7	*Alchornea cordifolia*	Euphorbiaceae	-	-	8	-	-	1.4	-	-	1.0	-	-	1.2	LC
8	*Allophylus africanus*	Sapindaceae	6	-	-	1.3	-	-	0.5	-	-	0.9	-	-	LC
9	*Anthocleista djalonensis*	Loganiaceae	-	11	-	-	1.6	-	0.1	1.5	-	-	1.5	-	LC
10	*Anogeissusleiocarpa*	Combretaceae	33	-	-	7.0	-	-	14.0	-	-	10.5	-	-	LC
11	*Annona squamosa*	Annonaceae	-	-	10	-	-	1.7	-	-	2.8	-	-	2.3	LC
12	*Anthocleista djalonensis*	Loganiaceae	1	-	-	0.2	-	-	0.1	-	-	0.1	-	-	LC
13	*Anthocleista nobilis*	Loganiaceae	-	-	8	-	-	1.4	-	-	0.6	-	-	1.0	LC
14	*Antidesma venosum*	Phyllanthaceae	2	-	-	0.4	-	-	0.1	-	-	0.3	-	-	LC
15	*Artocarpus altilis*	Moraceae	-	-	14	-	-	2.4	-	-	2.0	-	-	2.2	LC
16	*Bobgunnia madagascariensis*	Fabaceae	1	-	-	0.2	-	-	0.0	-	-	0.1	-	-	LC
17	*Bombax buonopozense*	Bombacaceae	4	1	-	0.9	0.1	-	1.1	0.6	-	1.0	0.4	-	LC

RD is Relative Density; RDo is Relative Dominance; IVI is Importance Value Index, '-' is not present; NA is not available, LC is Least Concern; VU is Vulnerable; EN is Endangered; NT is Near Threatened.

Table 4.5: Continued…

S/N	Species	Families	Frequency			Relative Density (RD%)			Relative Dominance (RDo%)			Importance Value Index (IVI%)			IUCN Status
			CFA	FR	SG	CFA	FR	SG	CFA	FR	SG	CFA	FR	SG	
18	*Burkea africana*	Caesalpinioideae	-	46	-	-	6.5	-	-	4.6	-	-	5.5	-	LC
19	*Canarium schweinfurthii*	Burseraceae	-	-	8	-	-	1.4	-	-	0.6	-	-	1.0	LC
20	*Ceiba pentandra*	Malvaceae	4	-	9	0.9	-	1.6	3.6	-	7.1	2.2	-	4.3	LC
21	*Cola gigantea*	Sterculiaceae	-	-	45	-	-	7.9	-	-	14.6	-	-	11.2	LC
22	*Combretum nigricans*	Combretaceae	-	-	4	-	-	0.7	-	-	0.2	-	-	0.5	LC
23	*Crescentia cujete*	Bignoniaceae	2	-	-	0.4	-	-	0.1	-	-	0.3	-	-	LC
24	*Crossopteryxfebrifuga*	Rubiaceae	-	-	8	-	-	1.4	-	-	0.3	-	-	0.8	LC
25	*Daniellia oliverii*	Caesalpinioideae	7	114	24	1.5	16.1	4.2	2.1	7.4	8.5	1.8	11.8	6.4	NA
26	*Detarium microcarpum*	Fabaceae	1	2	-	0.2	0.3		0.0	0.2		0.1	0.2	0.0	NA
27	*Dialiumguineense*	Fabaceae	16	24	88	3.4	3.4	15.4	1.7	2.0	6.8	2.5	2.7	11.1	LC
28	*Elaeis guineensis*	Palmaceae	64	-	34	13.6	-	5.9	7.5	-	6.5	10.6	-	6.2	LC
29	*Erythrophleum suaveolens*	Euphorbiaceae	8	49	-	1.7	6.9	-	2.8	12.2	-	2.2	9.5	-	LC
30	*Eugenia uniflora*	Myrtaceae	23	-	-	4.9	-	-	0.7	-	-	2.8	-	-	LC
31	*Ferruginous bridelia*	Euphorbiaceae	-	-	4	-	-	0.7	-	-	1.4	-	-	1.0	NA
32	*Ficus exasperate*	Moraceae	-	-	1	-	-	0.2	-	-	0.1	-	-	0.2	LC
33	*Ficus platyphylla*	Moraceae	4	-	-	0.9	-	-	0.7	-	-	0.8	-	-	NA
34	*Ficus sur*	Moraceae	7	2	-	1.5	0.3	-	1.2	0.1	-	1.3	0.2	-	LC
35	*Ficus sycomorus*	Moraceae	-	2	-	-	0.3	-	-	0.2	-	-	0.3	-	LC
36	*Fluggea virosa*	Euphorbiaceae	1	-	-	0.2	-	-	0.4	-	-	0.3	-	-	LC

RD is Relative Density; RDo is Relative Dominance; IVI is Importance Value Index, '-' is not present; NA is not available, LC is Least Concern; VU is Vulnerable; EN is Endangered; NT is Near Threatened.

Table 4.5: Continued

S/N	Species	Families	Frequency			Relative Density (RD%)			Relative Dominance (RDo%)			Importance Value Index (IVI%)			IUCN Status
			CFA	FR	SG	CFA	FR	SG	CFA	FR	SG	CFA	FR	SG	
37	*Gmelina arborea*	Verbenaceae	46	296	63	9.8	41.7	11.0	5.0	49.5	7.1	7.4	45.6	9.1	LC
38	*Hannoa undulata*	Simarcubaceae	11	-	-	2.3	-	-	1.0	-	-	1.6	-	-	LC
39	*Hura crepitans*	Euphorbiaceae	-	-	6	-	-	1.0	-	-	0.2	-	-	0.6	NT
40	*Hymenocardiaacida*	Hymenocardiaceae	-	-	8	-	-	1.4	-	-	0.1	-	-	0.8	LC
41	*Irvingia gabonensis*	Irvingiaceae	-	-	2	-	-	0.3	-	-	0.4	-	-	0.4	NA
42	*Isoberlinia doka*	Caesalpiniodeae	7	1	-	1.5	0.1	-	2.3	0.1	-	1.9	0.1	-	LC
43	*Khaya grandiflora*	Meliaceae	-	4	-	-	0.6	-	-	0.8	-	-	0.7	-	LC
44	*Khaya senegalensis*	Meliaceae	3	10	84	0.6	1.4	14.7	0.1	0.9	11.3	0.4	1.1	13.0	NA
45	*Kigelia africana*	Bignoniaceae	2	-	4	0.4	-	0.7	0.2	-	0.9	0.3	-	0.8	NA
46	*Landolphia owariensis*	Apocynaceae	4	-	-	0.9	-	-	0.2	-	-	0.5	-	-	NA
47	*Lannea spp*	Anacardiaceae	3	1	-	0.6	0.1	-	0.1	0.1	-	0.4	0.1	-	LC
48	*Lophira lanceolata*	Rubiaceae	-	7	-	-	1.0	-	-	0.9	-	-	0.9	-	LC
49	*Maranthes polyandra*	Chrysobalanaceae	-	9	-	-	1.3	-	-	0.6	-	-	0.9	-	LC
50	*Markhamia tomentosa*	Bignoniaceae	-	-	12	-	-	2.1	-	-	1.2	-	-	1.6	LC
51	*Milicia excelsa*	Moraceae	10	-	5	2.1	-	0.9	5.4	-	0.3	3.8	-	0.6	LC
52	*Mitragyna inermis*	Rubiaceae	3	1	-	0.6	0.1	-	0.1	0.1	-	0.4	0.1	-	LC
53	*Monotes kerstingii*	Dipterocarpaceae	-	-	9	-	-	1.6	-	-	2.8	-	-	2.2	EN
54	*Newbouldia laevis*	Bignoniaceae	-	-	18	-	-	3.1	-	-	0.8	-	-	2.0	LC
55	*Parkia biglobosa*	Mimosaideae	-	-	5	-	-	0.9	-	-	1.8	-	-	1.3	NA
56	*Prosopis africana*	Fabaceae	-	-	10	-	-	1.7	-	-	2.1	-	-	1.9	LC

RD is Relative Density; RDo is Relative Dominance; IVI is Importance Value Index, '-' is not present; NA is not available, LC is Least Concern; VU is Vulnerable; EN is Endangered; NT is Near Threatened.

Table 4.5: Continued

S/N	Species	Families	Frequency			Relative Density (RD%)			Relative Dominance (RDo%)			Importance Value Index) (IVI%)			IUCN Status
			CFA	FR	SG	CFA	FR	SG	CFA	FR	SG	CFA	FR	SG	
57	*Prunus africana*	Rosaceae	27	-	-	5.7	-	-	2.8	-	-	4.3	-	-	VU
58	*Pterocarpus erinaceus*	Fabaceae	-	7	-	-	1.0	-	-	1.1	-	-	1.0	-	LC
59	*Sarcocephalus latifolius*	Rubiaceae	-	6	-	-	0.8	-	-	1.5	-	-	1.1	-	LC
60	*Senna siamea*	Fabaceae	-	4	-	-	0.6	-	-	0.2	-	-	0.4	-	LC
61	*Spondias mombin*	Anacardiaceae	28	-	12	6.0	-	2.1	10.0	-	2.7	8.0	-	2.4	LC
62	*Sterculia setigera*	Malvaceae	64	-	-	13.6	-	-	20.8			17.2		-	NA
63	*Stereospermum kunthianum*	Apocynaceae	-	1	-	-	0.1	-	-	-	-	-	0.1	-	LC
64	*Strophanthus hispidus*	Apocynaceae	-	2	-	-	0.3	-	-	0.3		-	0.3	-	LC
65	*Strychonos spinosa*	Loganiaceae	2	49	-	0.4	6.9	-	0.4	5.6		0.4	6.2	-	NA
66	*Tectona grandis*	Lamiaceae	32	-	-	6.8	-	-	5.1			5.9		-	EN
67	*Terminalia macroptera*	Combretaceae	-	-	21	-	-	3.7			5.5	-	-	4.6	LC
68	*Tetrapleura tetraptera*	Fabaceae	5	-	-	1.1	-	-	2.0	-	-	1.5	-	-	VU
69	*Trema orientale*	Ulmaceae	14	-	-	3.0	-	-	1.5	-	-	2.3	-	-	LC
70	*Uapaca heudelotii*	Phyllanthaceae	-	-	1	-	-	0.2		-	0.0		-	-	LC
71	*Uvaria chamae*	Annonaceae	10	-	1	2.1	-	0.2	5.3	-	0.1	3.7		0.2	LC
72	*Vitellaria paradoxa*	Sapotaceae	-	1	-	-	0.1	-		0.0	-	-	0.1	-	LC
73	*Vitex doniana*	verbenaceae	6	31	1	1.3	4.4	0.2	0.7	5.2	0.2	1.0	4.8	0.2	LC
	Total		470	709	573	100	100	100	100	100	100	100	100	100	-

RD is Relative Density; RDo is Relative Dominance; IVI is Importance Value Index, '-' is not present; NA is not available, LC is Least Concern; VU is Vulnerable; EN is Endangered; NT is Near Threatened.

4.2 Soil Properties and Soil Organic Carbon

4.2.1 Soil Physical Properties

The results of soil physical properties for the three forest management types investigated in this study are presented in Table 4.6. Forest Reserve had the highest mean percentage (75.0±4.47%) sand content, followed by CFA with a mean sand content of 74.8±2.48%, whileSG had the lowest mean percentage sand content of 60.0±3.29 % compared to the other forest management types. Results revealed that CFA and FR soils had equal mean silt content of 6.4±1.10% for each, while SG had a lower mean silt content of 5.4±1.10%. The soil of the SG site had the highest mean percentage clay content of 34.6±3.29%, followed by 18.8±4.24% clay content for CFA while FR had the lowest percentage mean clay of 18.6±.55% (Table 4.6).

The pH, sand, clay, and silt values of the three forest management types were subjected to a one-way analysis of variance, and the results revealed a significant difference ($p<0.05$) in their soil physical properties, except silt content that showed no significant difference ($p=1.116$) (Table 4.6). The results of mean separation indicated that CFA and FR had statistically similar sand content, but both CFA and FR had significantly higher sand content than SG. (60.0±3.29%). Thus, it appears that the soil texture in SG is different and contains less sand than those of CFA and FR. On the other hand, there existed a significantlyhigher clay content in the SG site (34.6±3.29%) than those of FR (18.18±4.23%) and CFA (18.6±5.55%), which were not significantly different from each other (Table 4.6).

Based on the mean soil pH values of the study areas (Figure 4.3), the soils of the forest reserve are generally acidic, however, those of the community forest area and sacred grove are neutral, judging from their mean soil pH values of 4.82±1.89, 5.90±0.14, and 6.06±0.08 for forest reserve, community forest area and sacred groves, respectively (Figure 4.3).

Table 4.6: Soil Physical Properties of Three Forest Management Types in Benue State, Nigeria

Forest types	**Sand (%)**	**Silt (%)**	**Clay (%)**
CFA	74.8 ± 2.48^{a}	6.4 ± 1.10^{a}	18.8 ± 4.23^{b}
FR	75.0 ± 4.47^{a}	6.4 ± 1.10^{a}	18.6 ± 5.55^{b}
SG	60.0 ± 3.29^{b}	5.4 ± 1.10^{a}	34.6 ± 3.29^{a}
p-value	*0.000*	*0.116*	*0.000*

Note: Means on the same columns with different superscripts (alphabets) are significantly different ($p \leq 0.05$)

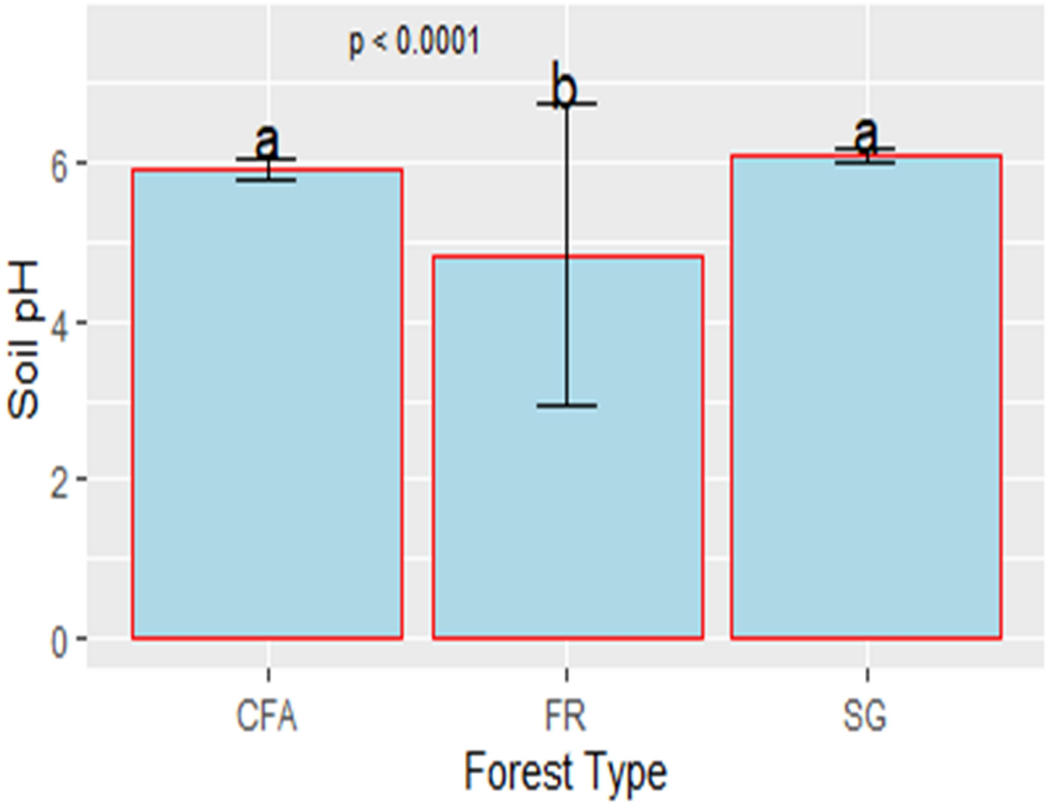


Figure 4.1: Soil pH of Three Forest Management Types in Benue State, Nigeria

Note: Bars with different superscripts (alphabets) are significantly different ($p \leq 0.05$)

4.2.2 Soil Chemical Properties

The results of the chemical properties of the soils of the three forest management types are presented in Table 4.7. Magnesium (Mg) content (0.97 Cmol/kg) was highest in the soil from SG. The magnesium content of the community forest area was 0.79 Cmol/kg, which is slightly lower than that of SG. With a magnesium content of 0.77±0.23 Cmol/kg, the Forest Reserve soil had the lowest magnesium content of the three management types. The mean Nitrogen (N) content of the soils of the study area ranged from 0.22±0.05 % in CFA to 0.23±0.16 % in FR and 0.28±0.0 % for soils under SG. Soil from SG had higher nitrogen levels compared to soil under CFA, indicating better soil fertility and nutrient availability.

Phosphorus content ranged from 2.70±0.70 ppm in CFA to 2.71±0.70 ppm for soil sourced from FR and 3.67±0.02 ppm for soils under SG, indicating that the highest soil Phosphorus content was obtained under SG while the lowest value was from CFA soils. The soils from SG had the highest potassium (K) content of 0.20 ± 0.02Cmol/kg, followed by soils from CFA with a Potassium content of 0.16±0.02 Cmol/kg, while the lowest soil Potassium content (0.14±0.07 Cmol/kg) was from soil from Forest Reserve. The level of sodium (Na) was similar across the three forest management categories, especially between CFA and FR. Results indicated that soils from SG had a mean Na content of 0.18 ±0.01 Cmol/kg, while soils from CFA and FR had Na contents of 0.15 ±0.03 Cmol/kg and 0.15 ±0.07 Cmol/kg, respectively.

The results of the Analysis of Variance indicated that there were no significant differences in the N (%), P (ppm) and Na (Cmol/kg) contents of the soils from the three forest management types in the study area. However, there were significant differences ($p<0.05$) in the soil Mg (Cmol/kg) and Ca (Cmol/kg) contents of the soils from the three forest management types. The Sacred Grove had the highest K (potassium) content, followed by the Community Forest Area, with the Forest Reserve having the lowest.

Table 4.7: Soil Chemical Properties of Different Forest Management in the Study Area

Forest types	**Mg (Cmol/kg)**	**N (%)**	**P (ppm)**	**K (Cmol/kg)**	**Na (Cmol/kg)**	**Ca (Cmol/kg)**
CFA	0.79±0.00^{b}	0.22±0.05^{a}	2.70±0.26^{a}	0.16±0.02^{ab}	0.15±0.03^{a}	0.99±0.03^{b}
FR	0.77±0.23^{b}	0.23±0.16^{a}	2.71±1.46^{a}	0.14±0.07^{b}	0.15±0.07^{a}	0.96±0.03^{b}
SG	0.97±0.00^{a}	0.28±0.00^{a}	3.67±0.02^{a}	0.20±0.02^{a}	0.18±0.01^{a}	1.24±0.01^{a}
***p*-value**	**0.041**	**0.570**	**0.110**	**0.054**	**0.375**	**0.042**

Note: means on same column with different superscripts is significantly different ($p \leq 0.05$)

Table 4.8 presents the percentage of soil organic carbon (OC) and soil organic matter (OM) storage for three different forest types. The average OC storage percentage was estimated at 1.82±0.02 under CFA, while its OM content was 3.13±0.03%. The FR soil yielded an organic carbon content of 1.83±72.7% and an OM content of 3.12±0.06%. The OC contents and OM content of the Sacred Grove were 1.80±0.01% and 3.10±0.02%, respectively. The results from the analysis of variance revealed that the soil organic carbon (OC %) and organic matter (OM %) of the three forest management types did not differ significantly (p>0.05(Table 4.8).

Table 4.8: Soil Organic Carbon and Organic Matter Storage of the three Forest Management Types

Forest Management Type	OC (%)	OM (%)
CFA	1.82 ± 0.02^{a}	3.13 ± 0.03^{a}
FR	1.83 ± 72.7^{a}	3.12 ± 0.06^{a}
SG	1.80 ± 0.01^{a}	3.10 ± 0.02^{a}
p-value	0.391	*0.528*

Note: means on same column with different superscripts is significantly different ($p \leq 0.05$)

4.3 Tree and Stand Growth Characteristics

Figure 4.1 shows the individual trees' Dbh distribution for the three forest management types. Generally, the diameter distribution of trees within the three forest types followed the inverse-J diameter distribution pattern typical of natural tropical forests (Figure 4.4). At the FR, 511 trees fell within the lower diameter class of 10 - 25 cm, 164 trees were distributed within the 25.1 - 40 cm diameter class, and only 2 trees were encountered within the large diameter class of 55.1 - 70 cm (Figure 4.4). Two hundred and twenty-three (223) trees were measured within the 10 - 25 cm diameter class in SG, which was followed by 195 trees within the 25.1 - 40 cm diameter class, while 76 and 46 trees occurred within the diameter distribution class of 40.1 - 55 and 55.1 - 70 cm, respectively.

For CFA, 152 trees were recorded within the lower diameter class of 10 - 25 cm, while diameter classes of 25.1 - 40 cm, 40.1 - 55 cm, and 55.1 - 70 cm had 160, 123, and 36 trees, respectively (Figure 4.4). The CFA and SG had few individual trees that occurred within the upper diameter classes of 70.1 - 85 cm, 85.1 - 10 cm, and 100.1 - 115 cm. Only CFA had an individual tree within the diameter of 130.1-145 cm, as shown in Figure 4.1.

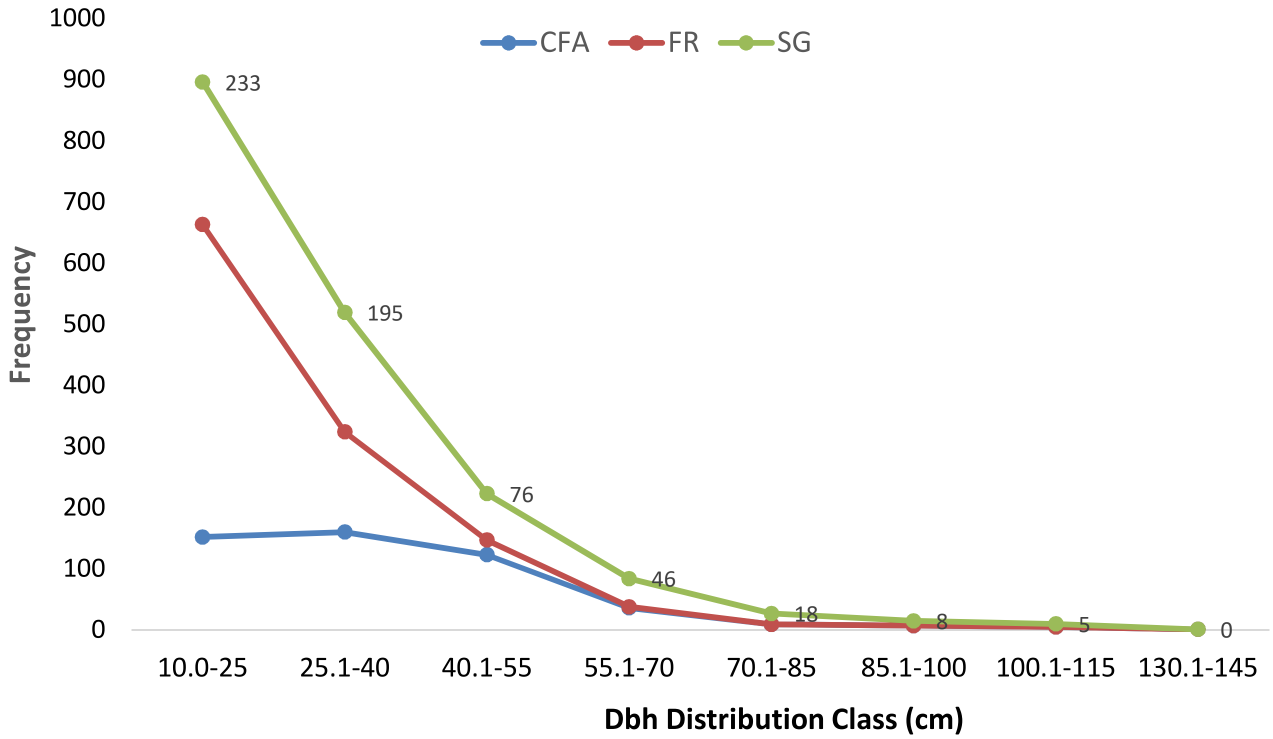


Figure 4.4: Diameter Distribution of trees per management type in the study area

The total height distributions of individual trees across three forest management types (CFA, FR, and SG) in the study area are shown in Figure 4.5. The results revealed that most trees in all three management types were concentrated in the lower height classes, with CFA and SG exhibiting a similar distribution pattern. The community forest area had 145 trees in the 5-14.9m height class, 155 trees in the 15-24.9m class, 80 trees in the 25-34.9m class, and 5 trees above 34.9m class. Similarly, SG had 417 trees in the 5-14.9m height class, 78 trees in the 15-24.9m class, 5 trees in the 25-34.9m class, and no trees above the 34.9 m height class.

In contrast, FR displayed a different height distribution pattern, with a significantly higher number of trees in the lower (5-14.9 m) class (446 trees) and fewer trees in the higher height classes (156 trees in the 15-24.9m class, 38 trees in the 25-34.9m class, and 2 trees above 34.9m class). The absence of trees in the uppermost (>34.9 m) class across all management types indicates that very tall trees are rare in the study area (Figure 4.5).

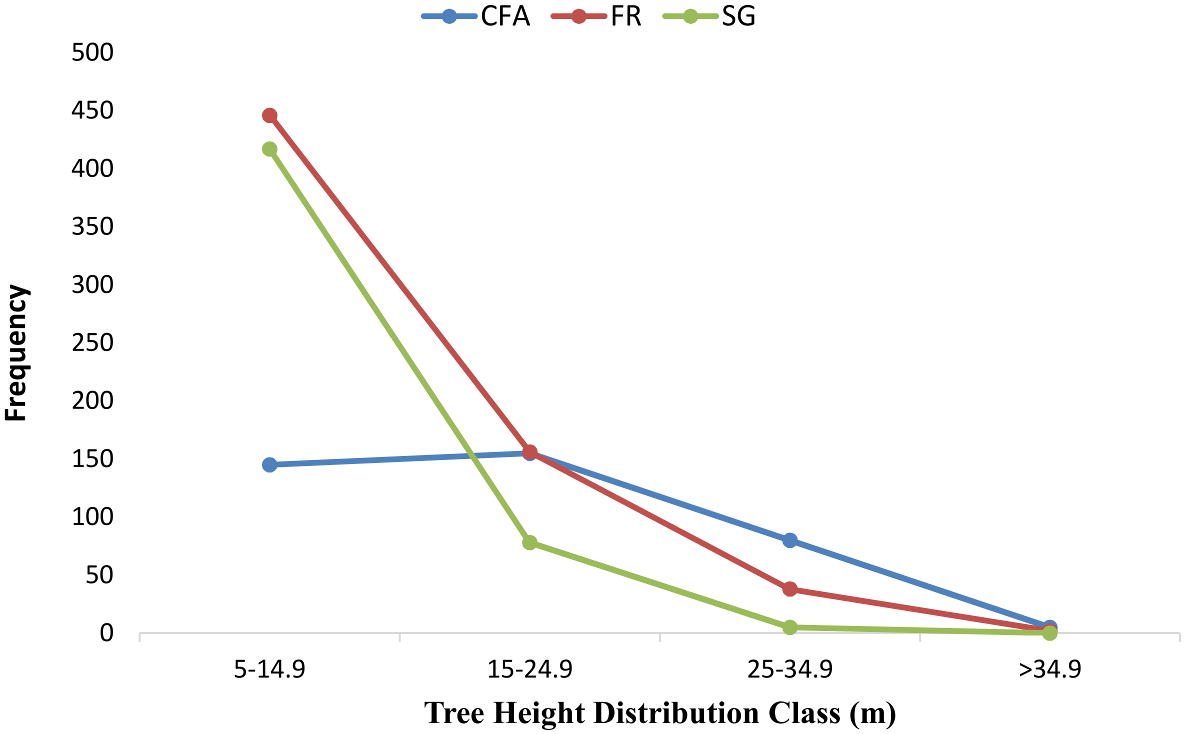


Figure 4.5: Tree total height distribution in the three forest management types

Table 4.9 shows the tree growth and yield variables across the different forest management types in the study area. Trees within the CFA management area were generally larger than those within the other two forest types, as indicated by the higher mean and maximum dbh values of 35.0 cm and 143.0 cm, respectively. This was followed by trees within the SG forest management type with mean and maximum dbh values of 30.5 cm and 110.8 cm, respectively. Trees within the FR forest management type had smaller dimensions than those within CFA and SG, as indicated by their lowest mean and maximum dbh values of 20.2 cm and 55.0 cm, respectively (Table 4.9).

The results (Table 4.10) showed the highest mean basal area (44.01 m^2/ha) and mean volume (656.71 m^3/ha) were recorded under the community forest area, followed by the Sacred Grove, which had a mean basal area of 39.41 m^2/ha and mean volume of 309.47m^3/ha. However, the Forest Reserve had the lowest mean basal area (29.88 m^2/ha) and mean volume (384.08m^2/ha). Based on this result (Table 4.9), the CFA and SG have a larger area coverage occupied by a cross-section of the tree diameter at the base and higher yield productivity than what was obtainable from FR.

The standard deviation and standard error values indicate the variability and precision of the measurements, respectively. The Community Forest Area had a mean tree height of 17.9 m, with a minimum of 5.6 m and a maximum of 39.9 m, indicating a high level of variability in tree heights (SD = 7.86) and moderate precision in the mean tree height (SE = 0.35). The Forest Reserve had a mean tree height of 13.7 m, with a minimum of 5.5 m and a maximum of 38.9 m, showing moderate variability in tree heights (SD = 5.66) and high precision in the mean tree height (SE = 0.21). The Sacred Grove had the lowest mean tree height of 11.3 m, with a minimum height of 5.5 m and a maximum of 29.0 m, indicating low variability in tree heights (SD = 4.35) and high precision in the mean tree height (SE = 0.17).

Table 4.9: Summary of Stand Growth Variables for the Forest Management Types in Benue State, Nigeria

Variables	Management types	Minimum	Mean	Stand. Dev.	Maximum
Dbh (cm)	CFA	5.5	34.99	18.68	143
	FR	5	20.22	8.49	55
	SG	5	30.5	18.91	110.8
Tree height (m)	CFA	5.6	17.9	7.86	39.9
	FR	5.5	13.7	5.66	38.9
	SG	5.5	11.3	4.35	29.0
Basal Area (m^2/ha)	CFA	41.70	44.01	13.04	46.31
	FR	26.41	29.88	11.40	33.35
	SG	29.81	39.41	11.36	49.02
Volume (m^3/ha)	CFA	614.66	656.71	186.35	698.76
	FR	312.07	384.08	148.97	456.09
	SG	292.89	309.47	87.14	326.05

The results presented in Table 4.10 show stand density estimated across three forest management types. A total of 9 plots were mapped, with the number of trees in each plot ranging from 59 to 117. A total of 1,881 individual trees were sampled across the three forest management types, with FR having 749, 621 from SG and 511 from CFA. Forest reserves have a higher tree density than the other two management types (Table 4.10). When calculated in terms of trees per hectare (ha), the mean stand density is highest in FR (792 trees/ha) and lowest in CFA (596 trees/ha). The forest reserve has a more intense stand density than the other two management types.

Table 4.11 shows the correlation matrix of growth variables (including Mean Diameter at Breast Height (DBH), Mean Basal Area (BA), Tree Density, Total Height (THt), and Volume) in the study area. A correlation matrix is a statistical tool use to measure the strength and direction of relationships between different variables. The values in the table indicate whether an increase in one variable is associated with an increase or decrease in another. The coefficient between the mean DBH and volume was 0.90, which indicates a strong positive relationship. This means that as the tree diameter increases, the volume of the tree also increases significantly. Since volume is directly influenced by trunk size, this positive correlation is expected in forest stand assessments. The correlation between mean DBH and mean basal area was -0.67, indicating a moderate negative relationship. This indicates that in areas where trees have larger diameters, the basal area per tree tends to be lower. One possible explanation is that stands with larger trees generally have lower stem densities, leading to a reduced cumulative basal area per tree.

The correlation coefficient between density and mean basal area was 0.48, showing a moderate positive relationship. This indicates that forests with a higher number of trees per unit area also tend to have a greater cumulative basal area. This relationship showed the role of density in determining stand structure and biomass accumulation. The relationship between tree density and total height is -0.08, which is a weak negative correlation. This indicates that tree height is only minimally influenced by tree density in the study area.

Height growth may be more dependent on factors such as species characteristics, soil nutrients, and competition for sunlight rather than the number of trees per unit area.

The correlation between volume and mean basal area was -0.72, indicating a strong negative relationship. This implies that forest stands with a higher basal area do not necessarily have the highest total volume. This is due to variations in tree distribution, differences in species composition, or the presence of smaller trees contributing to total basal area but not significantly affecting volume. The correlation between total height and volume was 0.44, indicating a moderate positive relationship. This means that taller trees tend to have greater volume, although the relationship is not as strong as the one observed between DBH and volume. This implies that while height contributes to volume, tree diameter plays a more dominant role in determining total biomass. The strong positive correlation between DBH and volume shows the importance of tree diameter in estimating total biomass. Contrarily, the negative relationship between basal area and volume implies that forest structure and species composition influence total volume accumulation.

Table 4.10: Mean Stand Density of Trees in the Study Area

Plots No.	**CFA**	**FR**	**SG**
1	90	102	61
2	59	96	64
3	100	93	88
4	60	101	68
5	59	69	57
6	72	98	64
7	71	117	115
8	-	73	75
9	-	-	29
Total	511	749	621
Mean/plot	73	97	74
Mean/ha	596	792	604

Table 4.11: Correlation Matrix of Growth Variables in the Study Area

Mean Variables	Mean Dbh	Mean BA	Density	THt
Mean Dbh	-			
Mean BA m^2	-0.67	-		
Density	-0.35	0.48	-	
THt	0.19	-0.20	-0.08	-
Volume	0.90	-0.72	-0.33	0.44

4.4 Volume Models for the Forest Management Types

Table 4.12 shows the estimated parameters of different non-linear volume models fitted to data collected for three forest management types in this study. The volume models fitted to the data include Logistic power [M1], Weibull [M2], Gompertz relation [M3], Ratkowsky [M4], Simple linear regression [5], Polynomial [M6], Power [M7], Single logarithm [8], and Reciprocal [9]. The models were calibrated and validated to obtain the best fit to the data collected from different forest management types (CFA, FR and SG) investigated in this study. To predict volume adequately for each forest management type, different models were fitted to the data and the best model was selected based on pre-determined criteria. The accuracy of volume estimates can be strongly impacted by volume model selection.

The results of volume models presented in Table 4.12 revealed that the coefficients of determination for all the models were positive. Some of the models had a negative intercept (M1 and M5) with a high coefficient of determination of 0.80 and 0.77, respectively, or a negative slope (M9) with a low coefficient of determination of 0.32 or both at intercept and slope (M2 with a high coefficient of determination of 0.79). Models M7, M8, and M9 had only one variable, models M1, M2, M3, and M4 had 2 variables, while model M6 had three variables. The volume models were all significant ($p<0.05$) (Table 4.12).

Table 4.12: Estimated Parameters for Volume Models in the Study Area

Model	b0	b1	b2	b3	R^2
Community Forest Area					
Logistic power model [M1]	9.78	60.54	-3.31	-	0.80
Weibull [M2]	-1.50	-0.13	0.32	-	0.76
Gompertz relation model [M3]	9.36	2.11	0.04	-	0.80
Ratkowsky model [M4]	8.03	4.69	0.09	-	0.81
Simple linear regression model [5]	-1.63	0.10	-	-	0.75
Polynomial model [M6]	1.62	24.93	3.42	-6.21	0.81
Power model [M7]	0.003	1.77	-	-	0.75
Single logarithm model [8]	-7.00	2.54	-	-	0.57
Reciprocal model [9]	3.08	-37.48	-	-	0.31
Forest Reserve					
Logistic power model [M1]	0.834	21.429	-3.093	-	0.31
Weibull [M2]	-1.760	-0.456	0.145	-	0.22
Gompertz relation model [M3]	0.789	1.965	0.112	-	0.31
Ratkowsky model [M4]	0.733	3.834	0.190	-	0.35
Simple linear regression model [M5]	-0.094	0.022	-	-	0.20
Polynomial model [M6]	0.369	4.215	-0.959	-0.337	0.28
Power model [M7]	0.012	1.139	-	-	0.18
Single logarithm model [M8]	-1.026	0.472	-	-	0.23
Reciprocal model [9]	0.784	-7.341	-	-	0.11
Sacred Grove					
Logistic power model [M1]	8.15	83.12	-2.46	-	0.63
Weibull [M2]	-0.64	-0.07	0.32	-	0.79
Gompertz relation model [M3]	6.76	1.76	0.03	-	0.81
Ratkowsky model [M4]	5.33	4.05	0.07	-	0.82
Simple linear regression model [5]	-0.78	0.05	-	-	0.77
Polynomial model [M6]	0.95	18.85	2.88	-3.37	0.82
Power model [M7]	0.00	1.65	-	-	0.79
Single logarithm model [8]	-4.08	1.51	-	-	0.59
Reciprocal model [9]	1.92	-23.13	-	-	0.32

M1….. M9 means model 1 to model 9; b_o, b_1, b_2, b_3 model coefficients.

Different statistical metrics (Akaike Information Criterion (AIC), Corrected Akaike Information Criterion (AICc), Bayesian Information Criterion (BIC) and Difference in AIC (dAIC)) (Table 4.12) were used to evaluate the fitted volume models for each management type with the view of selecting the best. The Ratkowsky model [M4] was the best-fitted model for FR, with the highest weighted score. The model had statistical metric values of 734.2, 734.29, 750.9 and 0.002 for AIC, AICc, BIC and dAIC, respectively, for volume data collected from FR. For volume data from SG, the Ratkowsky model was ranked the best-fitted model with a weighted score of 9.94E-01 and statistic metric values of 501.27, 501.38, 516.98 and 0.00 as AIC, AICc, BIC and dAIC, respectively. Ratkowsky (M4) model was the best fit for the data collected from this site. The model had the lowest statistic metrics of 644.23, 644.38, 658.74, and 0.00 for AIC, AICc, BIC and dAIC, respectively. The Ratkowsky model for volume data from CFA had the lowest weighted score of 9.26E-01 and thus ranked first and best. Therefore, the Ratkowsky model (M4) was the best-fitted model for volume prediction for the three sites in the study area given that it had the lowest statistic metrics and highest weight.

Figures 4.6 to 4.8 present the residual plots from the best-fitted model (Ratkowsky model) for stand volume estimation in each of the investigated forest types (CFA, FR and SG) in this study. Residual plots were used to assess the goodness of fit of a model by examining the distribution of residuals, which are the differences between observed and predicted values. On the residual plot, the x-axis represents the predicted volumes while the y-axis represents the residual values. The residuals on the positive and negative sides of the residual plot had a constant spread and were randomly spread around the center line of the plot and did not follow any systematic trend or pattern.

Table 4.13: Volume Model Statistic Metrics for the three forest types in the Study Area

Model ranks	Models No.	AIC	AICc	BIC	dAIC	Weight
			Forest Reserve			
1st	M4	734.20	734.29	750.90	0.00	0.34
2nd	M3	735.11	735.19	751.80	0.90	0.21
3rd	M1	735.23	735.32	751.93	1.03	0.20
4th	M8	736.92	736.97	749.44	2.72	0.09
5th	M2	738.05	738.14	754.75	3.85	0.05
6th	M5	738.13	738.18	750.65	3.93	0.05
7th	M6	738.27	738.40	759.14	4.07	0.04
8th	M7	739.50	739.55	752.02	5.29	0.02
9th	M9	747.20	747.25	759.72	13.00	5.05E-04
			Sacred Grove			
1st	M4	501.27	501.38	516.98	0.00	9.94E-01
2nd	M6	511.74	511.90	531.38	10.47	5.28E-03
3rd	M3	516.69	516.80	532.40	15.43	4.44E-04
4th	M1	522.45	522.56	538.16	21.19	2.50E-05
5th	M7	556.71	556.77	568.49	55.44	9.09E-13
6th	M2	561.76	561.87	577.47	60.50	7.26E-14
7th	M5	586.74	586.81	598.52	85.48	2.73E-19
8th	M8	812.44	812.51	824.22	311.17	2.67E-68
9th	M9	1002.64	1002.70	1014.42	501.37	1.34E-109
			Community Forest Area			
1st	M4	644.23	644.38	658.74	0.00	9.26E-01
2nd	M6	649.39	649.61	667.53	5.16	7.01E-02
3rd	M3	656.36	656.51	670.87	12.13	2.15E-03
4th	M1	656.48	656.63	670.99	12.25	2.02E-03
5th	M2	710.16	710.31	724.67	65.93	4.46E-15
6th	M7	716.91	717.00	727.80	72.68	1.53E-16
7th	M5	720.32	720.41	731.21	76.09	2.77E-17
8th	M8	867.68	867.76	878.56	223.44	2.79E-49
9th	M9	997.68	997.77	1008.57	353.45	1.64E-77

Note: AIC means Akaike Information Criterion; AICc means Corrected Akaike Information Criterion; BIC is Bayesian Information Criterion; dAIC means Difference in AIC.

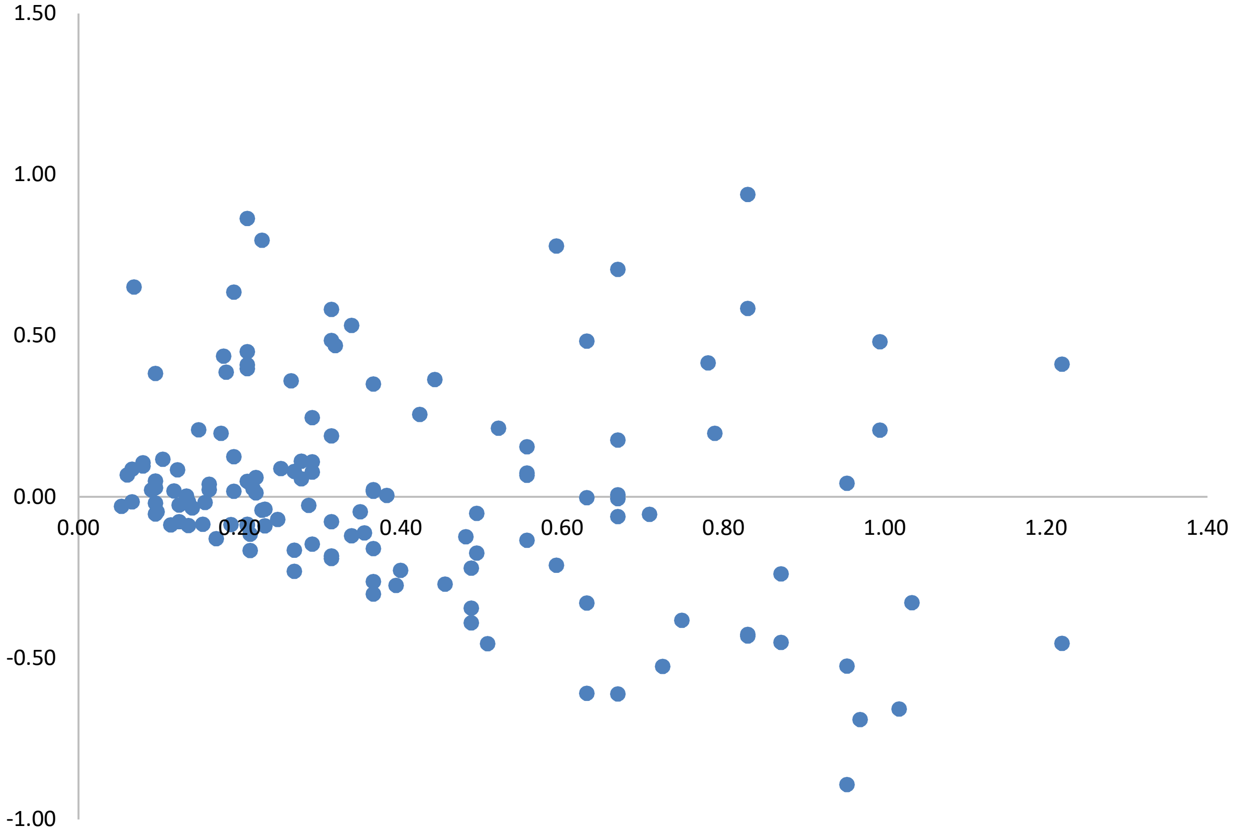


Figure 4.6: Residual plot of the fitted model (Ratkowsky model) for volume estimation in Forest Reserve, Benue State, Nigeria

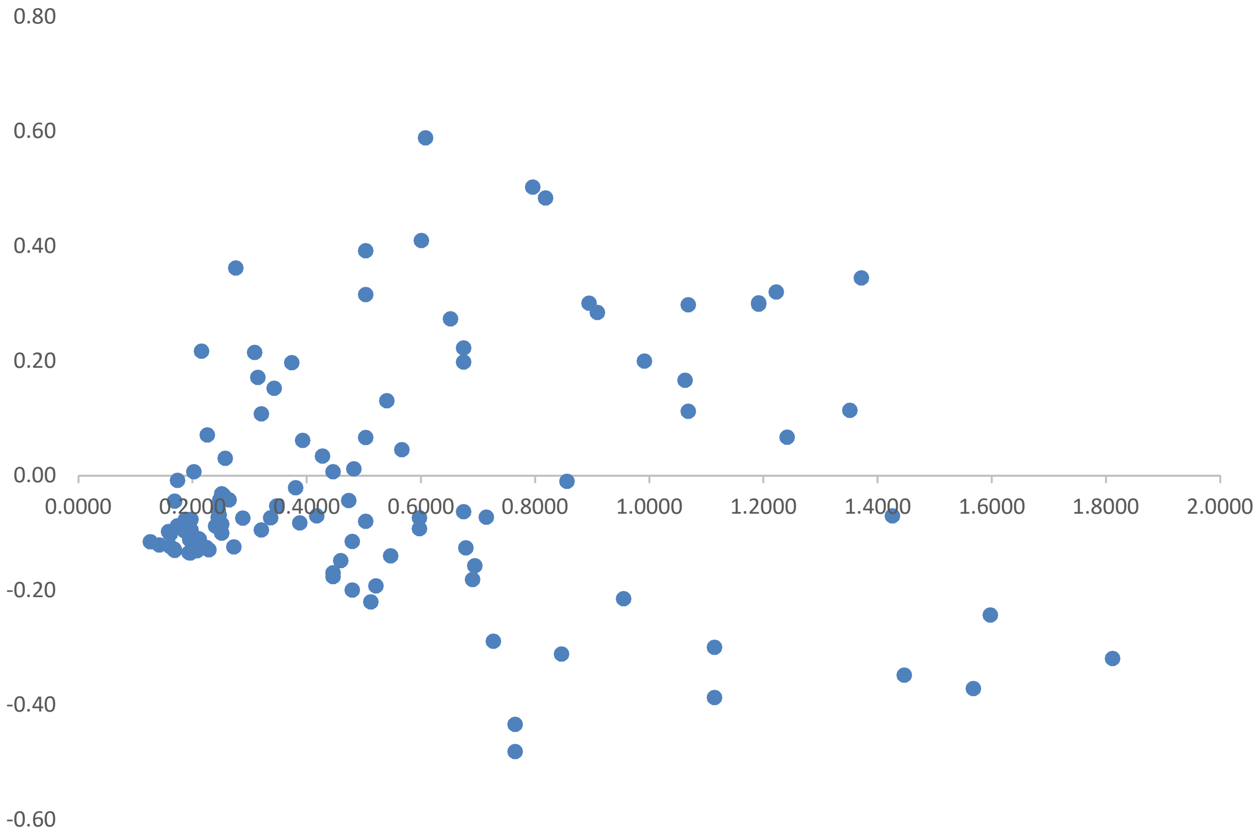


Figure 4.7: Residual plot of the best-fitted model (Ratkowsky model) for volume estimation in Sacred Grove, Benue State, Nigeria

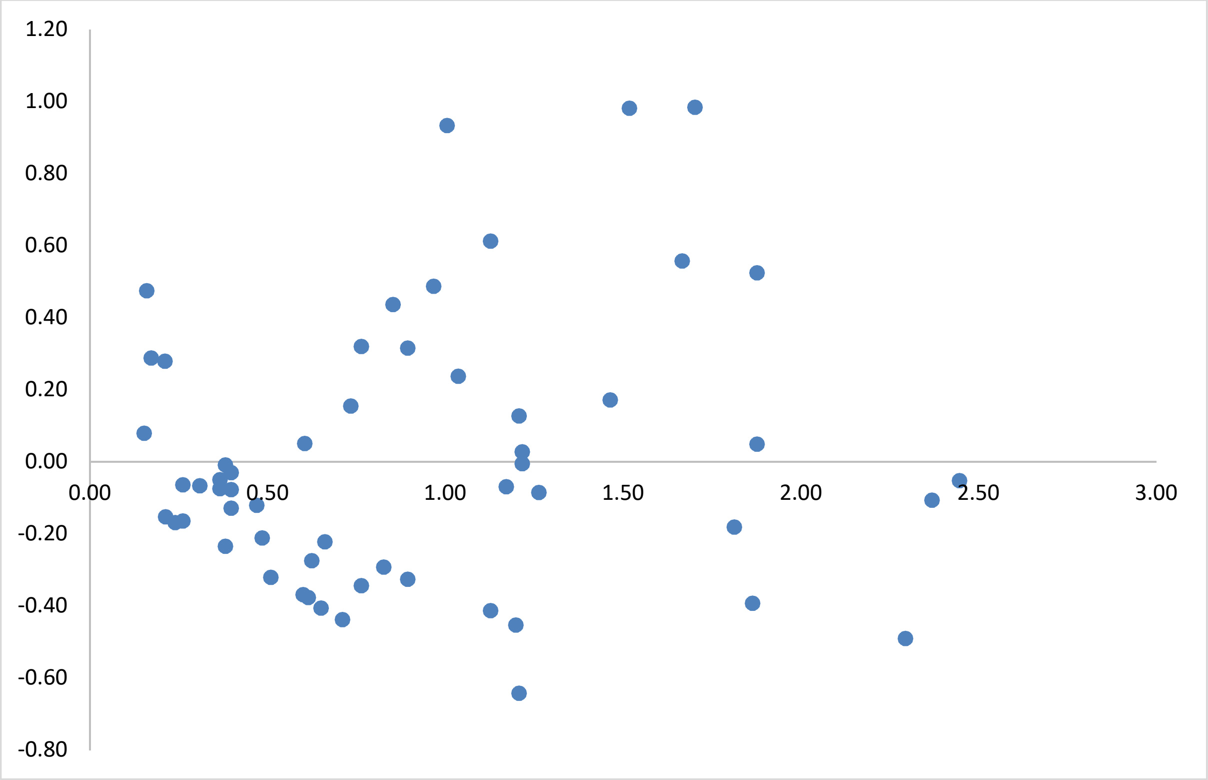


Figure 4.8: Residual plot of the best-fitted model (Ratkowsky model) for volume estimation in Community Forest Area, Benue State, Nigeria

The results of the student t-test (Table 4.14) were used to validate the selected models by comparing the observed and predicted volume for the three forest management types. There was no significant difference between the observed and predicted volumes for the three forest management types at a 0.05 significance level using the Ratkowsky model, which was the best-performing form for the three sites. It demonstrates that the selected model is suitable for predicting the volume of trees in the three forest management types in this study.

UnderFR, the t-test results showed a t-statistic of -0.85 with corresponding *p*-values of 0.20 for a one-tailed test, where the mean observed volume was 0.5 m^3 and the predicted volume was 0.54 m^3. The t-test results for SG indicated a t-statistic of 0.14 and *p*-values of 0.44 for a one-tailed test, with a mean observed volume of 0.75 m^3 and a predicted volume of 0.74 m^3. The student t-test results for CFA showed a t-statistic of -0.03, and a corresponding p-values of 0.49 for a one-tailed test. The mean observed volume in the area is 1.39 m^3, while the predicted volume is 1.40 m^3.

Table 4.14: Best-Fitted Model Validation on Observed and Predicted Volume in the Study Area

Parameters	*Volume*	Model 4
Forest Reserve		
Mean	0.50	0.54
Variance	0.21	0.21
Observations	157.00	157.00
Pooled Variance	0.21	
Hypothesized Mean Difference	0.00	
Degree of freedom	312.00	
t-Stat	-0.85	
P(T<=t) one-tail	0.20	
t Critical one-tail	1.65	
P(T<=t) two-tail	0.40	
t Critical two-tail	1.97	
Sacred Grove		
Mean	0.75	0.74
Variance	0.74	0.56
Observations	122.00	122.00
Pooled Variance	0.65	
Degree of freedom	242.00	
t Stat	0.14	
P(T<=t) one-tail	0.44	
t Critical one-tail	1.65	
P(T<=t) two-tail	0.89	
t Critical two-tail	1.97	
Community Forest Area		
Mean	1.39	1.40
Variance	1.76	1.59
Observations	68.00	68.00
Pooled Variance	1.68	
Hypothesized Mean Difference	0.00	
Degree of freedom	134.00	
t Stat	-0.03	
P(T<=t) one-tail	0.49	
t Critical one-tail	1.66	
P(T<=t) two-tail	0.97	

t Critical two-tail	1.98

Model 4 (Ratkowsky model) is the best-fitted model for volume estimation per site.

4.5 Biomass and Carbon Stock of Forest Management Types

The results of biomass production and carbon stock of the different forest management types in this study are presented in Table 4.15. The mean total biomass production was 485.39 tons per hectare in CFA, 301.14 tons per hectare in FR and 230.95 tons per hectare in SG. However, the maximum total biomass production was 732.79 tons per hectare in CFA, which is higher than the maximums under FR (451.05 tons/ha) and SG (429.92 tons/ha). The SG had the lowest minimum total biomass production of 80.28 tons per hectare, followed by FR (153.23 tons/ha) and CFA (248.64 tons/ha).

The total carbon yields across the study area show that CFA exhibited the highest mean total carbon yield, peaking at 242.70 tons per hectare (Table 4.15). The CFA and SG had mean total carbon yields of 242.70 tons/ha and 115.48 tons/ha, respectively. The maximum total carbon yield also varied widely, ranging from 366.39 tons/ha in CFA to 225.53 tons/ha in FR and 214.96 tons/ha in SG. The minimum total carbon yield was obtained in SG (40.14 tons/ha), followed by FR (76.62 tons/ha) and CFA (124.32 tons/ha).

The carbon dioxide sequestration potential of the forest management types was substantial, with mean CO_2 equivalents of 889.89 tons/ha in CFA, 552.10 tons/ha in FR, and 423.41 tons/ha in SGs. Forest Reserve exhibited a higher mean total carbon yield of 150.57 tons per hectare than what was estimated in SG 115.48 tons/ha. the mean CO_2 equivalent was highest in CFA (889.89 tons/ha), followed by FR (552.10 tons/ha), while SG had the lowest mean CO_2 equivalent (423.41 tons/ha) (Table 4.15).

Table 4.16 presents the results of an Analysis of Variance (ANOVA) for biomass and carbon stocks across three management types in the study area. The results showed significant differences (p= 0.0001) in TB, TC, and CO_2 Equiv. between the three management types. The CFA had the highest mean values for TB (485.39 tons/ha), TC (242.70 tons/ha), and CO_2 Equiv. (889.89 tons/ha). In contrast, FR has intermediate values for TB (301.14 tons/ha), TC (150.57 tons/ha), and CO_2 Equiv. (552.10 tons/ha), while SG has the lowest values for TB (230.95 tons/ha), TC (115.48 tons/ha), and CO2 Equiv. (423.41 tons/ha).

Table 4.15: Summary of Growth Yields per Management Type

	Maximum	**Mean**	**Minimum**
	Total Biomass (tons/ha)		
CFA	732.79	485.39	248.64
FR	451.05	301.14	153.23
SG	429.92	230.95	80.28
	Total Carbon (tons/ha)		
CFA	366.39	242.70	124.32
FR	225.53	150.57	76.62
SG	214.96	115.48	40.14
	CO_2 Equiv. (tons/ha)		
CFA	1,343.44	889.89	455.84
FR	826.93	552.10	280.92
SG	788.19	423.41	147.18

TB means total biomass, TC means total carbon, CFA means community forest area, FR means forest reserve, SG means sacred grove.

Table 4.16: Test of Significance for Biomass and Carbon Stocks in the Study Area

Management types	**Mean TB (tons/ha)**	**Mean TC (tons/ha)**	**Mean CO_2 Equiv.**
CFA	485.39 ± 165.51^{a}	242.70 ± 82.75^{a}	889.89 ± 303.43^{a}
FR	301.14 ± 98.13^{b}	150.57 ± 49.07^{b}	552.10 ± 17.91^{b}
SG	230.95 ± 103.54^{c}	115.48 ± 51.77^{c}	423.41 ± 189.82^{c}
***P*-value**	**0.0001**	**0.0001**	**0.0001**

Note: Means in the same column with different superscripts are significantly different at $p \leq 0.05$.

Table 4.17 shows the estimate of total biomass and carbon stock per forest stand for three forest types, which were highly different in forest size and carbon sequestration potential. The forest size varied substantially among the types, with SG covering the largest area of 75.19 ha, followed by FR with an area of 24.89 ha, while the CFA had the smallest area of 8.51 ha (Table 4.17). The total biomass production in SG was high (17,365.19 tons), higher than that of FR (7,495.48 tons) and CFA (4,130.71 tons). The total carbon stock per forest type showed a similar pattern, with SG storing 8,682.60 tons, FR storing 3,747.74 tons, and CFA storing 2,065.35 tons of biomass. The carbon dioxide equivalent per forest type showed high carbon sequestration potential of SG with 31,836.19 tons CO_2 equivalent compared to FR and CFA with 13,741.72- and 7,572.96-tons CO_2 equivalents, respectively (Table 4.17).

Table 4.17: Estimated Total Biomass and Carbon Contents per Forest Stands (Size)

		Stand production per unit area			**Total production for the forest types**		
Forest type	**Total Forestarea (ha)**	**Biomass (tons/ha)**	**Carbon (tons/ha)**	**CO_2 Equiv. (tons/ha)**	**Biomass (tons)**	**Carbon (tons)**	**CO_2 Equiv. (tons)**
CFA	8.51	485.39	242.70	889.89	4,130.71	2,065.35	7,572.96
FR	24.89	301.14	150.57	552.10	7,495.48	3,747.74	13,741.72
SG	75.19	230.95	115.48	423.41	1,7365.19	8,682.60	31,836.19

Table 4.18 presents the average yield per hectare of tree species across three forest management types. The CFA had dominant tree species such as *Daniellia oliverii*, with a basal area of 1.7 m^2/ha, volume of 26.2 m^3/ha, biomass of 18.2 tons/ha, carbon stock of 9.1 tons/ha, and CO_2 equiv. of 33.3 tons/ha; *Erythrophleum suaveolens* with a basal area of 1.7 m^2/ha, volume of 33.5 m^3/ha, biomass of 34.6 tons/ha, carbon of 17.3 tons/ha, and CO_2 equivalent of 63.5 tons/ha. Other significant species in the CFA include *Irvingia gabonensis*, basal area of 2.2 m^2/ha, volume of 12.0 m^3/ha biomass of 12.1 tons/ha, carbon of 6.0 tons/ha, and CO_2 equivalent of 22.1 tons/ha and *Fluggea virosa*, with BA of 1.8 m^2/ha, volume of 36.2 m^3/ha, biomass of 27.4 tons/ha, carbon of 13.7 tons/ha, and CO_2 equivalent of 50.2 tons/ha.

The FR had species such as *Ficus platyphylla*, with BA of 1.3 m^2/ha, volume of 20.5 m^3/ha, biomass of 17.1 tons/ha, carbon of 8.5 tons/ha, and CO_2 equivalent of 31.3 tons/ha. For *Gmelina arborea*, the BA, volume, biomass, carbon and CO_2 equivalent were 0.8 m^2/ha, 11.1 m^3/ha, 7.7 tons/ha, 3.8 tons/ha and 14.1 tons/ha, respectively. *Isoberlinia doka* and *Khaya grandiflora* also demonstrated high yields in the FR. Trees within the SG had relatively lower yields, with *Ficus sur*yielding BA of 1.0 m^2/ha, volume of 9.5 m^3/ha, biomass of 6.8 tons/ha, carbon of 3.4 tons/ha, and CO_2 equivalent of 12.5 tons/ha. Other species in the SG, such as *Khaya senegalensis, Hymenocardia acida,* and *Hannoa undulata*, also had relatively low yields (Table 4.18).

Table 4.18: The Yield of various tree species/ha in the different Forest Management Types in the Study Area

Species	**Community Forest Area**					**Forest Reserve**					**Sacred Grove**				
	BA	**Vol.**	**TB**	**TC**	**CO_2**	**BA**	**Vol.**	**TB**	**TC**	**CO_2**	**BA**	**Vol.**	**TB**	**TC**	**CO_2**
Acanthus montanus	0.4	2.7	1.9	1.0	3.5										
Afrormosia laxiflora											1.6	4.6	3.2	1.6	5.8
Afzelia Africana	0.7	2.7	2.5	1.3	4.7	0.9	10.9	10.1	5.1	18.6	1.7	12.7	11.8	5.9	21.6
Albizia lebbeck						0.6	5.5	5.9	2.9	10.8					
Alchornea cordifolia											1.1	6.1	4.4	2.2	8.0
Aleurites moluccanus	0.8	6.8	5.4	2.7	10.0										
Allophylus africanus	0.7	8.1	7.4	3.7	13.5										
Annona senegalensis						1.9	30.0	32.2	16.1	59.0	1.4	7.1	7.6	3.8	14.0
Annona squamosa											1.7	14.8	11.4	5.7	20.9
Anogeissusleiocarpa	2.1	31.8	20.4	10.2	37.5										
Anthocleista djalonensis	0.4	4.7	2.9	1.4	5.2	0.6	5.7	3.5	1.7	6.4	1.4	4.6	2.8	1.4	5.1
Anthocleista nobilis											0.7	6.0	3.8	1.9	7.0
Antidesma venosum	0.6	6.2	5.2	2.6	9.5										
Artocarpus altilis											0.9	3.3	2.3	1.2	4.2
Bobgunnia madagascariensis	1.0	4.9	2.9	1.4	5.3										
Bombax buonopozense	1.3	23.0	19.4	9.7	35.6	1.3	24.0	20.2	10.1	37.1					
Burkea africana						0.4	6.3	6.0	3.0	11.0					
Canarium schweinfurthii											0.7	4.5	2.7	1.3	4.9
Ceiba pentandra	4.3	81.8	55.6	27.8	102.0						3.9	22.3	15.2	7.6	27.9
Citrus aurantifolia											0.9	7.9	7.0	3.5	12.8
Cola gigantea											1.7	12.0	8.2	4.1	15.0

BA is basal area (m^2/ha), Vol is volume (m^3/ha), Tree biomass (tons/ha), Tree carbon (tons/ha) and CO_2 is Carbon Dioxide (tons/ha)

Table 4.18: Cont.'

Species	Community Forest Area					Forest Reserve					Sacred Grove				
	BA	Vol.	TB	TC	CO2	BA	Vol.	TB	TC	CO2	BA	Vol.	TB	TC	CO2
Combretum nigricans											0.6	6.2	6.4	3.2	11.8
Crescentia cujete	0.4	1.9	1.2	0.6	2.2										
Crossopteryxfebrifuga											0.3	3.0	2.9	1.4	5.2
Daniellia oliverii	1.7	26.2	18.2	9.1	33.3	0.4	4.5	3.1	1.5	5.7	1.4	8.4	5.9	2.9	10.7
Detarium microcarpum	0.4	3.3	3.0	1.5	5.5	0.4	6.3	5.7	2.8	10.4					
Dialiumguineense	1.1	11.8	7.6	3.8	14.0	0.4	4.6	2.9	1.5	5.4	0.6	5.2	3.4	1.7	6.2
Erythrophleum suaveolens	1.7	33.5	34.6	17.3	63.5	1.0	17.4	18.0	9.0	33.0					
Eugenia uniflora	0.4	2.7	2.8	1.4	5.1										
Ferruginous bridelia											1.5	6.9	6.2	3.1	11.3
Ficus exasperata											1.4	3.5	2.5	1.3	4.7
Ficus platyphylla	1.3	20.5	17.1	8.5	31.3										
Ficus sur	1.0	9.5	6.8	3.4	12.5	0.2	0.9	0.7	0.3	1.2					
Ficus sycomorus						0.5	5.1	3.4	1.7	6.2					
Fluggea virosa	1.8	36.2	27.4	13.7	50.2										
Gmelina arborea	0.8	11.1	7.7	3.8	14.1	0.7	8.6	6.0	3.0	11.0	0.9	9.6	6.7	3.3	12.2
Hannoa undulata	0.8	6.5	4.6	2.3	8.5										
Hura crepitans											0.9	5.5	2.6	1.3	4.7
Hymenocardiaacida											0.3	2.5	2.0	1.0	3.6
Irvingia gabonensis											2.2	12.0	12.1	6.0	22.1
Isoberlinia doka	1.5	11.7	11.5	5.8	21.1	0.5	4.8	4.7	2.4	8.6					
Khaya grandiflora						0.6	8.8	9.3	4.7	17.1					
Khaya senegalensis	0.8	6.6	4.9	2.4	8.9	0.4	4.0	2.9	1.5	5.3	1.0	8.7	6.4	3.2	11.7

BA is basal area (m^2/ha), Vol is volume (m^3/ha), Tree biomass (tons/ha), Tree carbon (tons/ha), and CO_2 is Carbon Dioxide (tons/ha)

Table 4.18: Cont.'

Species	**Community Forest Area**					**Forest Reserve**					**Sacred Grove**				
	BA	**Vol.**	**TB**	**TC**	**CO_2**	**BA**	**Vol.**	**TB**	**TC**	**CO_2**	**BA**	**Vol.**	**TB**	**TC**	**CO_2**
Kigelia africana	0.7	4.5	3.6	1.8	6.7						1.3	4.7	3.8	1.9	6.9
Landolphia owariensis	0.5	7.1	8.4	4.2	15.4										
Lannea spp	0.3	4.6	3.2	1.6	5.9	0.3	3.0	2.1	1.1	3.9					
Lophira lanceolata						0.6	7.1	7.0	3.5	12.9					
Maranthes polyandra						0.7	14.1	10.9	5.4	19.9					
Markhamia tomentosa											0.9	7.6	7.1	3.6	13.1
Milicia excelsa	2.8	37.2	30.5	15.3	55.9						0.7	11.1	9.1	4.5	16.6
Mitragyna inermis	0.2	1.1	0.5	0.2	0.9	0.2	1.7	0.7	0.4	1.3					
Monotes kerstingii											1.3	12.7	11.2	5.6	20.6
Newbouldia laevis											0.4	4.3	3.3	1.6	6.0
Parkia biglobosa											2.1	14.7	10.0	5.0	18.4
Prosopis africana											1.2	4.4	3.1	1.5	5.6
Prunus africana	0.8	8.1	7.2	3.6	13.1										
Pterocarpus erinaceus						0.7	9.7	8.5	4.2	15.5					
Sarcocephalus latifolius						0.6	4.9	4.9	2.4	9.0					
Senna siamea						0.3	4.3	3.8	1.9	7.0					
Spondias mombin	1.9	32.0	23.0	11.5	42.1						1.5	9.0	6.5	3.2	11.8
Sterculia setigera	1.7	24.5	18.8	9.4	34.5										
Stereospermum kunthianum						0.5	1.9	1.6	0.8	2.9					
Strophanthus hispidus						0.6	4.3	3.2	1.6	5.9					
Strychonos spinosa	1.2	17.9	17.6	8.8	32.3	0.5	7.4	7.3	3.6	13.3					
Tectona grandis	1.4	24.2	15.0	7.5	27.4										

BA is basal area (m^2/ha), Vol is volume (m^3/ha), Tree biomass (tons/ha), Tree carbon (tons/ha), and CO_2 is Carbon Dioxide (tons/ha)

Table 4.18: Cont.’

Species	Community Forest Area					Forest Reserve					Sacred Grove				
	BA	**Vol.**	**TB**	**TC**	**CO_2**	**BA**	**Vol.**	**TB**	**TC**	**CO_2**	**BA**	**Vol.**	**TB**	**TC**	**CO_2**
Terminalia macroptera											1.3	7.2	6.4	3.2	11.8
Tetrapleura tetraptera	1.9	32.3	26.8	13.4	49.2										
Trema orientale	0.9	9.7	4.3	2.1	7.9										
Uapaca heudelotii											0.7	3.6	2.8	1.4	5.2
Uvariachamae	2.5	43.5	36.7	18.3	67.3						0.5	5.2	4.4	2.2	8.1
Vitellaria paradoxa						0.1	0.6	0.6	0.3	1.1					
Vitex doniana	1.1	17.5	12.6	6.3	23.1	0.7	8.1	5.8	2.9	10.7	0.6	6.2	4.4	2.2	8.1

BA is basal area (m^2/ha), Vol is volumem^3/ha), Tree biomass (tons/ha), Tree carbon (tons/ha), and CO_2 is Carbon Dioxide (tons/ha)

Table 4.19 presents the TB and TC stocks of dominant tree species across three forest management types in this study. A total of 46 tree species were identified as dominant tree species based on high TB yield of 5 tons/ha and above. Of these, only *Gmelina arborea* was found in the three forest types, while the remaining 43 species were identified in either two forest types or only one. *Gmelina arborea* showed different TB and TC estimates in CFA (7.69 tons/ha, 3.85 tons/ha), FR (5.99 tons/ha, 3.00 tons/ha), and Sacred Grove (6.66 tons/ha, 3.33 tons/ha).

Afzelia africana had a TB of 10.13 tons/ha and stored 5.07 tons/ha of TC and Co_2equav. 18.58 tons/ha in the CFA area. The TB and TC in FR were estimated at 11.81 tons/ha and 5.90 tons/ha, respectively, with a CO_2 equivalent of 21.65 tons/ha. *Albizia lebbeck* showed a TB yield of 5.89 tons/ha, a TC storage of 2.94 tons/ha, and 10.80 tons CO_2 tons/ha in CFA. *Aleurites moluccanus* had a TB yield of 5.43 tons/ha and a TC storage of 2.71 tons/ha, with an estimated 9.95 tons/ha as CO2 equiv. within the CFA area.

Isoberlinia doka had a TB value of 11.52 tons/ha, with a TC storage value of 5.76 tons/ha of and 21.11 tons/ha of CO_2 within CFA. *Milicia excelsa* showed a high TB yield in CFA (30.51 tons/ha) and FR (9.08 tons/ha). A TC storage of 15.25 tons/ha and 4.54 tons/ha, representing 55.93 tons/ha of CO_2 equiv. and 16.64 tons/ha of CO_2 equivalent, under CFA and FR, respectively. *Uvariachamae* had the highest TB and TC values in CFA, totalling 36.68 tons/ha and 18.34 tons/ha respectively, and 67.25 tons/ha of CO_2 equiv.

Table 4.19: Dominant Tree Species Mean Biomass and Carbon per Forest Management

Species	**Community Forest Area (tons/ha)**			**Forest Reserve (tons/ha)**			**Sacred Grove (tons/ha)**		
	TB	**TC**	**CO_2**	**TB**	**TC**	**CO_2**	**TB**	**TC**	**CO_2**
Afzelia africana				10.13	5.07	18.58	11.81	5.90	21.65
Albizia lebbeck				5.89	2.94	10.80			
Aleurites moluccanus	5.43	2.71	9.95						
Allophylus africanus	7.38	3.69	13.53						
Annona senegalensis				32.16	16.08	58.97	7.62	3.81	13.97
Annona squamosa							11.39	5.69	20.88
Anogeissusleiocarpa	20.43	10.22	37.46						
Antidesma venosum	5.20	2.60	9.54						
Bombax buonopozense	19.41	9.70	35.58	20.24	10.12	37.11			
Burkea africana				5.99	3.00	10.99			
Ceiba pentandra	55.64	27.82	102.00				15.20	7.60	27.87
Cola gigantea							8.17	4.09	14.99
Combretum nigricans							6.43	3.21	11.78
Daniellia oliverii	18.18	9.09	33.34				5.85	2.93	10.73
Detarium microcarpum				5.66	2.83	10.38			
Dialiumguineense	7.61	3.80	13.95						
Erythrophleum suaveolens	34.62	17.31	63.47	17.99	8.99	32.97			
Ferruginous bridelia							6.15	3.08	11.28
Ficus platyphylla	17.08	8.54	31.31						
Ficus sur	6.84	3.42	12.53						
Fluggea virosa	27.39	13.70	50.22						
Gmelina arborea	7.69	3.85	14.10	5.99	3.00	10.98	6.66	3.33	12.21
Irvingia gabonensis							12.07	6.03	22.12

Table 4.19: Cont.'

Species	Community Forest Area (tons/ha)			Forest Reserve (tons/ha)			Sacred Grove (tons/ha)		
	TB	**TC**	**CO_2**	**TB**	**TC**	**CO_2**	**TB**	**TC**	**CO_2**
Isoberlinia doka	11.52	5.76	21.11						
Khaya grandiflora				9.35	4.67	17.14			
Khaya senegalensis							6.36	3.18	11.66
Landolphia owariensis	8.42	4.21	15.44						
Lophira lanceolata				7.02	3.51	12.88			
Mangifera indica	14.54	7.27	26.65						
Maranthes polyandra				10.87	5.44	19.93			
Markhamia tomentosa							7.14	3.57	13.09
Milicia excelsa	30.51	15.25	55.93				9.08	4.54	16.64
Monotes kerstingii							11.22	5.61	20.58
Parkia biglobosa							10.02	5.01	18.38
Prunus africana	7.17	3.58	13.14						
Pterocarpus erinaceus				8.47	4.24	15.53			
Spondias mombin	22.97	11.48	42.11				6.45	3.23	11.83
Sterculia setigera	18.84	9.42	34.54						
Strychonos spinosa	17.63	8.81	32.32	7.27	3.63	13.32			
Tectona grandis	14.95	7.48	27.41						
Terminalia macroptera							6.42	3.21	11.77
Tetrapleura tetraptera	26.85	13.42	49.22						
Uvariachamae	36.68	18.34	67.25						
Vitex doniana	12.60	6.30	23.11	5.82	2.91	10.67			

CHAPTER FIVE

5.0 DISCUSSION

5.1. Biological Diversity Status of the Different Forest Management Types

The differences in the frequency of occurrence (CFA=38, FR=28 and SG=35) of tree species across the three forest management types could be an indication of the influence of different ecological conditions and management practices on tree species composition in the study area. Comparing the differences in the frequency of occurrence of tree species across the three forest management types with findings from other studies, it is suspected that variations in ecological conditions, anthropogenic activities and management practices played significant roles in shaping tree species occurrences and composition. A report by Bentsi-Enchill *et al.* (2022) on tropical forest reserves in the Atewa Range (Ghana), reported that undisturbed (protected) forests had higher species diversity and frequency than stressed (disturbed) forests, where human activity and logging were more prevalent. Another study by Paudel and Sah (2015) compared the structure, composition, and diversity of trees, shrubs, saplings, seedlings and herbaceous species of community- and government-managed forests in the lowlands of eastern Nepal, India. Their result indicated that the community-managed forest had higher species diversity than the government-managed forest, which is similar to the results of the present study, which revealed that the CFA had higher species diversity than FR, which is a government-managed forest. Sinthumule (2024) reported that SGs, protected by cultural taboos (a form of community method), offer a relatively undisturbed environment that supports the survival of local biodiversity (a variety of plants and animal species that are endemic), making them critical refuges for biodiversity. This view is supported by the relatively high species diversity index of SG in this study, which is higher than the diversity index of FR. This indicates that management practices can either enhance or degrade forest composition, which could explain the variations observed in the current study area.

The low presence of *Afzelia africana* in the CFA could be an indication of less soil-favourable conditions for its growth in this forest type compared to FR and SG. On the other hand, the higher frequency of *A. africana* in SG signifies more suitable habitats or management practices that promote the growth and survival of the species found in the forest type (SG). However, the presence of *A. africana* as an economic and endangered species in FR contradicts the report of Adekunle *et al*. (2013), who reported that essential tree species with high market value and demand are usually identified in the forest reserves and cut by loggers without any regard to their sizes and prevailing logging policies. The presence of *Afrormosia laxiflora*, *Albizia lebbeck* and *Dialium guineense* across the three forest types could be an indication that the species can thrive in different habitats and withstand different forest management types. The result from a study conducted by Esor *et al.* (2023) is in line with this finding by confirming that species such as *Afrormosia laxiflora, Albizia lebbeck, and Dialium guineense can* thrive across various habitats and under different forest management types. For instance, Esor *et al.* (2023) found that these species are resilient and can adapt to a wide range of ecological conditions, from protected forest reserves to more disturbed forest areas. Thus, the presence of these species in the CFA, FR, and SG indicates their ability to withstand varying management practices. The higher occurrence of *Daniellia oliverii* in FR compared to CFA and SG implies a potential preference for the species for soil status in FR. *Daniellia oliverii* may prefer soils with higher nutrient levels, often better maintained in managed reserves like the FR due to selective logging and controlled human activities that enhance soil conditions.

IVI serves as a valuable tool for prioritizing conservation actions and allocating resources effectively to protect vulnerable species and maintain overall ecosystem health. Variations in RDo and IVI values across the different forest management types revealed species representation within each forest type. While some species exhibit consistent dominance and importance across all forest management types, others show variability, suggesting differences in habitat suitability and management practices. The low RDo and IVI values observed for some species in this study can be attributed to their limited abundance and distribution within the study area. Factors such as habitat specialization, competition with other species, and anthropogenic disturbances like farming, deforestation, forest degradation, logging, etccan adversely affect the population size and distribution of species, leading to their low importance value indices (Russo *et al.,* 2005). The conservation status of tree species (e.g. under the IUCN categorization) can inform their conservation prioritization. For exapmle, the tree species (e.g. *Tetrapleura tetraptera)* classified as Vulnerable (VU), or listed as Endangered (e.g. *Monotes kerstingii*), require urgent conservation attention due to their declining populations and threats to their survival.

The variation in Importance Value Index (IVI), RD, and Relative Dominance (RDo) values observed among different tree species across various forest management types could be attributed to management type and disturbance level, among other factors, since only a few species appeared across three or two forest types. This result aligns with the reports of Senbeta and Denich (2006) and Poudyal *et al. (*2019), who reported that species well-adapted to the management regime of one specific forest type exhibited higher dominance and importance values.

The results revealed that only six tree species (*Khaya senegalensis, Gmelina arborea, Dialium guineense, Daniellia oliverii, and Afzelia africana)* were common to the three forest types in this study (CFA, FR and SG), which suggests that there is a high variation of species among the three forest types The presence of a few common species across different forest types indicates that unique ecological conditions and management practices influence species composition and distribution. Factors like soil fertility, moisture, and human intervention shape which species thrive in each forest type. This finding aligned with the report of Adekunle *et al.* (2013) and Thammanu *et al.* (2020). Thammanu *et al.* (2021) studied the environmental factors influencing differences in the biodiversity of stands in a community forest in Northern Thailand, their result revealed that environmental factors (elevation, distance to streams, soil moisture, organic matter, and distance to communities) significantly ($p<0.005$) influenced the diversity and distribution of tree species in the community forest. Adekunle *et al*. (2013) showed that managed forests, like reserves, support species that thrive in higher soil fertility, while culturally protected areas sustain those adapted to lower disturbance. This indicates that environmental factors and forest management play key roles in determining species diversity across habitats.

Furthermore, the variations in species compositions could be attributed to the different management practices of the forests in this study. Qianwen *et al.* (2022) attributed variations in species composition to diverse ecological conditions, management practices, species interactions, and successional stages within each forest management type. Factors such as management systems, forest structure, forest boundary and fire intensity contribute to the observed differences in species distribution. Varying management practices (such as logging intensity, fire management, and habitat restoration efforts) play a significant role in shaping the composition of tree species within forest ecosystems (Driscoll *et al.,* 2010). Song *et al.* (2019) reported that species richness and diversity declined with increasing elevation, and species similarity between adult trees and seedlings decreased with elevation. Also, temperature had a great impact on species distribution at higher elevations, while the influence of soil moisture diminished. However, the genetic makeup of trees in the forest types could also influence this result as reported by Akinnagbe *et al.* (2019), who reported that tree populations, species, or taxa can differ greatly in genetic diversity due to internal characteristics such as reproductive system size and genome structure, or external characteristics such as age, density, and distribution, as well as geographic or environmental factors like human impacts. Competitive interactions among tree species due to management effects could be another factor influencing tree species composition and patterns. Tree species compete differently for resources such as light, water, and nutrients, leading to differential success in establishing and maintaining populations (Stoll and Bergius, 2005). The higher tree species diversity in CFA and SG may have been influenced by effective conservation practices and lower levels of human impact than in FR. Melinda and Alan (2003) opined that widespread stressor, such as land-use change, fragmentation, and biotic invasions, are among the drivers of species loss in natural ecosystems like the forest types in this study.

The Community Forest Area (0.53) and SG (0.55) exhibited significantly higher values of species evenness, indicating a more balanced distribution of tree species. This indicates that species within these forests are more equally represented, with no single species overwhelmingly dominating. However, FR had a lower evenness value (0.29), which implies a higher level of dominance by a few species, likely due to increased disturbance or reduced regeneration in this forest type. The Menhinick Index further revealed differences in species richness, with CFA (1.75) showing the highest species richness and FR (1.05) having the lowest species richness, indicating that species diversity in FR is significantly reduced compared to CFA and SG. The higher Menhinick values in CFA and SG indicated a larger variety of species relative to the number of individuals, which may reflect less disturbance and better ecological stability in these forests. Similarly, the Margalef Index showed that CFA (6.01) had the highest species richness, with FR (4.11) having the lowest value. This further supports the idea that CFA and SG have more diverse tree species populations, while FR may have experienced reduced biodiversity, potentially due to greater human impact or other environmental stressors. These findings are consistent with the existing literature on similar ecosystems. Sacred groves are often recognized for their high diversity, as they are culturally protected and experience less human disturbance. For instance, Bharathi and Prasad (2017) reported that in SGs in India, tree species diversity tends to decline with increased human activity, mirroring the relatively high diversity indices in SG.

Forest reserves are often subjected to logging and other forms of exploitation, leading to reduced species richness and more uneven species distribution, as seen in the low evenness and species richness indices in this study. Similar studies in tropical and subtropical forests have shown that disturbances are negatively associated with tree species richness (Cardelús *et al.,* 2019). On the other hand, community-managed forests like CFA tend to exhibit higher diversity and more even species distribution due to local conservation efforts and sustainable management practices. This aligns with research from tropical ecosystems, where community involvement in forest management often results in enhanced biodiversity conservation. Variations in habitat structure and quality, such as disturbance regimes, could be responsible for the influence of species richness in the area. Chaudhary *et al.* (2016) reported that some types of management have high effects on forest species due to differences in habitat structure and continuity or microclimatic conditions after the harvest.

The variation in species richness was due to some factors (high impact of anthropogenic activities and land conversion), which negatively affected species richness as observed in FR. This is in line with the report of the National Space Research and Development Agency (2023), which stated that forests have declined while cultivated land and artificial surfaces have increased in Tukoki and Maje-abuchi reserves, and deforestation appears to be more pronounced. Kung'u *et al*. (2023) reported that human presence and activity at both the plot and landscape level explain variation in vegetation structure. Deforestation and fragmentation, over-exploitation, invasive species, and climate change are the main drivers of tropical forest biodiversity (Dar *et al*., 2022). The Forest areas in Benue State have experienced high levels of human disturbance. Akpa *et al.* (2022), reported a significant positive relationship between wood collection and deforestation in Benue State, forecasting that deforestation in Benue State will increase significantly between 24.4% and 44.7%. According to Kurayemen *et al.* (2013), the people of Benue State are principally engaged in agricultural activities, which accounts for a greater percentage of forest degradation in the state.

The CFA and SG areas have lower rates of deforestation, probably due to their nature of management. For instance, SG are revered as sacred sites and protected from human disturbance (Singh *et al.,* 2017; Onyekwelu, 2021; Adeyanju *et al.,* 2022), which contributes to their rich species compared to less protected areas, such as the FR (Onyekwelu, 2021). This result agreed with the report of Vuyiya *et al.* (2014), who revealed a negative influence of human activities on the forest. The analysis of variance conducted on the Margalef indices in this study confirmed the significant differences in species richness between the different forest management types. The lack of significant difference between the CFA and SG implies similar levels of species richness in these two forest management types, while the species richness of both forest types was significantly higher than that of FR.

The comparison of biodiversity indices values across different forest management types indicated variations in species evenness and equitability indices, indicating potential differences in ecosystem structure and balance. The higher value of species evenness observed in SG compared to CFA and FR indicated that species within the SG were more evenly distributed. This indicates that the SG is a more stable and balanced ecosystem where various species coexist in harmony. In contrast, the lower species evenness value of FR implies a more skewed distribution of species, potentially due to disturbances in the area. Similarly, the higher equitability index in SG compared to CFA and FR indicates a more equitable distribution of tree species abundance within the SG ecosystem. This implies that in the SG, resources are utilized more evenly among species in less disturbed ecosystems, leading to a balanced ecological community, which aligns with the work of Dumbrell *et al.* (2008), who showed that biodiversity increased after moderate disturbance, but it decreased in large disturbances.

The frequency and intensity of natural disturbances, such as wildfires and insect outbreaks, can shape species composition by creating openings for certain species to establish and thrive (Simler-Williamson *et al.,* 2021). Human-induced disturbances (logging and land conversion), also influence species composition. Variations in habitat structure, such as soil type, elevation, and microclimate, have been reported to also influence species composition (Mantilla-Contreras *et al.,* 2012).

Forest areas with little or high human activities (as evidenced under FR) have different species compositions compared to more pristine or less disturbed areas (under CFA and SG). Rudnick *et al.* (2012) pointed out that land connectivity, proximity to other forested areas or barriers to dispersal, such as rivers or mountains and/or settlements, affect species exchange and lead to differences in species composition and colonization patterns. The degree of human disturbance and natural disturbances (e.g. fire, storms) impact the distribution and abundance of tree species (Dornelas, 2010). Forest ecosystems (e.g. CFA and SG) with minimal human disturbance support better species compositions and richness (Bharathi and Prasad, 2017; Ekanayake *et al.,* 2020; Cardelús *et al.,* 2019) compared to areas with higher disturbance levels (e.g. FR), as demonstrated by the results of this study in which CFA and SG consistently had comparable biodiversity indices, which were significantly higher than the biodiversity indices of FR (Table 3). Ekanayake *et al.* (2020) reported that the community forest programme increased seedling and sapling density to a significant degree and reduced human disturbances. Similarly, Bharathi and Prasad (2017) reported that tree species diversity and basal area decreased as human disturbance increased in the four sacred groves of Kushalnagar, Karnataka. Cardelús *et al.* (2019) found that disturbances led to a decrease in tree species richness in the Sacred Church Forest in Ethiopia.

The presence or absence of certain species in different forest management types reflect their habitat preferences, adaptability to environmental conditions, and/or management impacts in each ecosystem. The dispersal abilities of tree species can affect their distribution patterns across different forest management types (Datta and Rawat, 2008). Species with efficient dispersal mechanisms is more widespread, while others may be restricted to specific habitats (Croteau, 2010). Deforestation, land conversion, and habitat fragmentation can shape species composition and distribution patterns (Whitlock *et al.,* 2019).

5.2 Soil Properties and Soil Organic Carbon

Soil texture analysis revealed a predominant sand composition, with sand constituting over 65% of the soil particle size distribution (range: 60.0 - 75.0%) of the three forest management types. In contrast, the amounts of silt and clay (silt range: 5.4 to 6.4%, and clay: 17.1 to 34.6%) in the three forest types were lower, confirming the prevalence of sandy soils in the three forest types. A comparison of the soil physical properties of the CFA and SG revealed differences in their texture, particularly in the proportions of sand and clay, indicating the influence of forest management types, among other factors on the physical properties of the soils in the study forests.

The sand and silt contents of the soils under the forest management types in this study are lower than the values of sands (71.2 to 84.2%) and silts (7.4 to 10.4%) reported for Gambari Forest Reserve, Nigeria, by Opeyemi *et al.* (2020). However, the clay content (range: 17.1 – 34.6%) recorded in this study is higher than the value reported for the soils of the Gambari Forest Reserve (Opeyemi *et al.,* 2020). The results of soil physical properties in this study aligned with the report of Unanaonwi and Chinevu (2013), who studied and reported sand content of 74.96%, clay contents of 17.04%, and silt content of 8% in forest soils of Southern Guinea Savanna in Nasarawa state, Nigeria. The result of this study is consistent with the report of Schweizer *et al.* (2021), who reported a clay value of between 18% and 37% in an arable toposequence in the north of Munich, Germany.

It has been demonstrated that soils with higher clay content tend to have greater carbon storage capacity due to higher organic matter content and better aggregation (Han *et al*., 2010; Ontl and Schulte, 2012). Thus, SG soils with the highest clay content can store more carbon than soils with low clay content (such as CFA and FR). This result is in line with the report of Han *et al*. (2010) and Ontl and Schulte (2012), who opined that soils with high clay content have high carbon storage capacity due to high organic matter content and better aggregation. The variation in soil physical properties impacts soil biodiversity and habitat quality (Doula and Sarris, 2016), ultimately influencing ecosystem health and resilience (Burton *et al.,* 2022). Soil structure and stability can also be affected by variations in sand, silt, and clay contents (Santos *et al*., 2018). Going by the submission of Yudina and Kuzyakov (2023), it can be argued that the soils of SG, which have higher clay content (34.6±3.29), exhibited superior structural stability and water retention capability. However, excessive clay content can lead to poor drainage and aeration (Obia *et al.,* 2018). Fisher and Binkley (2000) reported that the primary distinction between soil textures lies in the surface areas of various particle sizes, which impact water potential, organic matter binding, cation exchange, and overall biotic activity.

Soils under CFA and FRwith high sand contents (74.8±2.48% and 75.0±4.47 %, respectively), have been associated with high soil texture that is associated with high water filtration rate (drainage) but low water and nutrient retention capacity (Ma *et al*., 2016; Anaba *et al*., 2020), especially during heavy rainfall period. Soil texture affects water infiltration rates and erosion susceptibility (Ma *et al*., 2016; Santos *et al.,* 2019). Consequently, it can be inferred that SG soils with high clay content (34.6±3.29%) have low water infiltration rates but better water retention rates, which is similar to the observation of Munnaf *et al.* (2020). This will potentially influence vegetation productivity and composition (Santos *et al.,* 2018).

Variations in soil physical properties can be crucial to ecosystem health, biodiversity conservation, and land productivity. Changes in soil texture (sand, silt, and clay content) can impact drainage, aeration, and soil water retention, affecting plant root growth, soil structure, and ecosystem resilience (Yudina and Kuzyakov, 2023). The differences in sand, silt, and clay contents of the three forest management types in this study is an indication that forest management types can have different degrees of influence on soil structure, water filtration and retention, and soil productivity (Grigal, 2000; Mayer *et al.,* 2020).

Soil nutrients are essential for plant growth and development (White and Brown, 2010). Variations in nutrient availability among different forest management types affect plant communities, potentially influencing ecosystem structure and function (Ma *et al*., 2023; Nguyen *et al.,* 2022). Soils with higher levels of essential nutrients have greater fertility and productivity, promoting tree growth and vegetation (Freyer *et al*., 2023). Conversely, nutrient-poor soils may require additional nutrient inputs such as fertilizers to sustain forestry activities (Vanlauwe *et al*., 2023).

The soil pH from this study was slightly acidic to neutral (4.82 to 6.07), this range provides the best growing conditions in an ecosystem and influences the uptake of nutrients by plants (Dewangan *et al.,* 2023; Opeyemi *et al.,* 2020). The significant differences (p=0.001) in soil pH indicate variations in soil alkalinity and acidity across the forest management types. Differences in soil pH have important implications for soil fertility and nutrient availability, as pH affects nutrient solubility and availability for plant growth (Miller, 2016; Khaidem *et al.,* 2018). Soil pH was found to be highest under SG (6.07±0.08), and CFA (5.90± 0.14), while FR had the lower (4.82±1.89) pH level. The acidic soil observed in FR can lead to restrictions in the availability of essential nutrients such as phosphorus and calcium (Johan *et al.,* 2021; Barrow and Hartemink, 2023). Neutral soils (as recorded in CFA and SG) and alkaline soil make a more conducive environment for nutrient absorption and enhanced plant growth (Ferrarezi *et al.,* 2022) and influence microbial organisms as well as aid in nutrient cycling and ecosystem functioning (DeLuca *et al.,* 2019).

The soil pH level in this study (between 4.82 and 6.07) is within the range of the values recorded by Atiku and Noma (2011), who reported a soil pH range of 4.23 to 6.94 in the Wassaniya Forest Reserve. Opeyemi *et al.* (2020) reported a slightly acidic to neutral soil (pH range: 5.90 - 6.60) for soils of the Gambari Forest Reserve, Southwestern Nigeria, which is marginally higher than the values recorded in this study. Our results are within the range reported by Yekini *et al*. (2022), who recorded a 5.80 to 7.90 (with a mean value of 6.85) pH level for two Sacred Forests in Adamawa State, Nigeria. The pH value in SG in this study is lower than the pH range of 7.30 to 7.55 reported for two sacred forests in Southwestern Nigeria (Oyelowo *et al.,* 2021). A study conducted in the tropical rainforest ecosystem of southwestern Nigeria by Onyekwelu *et al.* (2014) reported a pH range of 5.5 – 6.7 which is higher than recorded in this study. Amonum *et al.* (2020) reported neutral soil (pH value of 6.30) for the forest reserve in Ilorin, Nigeria, which is contrary to the acidic soil (pH value of 4.82±1.89) recorded in FR in this study. Among other related factors, variations in management practices could be responsible for the pH variation in the soils of the study area.

The soil nutrient contents (magnesium (Mg), potassium (K), and calcium (Ca)) varied across the forest management types, indicating that soil fertility status may be related to management types. The significant differences in Mg, K, and Ca contents across the management types can influence reforestation and regeneration practices (Mayer *et al.,* 2020). High concentrations of Mg, N, P, and K were recorded in the SG soil, which may be an indication of soil fertility and nutrient accessibility in this forest type. The CFA had a slightly lower concentration of N, P, and K than SG, while FR had the lowest contents. Sodium content was similar across all three management types. Sacred Grove (3.67 Cmol/kg) had the highest potassium content, which was not statistically significant (p=0.054) from that of CFA (2.71 Cmol/kg) and FR (2.70 Cmol/kg). Sacred grove soil had the highest magnesium content (0.97 Cmol/kg), which is essential for photosynthesis and chlorophyll synthesis (Li *et al.,* 2018). High magnesium content in soil is correlated with increased plant growth and ecosystem productivity (Wang *et al*., 2020).

Sacred Grove had the highest magnesium content (0.97 Cmol/kg), essential for photosynthesis and chlorophyll synthesis (Li *et al.,* 2018). Higher magnesium levels in soil are correlated with increased plant growth and ecosystem productivity (Wang *et al*., 2020). The high K content (0.20 Cmol/kg) in SG soils implies the availability of essential nutrients for physiological processes in plants, such as water uptake, enzyme activation, and osmoregulation (Hasanuzzaman *et al.,* 2018). The diversity of tree species influences the amount of carbon in the soil and the availability of nutrients (Olsson *et al.,* 2012; Shanin *et al.,* 2014). Soil with higher potassium levels significantly enhances plant health and boosts its ability to withstand environmental stress (Wang *et al*., 2013; Hasanuzzaman *et al.,* 2018). These findings imply that the SG management type had a more favourable soil chemical profile, yielding a more fertile and nutrient-rich soil environment. In contrast, the FR had the lowest soil nutrient content, indicating the need for soil improvement or conservation practices to enhance soil fertility.

Contrary to the results of this study, Amonum *et al*. (2020) reported lower Na, Mg, Pg and Ca in soils under different land-use systems. For instance, Amonum *et al.* (2020) reported sodium contents of 0.06 to 0.15 Cmol/kg, potassium of 0.27 to 0.43 Cmol/kg, magnesium of 0.0 to 0.18 Cmol/kg, and calcium of 0.57 to 1.09 Cmol/kg. The Mg, N, P, K, and Na contents in different forest management types were lower than those reported by Onyekwelu *et al.* (2008) in primary degraded tropical rainforest ecosystems in southwestern Nigeria. However, the calcium value (0.96 to 1.24 Cmol/kg) in this study was higher than the calcium value (0.67 to 0.91 Cmol/kg) reported by Onyekwelu *et al.* (2008).

The result of this study is at variance with what was reported by Abdul Rashid *et al.* (2024) for soil physicochemical properties in the parklands of northern Nigeria. Abdulrashid *et al.* (2024) reported higher Ca (1.86 to 2.21 Cmol/kg), P (3.83 to 5.73 Cmol/kg) and K (0.19-0.25 Cmol/kg) while OC (0.49 to 0.51 %), N (0.04 to 0.05%), Mg (0.55 to 0.71 Cmol/kg) and Na (0.80 to 0.9 Cmol/kg) were lower for Bauchi, Jigawa, and Kano States than what was recorded in this study. The Mg, N, P, K, and Ca values in this study were lower than the values reported by Watanabe *et al.* (2020) for a Teak plantation in Ghana which contained total N content of 1.3 ± 0.5 g kg^{-1}, P content of 3.69 ± 1.86 mg kg^{-1}, exchangeable Ca content of 6.17 ± 4.61 Cmol/kg, Mg content of 1.23 ± 0.81 Cmol/kg, and exchangeable K of 0.15 ± 0.07 Cmol/kg. In comparison with the above results of some research workers (Onyekwelu *et al.,* 2008; Onyekwelu *et al.,* 2014; Dachung *et al*., 2019; Akinde *et al*., 2020; Egwunatum *et al.,* 2020; Watanabe *et al.,* 2020), it is evident that the concentration of Ca, K, Mg, Na, N, and P were low across the soils of the studied forest management types. This may be attributed to fast litter decomposition or seepage (Kerenku *et al*., 2010). Kerenku *et al.* (2010) reported that most Nigerian soils have low nutrient values linked to leaching from heavy tropical rainfall and low levels of nutrients in the parent rock.

The effects of land management on soil properties vary depending on several factors (Negasa *et al*., 2016; Kebebew *et al.,* 2022). Adapting land management practices to the unique soil conditions of each forest type can enhance sustainability and mitigate potential. The observed differences in soil chemical properties among the three forest management types can be attributed to various factors, including soil composition, land management practices, and environmental conditions (Selassie *et al*., 2015; Akinde *et al.,* 2020; Haile *et al*., 2022).

The OC contents (1.80 % to 1.83 %) across the forest management types in this study were relatively low, though higher than the values (0.1 to 0.16%) for the soils of the Wassaniya forest reserve (Atiku and Noma, 2011). Akpa *et al.* (2016) found a high average soil OC content of 1.41% (range: 0.42% to 2.4%) in the upper 30 cm of various agroecological zones of Nigeria, which is higher than the results obtained in this research. Egwunatum *et al*. (2020) studied the soils of Ogwashi-Uku Forest Reserve, Delta State, Nigeria and reported 3.02% soil OC in Bamboo plantations and 1.66% in *Gmelina arborea* plantations, which are higher than the values reported in this study. The OM levels observed in this research are comparatively lower than the values reported for the Igbo-Ile and Igbo-Oba sacred groves by Oyelowo *et al.* (2021), who reported a soil OM content range of 5.24% to

6.0% in 0-15 cm soil depth, and 4.5% to 4.6% in 15-30 cm depth. The OM value in all forest types examined in this study surpasses the OM levels (range: 0.17% to 0.24%) reported by Atiku and Noma (2011).

The p-values for OC and OM are greater than 0.05 (0.391 and 0.528, respectively), indicating no significant differences in OC and OM contents across the three forest management types. Thus, excluding all other factors, it is taken that forest management types have comparable effects on soil OC and OM contents. This similarity in OC and OM contents of the forest management types could be attributed to various factors, including relatively similar tree species and composition and identical ecological zones, as opined by research workers in different ecosystems (Liu *et al.,* 2016). The OM and OC contents of the three forest management types were similar, indicating close similarity in management effect (Pérez-Cruzado *et al.,* 2014; Lu *et al.,* 2019; Giweta, 2020).

5.3 Tree and Stand Growth Characteristics

Most (511) of the individual trees in FR were within the lower diameter class (10-25 cm), with fewer (2) trees found in the largest diameter class (55.1-70 cm). However, SG had a slightly more even diameter distribution, with most (223) trees in the lowest diameter class (10-25 cm) and a good number (46) of the trees observed in the middle diameter class distribution (55.1-70 cm). The CFA displayed a different diameter distribution pattern than the FR and SG, with fewer trees (152) in the lower diameter class and upper classes, including one tree stand in the uppermost diameter class (130.1-145 cm). The CFA and SG had a few individual trees in the upper diameter classes (70.1 cm to 115 cm), whereas no trees were found in this diameter class in the FR. Thus, this finding indicates that forest management types influence the diameter distribution of trees, with CFA and SG having more mature or older tree populations than FR. Thus, it is suspected that minimal anthropogenic activities such as tree felling (deforestation) were experienced in the CFA and SG than in FR. This was largely due to the high restrictions on human access by the chief priests (for SG) and community leaders (for CFA) than in the forest reserve.

Forest reserves, one of the forest management systems, have been solely controlled by state authorities and agencies, fully or partially excluding the surrounding communities living near these resources (Onyekwelu and Olusola, 2014). Due to the ineffective monitoring of forest reserves, there is wide-scale encroachment and other anthropogenic activities in forest reserves. Consistent with the report of Boadi *et al.* (2017), the findings of this research support the view that the non-involvement of local communities in forest protection strategies often leads to conflicts between government agents and surrounding communities living on the outskirts of forests, which could affect forest productivity.

An inverse-J diameter distribution pattern, characteristic of natural tropical forests, was observed for the diameter distribution of individual trees across the three forest management types. This pattern of diameter distribution signifies the regeneration ability of the forest ecosystems (Chenge *et al.,* 2019). Smaller trees within the lower diameter distribution class will mature and replace the larger trees in the upper diameter class if sustainable management is adopted. The occurrence of natural regeneration over a given period (when there is little to no disturbance), results in declining of lower diameter distribution from small to large diameter class (Djomo, 2011).

Larger trees were enumerated in the CFA and SG than in the FR forest management type. The CFA had the highest mean diameter at breast height (35.0 cm) and the highest maximum Dbh (143.0 cm). Trees with smaller sizes were dominant in FR, with fewer large and mature trees encountered than in CFA and SG. The low occurrence of mature trees with larger Dbh in FR could be because of anthropogenic activities, soil factors or management effects. Bentsi-Enchill *et al.* (2022), Anthropogenic disturbances (illegal logging, farming, mining) contribute to reduced tree species diversity, density of stands and removal of mature trees in an upland evergreen forest of Ghana, West Africa. Also, Tenzin and Hasenauer (2016) stated that anthropogenic disturbances due to management have a higher impact on changes in biodiversity than what would occur under natural conditions.

To assess the structural stability of an ecosystem, growth, maturity, assortment structure, and volume output, the tree diameter distribution pattern is an important element in sustainable forest management (Egonmwan and Ogana, 2020). Understanding the diameter distributions of forest ecosystems eases the prediction of growth and harvesting of any given forest stand (Ekpa *et al.* 2014). Diameter distribution plays a vital role in sustainable forest management during decision-making (such as prescribing silvicultural treatments and planning fire prevention measures) by forest managers (Carretero and Alvarez, 2013). There was high variability in tree height distribution within the CFA, with a mean tree height of 17.9 m, while the FR and SG had moderate and low variability, respectively. Most individual trees (273) were concentrated within the lower height distribution class of 10 - 15 meters under the FR. The dominance of individual trees in the upper-class height distribution in FR indicates continuous succession. The dominance of individual trees standing in the lower-height classes indicates that the forests have younger trees, which implies the regeneration of stands due to competition. This is in line with the report of Lula *et al.* (2021), which stated that lower growth of naturally regenerated stands may be partly due to competition from seed or shelter trees.

The CFA had an uneven height distribution pattern, with individual trees appearing scattered across different height distribution classes. This difference indicates a clear, diverse structure with growth rates or forest succession stages (Chenge *et al.,* 2019). The low frequency of tall trees in the upper-class height distribution (≥35 meters) suggests a significant decline in the number of trees as they progress from the lower-class to the upper-class height categories, indicating fewer trees reaching greater heights. The presence of taller trees in the upper height class could be an indication of individual trees with better height growth potential and thus growing faster in search of light for effective competition (King, 1990). Age, species composition, and previous disturbances are factors that may have influenced the sparse distribution of trees in the upper-height classes. The presence of different tree height covers creates niches for varieties of fauna species, especially avian species (Kebrle *et al.,* 2021).

The basal area of a tree is the cross-sectional area of tree trunks at breast height (Oyebade and Anaba, 2018). The CFA had the highest (44.01 m^2/ha) mean basal area, indicating a larger area coverage occupied by the cross-section of tree diameters at the base. The FR had the lowest mean (29.88 m^2/ha) basal area, indicating a less dense forest. In comparison with the reports of Onyekwelu *et al.* (2022) and Aigbe and Ekpa (2015), the basal areas of the sacred groves of Osun Osogbo, Igbo Olodumare, Idanre Hills, and Ogun Onire were reported (Onyekwelu *et al.,* 2022) to be 32.69, 51.83, 44.85, and 40.70, respectively, which is within the values of mean basal area (20.88 – 44.01 m^2/ha) in this study. Aigbe and Ekpa reported a basal area of 102.8 m^2 in Afi Forest Reserve, a tropical rainforest in Cross River State, Nigeria, which is higher than the basal area in this study. Adeyemi (2016) reported a basal area ranging from 10.6 to 27.42 m2 at various locations in Oban Forest, Nigeria, which is lower than the basal area from this study area.

The result of yield (volume) in the study shows CFA yielded the highest (656.71m^3/ha) mean volume while the FR had the lowest mean volume (384.08m^3/ha), indicating less productive forest than CFA. This result indicates that forest management types have influenced the forest yield of this study area either directly or indirectly. Tree yield (volume) is the total amount of wood (including its stem and branches) that a tree produces (Kunz *et al.,* 2017). By evaluating the tree volume, one can estimate the amount of biomass or wood in the trees (FAO, 2000). Tree volume is an important aspect of forest yield used in decision-making for sustainable yield management of forest ecosystems (Giuntoli *et al.*, 2022).

Tree density per unit area is an important parameter in forestry because it is used to assess forest structure and stocking, among others. The tree density recorded in this study was the highest (1,552 trees per hectare) under the FR management, while CFA had the lowest (1,168 trees per hectare) density of trees. The highest mean stand density of FR is an indication of how densely populated the forest reserve in the study area is. Though significantly populated with trees, SG (1.184 individual trees per hectare) and CFA (1,168 trees per hectare) had comparable stand density but lower than the mean stand density for FR. The lower tree density of SG and CFA revealed that both forest management types had more open canopies than FR. It has been demonstrated that tree species diversity and stand density could be affected by the extent of regeneration and mortality gaps (Kane and Pokorny, 2020). Gap formation is the single most critical event that defines the composition and spatial structure of tropical forests (Karsten *et al.,* 2013) because of its frequent occurrences in the tropics (Fischer *et al.,* 2016).

The tree densities across the forest types are higher than in some studies conducted in the tropical forests. For instance, this result is higher than the density of 100 to 300 ha^{-1} reported by Onyekwelu *et al.* (2008) for rainforest ecosystems in southwestern Nigeria. Also, the tree density in this study is higher than the range of 61 to 317 individuals/ha given by Malimbwi *et al.* (2005) for Mvomerodistrict forests reserve in the Morogoro Region of Tanzania, East Africa as well as the 512 individuals/ha recorded in Zaraninge in Tanzania (Mligo *et al*., 2009). About 436 individual trees per hectare were recorded at Kwamgumi Forest (Doggart *et al.,* 1999) as well as 837 individual trees per ha at Mpanga Forest (Doody *et al.,* 2001), which are both lower than the densities of the three forest management types in this study.

This finding indicates a positive interaction (48%) between mean BA and density and demonstrates a linear relationship. The findings of Chang-Yang *et al.* (2021) and Xiang *et al.* (2016) support this result, which reported that stand density plays a significant role in influencing the growth and recruitment of forest trees. In line with this finding, Ouyang *et al.* (2019) reported that increased stand density can lead to increased carbon accumulation and crown filling. Planting distance, age or tree size, and management regime are a few factors influencing stand density variation, as observed by Ouyang *et al.* (2019) and Kholdaenko *et al.* (2022). Despite the high rate of anthropogenic activities (deforestation and degradations) observed in FR, the forest type (forest reserve) had very close distances among the trees, whereas CFA and SG showed wider spacing between the trees. Kacholi (2019) noted that soil characteristics, microclimatic variables, anthropogenic disturbances, and natural events could contribute to variations in tree stand density in forests, factors that are suspected to be at play in the study area. The high density of trees, particularly in FR, can yield many benefits for ecosystem services and biodiversity. Higher stand densities can raise forest productivity (Na *et al.,* 2021). Thus, these sites can serve as a home to diverse species and support ecological processes (soil stability, water control, and carbon sequestration).

5.4 Volume Models for the Three Forest Management Types

The results of volume model calibration revealed that nine volume prediction models fixed in this study were statistically significant (p=0.000). This implies that each model explains a high percentage of the variance associated with tree volume in the studied forests. The models calibrated and validated were carried out to ensure the best fit for volume under each forest management type. All the models had positive coefficients of determination, indicating a good fit for the data from the study area. A few models (such as M1 and M5) had negative intercepts but high coefficients of determination (0.80 and 0.77, respectively), whereas others, such as M9, had negative slopes but lower coefficients of determination (0.32). The models incorporated different numbers of independent variables; some had only one independent variable (e.g., M7, M8, and M9), while others had two (e.g. M1, M2, M3, and M4) and three (e.g. M6). Importantly, all volume models were significant ($p<0.05$), indicating that the models conformed with the assumptions of regression and thus could be used for predicting volume across forest management types.

Different statistical metrics (Akaike Information Criterion (AIC), Corrected Akaike Information Criterion (AICc), Bayesian Information Criterion (BIC), and Difference in AIC (dAIC)) were evaluated and ranked to select the best-fit volume models for each forest management type. The Ratkowsky model demonstrated superior performance, with the lowest AIC, AICc, BIC, and dAIC values, indicating a better fit to the measured data. The weighted scores for the Ratkowsky model were highest under CFA (9.26E-01), FR (0.34), and SG (9.94E-01). This consistent performance across different metrics and management types is evidence that the Ratkowsky model is the best-fitted model for volume prediction in the study area.

Residual plots were assessed for each model, which served as a visual representation of the goodness of fit of the Ratkowsky model for stand volume estimation in each of the three forest types. These plots are important tools in regression analysis, which allows an examination of the distribution of residuals (representing the differences between observed and predicted values). A key observation from these plots is that the residuals on both the positive and negative sides have a constant spread and are randomly scattered around the center line without following any systematic trend or pattern. This indicates a good fit of the Ratkowsky model and their suitability for volume estimation at each site in the studied forest management types in this study.

Residual plots are crucial for evaluating a model's goodness of fit and identifying patterns or trends in error (Ribeiro and Moniz, 2020). This result indicates a continuous spread of the residuals at both positive and negative sides, implying that the residuals exhibited homogeneous variance throughout. A constant spread signifies that the performance of a model is consistent at all volume prediction levels (Makariou *et al*., 2021). The random scatter depicts that the Ratkowsky model does better by capturing the underlying patterns in the data. The residuals' continuous "breath" on both sides indicates the residual range holds steady throughout the anticipated volumes. The consistent spread and breath, as well as the random distribution of the validated data points, confirmed that the model performed well across all sites. This shows a steady performance across various prediction levels, further validating the Ratkowsky model's robustness in volume estimation.

To assess the plausibility (suitability and reliability) of the fitted models for tree volume prediction across the forest management types (CFA, FR, and SG), the model was validated using a student t-test. The t-test was not statistically significant under FR, implying the difference between the observed and predicted volumes revealed no significance (Räty *et al.,* 2022). In the SG, the t-test result was not statistically significant, indicating that the observed volume aligns closely with the predicted volume. Similarly, for the CFA, the t-test was not statistically significant, indicating that the observed and predicted volumes are closely identical. The lack of significance across all management types indicates that the observed data matches well with the predictions, thus, the models are adopted for volume estimations for the area (Egonmwan and Orukpe, 2022). Thus, the results of the validation test indicate the suitability of the Ratkowsky model for predicting tree volumes across the forest management types. Accurate volume prediction is important for sustainable forest management practices (Popoola and Ushi, 2023). The superior performance of the Ratkowsky model over the other model types indicates its potential as a reliable tool for predicting volume in different forest management types, enabling informed decision-making for forest managers and stakeholders.

The non-significant t-test results across all three forest management types (CFA, FR, and SG) indicate that the observed and predicted tree volumes closely match, reinforcing the suitability of the Ratkowsky model for volume estimation in this study area. Studies have demonstrated the effectiveness of different volume prediction models in various forest types. Adesuyi *et al.* (2020) Fitted non-linear models for tree volume estimation in the strict nature reserve, in South-West, Nigeria. The Ratkowsky model ranked best of the six models generated when data from each family were combined. Salami *et al.* (2021) adjudged the Ratkowsky model as the best fit for tree height-diameter models for Arakanga Forest Reserve, Abeokuta, Ogun State. Ratkowsky's models provided reliable predictions due to their ability to account for tree allometry variations. In contrast, Ariyo *et al.* (2019) used the volume model recommended by FORMECU (1999) to estimate the volume of individual trees in Ibadan, Oyo State, Nigeria. Adebusuyi *et al.* (2020) fitted different tree volume models, among which the Schumacher model was adjudged the best fit for the tropical rainforest ecosystem in Ogun State, Nigeria. Similarly, Akindele and LeMay (2006) fitted data from common timber species in the tropical rainforest area of Nigeria for tree volume using the Schumacher–Hall's volume function, which was fitted to the data for each species group and yielded the best result. However, this discrepancy is likely due to differences in tree growth patterns and forest composition between tropical regions. Similarly, research by Akindele and LeMay (2006) in African rainforests revealed that species-specific volume equations tend to be more precise than generalized models, indicating that the effectiveness of a volume prediction model is influenced by forest type, species composition, and ecological conditions.

The Ratkowsky model's exceptional performance in this study indicates that it has the potential to be an accurate tool for estimating tree volume for different forest management regimes. Because precise volume estimation is necessary for carbon stock calculations, conservation planning, and wood yield evaluations. The consistency of this result with other studies (Akindele and LeMay, 2006; Salami *et al.,* 2021) further validates the importance of selecting appropriate models based on forest type and management objectives.

5.5 Total Biomass and Carbon Contents under the Forest Management Types

The highest mean TB yield (485.394 tons/ha) was obtained under CFA, followed by FR (301.14 tons/ha) and SG (230.95 tons/ha). This result indicated that CFA was more productive in terms of biomass accumulation influenced by higher tree species (38), mean Dbh (34.99 cm) and BA (44.01 m^2/ha). This result aligned with the report of Khanal *et al. (*2024), who reported that the diverse distribution of forest biomass reinforces established size-density relationships, attributing observed variations between tree size and density. Baul *et al.* (2021) reported that above- and below-ground tree biomass and carbon stocks correlated with tree species diversity. The result agrees with the report of Gamfeldt *et al.* (2013), who reported that biomass production in boreal forests is generally positively impacted by tree species richness.

Poor forest management often leads to unsustainable harvesting, lack of reforestation, and insufficient protection of tree species, allowing anthropogenic activities like logging or grazing to degrade the forest. Without proper management, natural regeneration is hindered, and only smaller, less diverse species dominate, which limits biomass accumulation and carbon storage potential compared to what was recorded in CFA. Effective management practices are crucial for improving forest health and enhancing its biomass and carbon sequestration capacity (Ameray *et al.,* 2021). Good forest management practice contributes significantly to global cost-effective carbon mitigation (Verma and Ghosh, 2022).

With the highest mean biomass and carbon content, CFA has the potential to play an important role in carbon sequestration, which helps mitigate climate change by increasing the amount of carbon stored in biomass. The forest type with the highest number of species

(CFA=38 species) yielded the highest biomass and carbon content, this implies that high species diversity influences biomass and carbon storage. Research workers such as Loreau and Hector (2001), Tilman *et al.* (2001), and Leps (2005) have established that higher biomass is produced in forest ecosystems with a mixture of coexisting species that have complementary niches than in less diverse ones. The efficient management of tree species makes it possible to manage carbon-sequestration forests and reduce climate change. This result aligns with research conducted by Shanin *et al*. (2014) on the effects of tree species composition on productivity and carbon dynamics across different sites in boreal forests. They reported that mixed stands were more productive than monoculture, and the highest yield was observed under mixtures of two coniferous species.

The primary drivers of forest biomass are forest structure (stand age, tree size, and density) management, tree species richness and diversity, and plot factors (stand origin, forest composition, and vegetation cover) (Becknell and Powers, 2014; Landuyt *et al.*, 2020; Zhang and Chen, 2015; Ali *et al.,* 2019). Numerous factors, such as site and stand characteristics that include species type, age, and stand density, affect the potential of forest plantations to absorb CO_2 (Bernal *et al.,* 2018; Kumi *et al.,* 2021).

The result of the Analysis of variance shows significant differences in the mean TB and TC across the forest management types. The Community Forest Area had significantly higher TB, TC and CO_2 equivalent emissions than under FR and SG. The species abundance and tree size are the key factors that caused this variation in the study area, which are directly or indirectly influenced by management effects (Li *et al.,* 2019; Niang *et al.,* 2024). Thus, the biomass of a forest is affected by several factors, including basal area, volume and tree size (Balderas Torres and Lovett, 2013; Brahma *et al.,* 2021). The higher total biomass in FR (at 301.14 t/ha), compared to SG (at 230.95 t/ha), can be directly linked to the high stand density recorded in FR. Stand density plays a critical role in determining total biomass, as a denser forest contains more trees that contribute to the accumulation of organic material. This relates to the report of Wassihun *et al. (*2019), who stated that forest stand density is a crucial functional and structural variable of forest ecosystems in the estimation of above-ground biomass/carbon stock. Similarly, Li *et al. (*2022), reported that stand density-induced changes in crown structure and biomass depend upon stand characteristics. In FR, the larger number of trees per hectare means more trunks, branches, and roots, resulting in higher carbon storage and biomass (Mensah *et al.,* 2020). In contrast, SG, with a lower tree density, has fewer trees contributing to the overall biomass, thus yielding a lower total biomass per hectare. This demonstrates how tree density influences the capacity of a forest to store carbon and maintain ecosystem productivity. This result aligned with the report of He *et al.* (2023), who demonstrated how site condition and density influence tree and crown development and biomass accumulation.

The result from CFA with the highest biomass accumulation (485.39 tons/ha) and carbon storage (242.70 tons/ha) is in line with the report of Ali *et al.* (2019), who reported that large-diameter, tall-stature and big-crown trees are the main forest stand structures that generally contributes a large fraction to aboveground biomass, and hence, play an important role in carbon storage. The high biomass accumulation in CFA can be related to effective conservation efforts in CFA, which contributed to higher carbon sequestration. This is in line with the report of Popo-Ola *et al.* (2012), who reported that the effectiveness and feasibility of carbon sequestration through forestry varies widely and depends on factors such as site, species and management practices. Mandal and van Laake (2015), reported that in the community forest management system, the local people work to transform unsustainable forests into sustainable areas to meet their local forest product demands without destroying the living forest biodiversity, thus resulting in high biomass production and carbon storage. The community forest system enables community members to develop, organize and work as an institution, thereby achieving maximum cooperation among members.

The higher density in the FR (749) and the large Dbh (143.0 cm) in the CFA sites influenced the total biomass. The total mean biomass (485.39) of the CFA site was high due to the moderate number (58) of large trees with DBH values between 70 and 143.0 cm in the area. Although the FR site had a high density, its individual tree biomass was insufficient to bridge the gap. The higher total biomass in FR than in SG was due to higher density, making up for the lower Dbh in FR. This finding indicates that the relationship between Dbh and density, among other ecological factors, can determine which site has higher total biomass with the influence of species composition and distribution. Mayer *et al.* (2020) discovered that stand density control had a negligible impact on the C pool.

Older trees are more likely to be found in the upper storey of a stand, whereas recruited trees are found in the middle and lower storeys (Zhang *et al.*, 2023). As saplings progressively reach the canopy, the dominance of these large canopy trees prevents new trees from being established (Fahey *et al.*, 2016). However, species diversity has indirect benefits for forest biomass by increasing the structural diversity of the stand due to differences in tree sizes (diameter or height) (Zhang and Chen, 2015; Mensah *et al.*, 2018). The results of this investigation were different from the reports of Zhang and Chen (2015) and Mensah *et al.* (2018) wherein CFA (485.39 t/ha) produced more biomass than FR (301.14 t/ha) and FR had higher yields than SG for biomass (230.95) and carbon contents (115.48 t/ha) despite having a high number of tree species than was recorded in FR.

There was a negative correlation between mean Dbh and density as indicated by the correlation coefficient of -0.35. The inverse relationship implies that larger trees occupy more space, reducing the number of trees per unit area (density). As trees grow, competition for resources increases, leading to self-thinning and reduced density. Dillon *et al.* (2019) reported an inverse relationship between the number of trees and their basal area. Mean Basal Area and density exhibited a moderate negative correlation (r = -0.48). Forrester and Pretzsch (2015) reported that stand density, in terms of variables (such as basal area, volume and biomass), is a strong determinant of stand growth and may often be a more important determinant of productivity than species interactions and biodiversity.

*Gmelina arborea*is the species with the highest biomass (280,788.92 kg per hectare) and carbon content (267.685 kg per hectare) under CFA. Thus, *G. arborea* could be a priority species for conservation in community-managed forests due to its role in carbon sequestration potential. According to Olajide *et al.* (2021), *Delonix regia* had the highest mean tree above-ground biomass and carbon stock, making it the species of choice for planting in Uyo Metropolis, Akwa Ibom State, Nigeria, to reduce global warming. The dominance of *G. arborea* across all forest management types could be an indication of its ecological importance and its relevance to the people and ecosystem of the study area, probably due to its ease of establishment, fast growth rate, high productivity (volume, biomass, etc) and potential in carbon sequestration (Onyekwelu *et al*., 2006).

The main contributors to biomass and carbon storage in FR were *Daniellia oliverii* and *Gmelina arborea.* Thus, these species can be said to be essential to the capacity of the FR ecosystem to maintain the carbon balance. For SG, the dominant species concerning carbon contents were *Dialium guineense, Gmelina arboreal, and Khaya senegalensis*. These high biomass and carbon contents of species revealed their crucial ecological role, making their conservation essential for safeguarding the distinctive biodiversity and critical carbon sequestration functions of forests. Under CFA, the dominant tree species (*Anogeissusleiocarpa, Ceiba pentandra, Erythrophleum suaveolens,* and *Fluggea virosa*) play an important role in biomass production and carbon accumulation in the area.

The result of tree species yields shows the necessity for enhancing strategies for sustainability and mitigating climate change. The distinct functions of forest reserves, sacred groves, and community forests in storing carbon and preserving biodiversity show their varying roles in ecosystem services, with community forests storing the highest biomass due to active management and local involvement, followed by forest reserves with structured conservation efforts, and sacred groves contributing primarily to biodiversity preservation through cultural protection but storing less biomass. This study revealed the role played by these ecosystems in the region in decreasing carbon emissions.

CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

A total of 1,881 individual trees were enumerated in this study, with 749, 621 and 511 individual trees under FR, SG and CFA, respectively. A total of 73 tree species distributed to 35 families were assessed in this study: CFA had 38 species from 25 families, 28 species from 16 families were found under FR, while 35 species from 24 families were found in SG. Most of the tree species were indigenous, with few exotic species (e.g., *Gmelina arborea and Tectona grandis*). *Khaya senegalensis* and *Gmelina arborea* were present across the three forest management types. A few families (Caesalpinioideae, Euphorbiaceae, Moraceae, and Fabaceae) were important across the forest management types. Malvaceae, Verbenaceae, and Fabaceae were the most important families in CFA, FR, and SG, respectively. Other important families in the study that contributed to higher total basal area production include Anacardiaceae, Rubiaceae, Annonaceae, and Sterculiaceae.

The Shannon-Wiener species diversity index of 3.00, 2.97, and 2.11 were recorded under CFA, SG, and FR, respectively, with significant differences. Thus, FR had the least diverse tree species compared to CFA and SG. The Margalef richness index was highest (6.01) under CFA and lowest (4.11) under the FR. The highest tree species evenness value of 0.55 was recorded under SG, and the lowest value (0.29) was under FR, indicating a high disparity in tree species richness. CFA and SG supported richer and more diverse tree communities than FR.

Sterculia setigera (RDo: 14.63%), *Anogeissus leiocarpa* (RDo: 11.25%), and *Spondias mombin* exhibited high RDo values, indicating their importance in the floristic compositions of the study area. *Gmelina arborea* had the highest RDo, while species like *Erythrophleum suaveolens* and *Vitex doniana*had the lower RDo values under FR. *Afzelia africana* and *Daniellia oliverii* had high RDo values in SG. Some species, like *Detarium microcarpum* and *Kigelia africana*, consistently showed low RDo values across the forest management types, indicating their lower abundance and floristic importance. *Gmelina* *arborea* had high IVI values across FR, SG, and CFA. *Sterculia setigera* had the highest relative density, while *Fluggea virosa* had the lowest RD value in CFA. In FR, *Erythrophleum suaveolens* had the highest IVI at 9.5%, while in SG, *Khaya senegalensis* ranked highest with an IVI of 13%. *Afzelia africana, Prunus africana,* and *Tetrapleura tetraptera* were the vulnerable species in CFA, while *Afzelia africana* was the only tree species in FR and SG that was identified as vulnerable. *Tectona grandis* and *Monotes kerstingii* were identified as endangered species in CFA and SG, respectively. *Hura crepitans* was classified as near threatened under SG.

Soil physical properties varied significantly across the study area, with distinct differences in sand, clay, and silt, indicating unique ecosystem conditions in each forest management type. Soils from SG exhibited superior chemical properties, with significantly higher magnesium, nitrogen, phosphorus, and potassium than CFA and FR, indicating richer nutrient availability in SG soils. Soil organic carbon (OC) and organic matter (OM) content showed minimal variations across the three forest management types.

The diameter distribution of individual trees in the three forest management types followed an inverse-J pattern typical of natural tropical forests. The study revealed significant differences in tree growth, yield, and stand density across the three forest management types. Trees in the CFA exhibited the largest sizes, as evidenced by higher mean and maximum DBH values, and they also recorded the highest basal area and volume per hectare, indicating greater productivity. The Sacred Grove followed closely, while the Forest Reserve (FR) had the lowest tree dimensions and the lowest basal area and volume, indicating lower yield. However, FR had the highest stand density, with more trees per hectare than CFA and SG. These findings revealed the trade-off between tree size and stand density across the different forest management types, with CFA and SG supporting larger trees and higher productivity and FR containing a denser, albeit smaller, tree population. This indicates varying forest dynamics, with CFA and SG focusing on quality growth and yield, while FR maintains higher tree density.

The Ratkowsky model was deemed the best-fitted model for volume prediction based on its lowest statistical metrics and highest weight across all sites. The results of model validation show that the selected models are appropriate for predicting volume in the three forest management types.

There was significant variation in biomass and carbon contents across the forest management types, with CFA emerging as the most efficient carbon sink, with an average biomass of 485.39 tons/ha and total carbon of 242.7 tons/ha. In contrast, SG exhibited the lowest average biomass and carbon storage capacity, with a mean total biomass of 230.95 tons/ha and total carbon of 115.48 tons/ha. Forest Reserve demonstrated moderate carbon storage potential, with a mean biomass of 301.14 tons/ha and total carbon contents of 150.57 tons/ha. Thus, tree species composition, richness, tree size, and density play an important role in biomass accumulation and carbon sequestration.

6.2 Recommendations

Based on the results of this study, it is recommended that:

i. to maintain forest ecosystem resilience, preserving the diversity of tree species is paramount, particularly families (Caesalpinioideae, Euphorbiaceae, Moraceae, and Fabaceae), as these are consistently important across all forest types.

ii. there is a need to conserve and protect CFA, which stores the highest carbon content for climate change mitigation and resilience. Sustainable forest management practices (such as the preservation of tree species) should be promoted in FR to improve carbon sequestration.

iii. selective logging and thinning in CFA and SG should be occasionally encouraged to promote healthy regeneration and maintain ecosystem balance. This technique will help to prevent diseases and insect infestation within the forest estate and to gain more support from the host communities.

iv. Regular monitoring of forest growth, biomass, and carbon storage is necessary foradaptive management strategies. Further research is required to investigate the ecological and socioeconomic factors influencing forest management outcomes in different forest types.

v. Policies should be developed to encourage sustainable forest management and carbon sequestration practices. Local communities should be engaged in forest management decisions to ensure their livelihoods and interests are aligned with conservation goals.

vi. Finally, restoring degraded forests, prioritizing areas with high carbon sequestration potential can enhance carbon storage.

CONTRIBUTION TO KNOWLEDGE

This study contributed to the existing body of knowledge in forest ecology and biometrics.

i. Updated knowledge on tree species diversity is gained from the study area. The study established that a total of 38 tree species from 25 families were found in CFA: 28 tree species from 16 families in FR and 35 tree species from 24 families in SG. Caesalpinioideae, Euphorbiaceae, Moraceae, and Fabaceae families were consistently important across all three forest management types. The dominance of Malvaceae in CFA, Verbenaceae in FR, and Fabaceae in SG indicates the varying composition of forest management types. The inverse-J shape diameter distribution in the study area indicates a healthy regeneration pattern. The status of tree species based on the 2023 IUCN categorization showed three vulnerable species (*Afzelia africana, Prunus africana, and Tetrapleura tetraptera*) in CFA, while *Afzelia africana* is tagged vulnerable in FR and SG. *Tectona grandis* is the only endangered species in CFA. *Monotes kerstingii* is the only tagged endangered species in SG.

ii. The study provided updated knowledge of the status of the soil's physicochemical properties and soil carbon storage in the study area. Sacred grove exhibited a distinct soil texture characterized by lower sand content, with higher magnesium and potassium contents, indicating superior soil fertility and nutrient availability. In contrast, CFA and FR showed similar soil physical properties and lower magnesium and potassium contents, indicating a divergence from SG. Soil OC and OM storage across the three forest management types were similar.

iii. Knowledge was gained on total biomass and Carbon contents across the three forest management types. The forest management types significantly impacted carbon storage, with CFA producing the highest capacity (485.39 tons/ha biomass, 242.70 tons/ha carbon), followed by FR (301.14 tons/ha biomass, 150.57 tons/ha carbon), and SG, which had the lowest biomass and carbon yield (230.95 tons/ha biomass, 115.48 tons/ha carbon).

iv. The Ratkowsky model form is the best-fitted model for volume estimation per site; the performance of the fitted model was biologically plausible with no significant difference between the observed and predicted volume per management types. Therefore, the best-fitted volume model should be used for tree volume prediction for the three forest management types (i.e., CFA, FR, and SGs) in the study area.

REFERENCES

Abah, R.C and Petja, B.M. (2017). Increased streamflow dynamics and implications for flooding in the Lower River Basin. *African Journal of Environmental Science and Technology*, 11 (10), 544-555.

Abdulrashid, I., Adeduntan, S. A., Adekunle, V. A. J., and Wali, B. R. (2024). Assessment of soil physicochemical properties in the parklands of Northern Nigeria. *African Journal of Environmental Science and Resource Recovery*, 7(1). DOI: 10.52589/AJENSR-NJGUL6F1

Abere F, Belete Y, Kefalew A, Soromessa T (2017) Carbon stock of Banja Forest in Banja district, Amhara region, Ethiopia: an implication for climate change mitigation. *Journal of Sustainable Forest;* 36(6):604–622

Adam R. Martin, Grant M. Domke, Mahendra Doraisami and Sean C. Thomas (2021). Carbon fractions in the world's dead wood; *Nature communication;* 12:889: 9 pages.

Adebusuyi, T. S., Adesuyi, F. E., and Akinbowale, A. S. (2020). Volume models for tropical rainforest ecosystem in Ogun State, Nigeria. International *Journal of Recent Advances in Multidisciplinary Research*, 7(1), 5533-5538.

Adekunle V. A. J. (2006). Conservation of Tree Species Diversity in Tropical Rainforest Ecosystem of South-west Nigeria. *Journal of Tropical Forest Science,* 18(2): 91 101.

Adekunle VAJ, Adewole OO, Akindele SO. (2013). Tree species diversity and structure of a Nigerian strict nature reserve, *Tropical Ecology*, 54(3), 275-289.

Adeyanju, O.S. (2020). Drivers of Biodiversity Conservation in Sacred Groves: A Comparative Study of Three Sacred Groves in South-West Nigeria. A Master of Science Thesis Submitted in Partial Fulfillment of The Requirements for The Degree of Master of Science into Tthe Faculty of Graduate and Postdoctoral Studies (Forestry), The University of British Columbia (Vancouver), Canada. 98pg.

Adeyemi, A. A. (2016). Site quality assessment and allometric models for tree species in the Oban Forest, Nigeria. *Journal of Sustainable Forestry*, *35*(4), 280–298. https://doi.org/10.1080/10549811.2016.1168306

Agbelade A. D. and Lawal A. (2019): Volume Yield and Carbon Hoard in Two Community-Managed Forests of Ekiti State, Southwest, Nigeria*; Forests and Forest Products Journal;* 19:127-135.

Agbelade, A. D., Onyekwelu, J. C., and Apogbona, O. (2016). Assessment of urban forest tree species population and diversity in Ibadan, Nigeria. *Environment and Ecology Research, 4*(4), 185–192. https://doi.org/10.13189/eer.2016.040401

Aghimien E.V. (2019). Above-ground carbon stock estimation using Pleiades satellite imagery of the secondary forest ecosystem in Ibadan, Nigeria. *Forest Res Eng Int J.* 2019; 3(2):46-54.

Aigbe, H.I. and Ekpa, N.E. (2015): Modelling Tree Volume in Tropical Rainforest of Afi River Forest Reserve in Cross River State, Nigeria. *International Journal of Scientific and Engineering Research* 6(12):546-556

Aigbe, H. I. and Omokhua, G. E. (2015). Tree species composition and diversity in Oban Forest Reserve, Nigeria. *Journal of Agricultural Studies*, 3(1), 10-24.

Aioub M. and Naghi, S. (2021). Sacred Groves: A Pattern of Zagros Forests for Carbon Sequestration and Climate Change Reduction, 11 May 2021, Preprint (Version 2) available at Research Square [https://doi.org/10.21203/rs.3.rs-270508/v2]

Ajayi, S. and Odey, P. O. (2012). Individual Tree Volume Equation for A Plantation of Tectona Grandis in the Cross River University of Technology (Crutech), Obubra, Cross River State, Nigeria. *Nigerian Journal of Agriculture*, *Food and Environment*, 8(2), 12-17

Ajibola, A. (2021). Importance of forest: Forest reserves in Nigeria; Agricultural Science, Len Academy. 2pg. https://www.len.com.ng/csblogdetail/571/Importance-of-forest--Forest-reserves-in-Nigeria.

Akinde, B. P., Olakayode, A. O., Oyedele, D. J., and Tijani, F. O. (2020). Selected physical and chemical properties of soil under different agricultural land-use types in Ile-Ife, Nigeria. *Heliyon*, 6, e05090. doi: 10.1016/j.heliyon.2020.e05090

Akindele, S., and LeMay, V. (2006). Development of tree volume equations for common timber species in the tropical rain forest area of Nigeria. *Forest Ecology and Management*, 226(1-3), 41-48. https://doi.org/10.1016/j.foreco.2006.01.022

Akinnagbe, A., Gailing, O., Finkeldey, R., and Lawal, A. (2019). Towards Conservation of Genetic Variation of Tropical Tree Species with Differing Successional Status: The Case of Mansonia altissima A. Chev and Triplochiton scleroxylon K. Schum. *Tropical Conservation Science*, 12, 1-9. https://doi.org/10.1177/1940082919864267

Akintola Omigbodun (2013). Cameroon, the River Benue and Nigeria, Vanguard Newspaper, 3rd July 2013 (https://www.vanguardngr.com/2013/07/cameroon-the-river-benue-and-nigeria/). *Retrieved 5th November 2021.*

Akpa, A., Onuh, S., Kabuk, V., and Julian, C. (2022). An assessment of the impact of round wood collection on deforestation in Benue State, Nigeria. *Journal of Environmental and Geographical Studies*, 1(2), 1-13. DOI: 10.58425/jegs.v1i2.85.

Akpa, S. I. C., Odeh, I. O. A., Bishop, T. F. A., Hartemink, A. E., and Amapu, I. Y. (2016). Total soil organic carbon and carbon sequestration potential in Nigeria. *Geoderma,* 271: 202-215.

Akpen, G.D.; Aho, M.I. and Adejo, M. G. (2019). Aquifer Characteristics of Some Local Government Areas of Benue State, Nigeria; *Nigerian Journal of Technology (NIJOTECH);* 38 (1): 233 – 241.

Alamgir M, Al-Amin M. (2007). Organic carbon storage in trees within different Geopositions of Chittagong (South) Forest Division, Bangladesh; *Journal Forest Resource*;18:174–80.

Ali, A., Chen, H. Y. H., You, W.-H., and Yan, E.-R. (2019): Multiple abiotic and biotic drivers of aboveground biomass shift with forest stratum. *Forest Ecology and Management;* 436: 1-10.

Ameray, A., Bergeron, Y., Valeria, O., Montoro Girona, M., and Cavard, X. (2021). Forest carbon management: A review of silvicultural practices and management strategies across boreal, temperate, and tropical forests. *Current Forestry Reports*, 7(3), 245–266. https://doi.org/10.1007/s40725-021-00151-w

Amonum J. I. and Japheth, H. D. (2019a). Application of Developed Crown-Bole Diameter Model to Stand Density and Stock Control on Open-Grown Trees of *Prosopis africana (Guill and Perr) Taub. Journal of Applied Tropical Agriculture,* 24(2), 32-39.

Amonum, J. I., ISSA, S. and Amusa, T. O. (2020). Effect of Vegetation Types on the Physicochemical Properties of Soils under Different Land Use. *International Journal of Forestry and Horticulture,* 6 (2), 16-25.

Amonum, J.I., Dau J. H. and Gbande, S. (2016). Composition And Distribution of Economic Tree Species In Nagi Forest Reserve, Benue State, Nigeria. *Journal of Research in Forestry, Wildlife and Environment,* 8(4), 101-108.

Amonum, J.I; Ikyaagba, E.T and Dawaki, S.A (2019b): Flora Diversity and Distribution in Falgore Game Reserve, Kano State, Nigeria; *Journal of Applied Life Sciences International;* 20(3): 1-13.

Anaba, B. D., Yemefack, M., Abossolo-Angue, M., Ntsomboh-Ntsefong, G., Bilong, E. G., Ngando Ebongue, G. F., and Bell, J. M. (2020). Soil texture and watering impact on pot recovery of soil-stripped oil palm (Elaeis guineensis Jacq.) seedlings. *Heliyon*, *6*(10). https://doi.org/10.1016/j.heliyon.2020.e05310

Anaya JA, Chuvieco E, Palacios-Orueta A (2009). Aboveground biomass assessment in Colombia: A remote sensing approach. *Forest Ecology and Management* 257: 1237-1246.

Arasa-Gisbert R, Vayreda J, Román-Cuesta RM, Villela SA, Mayorgab R, Retana J (2018): Forest diversity plays a key role in determining the stand carbon stocks of Mexican forests. *Forest Ecology Management,* 415-416:160–171

Araujo, T.M., Higuchi, N., and Carvalho Jr. J.A. (1999). Comparison of formulae for biomass content determination in a tropical rain forest in the state of para, Brazil. *Forest Ecology and Management*, 117, 43–52.

Ariyo, O. C., Usman, M. B., Emeghara, U. U. and Ariyo, M. O. (2019). Diameter at Breast Height: An Index of Tree Volume Estimation in Block a Forest of International Institute of Tropical Agriculture (IITA), Ibadan, OyoState, Nigeria. *Nigerian Journal of Forestry*, 49 (2) 110 - 119

Atiku, M., and Noma, S. S. (2011). Physicochemical properties of the soils of Wassaniya Forest Reserve, Tangaza Local Government, Sokoto State. *Nigerian Journal of Basic and Applied Science*, 19 (1): 93-96.

Attua, E.M and Pabi, O. (2013). Tree species composition, richness, and diversity in the northern forest savanna ecotone of *Ghana. Journal of Applied Bioscience,* 67:5437-5448.

Avitabile, V.; Baccini, A.; Friedl, M.A.; Schmullius, C. (2012). Capabilities and limitations of Landsat and land cover data for aboveground woody biomass estimation of Uganda. *Remote Sensing Environ*., 117, 366–380.

Baccini A, Friedl MA, Woodcock CE, Warbington R (2004). Forest biomass estimation over regional scales using multisource data. *Geophysical Research Letters* 31: 1-4.

Badreldin N, Sanchez-Azofeifa A. (2015). Estimating forest biomass dynamics by integrating multi-temporal Landsat satellite images with ground and airborne LiDAR data in the Coal Valley Mine, Alberta, Canada. *Remote Sensing* 7: 2832–2849.

Bailey, R.L. (1979). The potential of Weibull-type functions as flexible growth curves: Discussion. *Canadian Journal of Forest Research* 10: 117–118.

Balderas Torres, A., and Lovett, J. C. (2013). Using basal area to estimate aboveground carbon stocks in forests: La Primavera Biosphere's Reserve, Mexico. Forestry: *An International Journal of Forest Research,* 86(2), 267-281. https://doi.org/10.1093/forestry/cps084.

Banskota, K, Karky, B.S. and Skutsch, M. (2008). Reducing Carbon Emissions, through Communitymanaged Forests in the Himalaya, International Centre for Integrated Mountain Development.

Barau, B.W., Buba, U., Maikeri, T.C, Tukur, K.U., Gabuin, T.G., Kabir, F.M., Thomas, T.L.1 And Danba, E.P. (2015). Tree Species Diversity in Kakulu Forest of Zing L.G.A., Taraba State, Nigeria; *Ethiopian Journal of Environmental Studies and Management*; 8(Suppl. 2): 916 – 925.

Barker, S. and Ridgwell, A. (2012). Ocean Acidification. *Nature Education Knowledge* 3(10):21.

Barreto, P. A., Gama-Rodrigues, E. F., Gama-Rodrigues, A. C., Fontes, A. G., Polidoro, J. C., Moço, M. K. S., *et al*. (2011). Distribution of oxidizable organic C fractions in soils under cacao agroforestry systems in southern Bahia, Brazil; *Agrofor. Syst.* 81, 213–220.

Barrow, C. J (2006). Environmental Management for Sustainable Development. Routledge, London, 454pp.

Batista, J.L.; Couto, H.T.Z.; Marquesini, M. (2001). Performance of height-diameter relationship models: analysis in three forest types. *Scientia Forestalis* 60: 149–163.

Batjes NH, van Wesemael B (2015): Measuring and monitoring soil carbon. In: Banwart SA, Noellemeyer E, Milne E (eds) Soil Carbon: Science, Management and Policy for Multiple Benefits. CAB International, Wallingford

Baul, T.K., Chakraborty, A., Nandi, R., Mohiuddin, M., Kilpelainen, A. and Sultana, T. (2021): Effects of tree species diversity and stand structure on carbon stocks of homestead forests in Maheshkhali Island, Southern Bangladesh. *Carbon Balance Manage* 16, 11.

Becknell, J. M. and PowersJennifer S. (2014). Stand age and soils as drivers of plant functional traits and aboveground biomass in the secondary tropical dry forest. *Canadian Journal of Forest Research*. 44(6): 604-613.

Bentsi-Enchill, F., Damptey, F. G., Pappoe, A. N. M., Ekumah, B., and Akotoye, H. K. (2022). Impact of anthropogenic disturbance on tree species diversity, vegetation structure and carbon storage potential in an upland evergreen forest of Ghana, West Africa. *Trees, Forests and People*, 8, 100238. https://doi.org/10.1016/j.tfp.2022.100238

Benue State. *Nigerian Investment Promotion Commission*. 7 January 2019. Retrieved 14 June

Bernal, B., Murray, L. T., and Pearson, T. R. (2018). Global carbon dioxide removal rates from forest landscape restoration activities. *Carbon balance and management*, *13*(1), 1-13.

Bhandarkar, S. and Bhandarkar, W. (2013). A study on seasonal variation of physicochemical properties in some freshwater lotic ecosystems in Gadchiroli District Maharashtra. *Int. J. of Life Sciences,* 1(3): 207-215.

Bharathi, S., and Prasad, A.G.D. (2017). Diversity, population structure and regeneration status of arboreal species in the four sacred groves of Kushalnagar, Karnataka. *Journal of Forestry Research*, 28, 357-370.

Bhat, D. M. and, N. H. Ravindranath (2011). Above-ground standing biomass and carbon stock dynamics under varied anthropogenic pressure in the Tropical rain forest of Uttar Kannada District, Western Ghats, India. *Taiwania,* 56(2): 85–96

Bhattarai, P.T.; Skutsch, M.; Midmore, J.D. and Rana, B.E. (2012): The Carbon Sequestration Potential of Community-based Forest Management in Nepal; *The International Journal of Climate Change*: Impacts and Responses; 3 (2): 233-253.

Bhunia, O. S., Shit, P. K., Pourghasemi, H. R., andEdalat, M. (2019). Prediction of Soil Organic Carbon and its Mapping Using Regression Analyses and Remote Sensing Data in GIS and R. In H. R. Pourghasemiand C. Gokceoglu (Eds.), *Spatial Modeling in GIS and R for Earth and Environmental Sciences* (pp. 429-450). Elsevier. ISBN 9780128152263. doi:10.1016/B978-0-12-815226-3.00019-3.

Boadi, S., Nsor, C., Yakubu, D., Emmanuel, A., and Osei Owusu, A. (2017). Conventional and Indigenous Biodiversity Conservation Approach: A Comparative Study of Jachie Sacred Grove and Nkrabea Forest Reserve. *International Journal of Forestry Research*, 2017, 1-8. 10.1155/2017/1721024.

Bordoloi, R., Das, B., Tripathi, O.P., Sahoo, U.K., Nath, A.J., Deb, S., Das, D.J., Gupta, A., Devi, N.B., Charturvedi, S.S., Tiwari, B.K., Paul, A. and Tajo, T. (2022). Satellite-based integrated approaches to modelling spatial carbon stock and carbon sequestration potential of different land uses of Northeast India; *Environmental and Sustainability Indicators;* Volume 13: 1-11.

Borokini T. I., Okere A. U., Giwa A. O, Daramola B. O. and Odofin W.T. (2010). Biodiversity and conservation of plant genetic resources in the Field Gene bank of the National Centre for Genetic Resources and Biotechnology, Ibadan, Nigeria. *International Journal of Biodiversity and Conservation,* 2(3): 037-050.

Bot, A., and Benites, J. (2005). The importance of soil organic matter: key to drought-resistant soil and sustained food production. FAO Soils Bulletin 80. Food and Agriculture Organization of the United Nations.

Bouyoucos, G. J. (1962). Hydrometer method improvement for making particle size analysis of soils. *Journal of Agronomy* 54, 179-186.

Brahma, B., Nath, A. J., Deb, C., Sileshi, G. W., Sahoo, U. K., and Kumar Das, A. (2021). A critical review of forest biomass estimation equations in India. *Trees, Forests and People*, 5, 100098. https://doi.org/10.1016/j.tfp.2021.100098.

Brown S. (1997). Estimating Biomass and Biomass Change of Tropical Forests: a Primer. FAO Forestry Paper - 134. FAO, Rome. https://www.fao.org/3/w4095E/w4095e00.htm#Contents (accessed 10/07/2023)

Brown, S., Gillespie, A.J.R. and Lugo, A.E. (1989). Biomass estimation methods for tropical forests with applications to forest inventory data. *Forest Science*, 35(4): 881–902. 101, 120.

Bunde, B.M; Tella, I.; Saka, G.M; Isaac, N.; Solomon, G. and Chapman, H. (2018). Sustainability, Population and Structure of Woody Species Composition of Taraba State Forests; *Asian Journal of Research in Agriculture and Forestry;* 2(4): 1-13.

Burhenne-Guilmin, F. (2011). Guidelines for Protected Areas Legislation. IUCN. ISBN 9782831712451.

Burivalova, Z., Şekercioğlu, Ç. H., and Koh, L. P. (2014). Thresholds of logging intensity to maintain tropical forest biodiversity. Current Biology, 24(16), 1893-1898. http://dx.doi.org/10.1016/j.cub.2014.06.065

Burton, V. J., Contu, S., De Palma, A., Hill, S. L. L., Albrecht, H., Bone, J. S.,Purvis, A. (2022). Land use and soil characteristics affect soil organisms differently from above-ground assemblages. *BMC Ecology and Evolution*, 22(1), 135. https://doi.org/10.1186/s12862-022-02089-4

Cai, Z. Q., Poorter, L., Han, Q., and Bongers, F. (2008): Effects of light and nutrients on seedlings of tropical Bauhinia lianas and trees. *Tree Physiology*, *28*, 1277–1285.

Canadell JG, Le Quéré C, Raupach MR, Field CB, Buitenhuis ET, Ciais P, Conway TJ, Gillett NP, Houghton RA, Marland G (2007): Contribution to accelerating atmospheric CO2 growth from economic activity, carbon intensity and efficiency of natural sinks. *Proc Natl Acad Sci* 104(47):18866–18870.

Cardelús, C. L., Woods, C. L., Mekonnen, A. B., Dexter, S., Scull, P., and Tsegay, B. A. (2019). Human disturbance impacts the integrity of sacred church forests, in Ethiopia. *PLOS ONE*, 14(3), e0212430. https://doi.org/10.1371/journal.pone.0212430

Carretero AC andÁlvarez ET (2013): Modelling diameter distributions of QuercussuberL. stands in "Los Alcornocales" Natural Park (CádizMálaga, Spain) by using the two parameter Weibull functions. *Forest Systems* 22(1): 15–24.

Chang-Yang, Chia-Hao and Needham, Jessica and Lu, Chia-Ling and Hsieh, Chang-Fu and Sun, I Fang and McMahon, Sean. (2021). Closing the life cycle of forest trees: The difficult dynamics of seedling-to-sapling transitions in a subtropical rain forest. *Journal of Ecology*; 109:705–2716.

Chaudhary, A., Burivalova, Z., Koh, L. and Hellweg, S. (2016): Impact of Forest Management on Species Richness: Global Meta-Analysis and Economic Trade-Offs. *Sci Rep* 6, 23954.

Chave, J., Andalo, C., Brown, S., Cairus, M.A, Chambers, J.Q., Folster, H., Fromard F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawi H., Puig H., Reins B., Yamakura T. (2005). tree allometry and improved estimation of carbon and balance in tropical forests. *Oecologia* 145.87-99

Chen, L.; Ren, C.Y.; Zhang, B.; Wang, Z.M.; Liu, M.Y. (2018). Quantifying urban land sprawl and its driving forces in Northeast China from 1990 to 2015. *Sustainability*, 10, 188.

Chen, S., Saby, N. P. A., Martin, M. P., Barthès, B. G., Gomez, C., Shi, Z., Arrouays, D. (2023). Integrating additional spectroscopically inferred soil data improves the accuracy of digital soil mapping. *Geoderma*, *433*, 116467.

Chen, X. (2006): Tree Diversity, Carbon Storage, and Soil Nutrient in an Old-Growth Forest at Changbai Mountain, Northeast China; *Communications in Soil Science and Plant Analysis;* 37: 363–375.

Chenge, B.I and Osho, J.S.A (2018). Mapping tree aboveground biomass and carbon in Omo Forest Reserve Nigeria using Landsat 8 OLI data. *Southern Forests,* (80)1, 1–10.

Chenge, I.B., Chukwu, O., Japheth, H.D. and Yager, G. O (2019): Tree Species Diversity and Forest Structure of a Natural Forest in Shasha Natural forest, Nigeria; Forestry Association of Nigeria, Abuja.

Chornesky, E. A., and Randall, J. M. (2003). The Threat of Invasive Alien Species to Biological Diversity: Setting a Future Course. *Annals of the Missouri Botanical Garden*, *90*(1), 67–76. https://doi.org/10.2307/3298527

Client Earth Report (2014). What is effective community forest management? https://www.clientearth.org/latest/latest-updates/opinions/what-is-effective-community-forest-management/. Accessed 12/7/2023.

Croteau, E. K. (2010). Causes and Consequences of Dispersal in Plants and Animals. *Nature Education Knowledge* 3(10):12.

Cunningham, S., Mac Nally, R., Baker, P., Cavagnaro, T., Beringer, J., Thomson, J., and Thompson, R. (2015). Balancing the environmental benefits of reforestation in agricultural regions. *Perspectives in Plant Ecology, Evolution and Systematics*, 17(4), 301-317. https://doi.org/10.1016/j.ppees.2015.06.001

Curtis, P.G., Slay, C.M., Harris, N.L., Tyukavina, A., Hansen, M.C., 2018. Classifying drivers of global forest loss. *Science* 361 (6407), 1108–1111.

Daba, D. E., and Soromessa, T. (2019). Allometric equations for aboveground biomass estimation of Diospyros abyssinica (Hiern) F. White tree species. *Ecosystem Health and Sustainability,* 5(1), 86–97. DOI:10.1080/20964129.2019.1591169

Dachung, G., Anjembe, B., and Amonum, J. I. (2019). Changes in chemical properties as influenced by teak (*Tectona grandis*) plantation on tropical soil in Akanga Forest Reserve of Nasarawa State, Nigeria. *International Journal of Agriculture, Environment and Bioresearch,* 4(5), 16-29

Dacumos, A. (2006). Biodiversity and Conservation (2nd ed.). Psychology Press. ISBN 9780415342995.

Dagba, B.I., Sambe, L. N, and Shomkegh S. A. (2013). Totemic beliefs and biodiversity conservation among the Tiv People of Benue State, Nigeria. *Journal of Natural Sciences Research*, 3 (8): 145-149.

Danks, C. and Fortmann, L. (2004): Social and Collaborative Forestry | Forest and Tree Tenure and Ownership; Editor(s): Jeffery Burley, *Encyclopedia of Forest Sciences, Elsevier,* 2004: 1157-1162.

Dar, J.A, Subashree K., Raha D., Kumar A., Khare P.K., Khan M.L. (2019): Tree diversity, biomass and carbon storage in sacred groves of Central India. *Environ Sci Pollut Res Int.;* 26(36): 37212-37227.

Datta, A., and Rawat, G. S. (2008). Dispersal modes and spatial patterns of tree species in a tropical forest in Arunachal Pradesh, northeast India. *Tropical Conservation Science*, 1(3): 163-185.

Dau, J. H. and Chenge, I. (2016). Growth space requirements models for *Prosopis Africana* (Guill and Perr) Taub tree species in Makurdi, Nigeria. *European Journal of Biological Research,* 6 (3), 209-217.

Day, M., Baldauf, C., Rutishauser, E., and Sunderland, T. C. H. (2014). Relationships between tree species diversity and above-ground biomass in Central African rainforests: Implications for REDD. *Environmental Conservation*, 41(1), 64–72. doi:10.1017/S0376892913000295

Day, P. R. (1965). Hydrometer method of particle size analysis, *American Society of Agronomy.*

de Oliveira, C. P., Francelino, M. R., Daher, M., de Araújo, E. J. G., Sanches, L. de S., de Andrade, K. D. C., and de Campos, J. S. N. (2019). Estimation of the aboveground biomass and carbon stocks in open Brazilian Savannah developed on sandy soils. *Carbon Balance and Management*, 14(1), 5. https://doi.org/10.1186/s13021-019-0121-0

Death, R. (2008). Margalefs Index; Massey University, Palmerston North, New Zealand © 2008 Elsevier.https://www.ecologycenter.us/population-dynamics-2/margalefs-index.html.

Deb, D.; Singh, J.P.; Deb, S.; Datta, D.; Ghosh, A.; Chaurasia, R.S. (2017). An alternative approach for estimating above ground biomass using Resourcesat-2 satellite data and artificial neural network in Bundelkhand region of India. *Environ. Monit. Assess*, 189, 576.

DeLuca, T., Pingree, M., and Gao, S. (2018). Assessing soil biological health in forest soils. *Developments in Soil Science*, *36*, 397-426. https://doi.org/10.1016/B978-0-444-63998-1.00016-1

Deo, R., Russell, M., Domke, G., Andersen, H.-E., Cohen, W., and Woodall, C. (2017a). Evaluating Site-Specific and Generic Spatial Models of Aboveground Forest Biomass Based on Landsat Time-Series and LiDAR Strip Samples in the Eastern USA. *Remote Sensing*, *9*(6), 598.

de Oliveira, C. P., Francelino, M. R., Daher, M., Araújo, E. J. G., Sanches, L. S., Andrade, K. D. C., & Campos, J. S. N. (2019). Estimation of the aboveground biomass and carbon stocks in open Brazilian Savannah developed on sandy soils. *Carbon Balance Manage* **14**, 5. https://doi.org/10.1186/s13021-019-0121-0

Devi, N. B., Lepcha, N. T., Mahalik, S. S., Dutta, D., andTsanglao, B. L. (2021). Urban sacred grove forests are potential carbon stores: A case study from the Sikkim Himalaya. *Environmental Challenges*, 4, 100072.

Dewangan, S. K., Shrivastava, S., Kumari, L., Minj, P., Kumari, J., and Sahu, R. (2023). The effects of soil pH on soil health and environmental sustainability: A review. *Journal of Emerging Technologies and Innovative Research*, 10 (6): 611-616.

Díaz, S., Settele, S., Brondízio, E. S., Ngo, H. T., Guèze, M., Agard, J., ... and Zayas, C. N. (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy (enlínea). Platform on Biodiversity and Ecosystem Services (eds.). IPBES secretariat, Bonn, Germany. Consultado 5 sept. 2021.

Dillon, K. T., Henderson, A. N., Lodge, A. G., Hamilton, N. I., Sloat, L. L., Enquist, B. J., Price, C. A., and Kerkhoff, A. J. (2019). On the relationships between size and abundance in plants: Beyond forest communities. *Ecosphere,* 10(9), e02856. https://doi.org/10.1002/ecs2.2856

Djomo AN, Knohl A, Gravenhorst G (2011). Estimations ecosystem carbon of total pools distribution and carbon biomass current annual increment of a moist tropical forest," *Forest Ecology and Management*, 261 (8), 1448–1459.

Doggart N, Dilger MS, Cunneyworth P and Fanning E (1999). Vegetation in Kwamgumi Forest Reserve: A Biodiversity Survey. pp. 13-45 from East Usambara Conservation Area Management Programme Technical Paper No. 40. Frontier Tanzania: Forestry and Beekeeping Division, Dar es Salaam, Tanzania and Metsähallitus Consulting Vantaa, Finland.

Domke, G.M., Perry, C.H., Walters, B.F., Woodall, C.W., Russell, M.B., Smith, J.E. (2016). Estimating litter carbon stocks on forest land in the United States. *Sci Total Environ* 557–558:469–478.

Doody, K.Z., Ntemi, A., Killenga, R. and Beharrell, N.K. (2001). Vegetation in Mpanga Village Forest Reserve: A biodiversity survey. pp. 9-39 from East Usambara Conservation Area Management Programme Technical Paper No. 51. Frontier Tanzania: Forestry and Beekeeping Division, Dar es Salaam, Tanzania and Metsähallitus Consulting Vantaa, Finland.

Dornelas, M. (2010). Disturbance and change in biodiversity. *Philosophical Transactions of the Royal Society of London. Series B, Biological sciences*, *365*(1558), 3719–3727.

Doula, M., and Sarris, A. (2015). Soil Environment. *Environment and Development*, 213-286. https://doi.org/10.1016/B978-0-444-62733-9.00004-6

Drake, J.B., Dubayah, R.O., Clark, D.B., Knox, R.G., Blair, J.B., Hofton, M.A., Chazdon, R.L., Weishampel, J.F. and Prince, S. (2002). Estimation of tropical forest structural characteristics using large-footprint lidar. *Remote Sensing of Environment,* 79 (2–3), 305– 319.

Driscoll, D., Lindenmayer, D., Bennett, A., Bode, M., Bradstock, R., Cary, G., Clarke, M., Dexter, N., Fensham, R., Friend, G., Gill, M., James, S., Kay, G., Keith, D., Macgregor, C., Russell-Smith, J., Salt, D., Watson, J., Williams, R., and York, A. (2010). Fire management for biodiversity conservation: Key research questions and our capacity to answer them. Biological Conservation, 143, 1928-1939.

Dudley, N. (Editor) (2008). Guidelines for Applying Protected Area Management Categories. Gland, Switzerland: IUCN. x + 86pp. WITH Stolton, S., P. Shadie and N. Dudley (2013). IUCN WCPA Best Practice Guidance on Recognising Protected Areas and Assigning Management Categories and Governance Types, Best Practice Protected Area Guidelines Series No. 21, Gland, Switzerland: IUCN. xxpp.

Dumbrell, A. J., Clark, E. J., Frost, G. A., Randell, T. E., Pitchford, J. W., and Hill, J. K. (2008). Changes in species diversity following habitat disturbance are dependent on spatial scale: Theoretical and empirical evidence. *Journal of Applied Ecology*, 45(5), 1531-1539. https://doi.org/10.1111/j.1365-2664.2008.01533.x

Ebuy J, Lokombe JP, Ponette Q, Sonwa D, Picard N. (2011). An allometric equation for predicting aboveground biomass of three species. *Journal of Tropical Science* 23, 125–132.

ECCC (Environment and Climate Change Canada) (2019). Canadian Environmental Sustainability Indicators: Greenhouse gas emissions. Consulted on Month day, year. Available at: www.canada.ca/en/environment-climate-change/services/environmentalindicators/greenhouse-gas-emissions.html.

Edet, I.D., Henry, M.I. and Augustine, U.O. (2012): Preliminary assessment of tree species diversity in Afi Mountain Wildlife Sanctuary, Southern Nigeria; *Agriculture and Biology Journal of North America* @www.schb.org/ABJNA.

Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (2006) IPCC guidelines for national greenhouse gas inventories, volume - IV agriculture, forestry, and other land use. Institute of Global Environmental Strategies (IGES), Hayama Ravindranath NH, Ostwald M (2008): Methods for estimating above ground biomass. In: Ravindranath NH, Ostwald M (eds) Carbon inventory methods: handbook for greenhouse gas inventory, carbon mitigation and round wood production projects, Springer Science + Business Media B.V, Netherlands

Egonmwan IY and Ogana FN (2020): Application of diameter distribution model for volume estimation in Tectonagrandis L. f. stands in the Oluwa forest reserve, Nigeria; Tropical Plant Research 7(3): 573–580.

Egonmwan, Y. I., and W. O. Orukpe. (2022). "Evaluation of Tree Volume Equations for Gmelina Arborea Roxb. Stand in Southwestern, Nigeria". *Asian Journal of Research in Agriculture and Forestry,* 8 (4):301-10. https://doi.org/10.9734/ajraf/2022/v8i4189.

Egwunatum A. E., Dolor D. E. and Umeh P. C. (2020): Evaluation of forest litter mineralization capacity on the growth of *Irvingia gabonensis*in Ogwashi-Uku Forest Reserve, Delta State, Nigeria; *Journal of Horticulture and Forestry;* 12(2):49-56.

Ekanayake, E. M. A. C., Shen, G. Q. P., Kumaraswamy, M. M., and Owusu, E. K. (2020). Identifying supply chain vulnerabilities in industrialized construction: an overview. *International Journal of Construction Management,* 22(8), 1464–1477. https://doi.org/10.1080/15623599.2020.1728487

Ekpa, N.E., Akindele, S.O. and Udofia, S.I. (2014). GmelinaarboreaRoxb. graded stands with the Weibull distribution function in Oluwa Forest Reserve, Nigeria. *International Journal of Agroforestry and Silviculture, 1*(9): 110–113.

El Moll, A. (2022). Water resources and climate change: Regional, national and international perspective. Sustainable and Circular Management of Resources and Waste Towards a Green Deal, 309-336. https://doi.org/10.1016/B978-0-323-95278-1.00010-3.

Elvis P., Dijana V., Ivan M., Hrvoje M., Krunoslav I., Miroslav B. and Vladimir N. (2009). Forest biomass and sequestered carbon estimation according to main tree components on the forest stand scale. *Periodicum Biologorum*, 111 (4), 459–466.

Eneji, I. S., Obinna, O., and Azua, E. T. (2014). Sequestration and Carbon Storage Potential of Tropical Forest Reserve and Tree Species Located Within Benue State of Nigeria. *Journal of Geoscience and Environment Protection,*2, 157-166.

Environmental Protection Agency (EPA), *Inventory of U.S.* (2020): *Greenhouse Gas Emissions and Sinks, 1990-2018*, EPA 430-R-20-002, April 13, 2020.

Environmental Protection Agency Report (2018): https://www.epa.gov/report-environment/greenhouse-gases

Esor, P.E., Amonum, J.I., Agera, S.I.N. (2023). Forest Structure, Tree Species Diversity, and Distribution in Ukpon River Forest Reserve, Cross River State, Nigeria. *Int J Avian and Wildlife Biol*; 7(2):46-54. DOI: 10.15406/ijawb.2023.07.00189

Fabio, G., Robert, T., Beverly, L., André, A., Wayne, W., Alessandro, B., João, R.S., and Paulo, G. (2017). Estimating aboveground biomass in tropical forests: Field methods and error analysis for the calibration of remote sensing observations. *Remote Sensing, 9(1), 47. https://doi.org/10.3390/rs9010047*

Fahey, R. T., Stuart-Haëntjens, E. J., Gough, C. M., De La Cruz, A., Stockton, E., Vogel, C. S., and Curtis, P. S. (2016). Evaluating forest sub canopy response to moderate severity disturbance and contribution to ecosystem-level productivity and resilience. *Forest Ecology and Management*, (376), 135-147.

Fang, Z.; Bailey, R.L. 1998. Height-diameter models for tropical forests on Hainan Island in southern China. *Forest Ecology and Management* 110: 315–327

FAO (2020). Nigeria – National forest (carbon) inventory field manual. Abuja. https://doi.org/10.4060/cb2087en; 54 pp.

FAO (2005). The importance of soil organic matter Key to drought-resistant soil and sustained food production; FAO Soils Bulletin 80; Chief Publishing Management Service
Information Division FAO Viale delle Terme di Caracalla, 00100 Rome, Italy. Retrieved from https://www.fao.org/3/a0100e/a0100e05.htm. Accessed on 10thJuly, 2022

Fatoye, F. B. and Gideon, Y. B (2013). Geology and mineral resources of the Lower Benue Trough, Nigeria. *Advances in Applied Science Research*, 4(6).21-28.

Ferrarezi, R. S., Lin, X., Gonzalez Neira, A. C., Tabay Zambon, F., Hu, H., Wang, X., Huang, J., and Fan, G. (2022). Substrate pH Influences the Nutrient Absorption and Rhizosphere Microbiome of Huanglongbing-Affected Grapefruit Plants. *Frontiers in Plant Science*, *13*, 856937. https://doi.org/10.3389/fpls.2022.856937

Fischer, R., Bohn, F., Dantas de Paula, M., Dislich, C., Groeneveld, J., Gutiérrez, A. G., Kazmierczak, M., Knapp, N., Lehmann, S., Paulick, S., Pütz, S., Rödig, E., Taubert, F., Köhler, P., and Huth, A. (2016). Lessons learned from applying a forest gap model to understand ecosystem and carbon dynamics of complex tropical forests. *Ecological Modelling*, *326*, 124-133. https://doi.org/10.1016/j.ecolmodel.2015.11.018.

Fisher RF and Binkley D (2000). In: Ecology and management of forest soil. John Wiley and Soils Inc. New York.

Fonseca, W., Alice, F. E., and Rey-Benayas, J. M. (2012). Carbon accumulation in aboveground and belowground biomass and soil of different age native forest plantations in the humid tropical lowlands of Costa Rica. *New Forests,* 43(2), 197–211. https://doi.org/10.1007/s11056-011-9273-9

Fontaine, S., Barot, S., Barré, P., Bdioui, N., Mary, B., and Rumpel, C. (2007). The stability of organic carbon in deep soil layers is controlled by fresh carbon supply. *Nature* 450, 277–280.

FORMECU (1999). Forest Resources Study, Nigeria. Revised national report Vol. 2. Prepared for FORMECU by Break and Geomaticsforest ecosystems and their tree species utilization. T2-verlagsgessells Chaft, International, 224pp.

Forrester, D. I. and Pretzsch, H. (2015) Tamm Review: On the strength of evidence when comparing ecosystem functions of mixtures with monocultures. *Forest Ecology and Management,* 356, 41-53.

Freyer, B., Ellssel, P., Friedel, J. K., and Möller, K. (2023). The contribution of organic farming systems to soil fertility—A systems perspective. In M. J. Goss and M. Oliver (Eds.), Encyclopedia of Soils in the Environment (2ndEd), Academic Press: 135-145.

Furnival, G.M. (1961). An index for comparing equations used in constructing volume tables. *Forest Science*, 7(4), 337-341.

Gamfeldt, L., Snäll, T., Bagchi, R., Jonsson, M., Gustafsson, L., Kjellander, P., C., M., Fröberg, M., Stendahl, J., Philipson, C. D., Mikusiński, G., Andersson, E., Westerlund, B., Andrén, H., Moberg, F., Moen, J., and Bengtsson, J. (2013). Higher levels of multiple ecosystem services are found in forests with more tree species. *Nature Communications*, *4*(1), 1-8. https://doi.org/10.1038/ncomms2328

Gautam, C., Watanabe, T. andPadjadjaran, S. (2009): Assessment of role of community forests in CO_2 Sequestration, Biodiversity and Land Use Change; *Asia Pacific Network for Global Change Research,* ARCP2009-10NSY-Gautam: 125 pg.

Gee, G.W. and Bouder, J.W. (1986). Particle size analysis. In. Klute, A (ed.) Methods of soil analysis 2nd ed. No. 9 ASA. Inc. SSSA Madison, Washington D.C. 1986. 383-409.

Georgia Galidaki, Dimitris Zianis, Ioannis Gitas, Kalliopi Radoglou, VassiliaKarathanassi, Maria Tsakiri–Strati, Iain Woodhouse and Giorgos Mallinis (2017). Vegetation biomass estimation with remote sensing: focus on forest and other wooded land over the Mediterranean ecosystem. *International Journal of Remote Sensing*, 38 (7): 1940-1966.

Gibbs HK, Brown S, Niles JO, Foley JA (2007). Monitoring and estimating tropical forest carbon stocks. Making REDD a reality. *Environmental Research Letters,* 2, 1-13.

Giuntoli, J., Barredo, J. I., Avitabile, V., Camia, A., Cazzaniga, N. E., Grassi, G., Jasinevičius, G., Jonsson, R., Marelli, L., Robert, N., Agostini, A., andMubareka, S.

(2022). The quest for sustainable forest bioenergy: Win-win solutions for climate and biodiversity. *Renewable and Sustainable Energy Reviews*, 159. 112180.

Giweta, M. (2020): Role of litter production and its decomposition, and factors affecting the processes in a tropical forest ecosystem: a review. *Journal of Ecology Environment;* 44: 11. https://doi.org/10.1186/s41610-020-0151-2

Goel, S. and Agarwal, D. (2014): Carbon Dioxide, Editor(s): Philip Wexler, *Encyclopedia of Toxicology* (Third Edition), Academic Press: 675-677.

Goetz SJ, Baccini A, Laporte N, Johns T, Walker WS, Kellndorfer JM, Houghton RA, Sun M. (2009) Mapping and monitoring carbon stocks with satellite observations: a comparison of methods. *Carbon Balance Management* 4(2): doi: 10.1186/1750-0680-1184-1182.

Gompertz, B., (1825). On the Nature of the Function Expressive of the Law of Human Mortality, and on a New Mode of Determining the Value of Life Contigencies. Philosophical Transactions of the Royal Society of London, 115, 513-583. http://dx.doi.org/10.1098/rstl.1825.0026

González-Megías A., Menéndez R. (2012). Climate change effects on above- and below-ground interactions in a dryland ecosystem. *Phil. Trans. R. Soc. B* 367, 3115–3124.

Grant, N.K. (1971). The South Atlantic Benue Trough and Gulf of Guinea Cretaceous triple junction. *Geological Society of America Bulletin,* 82, 2295 – 2298.

Green, C., and Byrne, K. A. (2004). Biomass: Impact on the Carbon Cycle and Greenhouse Gas Emissions. In C. J. Cleveland (Ed.), Encyclopedia of Energy (pp. 223-236). Elsevier.

Grigal, D. F. (2000). Effects of extensive forest management on soil productivity. *Forest Ecology and Management*, *138*(1-3), 167-185. https://doi.org/10.1016/S0378-1127(00)00395-9

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., Herrera, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S. M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F. E., Sanderman, J., Silvius, M., Wollenberg, E., and Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, *114*(44), 11645-11650. https://doi.org/10.1073/pnas.1710465114

Guillaume, T., Damris, M., Kuzyakov, Y., (2015). Losses of soil carbon by converting tropical forest to plantations: Erosion and Decomposition estimated by δ13C. *Glob. Change Biol*. 21 (9), 3548–3560.

Gunlu A, Ercanli I, Baskent EZ, Cakır G. (2014). Estimating aboveground biomass using Landsat TM imagery. a case study of Anatolian Crimean pine forests in Turkey. *Annals of Forest Research,* 57, 289–298.

Haile, G., Itanna, F., Teklu, B., Agegnehu, G., and Wang, X. (2022). Variation in soil properties under different land use types managed by smallholder farmers in central Ethiopia. *Sustainable Environment*, *8*(1). https://doi.org/10.1080/27658511.2022.2093058

Han, Kyung-Hwa and Ha, Sang-Geun and Jang, Byoung-Choon. (2010). Aggregate Stability and Soil Carbon Storage as Affected by Different Land Use Practices. Proc.of Int. Workshop on Evaluation and Sustainable Management of Soil Carbon Sequestration in Asian Countries. Bogor, Indonesia Sept. 28-29, 2010: 114-124.

Hangarge LM, Kulkarni DK, Gaikwad VB, Mahajan DM (2015). Soil organic carbon (SOC) in selected sacred groves from Bhor region of western ghats, Maharashtra. *Asian J Environ Sci* 10(2):166–171

Hasanuzzaman, M., Bhuyan, M.H.M.B., Nahar, K., Hossain, M.S., Mahmud, J.A., Hossen, M.S., Masud, A.A.C., Moumita, and Fujita, M. (2018). Potassium: A vital regulator of plant responses and tolerance to abiotic stresses. *Agronomy*, 8 (3): 31. https://doi.org/10.3390/agronomy8030031

He, L., Zhang, X., Wang, X., Ullah, H., Liu, Y., and Duan, J. (2023). Tree Crown Affects Biomass Allocation and Its Response to Site Conditions and the Density of *Platycladus orientalis* Linnaeus Plantation. *Forests,* 14(12), 2433. https://doi.org/10.3390/f14122433

Hoover, K. and Riddle, A.A. (2023). Forest Carbon Data: In Brief. Congressional Research Service Report. https://crsreports.congress.gov R46313 U.S.

Houghton RA (2005). *Above-ground forest biomass and the global carbon balance. Global Change Biology,* 11: 945-958.

Hu, N., and Lan, J. C. (2020). Impact of vegetation restoration on soil organic carbon stocks and aggregates in a karst rocky desertification area in Southwest China. *Journal of Soils and Sediments,* 20, 1264-1275.

Hu, Y., Su, Z., Li, W., Li, J., and Ke, X. (2015). Influence of tree species composition and community structure on carbon density in a subtropical forest. *PLOS ONE*, 10(9), e0136984. 10. e0136984. 10.1371/journal.pone.0136984.

Husch, B., I. M. Charles and W. B. Thomas (2003). Forest Mensuration. The Ronald Press Company, New York, U. S. A. pp 120-123.

Ibrahim, M., Isah, A., Shamaki, S., and Audu, M. (2018). Carbon Stock Assessment in Majiya Fuelwood Reserve, Sokoto State, Nigeria. *Journal of Scientific Research and Reports, 18*(2), 1-12.

Ige, P. (2018). Above-ground biomass and carbon stock estimation of Gmelina arborea (ROXB) stands in Omo Forest reserve, Nigeria. *Journal of Research in Forestry, wildlife and the Environment,* 10 (4), 71-80.

Ikyaagba, E.T. (2008): Plant biodiversity and Ethno botanical potential of the University of Agriculture Makurdi Wildlife Park and Ikwe Game Reserves, Igbo Benue State Nigeria; (Unpublished thesis in the Department of Forest Resources Management University of Ibadan, *Ibadan Nigeria 1-123pp)*.

Intergovernmental Panel on Climate Change (IPCC) (2006a). Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe K. (Eds). Published: IGES, Japan.

Intergovernmental Panel on Climate Change (IPCC) (2006b). Guidelines for national greenhouse gas inventories, prepared by the National Greenhouse Gas Inventories Programme. Kanagawa. IGES.

IPCC (2001): Emission Scenarios. Special Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge.

IPCC (2003). IPCC good practice guidance for LULCF sector, Intergovernmental panel on climate change, Cambridge University Press, Cambridge, UK.

IPCC (2012): Glossary of terms. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 555-564.

Jae Soo Bae, Cheolmin Kim, Yeon-Su Kim, Sitti Latifah, Mansur Afifi, Larry A. Fisher, Soo Min Lee, In-Ae Kim, Jintaek Kang, Raehyun Kim and Jeong Soo Kim (2014). Estimation of carbon stock and carbon stock change. In. Opportunities for implementing REDD+ to enhance sustainable forest management and improve livelihoods in Lombok, NTB, Indonesia, *Center for International Forestry Research* 2014. pp.6. http.//www.jstor.com/stable/resrep02354.10.

Japheth H.D and Meer, B.B (2023): Structure, Alpha and Beta Diversity of Natural Forest Areas in Three Eco-Zones of Taraba State, Nigeria; *Journal of Forestry and Environmental Service. Journal of Forest and Environmental Science*, 39 (1): 1-12.

Japheth, H.D, Meer, B.B and Ubaekwe, R.E. (2023). Volume Equations for Sustainable Forest Management of Ngel-Nyaki Forest Area in Taraba State, Nigeria. *Nature Science* 2022; 20(1):52-60. doi:10.7537/marsnsj200122.06

Jhariya, M. K. (2017). Vegetation ecology and carbon sequestration potential of shrubs in tropics of Chhattisgarh, India. *Environ. Monit. Assess.* 189, 518. https ://doi.org/10.1007/s1066 1-017-6246-2 (2017).

Jianjun, C., Huijun, Z., Yanyan, Q. (2019). Biomass Allocation Between Above- and Below-ground andIt Impacted Factors of Shrubby Areas and Grasslands in Upper Heihe River Basin of China. *2018 International Conference on Biotechnology and Bioengineering (8th ICBB);* AIP Conf. Proc. 2079, 020026-1–020026-7

Jobbagy, E.G. and Jackson R.B (2000). The vertical distribution of soil carbon and its relation to climate and vegetation. *Ecol Appl;* 10:423–436.

Johan, P. D., Ahmed, O. H., Omar, L., and Hasbullah, N. A. (2021). Phosphorus transformation in soils following co-application of charcoal and wood ash. *Agronomy,* 11(10), 2010

Kaasalainen, S.; Holopainen, M.; Karjalainen, M.; Vastaranta, M.; Kankare, V.; Karila, K.; Osmanoglu, B. (2015). Combining Lidar and Synthetic Aperture Radar data to estimate forest biomass: Status and prospects. *Forests*, 6, 252–270.

Kacholi, D.S. (2019) Assessment of Tree Species Richness, Diversity, Population Structure and Natural Regeneration in Nongeni Forest Reserve in Morogoro Region, Tanzania. *Tanzania Journal of Science*, 45, 330-345.

Kafle, G. (2019). Vertical distribution of SOC stocks and nitrogen in a tropical community forest in Nepal. *International Journal of Forestry Research,* 2019, Article ID 3087570, 6 pages.

Kamruzzaman M, Ahmed S, Paul S, Rahman MM, Osawa A. (2018): Stand structure and carbon storage in the oligohaline zone of the Sundarbans mangrove forest, Bangladesh. *Forest Science Technology*; 14:23–28.

Kane, M. E., and Pokorny, R. (2020). Diversity of tree species in gap regeneration under tropical moist semi-deciduous forest: An example from Bia Tano Forest Reserve. *Diversity, 12*(8), 301. 10.3390/d12080301.

Karky, B. (2008): The Economics of Reducing Emissions from Community Managed Forests in Nepal. Himalaya: Ph.D. Thesis. University of Twente, The Netherlands.

Karky, B. S. and M. Skutsch. (2010). The cost of carbon abatement through community forest management in Nepal Himalaya. *Ecological Economics,* 69:666-672.

Karsten, R. J., Jovanovic, M., Meilby, H., Perales, E., and Reynel, C. (2013). Regeneration in canopy gaps of tierra firme forest in the Peruvian Amazon: Comparing reduced impact logging and natural, unmanaged forests. *Forest Ecology and Management*, 310, 663–671.

Katie, H. and Anne, A.R. (2020). Forest Carbon Primer; Congressional Research Report. www.crs.gov.

Kazemi, S., Hojjati, S., Fallah, A., andTafazoli, M. (2015). Effects of forest management on soil physical and chemical properties of Khalil-Mahale forest. *Journal of Forest Research and Development, 1(1),* 713-726.

Kebebew, S., Bedadi, B., Erkossa, T., Yimer, F., andWogi, L. (2022). Effect of land-use types on soil properties in Cheha District, South-Central Ethiopia. *Sustainability;* 14 (3): 1323. https://doi.org/10.3390/su14031323

Kebrle, D., Zasadil, P., Hošek, J., Barták, V., and Šťastný, K. (2021). Large trees as a key factor for bird diversity in spruce-dominated production forests: Implications for conservation management. *Forest Ecology and Management*, *496*, 119460. https://doi.org/10.1016/j.foreco.2021.119460

Kendie, G.; Addisu, S. and Abiyu, A. (2019). Biomass and soil carbon stocks in different forest types, Northwestern Ethiopia. *International Journal of River Basin Management,*19:1, 123-129.

Kent, M., and Coker, P. (1992). Vegetation Description and Analysis: A Practical Approach (pp. 167-169). New York: John Wiley and Sons.

Kerenku T.A, Iorkua, S.A. and Aii, V. (2010). Soil physicochemical properties under different land surfaces around the Tarhembesetrlement area of Benue State. *A Journal of Environmental Design,* 5(1), 7-11.

Khaidem, J., Thounaojam, T., and Meetei, T. T. (2018). Influence of soil pH on nutrient availability: A review; Journal *of Emerging Technologies and Innovative Research: 5(12):* 707-713.

Khan, M. L., Khumbongmayum, A. D., and Tripathi, R. S. (2008). The Sacred Groves and Their Significance in Conserving Biodiversity: An Overview. *International Journal of Ecology and Environmental Sciences,* 34(3), 277–291.

Khanal, S., Nolan, R. H., Medlyn, B. E., and Boer, M. M. (2024). Disentangling contributions of allometry, species composition and structure to high aboveground biomass density of high-elevation forests. *Forest Ecology and Management*, *554*, 121679. https://doi.org/10.1016/j.foreco.2023.121679

Kholdaenko, Y. A., Belokopytova, L. V., Zhirnova, D. F., Upadhyay, K. K., Tripathi, S. K., Koshurnikova, N. N., Sobachkin, R. S., Babushkina, E. A., and Vaganov, E. A. (2022). Stand density effects on tree growth and climatic response in Picea obovataLedeb. Plantations. *Forest Ecology and Management*, *519*, 120349. https://doi.org/10.1016/j.foreco.2022.120349

Khresat, S., Al-Bakri, J. and Al-Tahhan, R (2008). Impacts of land use/cover change on soil properties in the Mediterranean region of northwestern Jordan. *Land Degradation and Development.* 19, 397–407.

Kim C, Jeong J, Kim R, Son Y, Lee KH, *et al*. (2011). Allometric Equations and Biomass Expansion Factors of Japanese Red Pine on the Local Level. *Landscape Ecology Engineering,* 7: 283-289.

King, D. A. (1990). The Adaptive Significance of Tree Height. *The American Naturalist*, *135*(6), 809–828.

Konstantinavičienė, J. and Vitunskienė, V. (2023). Definition and classification of potential forest wood biomass in terms of sustainable development: A Review. *Sustainability* 2023, 15, 9311.

Kumar R, Pandey S, Pandey A (2006): Plant roots and carbon sequestration. *Current Science* 9: 885-890.

Kumi, J. A., Kyereh, B., Ansong, M., and Asante, W. (2021). Influence of management practices on stand biomass, carbon stocks and soil nutrient variability of Teak plantations in a dry semi-deciduous forest in Ghana. *Trees, Forests and People*, 3: 1-7. 100049.

Kung'u, G. N., Cousseau, L., Githiru, M., Habel, J. C., Kinyanjui, M., Matheka, K., Schmitt, C. B., Seifert, T., Teucher, M., Lens, L., and Apfelbeck, B. (2023). Anthropogenic activities affect forest structure and arthropod abundance in a Kenyan biodiversity hotspot. *Biodivers Conserv* 32, 3255–3282. https://doi.org/10.1007/s10531-023-02652-5

Kunz, M., Hess, C., Raumonen, P., Bienert, A., Hackenberg, J., Maas, H.-G., Haerdtle, W., Fichtner, A., andOheimb, G. (2017). Comparison of wood volume estimates of young trees from terrestrial laser scan data. *iForest - Biogeosciences and Forestry;* 10: 451-458. https://doi.org/10.3832/ifor2151-010

Kurayemen, C., Gyata, B. A., and Emmanuel, A. (2013). Minimizing the effect of land degradation in Benue State for sustainable food production. *Mediterranean Journal of Social Sciences*, 4(15), 93. DOI: 10.5901/mjss. 2013.v4n15p93.

Kuyah, S., Dietz, J., Muthuri, c., Jamnadass, R., Mwangi, P., Coe, R., Neufeldt, H. (2012). Allometric equations for estimating biomass in agricultural landscapes: I. Aboveground biomass. *Agric., Ecosyst. Environ*., 158: 216-224.

Kweku, D. W., Odum Bismark, A. M., Addae, M., Koomson, A. D., Kwakye, B. D., Ewurabena, A. O.-M., Asenso, T. Q., andBuanya, B. A. (2018). Greenhouse effect: Greenhouse gases and their impact on global warming. *Journal of Scientific Research and Reports*, 17(6), 1-9. https://doi.org/10.9734/JSRR/2017/39630.

Lal R (2005): Forests soil and carbon sequestration; *Forest Ecology and Management*, 220: 242-258.

Lal, R. (2008). Carbon sequestration. Philosophical Transactions of the Royal Society B 363, 815-830.

Lal, R.; Follett, R. F.; Stewart, B. A.; Kimble, J. M. (2007). Soil Carbon Sequestration to Mitigate Climate Change and Advance Food Security. *Soil Science* 172(12): 943-956.

Landuyt, D., Ampoorter, E., Bastias, C. C., Benavides, R., Müller, S., Scherer-Lorenzen, M., Valladares, F., Wasof, S., and Verheyen, K. (2020). Importance of overstorey attributes for under-storey litter production and nutrient cycling in European forests. *Forest Ecosystems*, 7, 45.

Leps, J. (2005). Diversity and ecosystem function. In: Van Der MaarelE (ed) Vegetation ecology. Blackwell Publishing, Oxford, pp 199–237

Li, H. X., Chen, Z. J., Zhou, T., Liu, Y., and Zhou, J. B. (2018). A high potassium-to-magnesium ratio affected the growth and magnesium uptake of three tomato (*Solanum lycopersicum* L.) cultivars. *Journal of Integrative Agriculture*, 17(12), 2813-2821.

Li, T., Xiong, Q., Luo, P., Zhang, Y., Gu, X., and Lin, B. (2019). Direct and indirect effects of environmental factors, spatial constraints, and functional traits on shaping the plant diversity of montane forests. *Ecology and Evolution,* 10(1), 557-568. https://doi.org/10.1002/ece3.5931

Li, Y., Ye, S., Luo, Y., Yu, S., and Zhang, G. (2023). Relationship between species diversity and tree size in natural forests around the Tropic of Cancer. *J. For. Res.* 34, 1735–1745. https://doi.org/10.1007/s11676-023-01616-3

Liu, G and Westman, C. J (2009). Biomass in a Norway spruce – Scots pine forest: a comparison of estimation methods. *Boreal Env. Res*. Vol. 14: 875 – 888.

Liu, Y., Li, S., Sun, X., and Yu, X. (2016). Variations of forest soil organic carbon and its influencing factors in east China. *Annals of Forest Science,* 73, 501–511. https://doi.org/10.1007/s13595-016-0543-8.

Lockhart, B.R.; Weih, C.R. and Smith, M.K., (2005): Crown Radius and Diameter at Breast Height Relationships for Six Bottomland Hardwood Species. *Journal of the Arkansas Academy of Science*, 59: 110-115.

Loreau M, Hector A (2001) Partitioning selection and complementarity in biodiversity experiments. *Nature* 412:72–76.

Lorenz, K., and Lal, R. (2010). Carbon sequestration in forest ecosystems. *Springer*. DOI 10.1007/978-90-481-3266-9

Lu, D., Chen, Q., Wang, G., Liu, L., Li, G., and Moran, E. (2014). A survey of remote sensing-based aboveground biomass estimation methods in forest ecosystems. *International Journal of Digital Earth,* 9(1), 63–105. https://doi.org/10.1080/17538947.2014.990526

Lu, D., Chen, Q., Wang, G., Moran, E., Batistella, M., Zhang, M. Laurin, G.V and Saah, D. (2012). Aboveground Forest Biomass Estimation with Landsat and LiDAR Data and Uncertainty Analysis of the Estimates. Hindawi Publishing Corporation *International Journal of Forestry Research* Volume, Article ID 436537, 16 pages.

Lu, M., Yang, M., Yang, Y., Wang, D., and Sheng, L. (2019). Soil carbon and nutrient sequestration linking to soil aggregate in a temperate fen in Northeast China. *Ecological Indicators*, 98, 869-878.

Lula, M., Trubins, R., Ekö, P. M., Johansson, U., and Nilsson, U. (2021). Modelling effects of regeneration method on the growth and profitability of Scots pine stands. *Scandinavian Journal of Forest Research,* 36(4), 263–274. https://doi.org/10.1080/02827581.2021.1908591

Luyssaert, S., Schulze, E.D., Borner, ¨ A., Knohl, A., Hessenmoller, ¨ D., Law, B.E., Ciais, P., Grace, J., (2008). Old-growth forests as global carbon sinks. *Nature* 455 (7210), 213–215.

Luyssaert, S; I. Inglima; Jung, M.J; Richardson, R.D; Reichstein, M.; Papale, D.; PIAO, S.L.; Schulze, E.D.; Wingate, L.; Matteucci, G.; Aragão, L.E.O.C.; Aubinet, M; Beer, C.; Bernhofer, C. (2017): CO_2 balance of boreal, temperate, and tropical forests derived from a global database; *Global Change Biol.*; 13: 2509–2537.

Ma, W., Zhang, X., Zhen, Q., and Zhang, Y. (2016). Effect of soil texture on water infiltration in semiarid reclaimed land. *Water Quality Research Journal*, 51(1), 33–41. https://doi.org/10.2166/wqrjc.2015.025

Ma, Y., Wang, C., Chen, Z., Yu, F., and Wan, J. (2023). Linking Forest Management Practices to the Functional Composition of Plant Communities. *Forests*, *14*(10), 1939. https://doi.org/10.3390/f14101939

Maestre, F.T., Reynolds, J.F. (2007). Biomass responses to elevated CO_2, soil heterogeneity and diversity: an experimental assessment with grassland assemblages. *Oecologia*, 151, 512–520. https://doi.org/10.1007/s00442-006-0577-y

Magurran AE. (2004). Measuring Biological Diversity. Blackwell Scientific Oxford, UK. Lu, D. (2006). The Potential and Challenge of Remote SensingBased Biomass Estimation. *International Journal of Remote Sensing* 27: 1297-1328.

Makariou, D., Barrieu, P., and Chen, Y. (2021). A random forest-based approach for predicting spreads in the primary catastrophe bond market. *Insurance: Mathematics and Economics*, *101*, 140-162. https://doi.org/10.1016/j.insmatheco.2021.07.003

Malimbwi RE, Shemweta DTK, Zahabu E, Kingazi SP, Katani JZ and Silayo DA 2005 *Forest inventory for Mvomero district, Morogoro-Tanzania.* FORCONSULT Report.

Mandal RA, Jha PK, Dutta IC, Thapa U, Karmacharya SB. (2016). Carbon sequestration in tropical and subtropical plant species in collaborative and community forests of Nepal; Advance Ecology; *Journal of Applied Ecology*, Article 1529703.

Mandal, R. A., and van Laake, P. (2015). Carbon sequestration in community forests: An eligible issue for CDM (A case study of Nainital, India). *Banko Janakari*, 15(2), 1-9.

Mandal, R. A., Dutta, I. C., Jha, P. K., and Karmacharya, S. (2013*): Relationship between carbon stock and plant biodiversity in collaborative forests in Terai*. Nepal: ISRN Botany.

Mantilla-Contreras, J., Schirmel, J., and Zerbe, S. (2012). Influence of soil and microclimate on species composition and grass encroachment in heath succession. *Journal of Plant Ecology,* 5(3), 249–259.

Manyam, H.I. and Japheth, H.D. (2022). The Prominence of Traditional and Religious Beliefs and Practices in Biodiversity Conservation. *Proceedings of the 8th Biennial Conference of the Forests and Forest Products Society,* Held at the Forestry Research Institute of Nigeria, Ibadan, Nigeria. 14th - 20th August 2022: 73-82.

Manyanda Bernardol John, Wilson Ancelm Mugasha, Emanuel F. Nzunda,1 and Rogers ErnestMalimbwi (2019). Biomass and Volume Models Based on Stump Diameter for Assessing Degradation of Miombo Woodlands in Tanzania; *Hindawi International Journal of Forestry Research* Volume 2019, Article ID 1876329, 15 pages.https://doi.org/10.1155/2019/1876329

Margono, B.A., Potapov, P.V., Turubanova, S., Stolle, F., Hansen, M.C., (2014). Primary forest cover loss in Indonesia over 2000–2012. *Nat. Clim. Change* 4 (8), 730–735.

Martin, A.R. and Thomas, S.C. (2011). A reassessment of carbon content in tropical trees. *PLoS ONE* 6. e23533.

Maru, Y., Gebrekirstos, A., and Haile, G. (2022). Indigenous Sacred Forests as a Tool for Climate Change Mitigation: Lessons from Gedeo Community, Southern Ethiopia. *Journal of Sustainable Forestry*, 42(3), 260–287. https://doi.org/10.1080/10549811.2021.2007490

Matthew R. Fisher (2019): Threats to Biodiversity: In Environmental Biology (Revised edition); Editor with content by OpenStax, Kamala Doršner, Alexandra Geddes, Tom Theis, and Jonathan Tomkin; published by Open Oregon Educational Resources: 342 pp.

Mayer, M., Prescott, C. E., Abaker, W. E., Augusto, L., Cécillon, L., Ferreira, G. W., James, J., Jandl, R., Katzensteiner, K., Laclau, J., Laganière, J., Nouvellon, Y., Paré, D., Stanturf, J. A., Vanguelova, E. I., and Vesterdal, L. (2020). Tamm Review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. *Forest Ecology and Management*, *466*, 118127. https://doi.org/10.1016/j.foreco.2020.118127

Mayers, J., Morrison, E., Rolington, L., Studd, K. and Turrall, S. (2013). Improving governance of forest tenure: a practical guide. Governance of Tenure Technical Guide No.2, International Institute for Environment and Development, and Food and Agriculture Organization of the United Nations, London and Rome.

McGee, G. G. (2000). The contribution of beech bark disease-induced mortality to coarse woody debris loads in northern hardwood stands of Adirondack Park, New York, USA. *Can. J. Res*. 30, 1453–1462.

Meer B.B and Tella, I. (2018). Assessment of Woody Species Diversity in Different Ecological Zones of Taraba State, Nigeria: A Strategy for Conservation; *Asian Journal of Research in Agriculture and Forestry;* 1(4): 1-12.

Mehtätalo, L., de-Miguel, S., Gregoire, T.G., (2015). Modelling height-diameter curves for prediction. *Can. J. For. Res*. 45, 826– 837.

Melieres, M. and Marechal, C. (2015). "Warming in the 20th century," in *Climate Change: Past, Present and Future* 1st ed., U.K.: Wiley, 2015, ch.29, sec.1:298-301

Melinda, S. and Alan, K. (2003). Dominant species maintain ecosystem function with non-random species loss. *Ecology Letters*; 6: 509 - 517.

Melissa Denchak (2019). NRDC (Natural Resources Defense Council) Report on Greenhouse Effect 101; retrieved from: https://www.nrdc.org/stories/greenhouse-effect-101/..............Accessed: 10th July, 2022.

Mensah, S., du Toit, B., and Seifert, T. (2018). Diversity–biomass relationship across forest layers: Implications for niche complementarity and selection effects. Oecologia, 187, 783–795. https://doi.org/10.1007/s00442-018-4144-0

Mensah, S., Noulekoun, F., E. and Ago, E.E. (2020): Aboveground tree carbon stocks in West African semi-arid ecosystems: Dominance patterns, size class allocation and structural drivers; *Global Ecology and Conservation;* 24 (2020) e01331: 11 pages.

Meragiaw, M., Woldu, Z., Martinsen, V., and Singh, B. R. (2021). Carbon stocks of above- and belowground tree biomass in Kibate Forest around Wonchi Crater Lake, Central Highland of Ethiopia. PLoS ONE, 16(7), e0254231. https://doi.org/10.1371/journal.pone.0254231

Miller, J. (2016). Soil pH Affects Nutrient Availability. Fact Sheet FS-1054; Published by university of Maryland extension solution in your community: 5 pg.. www.extension.umd.edu

Mitchard, E. T. A., Feldpausch, T. R., Brienen, R. J. W., Lopez-Gonzalez, G., Monteagudo, A., Baker, T. R., Lewis, S. L., Lloyd, J., Quesada, C. A., Gloor, M., ter Steege, H., Meir, P., Alvarez, E., Araujo-Murakami, A., Aragão, L. E. O. C., Arroyo, L., Aymard, G., Banki, O., Bonal, D., Brown, S., Brown, F. I., Cerón, C. E., Chama Moscoso, V., Chave, J., Comiskey, J. A., Cornejo, F., Corrales Medina, M., Da Costa, L., Costa, F. R. C., Di Fiore, A., Domingues, T. F., Erwin, T. L., Frederickson, T., Higuchi, N., Honorio Coronado, E. N., Killeen, T. J., Laurance, W. F., Levis, C., Magnusson, W. E., Marimon, B. S., Marimon Junior, B. H., Mendoza Polo, I., Mishra, P., Nascimento, M. T., Neill, D., Núñez Vargas, M. P., Palacios, W. A., Parada, A., Pardo Molina, G., Peña-Claros, M., Pitman, N., Peres, C. A., Poorter, L., Prieto, A., Ramirez-Angulo, H., Restrepo Correa, Z., Roopsind, A., Roucoux, K. H., Rudas, A., Salomão, R. P., Schietti, J., Silveira, M., de Souza, P. F., Steininger, M. K., Stropp, J., Terborgh, J., Thomas, R., Toledo, M., Torres-Lezama, A., van Andel, T. R., van der Heijden, G. M. F., Vieira, I. C. G., Vieira, S., Vilanova-Torre, E., Vos, V. A., Wang, O., Zartman, C. E., Malhi, Y., and Phillips, O. L. (2014). Markedly divergent estimates of Amazon forest carbon density from ground plots and satellites. *Global Ecology and Biogeography*, *23*(8), 935. https://doi.org/10.1111/geb.12168

Mligo C, Lyaruu H, Ndangalasi H and Marchant R (2009). Vegetation community structure, composition and distribution pattern in the Zaraninge Forest, Bagamoyo district, Tanzania. *J. East Afr. Nat. Hist.* 98: 223-239.

Montès, N., Gauquelin, T., Badri W., Bertaudiere V, Zaoui E.H. (2000). A nondestructive method for estimating above-ground forest biomass in threatened woodlands. *Forest Ecology and Management* 130. 37-46.

Moro, M. J., and Domingo, F. (2000). Litter Decomposition in Four Woody Species in a Mediterranean Climate: Weight Loss, N, and P Dynamics. *Annals of Botany*, 86(6), 1065–1071.

Muchoney DM, Strahler AH. (2002). Pixel- and site-based calibration and validation methods for evaluating supervised classification of remotely sensed data. *Remote Sensing of Environment* 81. 290–299.

Muhumuza, M., and Balkwill, K. (2013). Factors Affecting the Success of Conserving Biodiversity in National Parks: A Review of Case Studies from Africa. *International Journal of Biodiversity,* 798101.

Mulya, H.; Santosa, Y. and Hilwan, I. (2021). Comparison of four species diversity indices in mangrove community. Biodiversitas *Journal of Biological Diversity*. 22. 10.13057/biodiv/d220906.

Na, M., Sun, X., Zhang, Y., Sun, Z. and Rousk, J. (2021). Higher stand densities can promote soil carbon storage after the conversion of temperate mixed natural forests to larch plantations. *European Journal of Forest Research;* 140 (3): 373–386.

Navár J (2009). Allometric equations for tree species and carbon stocks for forests of Northwestern Mexico. *Forest Ecology and Management,* 257. 427-434.

Navarro M, Moya R, Chazdon RL, Ortiz E, Vilchez B. (2013). Successional variation in carbon content and wood specific gravity of four tropical tree species. *Bosque* 34. 33–43.

Naveed, A and Erwin, B. (2015). Species Richness, Alpha and Beta Diversity of Trees, Shrubs and Herbaceous Plants in the Woodlands of Swat, Pakistan. *Pakistan Journal of Botany,* 47(6): 2107-2113.

Neelo, J.; D. Teketay, K. Kashe, and W. Masamba (2015). Stand structure, diversity and regeneration status of woody species in open and ex-closed dry woodlands sites around Molapo farming areas of the Okavango Delta, Northeastern Botswana; *Open Journal of Forestry*, 5(4): 313–328.

Negasa, T., Ketema, H., Legese, A., Sisay, M., and Temesgen, H. (2016). Variation in soil properties under different land use types managed by smallholder farmers along the toposequence in southern Ethiopia. *Geodermal*, 290: 40–50

Nguyen, L. T., Ortner, K. A., Tiemann, L. K., Renner, K. A., and Kravchenko, A. N. (2022). Soil properties after one year of interseeded cover cropping in topographically diverse agricultural landscape. *Agriculture, Ecosystems and Environment*, *326*, 107803. https://doi.org/10.1016/j.agee.2021.107803

Niang, F., Marchand, P., Sambou, B., and Fenton, N. (2024). Exploring the effects of forest management on tree diversity, community composition, population structure and carbon stocks in sudanian domain of Senegal, West Africa. *Forest Ecology and Management*, 559, 121821. https://doi.org/10.1016/j.foreco.2024.121821.

Nodza, I.G., Onuminya, T.O. and Ogundipe, O.T. (2014). A Checklist of trees species growing in Akoka campus of University of Lagos, Nigeria; *International Journal of Science, Environment and Technology.* 3(3): 1021-1034.

Obia, A., Mulder, J., Hale, S. E., Nurida, N. L., and Cornelissen, G. (2018). The potential of biochar in improving drainage, aeration and maize yields in heavy clay soils. *PLOS ONE*, *13*(5), e0196794. https://doi.org/10.1371/journal.pone.0196794

Offiong, R.A., and Iwara, A.I. (2012). Quantifying the Stock of Soil Organic Carbon Using Multiple Regression Model in a Fallow Vegetation, Southern Nigeria. *Ethiopian Journal of Environmental Studies and Management*, 5(2): 166-172.

Ojo, O.S. (2016). Evaluation of Flora Diversity and Abundance in Awba Dam Tourism Centre, Ibadan, Nigeria; *Journal of Agriculture and Social Research*, Vol. 16, No. 1: 75-83.

Oke, O.S, Akindele, S.O. and Onyekwelu, J.C (2020). Biomass and Carbon Stock Assessment Of A Tropical Rain Forest Ecosystem in Nigeria; *Journal of Forestry Research and Management. Vol. 17(2).83-92.*

Oladoye, A.O., Bello, O.S, Basiru A.O, Ige, P.O and Ezenwenyi, J.U (2018). Above Ground Biomass and Carbon Stock of *Nauclea Diderrichii* (De Wild. and T. Durand) Merill Plantation in Omo Forest Reserve, Nigeria. *Journal of Forestry Research and Management,* 15(2), 95-111.

Oladoye, O., Saka, O. and Labode, P. (2015). Carbon stock in Teak stands of selected forest reserves in southwestern Nigeria. *Environment and Natural Resources Research*, 5 (3),109-115.

Olajide, O; Emah, E.U and Etigale, E.B (2021): Evaluation of carbon sequestration in above-ground biomass of three avenue tree species planted in Uyo Metropolis, Akwa Ibom State, Nigeria; *Journal of Agriculture and Environment;* 17 (1). 177-184

Olayode, O.O., Bada, O.S. and Popoola, L. (2015). Carbon Stock in Teak Stands of Selected Forest Reserves in Southwestern Nigeria. *Environment and Natural Resources Research*; 5 (3): 109-115.

Olsson, B. A., Hansson, K., Persson, T., Beuker, E., andHelmisaari, H. (2012). Heterotrophic respiration and nitrogen mineralisation in soils of Norway spruce, Scots pine and silver birch stands in contrasting climates. *Forest Ecology and Management*, (*269):* 197-205. https://doi.org/10.1016/j.foreco.2011.12.031

Olufunke O. Olayode, Saka. O. Bada and Labode Popoola (2015). Carbon Stock in Teak Stands of Selected Forest Reserves in Southwestern Nigeria; *Environment and Natural Resources Research*, Published by Canadian Center of Science and Education; 5 (3): 109-115.

Omofonmwan S. I. and Osa-Edoh G. I. (2008). The challenges of environmental problems in Nigeria. *Journal of Human Ecology*, 23(1): 53-57

Ontl, T. A. and Schulte, L. A. (2012). Soil Carbon Storage. *Nature Education Knowledge* 3(10):35: 1 - 10.

Onyekwelu, J. C., Agbelade, A. D., Stimm, B., andMosandl, R. (2024). Role of sacred groves in southwestern Nigeria in biodiversity conservation, biomass, and carbon storage. *Environmental monitoring and assessment*, *196*(3), 269.

Onyekwelu, J., Agbelade, A., Tolorunju, M., Lawal, A., Stimm, B., and Mosandl, R. (2022): Conservation potentials, tree species diversity, distribution, and structure of sacred groves in southwestern Nigeria. *Journal of Tropical Forest Science*, *34*(3), 334–346.

Onyekwelu, J.C (2004). Aboveground biomass production and biomass equations for even-aged Gmelina arborea (ROXB) plantations in southwestern Nigeria. *Biomass and Bioenergy*, 26(1), 39-46.

Onyekwelu, J.C (2007). Growth, biomass yield and biomass functions for plantation-grown *Naucleadiderrichii* in humid tropical rainforest zone of Nigeria. *Bioresource Technology,* 98, 2679 – 2687

Onyekwelu, J.C, Mosandl, R. and Stimm, B. (2008). Tree species diversity and soil status of primary and degraded tropical rainforest ecosystems in south-western Nigeria. *Journal of Tropical Forest Science, 20, 193-204.*

Onyekwelu, J.C. (2021). Can the fear of the gods sustain biodiversity conservation in sacred groves? *Academia Letters*, Article 635; 11pp.

Onyekwelu, J.C. and Olusola, J.A. (2014). Role of the sacred grove in in-situ biodiversity conservation in rainforest zone of south-western Nigeria, *Journal of Tropical Science,* 26(1), 5-15.

Onyekwelu, J.C., A. Lawal, Mosandl, R., Stimm, B.R. and Agbelade, D.A. (2020). Understory species diversity, regeneration, and recruitment potential of sacred groves in southwest Nigeria. *Tropical Ecology* 62, 427–442 (2021).

Opeyemi, A. O., Adewunmi, B. I., and Oluwaseyi, A. I. (2020). Physical and Chemical Properties of Soils in Gambari Forest Reserve Near Ibadan, Southwestern Nigeria., *Journal of Bioresource Management, 7* (2). DOI: https://doi.org/10.35691/JBM.0202.0132.

Osawaru, M.E., Ogwu, M.C. and Ahana, C.M. (2013). Current Status of Plant Diversity and Conservation In Nigeria. *Nigerian Journal of Life Sciences*. 3 (1): 1-25.

Osemeobo, G.J. (2013). Back to tradition: taboos in bio-conservation in Nigeria. *International Journal of Agricultural Sciences* 3 (1): 351-356.

Osman, A. I., Fawzy, S., Farghali, M., El-Azazy, M., Elgarahy, A. M., Fahim, R. A., Abdel Maksoud, M. I. A., Ajlan, A. A., Yousry, M., Saleem, Y., and Rooney, D. W. (2022). Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: *A review. Environmental Chemistry Letters,* 20, 2385–2485.https://doi.org/10.1007/s10311-022-01424-x

Ounban, W., Puangchit, L. and Diloksumpun, S. (2016). Development of general biomass allometric equations for *Tectona grandis Linn.f.* and *Eucalyptus camaldulensis Dehnh*. plantations in Thailand. *Agriculture and Natural Resources*, 50 (1): 48-53.

Ouyang, S., Xiang, W., Wang, X., Xiao, W., Chen, L., Li, S., Sun, H., Deng, X., Forrester, D. I., Zeng, L., Lei, P., Lei, X., Gou, M., and Peng, C. (2019). Effects of stand age, richness and density on productivity in subtropical forests in China. *Journal of Ecology*, *107*(5), 2266-2277. https://doi.org/10.1111/1365-2745.13194

Oyelowo, O. J., and Sulaiman, O. N. (2021). Physiochemical characteristics of soils in two sacred groves of Southwestern, Nigeria. *International Journal of Environmental Science;* 143-154.

Özçelik, R., Gül, A. U., Merganič, J., and Merganičová, K. (2008). Tree species diversity and its relationship to stand parameters and geomorphology features in the eastern Black Sea region forests of Turkey. *Journal of Environmental Biology*, 29(3), 291–298.

Page, S.E., Siegert, F., Rieley, J.O., Boehm Hans-Dieter, V., Jaya, A. (2002). The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, 420: 61-65.

Pan, Y.; Birdsey, R.A.; Fang, J.; Houghton, R.; Kauppi, P.E.; Kurz, W.A.; Phillips, O.L.; Shvidenko, A.; Lewis, S.L.; Canadell, J.G.; Philippe Ciais, Robert B Jackson, Stephen W Pacala, A David McGuire, Shilong Piao, Aapo Rautiainen, Stephen Sitch, Daniel Hayes (2011). A large and persistent carbon sink in the world's forests. *Science*, 333, 988–993.

Pang, D. B., Cui, M., Liu, Y. G., Wang, G. Z., Cao, J. H., Wang, X. R., Dan, X., and Zhou, J. (2019). Responses of soil-labile organic carbon fractions and stocks to different vegetation restoration strategies in degraded karst ecosystems in southwest China. *Ecol. Eng.* 138, 391-402.

Paudel, S., and Sah, J. P. (2015). Effects of different management practices on stand composition and species diversity in subtropical forests in Nepal: Implications of community participation in biodiversity conservation. *Journal of Sustainable Forestry*, 34(6), 738–760.

Pearson, R.G., Raxworthy, C.J, Nakamura, M., Peterson, A.T (2007) Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. *Journal of Biogeo*. 34: 102- 117.

Pérez-Cruzado, C., Sande, B., Omil, B., Rovira, P., Martin-Pastor, M., Barros, N., Salgado, J., and Merino, A. (2014). Organic matter properties in soils afforested with *Pinus radiata*. Plant and Soil, 374, 381-398. https://doi.org/10.1007/s11104-013-1896-5

Peter, F. and Martina, Z. (2019). Biodiversity Indices, Editor(s): Brian Fath, *Encyclopedia of Ecology (Second Edition), Elsevier*:337-346.

Phillip, M.S. (1994). Measuring Trees and Forests. 2nd edition. CAB International, Wallingford, 356 pp.

Picard N., Saint-André L., Henry M. (2012). Manual for building tree volume and biomass allometric equations: from field measurement to prediction. Food and Agricultural

Organization of the United Nations, Rome, and Centre de Coopération Internationaleen Recherche Agronomique pour le Développement, Montpellier

Picchio, R., Tavankar, F., Rafie, H., Rezae Kivi, A., Jourgholami, M., and Lo Monaco, A. (2022). Carbon storage in biomass and soil after mountain landscape restoration: *Pinus nigra* and *Picea abies* plantations in the Hyrcanian region. *Land,* 11(3), 422

Pielou, E. C. (1969). An Introduction to Mathematical Ecology. New York, NY, USA: Wiley. 286p.

Poorter, L., van der Sande, M. T., Thompson, J., Arets, E. J., Alarcón, A., Álvarez-Sánchez, J., Ascarrunz, N., Balvanera, P., Barajas-Guzmán, G., Boit, A., Bongers, F., Carvalho, F. A., Casanoves, F., Cornejo-Tenorio, G., Costa, F. R. C., de Castilho, C. V., Duivenvoorden, J. F., Dutrieux, L. P., Enquist, B. J., Fernández-Méndez, F., Finegan, B., Gormley, L. H. L., Healey, J. R., Hoosbeek, M. R., Ibarra-Manríquez, G., Junqueira, A. B., Levis, C., Licona, J. C., Lisboa, L. S., Magnusson, W. E., Martínez-Ramos, M., Martínez-Yrizar, A., Martorano, L. G., Maskell, L. C., Mazzei, L., Meave, J. A., Mora, F., Muñoz, R., Nytch, C., Pansonato, M. P., Parr, T. W., Paz, H., Pérez-García, E. A., Rentería, L. Y., Rodríguez-Velazquez, J., Rozendaal, D. M. A., Ruschel, A. R., Sakschewski, B., Salgado-Negret, B., Schietti, J., Simões, M., Sinclair, F. L., Souza, P. F., Souza, F. C., Stropp, J., ter Steege, H., Swenson, N. G., Thonicke, K., Toledo, M., Uriarte, M., van der Hout, P., Walker, P., Zamora, N., and Peña-Claros, M. (2015). Diversity enhances carbon storage in tropical forests. *Global Ecology and Biogeography,* 24, 1314–1328.

Popo-Ola, F., Aiyeloja, A. A., & Adedeji, G. (2012). Sustaining carbon sink potentials in tropical forest. Journal of Agriculture and Social Research, 12, 64-74.

Popoola, V. D., and Ushi, C. (2023). Volume models for Tectona grandis (Linn F.) in Mbavara Forest Reserve, Benue State, Nigeria. *Journal of Research in Forestry, Wildlife and Environment*, 15(3): 89-99.

Post, W.M. and Kwon, K.C. (2000). Soil Carbon Sequestration and Land-Use Change: Processes and Potential. *Global Change Biology*, 6, 317-327.

Poudyal, B. H., Maraseni, T., and Cockfield, G. (2019). Impacts of forest management on tree species richness and composition: Assessment of forest management regimes in Tarai landscape, Nepal. *Applied Geography*, 111; 102078.

Prabhat, S. (2010). *Difference Between AIC and BIC.* Difference Between Similar Terms and Objects. http.//www.differencebetween.net/miscellaneous/difference-between-aic-and-bic/.

Pradhan, M.B; Awasthi, D.K. and Bajracharya, M.R. (2012). Soil organic carbon stocks under different forest types in Pokharekhola sub-watershed: a case study from Dhading district of Nepal; *WIT Transactions on Ecology and The Environment*, Vol 157: 535-546.

Pyron, M. (2010): Characterizing Communities. *Nature Education Knowledge;* 3 (10):39.

Qianwen, E., Arif, M., Zhongxun, Y., Jie, Z., Xinrui, H., Dongdong, D., Fan, Y., and Changxiao, L. (2022). Plant species composition and diversity along successional gradients in arid and semi-arid regions of China. *Forest Ecology and Management,* 524, 120542.

Rahman, S., and Chima, C. D. (2018). Food Energy Availability from Agriculture at the Farm-Level in Southeastern Nigeria: Level, Composition and Determinants. *Agriculture,* 8(5), 69. https://doi.org/10.3390/agriculture8050069

Rana, E. B. (2008). REDD+ an option for Carbon Finance and Impact on Livelihoods of Forest Users in Nepal-a case study of Nepal's Community Forestry. An MSc thesis submitted to the School of Forest Science and Resource Management in University of Munich, Germany.

Ratkowsky, D.A., (1990). Handbook of nonlinear regression. Marcel Dekker, Inc., New York.

Räty, J., Varvia, P., Korhonen, L., Savolainen, P., Maltamo, M., and Packalen, P. (2022). A comparison of linear-mode and single-photon airborne LiDAR in species-specific forest inventories. IEEE *Transactions on Geoscience and Remote Sensing,* 60, 1-14. doi: 10.1109/TGRS.2021.3060670.

Ravindranath, N.H and Ostwald, M (2008): Carbon Inventory Methods: Handbook for Greenhouse Gas Inventory, Carbon Mitigation and Roundwood Production Projects. *Springer Science + Business Media* B.V 113-14.

Rawat, M., Vasistha, H. B., Manhas, R. K., and Negi, M. (2011). Sacred Forest of Kunjapuri Siddhapeeth, Uttarakhand, India. *Tropical Ecology*, 52(2), 219–221.

Ribeiro a, S.C, Lutz Fehrmann, Carlos Pedro Boechat Soares, Laércio Antônio Gonçalves Jacovine, Christoph Kleinn and Ricardo de Oliveira Gaspar (2011). Above- and belowground biomass in a Brazilian Cerrado, *Forest Ecology and Management,* 262 (3).491-499

Ribeiro, R.P. and Moniz, N. (2020): Imbalanced regression and extreme value prediction. *Mach Learn* 109, 1803–1835.

Riebeek, H. (2011). The Carbon Cycle. Introduction, The Slow Carbon Cycle, The Fast Carbon Cycle, Changes in the Carbon Cycle, Effects of Changing the Carbon Cycle, Studying the Carbon Cycle. 26 pg. https://earthobservatory.nasa.gov/features/CarbonCycle Archived from the original on 5 March 2016. Retrieved 5 April 2018.

Roy, D.P., Wulder, A.M., Loveland, R.T., Woodcock C.E., Allen, G.R., Anderson, C.M., Helder, D., Irons, R.J., Johnson, M.D., Kennedy, R., Scambos, A.T., Schaaf, B.C., Schott, R.J., Sheng, Y., Vermote, E.F., Belward, S.A., Bindschadler, R., Cohen, B.W., Gao, F.W., Hipple, D.J., Hostert, P., Huntington, J., Justice, O.C., Kilic, A., Kovalskyy, V., Z.P. Lee, L. Lymburner, J.G. Masek, J. McCorkel, Y. Shuai, R. Trezza, J. Vogelmann, R.H. Wynne, Z. Zhu (2014). Landsat-8: Science and product vision for terrestrial global change research; *Remote Sensing of Environment;* 145: 154-172.

Rudnick, D., Ryan, S., Beier, P., Cushman, S., Dieffenbach, F., Epps, C., Gerber, L., Hartter, J., Jenness, J., Kintsch, J., Merenlender, A., Perkl, R., Preziosi, D., andTrombulak, S. (2012). The Role of Landscape Connectivity in Planning and Implementing Conservation and Restoration Priorities. *Issues in Ecology*, 16, 1-20.

Saatchi, S. S., Harris, N. L., Brown, S., Lefsky, M., Mitchard, E. T., Salas, W., Zutta, B. R., Buermann, W., Lewis, S. L., Hagen, S., Petrova, S., White, L., Silman, M., and Morel, A. (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences*, *108*(24), 9899-9904. https://doi.org/10.1073/pnas.1019576108.

Sabina Cerruto Ribeiro, Lutz Fehrmann, Carlos Pedro Boechat Soares, Laércio Antônio Gonçalves Jacovine, Christoph Kleinn, Ricardo de Oliveira Gaspar (2011). Above- and belowground biomass in a Brazilian Cerrado; *Forest Ecology and Management* 262 (2011) 491–499.

Sabine, C.L. and Feely, R.A (2003). Carbon Dioxide, Editor(s): James R. Holton, Encyclopedia of Atmospheric Sciences, Academic Press: 335-343.

Sahu, S. C., Kumar, M., and Ravindranath, N. H. (2016). Carbon stocks in natural and planted mangrove forests of Mahanadi Mangrove Wetland, East Coast of India. *Current Science*, 110(12), 2253–2260. 10.18520/cs/v110/i12/2253-2260.

Salami, K. D., Shuaibu, R. B., Adekunle, V.A. J, and Ogunsola, J. D. (2021): Comparative Analysis of Density, Diversity and Similarity of Forest Tree Species in Three Selected States of Northern Nigeria; *Journal of Research in Forestry, Wildlife and Environment;* 13 (3):111-124.

Salas-Macías, A.C., Orihuela, A.C.J. and Abad, I.S. (2017). Estimation of above-ground live biomass and carbon stocks in different plant formations and the soil of dry forests of the Ecuadorian coast. *Food and Energy Security* 6(4): 1-7.

Sanders, N.J. and C. Rahbek (2012). The patterns and causes of elevational diversity gradients. *Ecography,* 35: 1–3.

Santoro, M., Cartus, O., Fransson, J. E., and Wegmüller, U. (2018). Complementarity of X-, C-, and L-band SAR Backscatter Observations to Retrieve Forest Stem Volume in Boreal Forest. *Remote Sensing*, 11(13), 1563. https://doi.org/10.3390/rs11131563

Santos, F., Abney, R., Barnes, M., Bogie, N., Ghezzehei, T. A., Jin, L., Moreland, K., Sulman, B. N., and Berhe, A. A. (2019). The role of the physical properties of the soil in determining biogeochemical responses to soil warming. *Ecosystem Consequences of Soil Warming*, 209-244. https://doi.org/10.1016/B978-0-12-813493-1.00010-7

Scharlemann, J. P., Tanner, E. V., Hiederer, R., and Kapos, V. (2014). Global soil carbon: understanding and managing the largest terrestrial carbon pool. *Carbon Management, 5(1), 81–91. https://doi.org/10.4155/cmt.13.77*

Schweizer, S.A., Mueller, C.W., Höschen, C.; Ivanov, P. and Kögel-Knabner, I. (2021). The role of clay content and mineral surface area for soil organic carbon storage in an arable toposequence. *Biogeochemistry* 156, 401–420. https://doi.org/10.1007/s10533-021-00850-3

Segura, M., Kanninen, M., (2005). Allometric models for tree volume and total aboveground biomass in a tropical humid forest in Costa Rica.*Biotropica* 37, 2–8.

Selassie, Y. G., Anemut, F., and Addisu, S. (2015). The effects of land use types, management practices and slope classes on selected soil physico-chemical properties in Zikre watershed, North-Western Ethiopia. *Environmental Systems Research*, *4*(1), 1-7.

Senbeta, F., and Denich, M. (2006). Effects of wild coffee management on species diversity in the Afromontane rainforest of Ethiopia. *Forest Ecology and Management;* 232: 68-74.

Senwo, Z. (2021). What is Soil Organic Carbon (SOC)? Open Access News Agriculture News. https://www.openaccessgovernment.org/what-is-soil-organic-carbon-soc/120702/.

Sevda Turkis, and Emire Elma (2018). Tree Species Diversity and Importance Value of Different Forest Communities Inyenice Forests. *Fresenius Environmental Bulletin*; 27 (6): 4440-4447.

Shanin, V., Komarov, A. and Mäkipää, R. (2014). Tree species composition affects productivity and carbon dynamics of different site types in boreal forests. *Eur J Forest Res* 133, 273–286. https://doi.org/10.1007/s10342-013-0759-1

Shapkota, J., and Kafle, G. (2021). Variation in Soil Organic Carbon under Different Forest Types in Shivapuri Nagarjun National Park, Nepal; *HindawiScientifica;* Volume 2021: 9pg. 1382687.

Shen Y, Yu S, Lian J, Shen H, Cao H, Lu H, Ye W. (2016). Tree aboveground carbon storage correlates with environmental gradients and functional diversity in a tropical forest. *Science Rep*.; 6:1–10.

Shirima, D.D., Ørjan Totlanda, Pantaleo K.T. Munishib, Stein R. Moe (2015). Relationships between tree species richness, evenness and aboveground carbon storage in montane forests and miombo woodlands of Tanzania. *Basic and Applied Ecology,* 16 (2015) 239–249.

Shiva Pokhrel, Chungla Sherpa (2020). "Analyzing the Relationship, Distribution of Tree Species Diversity, and Above-Ground Biomass on the Chitwan-Annapurna Landscape in Nepal", *International Journal of Forestry Research*, vol. 2020, Article ID 2789753, 10 pages.

Shrestha, L. J.; Devkota, M. P. and Sharma, B. K. (2016): Are Sacred Groves of Kathmandu Valley Efficient in Sequestering Carbon? *Journal of Botany;* Volume 2016, Article ID 7695154, 6 pages; Hindawi Publishing Corporation.

Shuaibu, R. B. and Ogunsola, J.D. (2018). Assessing the Diversity of Tree Species in Natural Forests within Dutsin-Ma Local Government Area, Katsina State, Nigeria; a Publication of the School of Agriculture and Agricultural Technology, Federal University of Technology, Yola-Nigeria. *Nigeria Journal of Tropical Agriculture,* 18: 155-162.

Shukla, K.M., Lal, R., Ebinger M. (2006). Determining soil quality indicators by factor analysis. *Soil and Tillage Research*, 87 (2): 194-204.

Simard, S.W., Perry, D.A., Jones, M.D., Myrold, D.D., Durall, D.M., and Molina, R. (1997) Net transfer of carbon between ectomycorrhizal tree species in the field. *Nature,* 388: 579–582.

Simler-Williamson, A. B., Metz, M. R., Frangioso, K. M., and Rizzo, D. M. (2021). Wildfire alters the disturbance impacts of an emerging forest disease via changes to host occurrence and demographic structure. *Journal of Ecology*, *109*(2), 676-691.

Šímová, I., & Storch, D. (2016). The enigma of terrestrial primary productivity: Measurements, models, scales and the diversity-productivity relationship. *Ecography,* 40. doi: 10.1111/ecog.02482.

Singh, S., Youssouf, M., Malik, Z. A., and Bussmann, R. W. (2017). Sacred Groves: Myths, Beliefs, and Biodiversity Conservation—A Case Study from Western Himalaya, India. *International Journal of Ecology; 2017: 1-12.*

Sinthumule NI (2024). Traditional taboos: informal and invisible protection of remaining patches of forest in Vhembe District in Limpopo, South Africa. *Front. Conserv. Sci.* 5:1423712. doi: 10.3389/fcosc.2024.1423712

Skog, E.K; Pingoud, K and Smith, E.J *(*2004). A Method Countries Can Use to Estimate Changes in Carbon Stored in Harvested Wood Products and the Uncertainty of Such Estimates; *Environmental Management;* 33 (Supplement 1): S65–S73; Springer-Verlag New York, LLC.

Song, Z., and Liu, Y. (2019). Fire Intensity Affects the Relationship between Species Diversity and the Utilization Stability of Dominant Species. *Forests,* 10, 207.

Spellerberg, I.F. (1991). monitoring Ecological change. *New York USA, Cambridge University. 112-140pp.*

Stoll, P. and Bergius, E. (2005). Pattern and process: Competition causes the regular spacing of individuals within plant populations. *Journal of Ecology*. 93. 395-403.

Subashree K, Dar JA, Javid Ahmad Dar a, Subbiah Karuppusamy b, Somaiah Sundarapandian (2020). Plant diversity, structure, and regeneration potential in tropical forests of Western Ghats, India. *Acta Ecologica Sinica,* 41: 259-284.

Sundarapandian, S.M, Amritha, S., Gowsalya, L., Kayathri, P., Thamizharasi, M., Dar, J.A., Srinivas, K., Gandhi, D.S, Subashree, K. (2016). Soil organic carbon stocks in different land uses in Pondicherry University campus, Puducherry, India. *Trop Plant Res* 3:10–17

Sundarapandian, S.M., Dar, J.A., Ghandi, D.S., Kantipudi, S., Subashree, K. (2013b). Estimation of biomass and carbon stocks in tropical dryforests in Sivagangai District, Tamil Nadu, India. *Int J Environ SciEng Re*s 4:66–76.

Tee F. C., Agbidye, F. S. and Ogwuche, J. A. (2014a). Indigenous Forest Conservation Practices in Benue State, Nigeria*, Journal of Agriculture, Forestry and the Social Sciences* (JOAFSS), 12 (1). 182-194.

Tee, T.N. and Ageende A. (2005). Community woodlot production as a sustainable forest management option in Benue State, Nigeria. In: Popoola, L and Oni, P.I. (eds.). Sustainable Forest Management in Nigeria- lessons and prospects. Proceeding of the 30th Annual FAN Conference held at Kaduna. Pp 371-388.

Tee, T.N.; Agbidye, F.S. and Tee, F.C. (2014b). Utilization of trees under indigenous conservation in Benue State, Nigeria. *African Journal of Agriculture, Technology and Environment*, 3(1): 7-19.

Tenzin, J., and Hasenauer, H. (2016). Tree species composition and diversity in relation to anthropogenic disturbances in broad-leaved forests of Bhutan. *International Journal of Biodiversity Science, Ecosystem Services and Management*, 12(4), 274–290. https://doi.org/10.1080/21513732.2016.1206038

Teobaldelli, N., Somogyi, Z. Migliavacca, M. and Usoltev, V. (2009). Generalized functions of biomass expansion factors for conifers and broadleaved by stand age, growing stock and site index, *Forest Ecology and Management,* 257. 1004-1013.

Thammanu, S., Marod, D., Han, H., Bhusal, N., Asanok, L., Ketdee, P., ... Chung, J. (2021). The influence of environmental factors on species composition and distribution in a community forest in Northern Thailand. *Journal of Forest Research,* 32(2), 649–662.

Thompson, J. N, Thompson, Michael B. and Gates, David M. (2023). Biosphere. Encyclopedia Britannica. https://www.britannica.com/science/biosphere

Tilman D, Reich PB, Knops J, Wedin D, Mielke T, Lehman C. (2001). Diversity and productivity in a long-term grassland experiment. Science.;294 (5543):843-5.

Timilsina, N., Staudhammer, C. L., Escobedo, F. J., and Lawrence, A. (2014). Tree biomass, wood waste yield, and carbon storage changes in an urban forest. *Landscape and Urban Planning*, 127, 18-27. https://doi.org/10.1016/j.landurbplan.2014.04.003

Tucker, Caroline M.; Cadotte, Marc W.; Carvalho, Silvia B.; Davies, T. Jonathan; Ferrier, Simon; Fritz, Susanne A.; Grenyer, Rich; Helmus, Matthew R.; Jin, Lanna S. (May 2017). "A guide to phylogenetic metrics for conservation, community ecology and macroecology: A guide to phylogenetic metrics for ecology". *Biological Reviews*. 92 (2): 698–715.

Turyahabwe N, Tweheyo M. (2010). Does forest tenure influence forest vegetation characteristics? A comparative analysis of private, local and central government forest reserves in Central Uganda. *The International Forestry Review*, 12(4).320-338.

Udawatta, R. P., Gantzer, C. J., Reinbott, T. M., Wright, R. L., Robert, P. A., II, and Wehtje, W. (2020). Influence of species composition and management on biomass production in Missouri. *Agricultur*e, 10(3), 75.

Udofia, S.I., Owoh, P.W., Attah, V.I. and Thomas, A.D. (2014). Assessment of plant species composition in Ayan Nsit sacred forest of Akwa Ibom State, Nigeria. *Nigerian Journal of Agriculture, Food and Environment* 10(2): 34-37.

UNH (University of New Hampshire) (2008): GLOBE Carbon Cycle; 7pp. (2015): *Pools, Fluxes and a word about units* [Online]. Diagram. http://globecarboncycle.unh.edu/CarbonPoolsFluxes.shtml Durham, NH 0382

United Nations Department of Economic and Social Affairs (UNDESA) (2022). https://population.un.org/wpp/…..World Population Prospects 2022

United Nations Development Programme (UNDP) (2009): Human Development Report Nigeria. 2008 – 2009, Achieving Growth with Equity; Published for the United Nations Development Programme (UNDP), Nigeria: 188 pg. https://hdr.undp.org/system/files/documents/nhdrnigeria2008-2009pdf.pdf

United Nations Framework Convention on Climate Change (UNFCCC) (2010). Framework Convention on Climate Change report; Ad Hoc Working Group on Long-term Cooperative Action under the Convention Twelfth session Tianjin, 4–9 October 2010 Item X of the provisional agenda, Distr.: General 13 August 2010.

chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://unfccc.int/resource/docs/2010/awglca12/eng/14.pdf

Van der Heijden, M.G.A., Klironomos, J.N., Ursic, M., Moutoglis, P., Streitwolf-Engel, R., Boller, T., Wiemken, A., and Sanders, I.R. (1998): Mycorrhizal fungal diversity determines plant biodiversity, ecosystem variability and productivity; *Nature,* 396: 69–72.

Van Reeuwijk, L. P. (1992). Procedures for soil analysis, 3rd Edition, *International Soil Reference and Information Center (ISRIC)* 34p.

Vance-Chalcraft, H. D., Willig, M. R., Cox, S. B., Lugo, A. E., and Scatena, F. N. (2010). Relationship between aboveground biomass and multiple measures of biodiversity in subtropical forest of Puerto Rico. *Biotropica*, *42*, 290–299.

Vanclay, J.K. (1994). Modelling Forest Growth and Yield, Applications to Mixed Tropical Forests, First edition, Royal Veterinary and Agricultural University Copenhagen, published by CAB International, Wallingford UK as ISBN 0 85198 913 6, 4. 223-250.

Vanlauwe, B., Amede, T., Bationo, A., Breman, H., Cardinael, R., Couëdel, A., Chivenge, P., Corbeels, M., Dobermann, A., Falconnier, G., Fatunbi, O., Giller, K., Harawa, R., Merckx, R., Palm, C., Powlson, D., Rusinamhodzi, L., Six, J., Singh, U., and Groot, R. (2023). Fertilizer and soil health in Africa: The role of fertilizer in building soil health to sustain farming and address climate change. *Report by International Fertilizer Development Center; 75pg.*

Vashum KT, and Jayakumar S (2012). Methods to Estimate Above-Ground Biomass and Carbon Stock in Natural Forests - A Review. *J Ecosyst Ecogr.,* 2.116.

Vendrapati, S. R., Boyina, R., and Rao, P. (2015). Carbon sequestration potential of tropical deciduous forests of Nallamalais, India. *Asian Journal of Plant Science and Research*, 2015, 5(3): 24-33.

Verma, Pragati & Ghosh, P. (2022). An analysis of forest management practices as a carbon mitigation strategy. International Journal of Ecology and Environmental Sciences, 3(2). 235-240.

Verwijst T, Telenius B (1999). Biomass estimation procedures in short rotation forestry. *For Ecol Manage,* 121,137–146. doi.https://doi.org/10.1016/S0378-1127(98)00562-3

Vorster, A. G., Evangelista, P. H., Stovall, A. E. L., and Ex, S. (2020). Variability and uncertainty in forest biomass estimates from the tree to landscape scale: the role of allometric equations. *Carbon Balance Manage* 15, 8: 1-20. https://doi.org/10.1186/s13021-020-00143-6.

Vuyiya, E., Konje, M., Tsingalia, H., Obiet, L., Kigen, C., Wamalwa, S., and Nyongesa, H. (2014). The impacts of human activities on tree species richness and diversity in Kakamega Forest, Western Kenya; *International Journal of Biodiversity and Conservation*; 6: 428-435.

Wakawa, L.D (2016). Biomass Estimation in Forest Ecosystems - A Review. *Journal of Research in Forestry, Wildlife and Environment,* 8(2):126-144.

Walkley, A. J. and Black, I. A. (1934). Estimation of Soil Organic Carbon by chromic acid titration method. *Soil Science* 37. 29-38.

Wang, B. and Wei, W. and Liu, C. and You, W. and Niu, X. and Man, R.Z. (2013). Biomass and carbon stock in moso bamboo forests in subtropical China: Characteristics and implications. *Journal of Tropical Forest Science*. 25. 137-148.

Wang, B., Xu, G., Li, Z., Cheng, Y., Gu, F., Xu, M., and Zhang, Y. (2024). Carbon pools in forest systems and new estimation based on an investigation of carbon sequestration. *Journal of Environmental Management,* 360, 121124. https://doi.org/10.1016/j.jenvman.2024.121124

Wang, Q., Wang, S., Xu, G., Fan, B., (2010). Conversion of secondary broadleaved forest into Chinese fir plantation alters litter production and potential nutrient returns. *Plant Ecol*. 209 (2), 269–278.

Wang, S.G. (2006). Model of China's Public Policy Agenda Setting. Chinese Social Science, No. 5, 86-99. DOI: 10.4236/ojps.2021.113035

Wang, Y.; Pyörälä, J.; Liang, X.; Lehtomäki, M.; Kukko, A.; Yu, X.; Kaartinen, H.; Hyyppä, J. In Situ (2019). Biomass Estimation at Tree and Plot Levels: What Did Data Record and What Did Algorithms Derive from Terrestrial and Aerial Point Clouds in Boreal Forest. *Remote Sensing Environ., 232*, 111309: 1-15.

Wang, Zheng and Hassan, Mahmood and Nadeem, Faisal and Wu, Liangquanand Zhang, Fusuoand Li, Xuexian. (2020). Magnesium Fertilization Improves Crop Yield in Most Production Systems: A Meta-Analysis. *Frontiers in Plant Science*. 10. 1727. 10.3389/fpls.2019.01727.

Wanlong Sun and Xuehua Liu (2020). Review on carbon storage estimation of forest ecosystem and applications in China; *Forest Ecosystems;* 7:4; 14pg.

Warneck, P. (2003). In-cloud chemistry opens a pathway to the formation of oxalic acid in the marine atmosphere. *Atmospheric Environment*, 37(17), 2423-2427. https://doi.org/10.1016/S1352-2310(03)00136-5

Wassihun, A. N., Hussin, Y. A., Van Leeuwen, L. M., and Latif, Z. A. (2019). Effect of forest stand density on the estimation of above ground biomass/carbon stock using airborne and terrestrial LIDAR derived tree parameters in tropical rain forest, Malaysia. *Environmental Systems Research,* 8(1), 1-15. https://doi.org/10.1186/s40068-019-0155-z

Watanabe, Y., Owusu-Sekyere, E., Masunaga, T., Buri, M. M., Oladele, O. I., and Wakatsuki, T. (2010). Teak (*Tectona grandis*) growth as influenced by soil physicochemical properties and other site conditions in the Ashanti region, Ghana. *Journal of Food, Agriculture and Environment*, 8(2), 1040-1045.

Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J., and Dokken, D.J. (eds) (2000). Land Use, Land-Use Change, and Forestry. Intergovernmental Panel on Climate Change (IPCC), Special report. Cambridge University Press, UK. 375 pp.

Wei, X., Li, Q., Liu, Y., Liu, S., Guo, X., Zhang, L., Niu, D., and Zhang, W. (2013). Restoring ecosystem carbon sequestration through afforestation: A sub-tropic restoration case study. *Forest Ecology and Management*, 300, 60-67. https://doi.org/10.1016/j.foreco.2012.06.018

Weiskopf, S. R., Rubenstein, M. A., Crozier, L. G., Gaichas, S., Griffis, R., Halofsky, J. E., ... and Whyte, K. P. (2020). Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of The Total Environment,* 733, 137782. ISSN: 0048-9697. DOI: 10.1016/j.scitotenv.2020.137782.

White, P., and Brown, P. (2010). Plant nutrition for sustainable development and global health. *Annals of Botany*, 105, 1073-1080. doi: 10.1093/aob/mcq085.

Whitlock, C., Colombaroli, D., Conedera, M., and Tinner, W. (2017). Land-use history as a guide for forest conservation and management. *The Journal of the Society for Conservation Biology*, 32 (1): 84–97..https://doi.org/10.1111/cobi.12960.

Wiersum, K.F. (2004). Social And Collaborative Forestry | Social and Community Forestry, Editor(s): Jeffery Burley, *Encyclopedia of Forest Sciences, Elsevier*: 1136-1143.

Wilkes, P., Disney, M., Vicari, V.B., Calders, K and Burt, A. (2018): Estimating urban above-ground biomass with multi-scale LiDAR; *Carbon Balance Manage (2018) 13:10.*

William, D., F, and Craig, B. S. (2020). Chapter 1 – Introduction- Reaching Net Zero, What are the greenhouse gases? *Elsevier,* 2020, Pages 1-8, ISBN 9780128233665, https://doi.org/10.1016/B978-0-12-823366-5.00001-4.

Xiang, W., Lei, X., Zhang, X., (2016). Modelling tree recruitment in relation to climate and competition in semi-natural Larix-Picea-Abies forests in northeast China. *Forest Ecology and Management,* 382: 100-109.

Yager, O.G.; Alarape, A.A. and Onuwa, A.O (2018). Preliminary Assessment of Fauna Species Diversity in IpinuIgede Community Range Forest in Oju Local Government of Benue State, Nigeria. *Asian Journal of Biology; 5*(4): 1-11.

Yang, L. Q., Luo, P., Wen, L., and Li, D. J. (2016). Soil organic carbon accumulation during post-agricultural succession in a karst area, southwest China. *Sci. Rep.* 6:37118. doi: 10.1038/srep37118.

Yang, Y. S., Guo, J. F., Chen, G. S., Xie, J. S., Cai, L. P., and Lin, P. (2004). Litterfall, nutrient return, and leaf-litter decomposition in four plantations compared with a natural forest in subtropical China. *Annals of Forest Science*, *61*(5), 465-476.

Yanow, K. (2018). Remote Sensing Platforms. The Geographic Information Science and Technology Body of Knowledge.

Yudina, A., andKuzyakov, Y. (2023). Dual nature of soil structure: The unity of aggregates and pores. *Geoderma*, *434*, 116478.

Zankan, J. A. A, Endas, L., Abubakar, Y. M. and Yakubu, I. B (2019). Tree Species Density and Diversity in Jemaa Local Government Area of Kaduna State, Nigeria; *FUDMA Journal of Science (FJS).* 3(2): 263.

Zeng Z, Chen A, Piao S, Rabin S, Shen Z. (2014). Environmental determinants of tropical forest and savanna distribution. a quantitative model evaluation and its implication. *Journal of Geophysical Research. Biogeosciences,* 119, 1432–1445.

Zhang, S., Zhang, X., Zhang, S., Zhang, J., Li, G., He, Y., Shao, J., Zhang, S., Yang, H., and Chen, H. (2023). Biomass-derived functional carbon material for CO2 adsorption and electrochemical CO2 reduction reaction. *Carbon Capture Science and Technology*, 9, 100135. ISSN: 2772-6568. DOI: 10.1016/j.ccst.2023.100135.

Zhang, X., Zhang, X., Han, H., Shi, Z., and Yang, X. (2019). Biomass Accumulation and Carbon Sequestration in an Age-Sequence of Mongolian Pine Plantations in Horqin Sandy Land, China. *Forests*, *10*(2), 197. MDPI AG. Retrieved from

Zhang, Y. and Chen, H. (2015). Individual size inequality links forest diversity and above-ground biomass. *Journal of Ecology*, 103(5):1245–1252.

Zomer, R.J., Bossio, D.A., Sommer, R. (2017). Global Sequestration Potential of Increased Organic Carbon in Cropland Soils. *Sci Rep* 7, 15554 (2017).