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Original Article

Assessment of Carbon Sequestration in Borgu Sector of Kainji Lake National Park, North-Central Nigeria

Adesoji Akinwumi Adeyemi, Folasade Esther Aderibigbe

Department of Forest Resources Management, University of Ilorin, Faculty of Agriculture, Ilorin, Nigeria

ABSTRACT

Trees species-based carbon-stock estimates are rare in Nigeria. Therefore, we investigated individual trees' abilities using non-destructive approach with systematic sampling technique. One hundred circular plots were laid, using pre-classified Landsat-OLI/TC image of Borgu Sector. Plot centres were located and marked with global positioning system receiver. The main plots with 12.61 m radius (500 m^2) were subdivided into subplots of 5.64 m radius (100 m^2). Trees with diameter at breast height (Dbh) ≥10 cm were measured in the main plots, while trees with ≥5 but <10 cm Dbh were considered in the subplots. Species identification and measurements were executed. Core samples were collected at breast height using 5 mm increment borer. Core samples were oven-dried at 70°C to constant weights. Wood densities were then calculated as oven-dried weights/fresh volumes. Above-ground carbon were determined as 50%-biomass. Soil samples were diagonally collected at three points within sample plots at two depths, using core sampler and soil auger for 600 samples. Samples were air-dried, ground and sieved through a 2 mm sieve. Core sampler and rings were used for measuring bulk density. Samples were oven-dried for 24 hours at 105°C. Soil organic matter was determined by Fe_2SO_4 titration of an acid-dichromate digestion, and organic carbon concentration was calculated. Tree carbon data were analyzed using allometric equations involving wood density, Dbh and tree-height and ANOVA. Thirty-five tree species in 16 families were encountered. *Detarium microcarpum* was the most frequently occurring (18.8%). Tree species richness, diversity and importance value indices were 2.852, 4.779, and 41.76 ± 35.41, respectively. *Vitellaria paradoxa* and *Afzelia africana* were the only vulnerable species identified. Trees with larger-Dbh sequestered more carbon. Consequently, *Adansonia digitata* with a mean Dbh of 111.4 ± 0.00 cm sequestered the highest amount (2.8 tons/ha), which were significantly different from others ($p < .05$). *Securidaca longipendiculata* had the least carbon stock (0.001 ton/ha). Meanwhile, soil carbon were higher in plots dominated by *Acacia kosiensis*, *V. paradoxa*, and *Grewia mollis* at 0.006758 ton/ha, averagely 0.073 ± 0.0021 ton/ha of carbon-stock and CO_2 of 0.271 ± 0.010 ton/ha sequestered, respectively.

Keywords: Carbon sequestration, individual trees, soil carbon, species diversity, wood density

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Corresponding Author:
Adesoji Akinwumi Adeyemi
e-mail:
adeyemi.aa@unilorin.edu.ng

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Introduction

Globally, there are substantial interests in tree caSectorbon accumulation because of the high rate of deforestation and loss of land to other forms of uses, limited carbon storage pools in above-ground and below-ground stocks across regions, as well as an increased rate of emissions (Tsegay & Meng, 2021). It was observed that above-ground tree and shrub woody biomasses are the largest visible carbon pools and are the most impacted by degradation and deforestation processes (Keenan et al., 2015). Thus, it is believed that trees would have the potential to contribute to reducing the concentration of CO_2 in the atmosphere. Photosynthesis converts carbon dioxide (CO_2) to biomass, thereby reducing the amount of carbon in the atmosphere, which is stored in plant tissues, above and below ground (Ahmedin et al., 2013). However, quantification of carbon sequestration by individual tree species has become a challenge (Jeyanny et al., 2011), especially in Nigeria due to the complexity of natural forests and the appropriateness of the conventional methods involving the complete removal of tree stems, which are, in most cases, destructive and do not give room for reassessments of the same sets of trees or data sources. Therefore, periodical assessment of carbon stored in the forest ecosystem, using allometric equations, is a veritable means of estimating CO_2 emissions in connection with deforestation and degradation (Vashum & Jayakumar, 2012).

The atmosphere contains about 800 Gt of carbon, while the land carbon stocks of forest trees and soils account for 2500 Gt across the globe (Raha et al., 2020). On the other hand, soil organic carbon (SOC) drives natural soil fertility (Cambule et al., 2014). Hence, assessing carbon stored in forest pools is crucial for mitigating climate change and regulating anthropogenic activities, through the development of appropriate management options that would aid carbon storage and sequestration (Baraloto et al., 2013).

Meanwhile, it may be difficult to regenerate the existing forests and establish new ones without adequate knowledge of the most suitable indigenous trees and their silvicultural requirements. Besides, knowledge of tree species diversity and carbon stock in Borgu Sector of Kainji Lake National Park (KLNP) is inadequate. Moreover, baseline data on tree species and carbon stock is unavailable for the area. It would be difficult to evolve a sustainable management strategy for the area without adequate knowledge of flora species distributions, abundance, and diversity as well as the ability of individual tree species to sequester carbon (Adeyemi et al., 2013). In most natural forests, flora diversity has been poorly documented due to challenges associated with forest and carbon stock inventories in the tropics (Adeyemi & Adeleke, 2020).

Despite the increasing attention on soil carbon, its knowledge in Borgu Sector of KLNP remains inadequate. Although global soil organic carbon estimates exist, values vary among locations. Besides, the specific case of the study area has not been documented. Therefore, the study assesses tree species diversity and carbon stock accumulation potentials in the area. It was estimated that the global extent of forest cover decreased by 50%, and continued to decrease at a rate of 5.2 million ha per annum (FAO, 2010). Thus, providing information on the status of tree species in the area will help to identify the rare, threatened, and endangered species for their conservation.

Establishment of protected areas has long been used as a conservation tool to preserve important forests and other related ecosystems along with their resources (Leberger et al., 2020). It has been observed that soil plays a key role in the global carbon pool. Even at the forest management level, a majority of carbon stocks are accounted for by the soil ecosystem, as the main carbon sink. Specifically, more than 60% of forest carbon is reported to be locked up in forest soil (e.g., Mohamed et al., 2017). Thus, providing reliable information on soil carbon stocks is essential for any conservation work and in the implementation of holistic mitigation strategies in order to improve atmospheric carbon (Budiman et al., 2013). Hence, this study aims to provide baseline data on the relative amounts of carbon stored by individual tree species in the area, as well as those found in the soil component within the area.

Material and Methods

The Study Area

The study was carried out in Borgu Sector of the Kainji Lake National Park, North-Central Nigeria. It covers an area of about 392,900 ha. The study area lies between latitudes 9º45′N and 10º25′N, and longitudes 3º40′E and 4º30′E in the Baruten and Kaiama Local Government Areas of Kwara State, and Borgu Local Government Area of Niger State in Nigeria (Figure 1). The mean temperature during the wet season is about 30ºC and drops to about 28ºC in the dry season as a result of the north-east harmattan winds. The mean annual rainfall is about 1100 mm, with the wet season lasting from May to November, and the dry season from December to April (Muhammed et al., 2017). The Borgu Sector is well-drained by Oli and Eri Rivers. River Oli flows in from outside Nigeria and drains the western part of the area, while River Eri drains the remaining northern one-third of the area. The topography consists of hills, extensive plains, and river valleys. The entire area is gently undulating with a quartzite ridge in a few places.

Taxonomic Data and Tree Mensuration

Systematic sampling technique was adopted using circular plots for the study. In order to ensure even distribution of the sample plots over

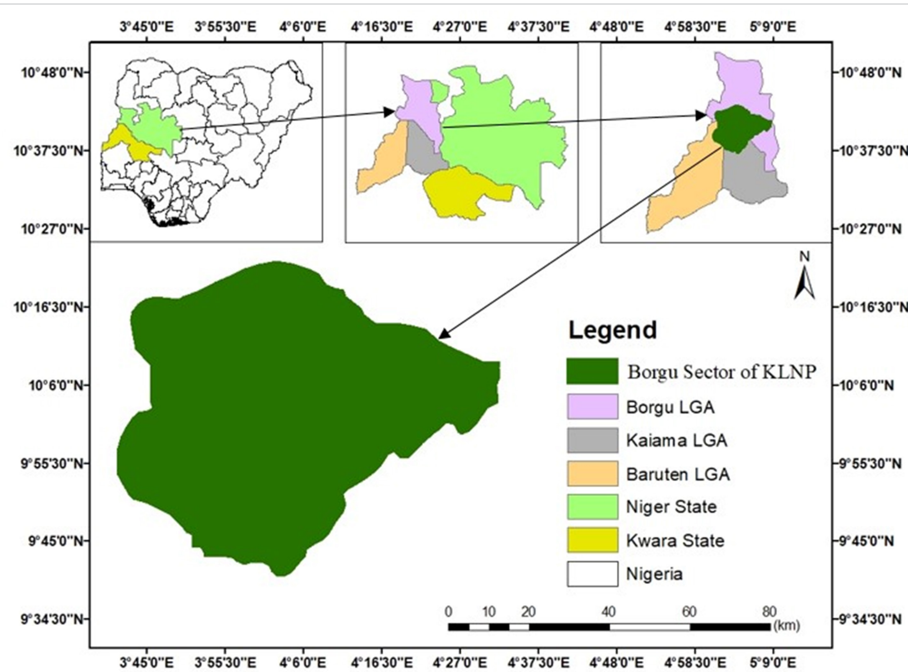

Figure 1.
Map of Borgu Sector of the Kainji Lake National Park.

the entire area, one hundred (100) sampling plots were laid across the site at 1 km intervals, using a pre-classified 2022 Landsat 8 OLI/TC image of the study area. The centers of the plots were then located on the ground and marked, using a geographic positioning system (GPS) receiver. For each point, the main plots with a radius of 12.61 m (500 m^2 in area) and subplot with a radius of 5.64 m (100 m^2 in area) were established. In the main plots, all trees with Dbh ≥10 cm were measured while in the subplots, only trees with Dbh <10 cm but ≥5 cm were considered (Figure 2). In each of the sampling plots, tree species identification was done with tree measurement. The diameter at breast height, middle and top of trees, as well as tree total and merchantable heights were measured using a diameter tape and a Spiegel Relaskop. All other important species with Dbh <5 cm were noted. All identified tree species were classified using the International Union for Conservation of Nature (IUCN) Red List of Threatened species (IUCN, 2023).

Soil Sampling

In order to determine the total soil organic carbon, it is necessary to measure both the organic carbon concentration and the bulk density of the soil. A total of 600 samples were taken in the sample plots within the area at two depths (i.e., 0–15 cm and 15–30 cm). Samples were air-dried, ground, and sieved through a 2-mm sieve. Bulk density (Mgm^{-3}) was measured with a core sampler and rings (with a fixed volume of 100 cm^{-3}; height = 6 cm; diameter = 5.3 cm) at each soil horizon, according to Black (1965). Samples were then oven-dried at 105°C for 24 hours. Soil organic matter was determined by Fe_2SO_4 titration of an acid-dichromate digestion (Walkley and Black, 1934), while soil organic carbon (SOC) was calculated using:

$$SOC = 0.58 \times SOM \quad (1)$$

Where: SOM = Soil organic matter concentration determined by dry combustion; 0.58 = Van Bemmelen constant, generally used for converting SOM to SOC.

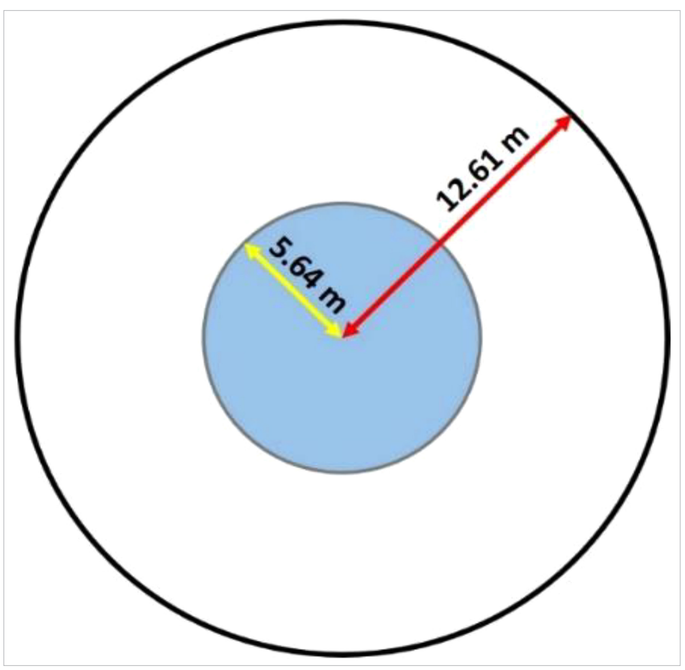

Figure 2.
Circular Plot Characteristics for Tree Species Inventory.

Tree Data Analysis

Data on tree species were analyzed using Shannon–Wiener diversity index, relative density for each species, tree species diversity, tree species richness, importance value index, above-ground and below-ground biomass, and estimation of carbon stock as well as total carbon stock.

Relative Density

Species relative density (RD) was determined using:

$$RD(\%) = \left(\frac{n_i}{N}\right) \times 100 \quad (2)$$

where n_i = Number of individual species; N = Total number of species in the sampled area.

Relative Frequency

The relative frequency of individual species was computed based on Narayan and Anshumali (2015), using:

$$Rf = \frac{n_q}{N_q} \times 100 \quad (3)$$

where Rf = Relative frequency of species; n_q = Total number of plots in which species occurred; Nq = Total number of plots studied.

Relative Dominance

The relative dominance of the species was computed based on Narayan and Anshumali (2015), as follows:

$$RD_o = \frac{BA_s}{BA_{Sp}} \times 100 \quad (4)$$

where BA_s = Total basal area of a species; BA_{Sp} = Total basal area of all species.

Importance Value Index (IVI)

The importance value index (IVI) was computed using:

$$\text{IVI} = \sum Rf + RD_o + RD \quad (5)$$

where Rf = relative frequency of species (%); RD_o = relative dominance of species (%); RD = relative density of species (%).

Species Diversity

Tree species diversity was computed using the Shannon–Wiener diversity index.

$$H' = -\sum_{t=1}^{S} P_i ln(P_i) \quad (6)$$

Where: S = total number of species in the community; P_i = proportion of S made up of the ith species; ln = natural logarithm.

Species Richness

Tree species richness in the area was computed using Margalef's Index of species richness (Margalef, 1958):

$$d = \frac{S}{\sqrt{N}} \quad (7)$$

where *S* is as defined above; N = The total number of individuals of all the tree species.

Basal Area Estimation

The basal area (BA) of individual trees was estimated using the formula of Husch et al. (2003):

$$BA = \frac{\pi Dbh^2}{4} \quad (8)$$

Wood Density Estimation

Wood density was determined using the core sampling method. A 5 mm increment borer was used. Core samples were collected from each of the measured trees in the sample plots at two alternating points in the breast-height region (at 1.3 m above ground level). The fresh volumes of the core samples were obtained from the measured lengths of the core samples and the diameter of the increment borer. The weight of the fresh samples was measured immediately after collection. The core samples were then oven-dried at 70°C to constant weights. Individual tree wood basic densities were then calculated as the oven-dried weight per fresh volume, following Guendehou and Lehtonen (2014).

Above-Ground Biomass

The general equation of Chave et al. (2014) was used to compute the above-ground biomass, as follows:

$$AGB = 0.0673\left(\rho \times Dbh^2 \times H\right)^{0.976} \quad (9)$$

where Dbh = diameter at breast height (cm); H = total tree height (m); ρ = wood density (g $cm{-}^{3}$).

Below-Ground Biomass

Below-ground biomass was estimated from AGB, as proposed by Cairns et al. (1997), standard method for estimation of below-ground biomass was obtained as 0.26 of above-ground tree biomass, i.e., root-to-shoot ratio. The equation developed by Cairns et al. (1997) to estimate below-ground biomass was used.

$$BGB = 0.26 \times AGB. \quad (10)$$

where AGB = above-ground biomass; 0.26 = conversion factor (or 26% of AGB).

Carbon Stock Estimation

Carbon stock was obtained using the equation proposed by Eneji et al. (2013), with a little modification, as follows:

$$\text{Carbon stock in standing tree} = \text{total biomass} \times 0.5 \quad (11)$$

$$\text{Total tree carbon stock} = 120\% \times \text{AGB} \quad (12)$$

Carbon has an atomic mass of 12 and oxygen has an atomic mass of 16. Therefore, CO_2 has an atomic mass of 44. This means that 1 kg of carbon will produce approximately 3.67 kg of CO_2. Thus, the amount of CO_2 sequestered by individual tree species is estimated as:

$$CO_2 = \text{Total tree carbon stock} \times 3.67 \quad (13)$$

Soil Carbon Estimation

In order to estimate soil carbon, soil bulk density was determined from the collected core sample, which gives a soil sample of known total volume (Vt). From this sample, the wet and dry bulk densities were determined. For the wet bulk density, the sample was weighed, giving the mass Mt. The sample was oven-dried and weighed to obtain the dry bulk density, giving the mass of soil solids, Ms. The addition of these two masses gives the total mass (bulk density):

$$Mt = Ms + Ml. \quad (14)$$

where Ml = mass of substances lost in oven drying; the dry and wet bulk densities were calculated as:

Dry bulk density = mass of soil/volume as a whole:

$$\rho b = \frac{Ms}{Vt} \quad (15)$$

Wet bulk density = mass of soil + liquids/volume as a whole:

$$\rho b = \frac{Ms}{Vt} \quad (16)$$

The soil organic carbon was estimated as proposed by James and Randall (2005):

$$SOC = OC \times \rho b \times D \times UCF \quad (17)$$

where OC = Organic carbon concentration (%); *pb* = Bulk density (gcm^3); D = Horizon thickness (cm); UCF = Unit conversion factor (= 100 cm^2).

Further Statistical Analyses

Descriptive statistics such as tables and graphs were used to summarize tree growth characteristics, and analysis of variance (ANOVA) was used to compare growth parameters, biomass, and carbon stocks among tree species.

Results

Tree Structural and Species Diversity in Borgu Sector of Kainji Lake National Park

Thirty-five tree species, belonging to 16 families, were encountered in the study area. *Detarium microcarpum* predominated with an RD of 3.75% (Table 1). The least-occurring species in the area, in terms of encounter rate (frequency), were *Bridelia ferruginea, Anogeissus leiocarpus, Diospyros mespiliformis, Adansonia digitata, Acacia kosiensis, Hymenocardia acida, Tamarindus indica, Daniella oliveri, Ficus sycomorus, Securidaca longipedunculata, Sterculia setigera, Strychnos spinosa, Bombax constatum, Prosopis africana, Lannea schimperi, Nauclea latifolia,* and *Vitex doniana*. Twenty-two (22) of the tree species encountered in the Borgu Sector were least concern (LC), based on the IUCN classification, representing 63% of the identified tree species, while 10 species have not been evaluated (NE) against the IUCN standard, representing

Table 1.
Tree Species Composition and Their IUCN Status in Borgu Sector of KLNP

SN	Species	Family	N	IUCN	Rf (%)	RD (%)	RDo	IVI
1	*Acacia gourmaensis*	Fabaceae	9	LC	45	3.6	2.20	50.8
2	*Acacia kosiensis*	Fabaceae	6	NE	35	2.4	0.47	37.87
3	*Adansonia digitata*	Malvaceae	<1	LC	5	0.1	20.24	25.34
4	*Afzelia africana*	Fabaceae	3	VU	40	1.2	7.95	49.15
5	*Annona senegalensis*	Annonaceae	7	LC	10	2.7	0.19	12.89
6	*Anogeissus leiocarpa*	Combretaceae	2	LC	25	0.7	1.17	26.87
7	*Bombax costatum*	Malvaceae	<1	LC	5	0.1	0.37	5.47
8	*Bridelia ferruginea*	Phyllanthaceae	<1	LC	10	0.2	0.04	10.24
9	*Burkea africana*	Fabaceae	18	LC	100	7.4	21.45	128.85
10	*Combretum molle*	Combretaceae	6	LC	30	2.4	0.10	32.5
11	*Combretum nigiricans*	Combretaceae	23	LC	85	9.2	2.15	96.35
12	*Crossopteryx febrifuga*	Rubiaceae	10	LC	80	4.2	4.30	88.5
13	*Daniella oliveri*	Fabaceae	1	LC	10	0.3	0.26	10.56
14	*Detarium microcarpum*	Fabaceae	46	LC	100	18.8	6.90	125.7
15	*Diospyros mespiliformis*	Ebenaceae	1	NE	5	0.6	0.12	5.72
16	*Entada Africana*	Fabaceae	4	LC	45	1.8	1.58	48.38
17	*Ficus sycomorus*	Moraceae	2	LC	25	0.7	0.42	26.12
18	*Gardenia aqualla*	Rubiaceae	5	NE	25	1.9	0.17	27.07
19	*Grewia mollis*	Malvaceae	13	LC	50	5.3	1.15	56.45
20	*Hymenocardia acida*	Phyllanthaceae	2	LC	20	0.7	0.48	21.18
21	*Lannea acida*	Anarcadiaceae	5	LC	50	2.0	3.33	55.33
22	*Lannea schimperi*	Anacardiaceae	<1	NE	5	0.1	0	5.1
23	*Maytenus senegalensis*	Celastraceae	17	NE	90	7.1	2.38	99.48
24	*Nauclea latifolia*	Rubiaceae	<1	NE	5	0.1	0	5.1
25	*Piliostigmathonningii*	Fabaceae	6	NE	60	2.5	0.69	63.19
26	*Prosopis africana*	Fabaceaae	<1	LC	10	0.2	0.19	10.39
27	*Pterocarpus erinaceous*	Fabaceae	3	NE	45	1.2	2.05	48.25
28	*Securidaca longipedunculata*	Polygalaceae	<1	NE	5	0.1	1.04	6.14
29	*Sterculia setigera*	Sterculiaceae	1	LC	20	0.3	1.03	21.33
30	*Stereospermum kunthianum*	Bignoniaceae	6	LC	70	2.6	3.10	75.7
31	*Strychnos spinosa*	Loganiaceae	3	NE	30	1.2	0.35	31.55
32	*Tamarindus indica*	Fabaceae	1	LC	5	0.5	0.92	6.42
33	*Terminalia glaucescens*	Combretaceae	19	LC	90	7.9	3.18	101.08
34	*Vitellaria paradoxa*	Sapotaceae	24	VU	95	9.9	11.03	115.93
35	*Vitex doniana*	Verbenaceae	<1	LC	5	0.1	0.01	5.11
					38.14 32.27	2.9 1.2	2.89 5.11	43.89 35.41

Note: IVI = importance value index; LC = least concern; N = trees per hectare; NE = not evaluated; RD = relative density; RDo = relative dominance; Rf = relative frequency; VU = vulnerable.

23% of the species. Two of the species are vulnerable, representing 6% (Table 1).

Four of the identified tree species had IVI >100, which were *Burkea africana* (128.85), *Detarium microcarpum* (125.7) followed by *Vitellaria paradoxa* (115.93) and *Terminalia glaucescens* (101.08), while *Vitex doniana* had the least values for relative density (0.02%), relative frequency, relative dominance (0.01) and importance value index (5.03) having less than a stem per hectare. The mean species importance value index was 43.89 ± 35.41. Table 2 presents tree diversity indices for the study area. Tree species richness and diversity indices for the area were 2.852 and 4.779, respectively.

Table 2.
Tree Species Diversity Indices and Richness Borgu Sector of KLNP

Diversity	Index Value
Shannon Weiner's	2.852
Margalef's	4.779
Number of species	35
Individuals/ha	245
Equitability	0.8022
Evenness	0.495

Table 3 presents tree structural characteristics in the study area. The Dbh ranged between 0.51 and 111.4 cm, with a mean of 6.02 ± 5.12 cm. Tree total height ranged between 0.7 and 17.5 m with a mean of 4.65 ± 2.34 m. Stem quality ranged between 0.1 and 6.1 m with a mean of 1.02 ± 0.89 m. Tree crown length (CL) and crown diameter were 3.50 ± 2.20 m and 3.34 ± 2.1 m, respectively. The mean BA was 0.005 ± 0.03 m^2 (Table 3). Table 4 presents tree diameter classes. Most of the tree species belonged to the class Dbh <10 cm (68.2%) with about 167 trees/ha. About 6 trees/ha were found to be above 30 cm in Dbh.

Tree Biomass and Carbon Stock in Borgu Sector of KLNP

The above- and below-ground biomass and carbon stock estimates across the sampled plot clusters within the study area are presented in Table 5. The mean AGB was 0.000742 ± 0.0012 ton/ha, while the average

Table 3.
Tree Structural Characteristics in Borgu Sector of KLNP

Variable	Trees/ha	Minimum	Maximum	Mean ± SD
Dbh (cm)	245	0.51	111.4	6.02 ± 5.12
THT (m)	245	0.7	17.5	4.65 ± 2.34
MHT (m)	245	0.1	7.5	1.56 ± 1.40
SQ	245	0.1	6.1	1.02 ± 0.89
CL (m)	245	0.3	20	3.50 ± 2.20
CD (m)	245	0.2	17.1	3.34 ± 2.10
BA (m^2)	245	0.0009	0.97	0.005 ± 0.03

Note: Dbh = Diameter at breast height; THT = Tree total height; MHT = Merchantable height; SQ = Stem quality; CL = Crown length; CD = Crown diameter; BA = Basal a.

Table 4.
Diameter Class of Trees in the Study Area

Diameter Class (cm)	Trees/ha	%
<10	167	68.2
10–20	60	24.5
20-30	11	4.5
>30	6	2.4
Total	245	100

Table 5.
Average Tree Carbon Stocks/ha in Borgu Sector of KLNP

Cluster	N/ha	AGB (ton/ha)	BGB (ton/ha)	AGCS (ton/ha)	BGCS (ton/ha)	TTCS (ton/ha)
1	174	0.000426	0.000111	0.000213	0.000055	0.000511
2	165	0.000524	0.000136	0.000262	0.000068	0.000629
3	226	0.000326	0.000085	0.000163	0.000042	0.000391
4	122	0.00052	0.000135	0.00026	0.000068	0.000624
5	266	0.000388	0.000101	0.000194	0.00005	0.000465
6	238	0.000224	0.000058	0.000112	0.000029	0.000269
7	296	0.000456	0.000119	0.000228	0.000059	0.000547
8	284	0.000549	0.000143	0.000275	0.000071	0.000659
9	222	0.000338	0.000088	0.000169	0.000044	0.000406
10	214	0.000235	0.000061	0.000117	0.000031	0.000282
11	298	0.000396	0.000103	0.000198	0.000051	0.000475
12	266	0.000648	0.000168	0.000324	0.000084	0.000777
13	274	0.000716	0.000186	0.000358	0.000093	0.000859
14	226	0.005632	0.001464	0.002816	0.000732	0.006758
15	275	0.000287	0.000075	0.000144	0.000037	0.000345
16	246	0.000869	0.000226	0.000435	0.000113	0.001043
17	279	0.000967	0.000251	0.000484	0.000126	0.001161
18	280	0.000401	0.000104	0.0002	0.000052	0.000481
19	297	0.000214	0.000056	0.000107	0.000028	0.000256
20	256	0.000717	0.000186	0.000358	0.000093	0.00086
Mean	245	0.000742	0.000193	0.000709	0.0000963	0.00089
SD	50	0.0012	0.00059	0.00015	0.0014	0.00030

Note: AGB = Above-ground biomass; BGCS = Tree below-ground; N/ha = Trees per hectare; SD = Standard deviation; TTCS = Total tree carbon stock.

Table 6.
Mean Separation (LSD) for Tree Carbon Stocks Among Tree Species (Dbh <10 cm)

Species	AGCS (tons/ha)	BGCS (tons/ha)	TTCS (tons/ha)
Acacia gourmaesis	0.002 ± 0.002$^{f\text{-}k,\ mnpsw}$	0.001 ± 0.001$^{f\text{-}k,\ mnpsw}$	0.003 0.002$^{f\text{-}k,\ mnpsw}$
Acacia khayensis	0.001 ± 0.001^{v}	0.0002 ± 0.0003^{v}	0.001 ± 0.001^{v}
Afzelia africana	0.009 ± 0.00^{ab}	0.002 ± 0.0^{ab}	0.01 ± 0.00^{ab}
Annona senegalensis	0.001 ± 0.002$^{g,\ i\text{-}j,\ n\text{-}q,\ w}$	0.0002 ± 0.0005$^{g,\ i\text{-}j,\ n\text{-}q,\ w}$	0.001 ± 0.002$^{g,\ i\text{-}j,\ n\text{-}q,\ w}$
Anogeissus leiocarpus	0.004 ± 0.001^{cdef}	0.001 ± 0.0003^{cdef}	0.004 ± 0.001^{cdef}
Bridelia ferruginea	0.0004 ± 0.001$^{f\text{-}w}$	0.0001 ± 0.0001$^{f\text{-}w}$	0.001 ± 0.001$^{f\text{-}w}$
Burkea africana	0.004 ± 0.003^{bcd}	0.001 ± 0.001^{bcd}	0.005 ± 0.004^{bcd}
Combretum molle	0.001 ± 0.001^{rtuv}	0.0001 ± 0.0002^{rtuv}	0.001 ± 0.001^{rtuv}
Combretum nigricans	0.002 ± 0.003^{mnopq}	0.0004 ± 0.001^{mnopq}	0.002 ± 0.003^{mnopq}
Crossopteryx febrifuga	0.003 ± 0.003^{fhm}	0.001 ± 0.001^{fhm}	0.004 ± 0.003^{fhm}
Daniella oliveri	0.003 ± 0.002$^{c\text{-}w}$	0.001 ± 0.001$^{c\text{-}w}$	0.004 ± 0.002$^{c\text{-}w}$
Detarium microcarpum	0.001 ± 0.001	0.0003 ± 0.0002	0.001 ± 0.001
Diospyros mespiliformis	0.003 ± 0.004$^{c\text{-}w}$	0.001 ± 0.001$^{c\text{-}w}$	0.003 ± 0.005$^{c\text{-}w}$
Entada africana	0.003 ± 0.003^{defhm}	0.001 ± 0.001^{defhm}	0.004 ± 0.003^{defhm}
Ficus circumorus	0.003 ± 0.004$^{d\text{-}w}$	0.001 ± 0.001$^{d\text{-}w}$	0.004 ± 0.005$^{d\text{-}w}$
Gardenia aqualla	0.001 ± 0.001^{stuvw}	0.0002 ± 0.0002^{stuvw}	0.001 ± 0.001^{stuvw}
Grewia mollis	0.001 ± 0.002^{klpq}	0.0004 ± 0.001^{klpq}	0.002 ± 0.003^{klpq}
Hymenocardia acida	0.003 ± 0.002^{defhm}	0.001 ± 0.0004^{defhm}	0.004 ± 0.002^{defhm}
Lannea acida	0.003 ± 0.002$^{e\text{-}w}$	0.001 ± 0.001$^{e\text{-}w}$	0.003 ± 0.002$^{e\text{-}w}$
Maytenus senegalensi	0.001 ± 0.001	0.0002±0.0003	0.001 ± 0.001
Piliostigma thonningii	0.001 ± 0.001^{uv}	0.0002±0.0003^{uv}	0.001±0.001^{uv}
Prosopis africana	0.004 ± 0.004$^{b\text{-}q}$	0.001 ± 0.001$^{b\text{-}q}$	0.005±0.005$^{b\text{-}q}$
Pterocarpus erinaceous	0.005 ± 0.002^{bcde}	0.001 ± 0.001^{bcde}	0.006±0.003^{bcde}
Seciridaca longipendiculata	0.0003 ± 0.0$^{d\text{-}w}$	0.0001 ± 0.0$^{d\text{-}w}$	0.001 ± 0.0$^{d\text{-}w}$
Sterculia setigera	0.004 ± 0.0$^{b\text{-}w}$	0.001 ± 0.0$^{b\text{-}w}$	0.004 ± 0.0$^{b\text{-}w}$
Stereospermus kumthianum	0.003 ± 0.002^{fghimnsw}	0.001 ± 0.001^{fghimnsw}	0.003±0.002^{fghimnsw}
Strycimos spinosa	0.001 ± 0.002$^{h\text{-}q}$	0.0003±0.0004$^{h\text{-}q}$	0.001±0.002$^{h\text{-}q}$
Tamarindus indica	0.012 ± 0.007^{a}	0.003 ± 0.002^{a}	0.015±0.008^{a}
Terminalia glaucescens	0.001 ± 0.001^{jloq}	0.0003±0.0004^{jloq}	0.002±0.002^{jloq}
Vitellaria paradoxa	0.005 ± 0.005^{bc}	0.001 ± 0.001^{bc}	0.006±0.006^{bc}
Vitex doniana	0.0003 ± 0.0$^{d\text{-}w}$	0.0001 ± 0.00$^{d\text{-}w}$	0.0003±0.00$^{d\text{-}w}$

Note: Means with the same letters as superscripts in each column are not significantly different.

BGB was 0.000193 ± 0.00059 ton/ha. The mean above-ground carbon stock and below-ground carbon stock were 0.000709 ± 0.00015 ton/ha and 0.0000963 ± 0.0014 ton/ha, respectively. The mean tree carbon stock was 0.00089 ± 0.00030 ton/ha.

Table 6 presents mean separation (LSD) results for tree above- and below-ground carbon stocks in the Borgu Sector of Kainji Lake National Park. *Detarium microcarpum* and *Maytenus senegalensis* were not significantly different in terms of mean carbon stocks with AGCS (0.001 ± 0.001 ton/ha; 0.001 ± 0.001 ton/ha), BGCS (0.0003 ± 0.0002 tons/ha; 0.001 ± 0.001 tons/ha), respectively, but significantly differ from other tree species in terms of mean biomass and carbon stock values. However, other species differ significantly from one another in terms of tree carbon stocks (Table 6).

The result of mean separation for species carbon stocks (Table 7) revealed that there were no significant differences among *Afzelia africana* (0.04 ± 0.02 ton/ha), *Anogeissus leiocarpa* (0.03 ± 0.02 ton/ha), *Bombax costatum* (0.04 ± 0.00 ton/ha), *Burkea africana* (0.02 ± 0.01 ton/ha), *Crossopteryx febrifuga* (0.02 ± 0.01 ton/ha), *Tamarindus indica* (0.03 ± 0.01 ton/ha) and *Vitellaria paradoxa* (0.03 ± 0.02 ton/ha) in terms of mean above-ground carbon stock, AGCS (Table 7). Similarly, there were no significant differences among *Acacia gourmaensis* (0.008 ± 0.001 ton/ha), *Entada africana* (0.01 ± 0.001 ton/ha), *Lannea acida* (0.01 ± 0.004 ton/ha), *Detarium microcarpum* (0.02 ± 0.00 ton/ha), *Ficus sycomorus* (0.02 ± 0.00 ton/ha), *Stereospermum kumthianum* (0.02 ± 0.01 ton/ha), *Pterocarpus erinaceous* (0.02 ± 0.01 ton/ha), *Sterculia setigera* (0.01 ± 0.004 ton/ha), and *Terminalia glaucescens* (0.01 ± 0.00 ton/ha). However, *Adansonia digitata* (2.4 ± 0.00 tons/ha) significantly differs from every

Table 7.
Mean Separation (LSD) for Tree Carbon Stocks for Species with Dbh >10 cm

Species	AGCS (tons/ha)	BGCS (tons/ha)	TTCS (tons/ha)casia
Acacia gourmaesis	$0.008 \pm 0.001^{d-j}$	$0.002 \pm 0.0002^{d-j}$	$0.01 \pm 0.001^{d-j}$
Afzelia africana	0.04 ± 0.02^{b}	0.01 ± 0.01^{b}	0.05 ± 0.03^{b}
Adansonia digitata	2.4 ± 0.0^{a}	0.01 ± 0.0^{a}	2.8 ± 0.0^{a}
Anogeissus leiocarpa	$0.03 \pm 0.02^{b-j}$	$0.01 \pm 0.01^{b-j}$	$0.03 \pm 0.02^{b-j}$
Burkea africana	0.02 ± 0.01^{i}	0.01 ± 0.003^{i}	0.02 ± 0.01^{i}
Bombax constratum	$0.04 \pm 0.0^{b-i}$	$0.01 \pm 0.0^{b-i}$	$0.05 \pm 0.5^{b-i}$
Crossopteryx febrifuga	$0.02 \pm 0.01^{h-j}$	$0.005 \pm 0.002^{h-j}$	$0.02 \pm 0.01^{h-j}$
Detarium microcarpum	$0.02 \pm 0.0^{b-j}$	$0.004 \pm 0.0^{b-j}$	$0.02 \pm 0.0^{b-j}$
Entada africana	$0.01 \pm 0.001^{c-j}$	$0.002 \pm 0.0003^{c-j}$	$0.01 \pm 0.001^{c-j}$
Ficus sycomorus	$0.02 \pm 0.0^{b-j}$	$0.004 \pm 0.0^{b-j}$	$0.02 \pm 0.0^{b-j}$
Lannea. acida	0.01 ± 0.004^{j}	0.003 ± 0.001^{j}	0.01 ± 0.01^{j}
Pterocarpus erinaceous	$0.02 \pm 0.01^{g-j}$	$0.004 \pm 0.002^{g-j}$	$0.02 \pm 0.01^{g-j}$
Sterculia setigera	$0.01 \pm 0.004^{e-j}$	$0.003 \pm 0.001^{e-j}$	$0.01 \pm 0.01^{e-j}$
Tamarindus indica	$0.03 \pm 0.01^{b-i}$	$0.01 \pm 0.003^{b-i}$	$0.04 \pm 0.01^{b-i}$
Stereospermum kumthianum	$0.02 \pm 0.01^{f-j}$	$0.004 \pm 0.002^{f-j}$	$0.02 \pm 0.01^{f-j}$
Terminalia glaucescens	$0.01 \pm 0.0^{b-j}$	$0.01 \pm 0.01^{b-j}$	$0.01 \pm 0.0^{b-j}$
Vitellaria paradoxa	0.03 ± 0.02^{b}	0.6 ± 0.0^{b}	0.04 ± 0.03^{b}

Note: Means with the same letters as superscripts in each column are not significantly different

other tree species. Similar trends were observed for tree below-ground (BGCS) and total-tree carbon stock (TTCS).

Soil Carbon Stock Accumulation in Borgu Sector of KLNP

Table 8 presents soil carbon stock, total forest carbon and CO_2 sequestered per hectare in Borgu Sector of Kainji Lake National Park. The results showed that soil carbon stock at a total depth of 30 cm (0–15 and 15–30 cm combined) was 0.07293 ± 0.00214 ton/ha. The total tree carbon of 0.00089 ± 0.0014 ton/ha (all tree species pooled) with a total forest carbon of 0.07382 ± 0.0026 ton/ha. The total CO_2 of 0.2709 ± 0.0096 ton/ha was sequestered. Details are shown in Table 8.

Table 8.
Estimated Total Soil Carbon Stocks in Borgu Sector of KLNP

Cluster	TTCS (ton/ha)	TSC (ton/ha)	TCS (ton/ha)	CO_2 (ton/ha)
1	0.00051	0.0763	0.0768	0.2819
2	0.00063	0.0762	0.0768	0.282
3	0.00039	0.0709	0.0713	0.2618
4	0.00062	0.0719	0.0725	0.266
5	0.00047	0.0721	0.0725	0.2663
6	0.00027	0.0746	0.0749	0.2749
7	0.00055	0.0758	0.0763	0.2801
8	0.00066	0.0721	0.0727	0.267
9	0.00041	0.0721	0.0725	0.266
10	0.00028	0.0721	0.0724	0.2656
11	0.00048	0.0707	0.0712	0.2613
12	0.00078	0.0735	0.0743	0.2726
13	0.00086	0.0746	0.0755	0.2771
14	0.00676	0.0739	0.0807	0.2962
15	0.00035	0.0724	0.0727	0.2668
16	0.00104	0.067	0.0681	0.2499
17	0.00116	0.0719	0.073	0.268
18	0.00048	0.0721	0.0726	0.2663
19	0.00026	0.0739	0.0742	0.2723
20	0.00086	0.0744	0.0753	0.2762
Mean	0.00089	0.07293	0.07382	0.27092
SD	0.0014	0.00214	0.0026	0.0096

Discussion

The presence of only 35 tree species in 16 families in Borgu Sector was lower compared to the figures reported for other protected areas, including 64 species in 23 families by Adeyemi and Taofeek (2020) for Old Oyo National Park, which may have some similarities with the study area, perhaps due to differences in the ecological zones, management options and levels of protection as well as general perceptions of the rural population towards conservation. The analysis of tree flora families in the study area showed that Fabaceae was predominant due to their adaptation to the ecosystem. The existence of variability in tree diversity within the study area was revealed by Shannon's diversity, which was moderately high (typical values usually ranged between 1.5 and 3.5 for high diversity ecosystems). The diversity index of 2.852 for the study area was higher than 2.0 (stipulated for a structurally-diverse ecosystem, especially a forest), as noted by Staudhammer and LeMay (2001). This is also consistent with the observation of Gentry et al. (2010), who noted that high species richness is a hallmark of many tropical forests, since it shows high diversity due to the availability of favorable growth and suitable soil conditions, as has been observed within the study area (Adekunle et al., 2013). This may have been influenced by structural and species composition (Huang et al., 2003). The richness index (4.779) also falls within the range of 4.54–23.41 reported by Kumar et al. (2010) and Sathish et al. (2013). There were three species with IVI >100, which depicts ecological dominance and relevance of the species within the area. The relative composition of tree species in the area indicated high values for such species as *Burkea africana, Detarium microcarpum,* and *Vitellarria paradoxa*. The abundance of *Detarium microcarpum* in the study area, a species often found in relatively poor soils (Kouyaté & Damme, 2006), may indicate poor fertility in most parts of the study area. There was, however, low density for species like *Prosopis africana*, which requires more fertile soils for optimal growth. Similarly, the abundance of *Burkea africana* in the area might be a reflection of its high adaptability to the forest site and prevailing micro-environmental conditions.

Meanwhile, the prevalence of small-sized trees (Dbh <10 cm) in the study area may suggest high regeneration and recruitment potentials, or a sign of previous over-exploitation in the area. The results also showed that fewer trees in the larger diameter category. This may be an indication of past incursion and a high rate of anthropogenic activities within the area, suggesting that larger trees may have been unsustainably exploited without appropriate replacements. This is similar to the findings of Chenge et al. (2020), who observed that large diameter trees represent key structures of forest ecosystems, and when removed, the structure of the forest may be redefined. The overall mean Dbh was 6.02 cm suggesting that most of the trees fell in the lower diameter class, which indicates the absence of large diameter trees important for supporting a higher diversity of fauna species in the area. The overall mean basal area recorded in this study was lower than 1.1091 m^2 reported by Ibe et al. (2014). A lower Dbh, basal area, and consequently, low tree carbon storage in the area could be attributed to the concentration of most trees in lower diameter classes. This is similar to the findings of Zhang et al. (2013). The low structural diversity in the study area may be detrimental to flora and fauna lives if no regeneration plan is in place, as rich flora and fauna diversities are closely linked to high structural diversity (Horak et al., 2019; Muller et al., 2010).

The low amount of total tree carbon stocks may be attributed to the low density of large trees in the study area. Studies have shown that high tree biomass in tropical forests is driven by the high density of large trees (Bastin et al., 2015; Bradford & Murphy, 2019). The area dominated by *Acacia kosiensis*, *Vitellaria paradoxa,* and *Grewia mollis* were higher in total forest carbon stocks relative to other parts of Borgu Sector. This is similar to the findings of Yusuf et al. (2019), who observed that the amount of carbon stocks in an area is influenced by species composition. Also, the higher biomass can also be attributed to higher tree density and large sizes (Kuyah et al., 2014). Other factors could be the age of the trees, management practices, human and natural disturbances, which are known to influence tree biomass (Tilahun et al., 2015). The significant differences among carbon stocks in different diameter classes are similar to the findings of Gebrewahid and Merressa (2020), who noted significant differences among different plant communities due to size variations and species growth dynamics.

The soil composition showed variability with increasing depths in terms of carbon stock accumulation in Borgu Sector, with an inverse relationship with soil depth. This is consistent with the report of Onyekwelu et al. (2007), who noted that sand content decreases with increasing depths, while clay and silt contents followed opposite trends. Similarly, all exchangeable cations were found to decrease with increasing soil depth, except Na, which increased with depth. It was observed that a large quantity of the carbon sequestered by the forest was stored in the soil.

Conclusion and Recommendations

The study has shown that the majority of the tree species encountered in the area were of the families Fabaceae and Combretaceae. However, most of them are IUCN-least concern species and fell in lower diameter classes, which resulted in low carbon sequestration capacities for most tree species in the area. Based on our findings, it is established that stand-level tree diameter distribution determines the amount of carbon stocks in individual tree species. This underscores the critical role of better forest management practices that tends to improve tree growth, with resultant effects on facilitating higher per unit area of productivity and improved forest ecosystem conditions.

Excessive exploitation or degradation of the flora diversity reduces the amount of CO_2 being sequestered. This leads to a larger percentage of carbon being buried in soil. Therefore, it becomes expedient to stem further diminution in order to reduce global warming while exploring better regeneration options that support rapid growth of trees in the area. The considerable variation in carbon accumulation between small and large-diameter trees suggests a need to discontinue any form of structural modification within the ecosystem. Consequently, factors that influence tree growth should be well monitored and controlled within the area in order to increase the population of trees with large stem diameters. Finally, it is worthy of note that the use of allometries, involving tree height, diameter, and wood density, proves to be appropriate in estimating carbon stock in the area, which presents an opportunity for a non-destructive estimation of carbon. Thus, a study of this nature can be adopted to periodically monitor the trends and developments of carbon stock within the Borgu Sector of the Kainji Lake National Park. This would guide decision-makers and drive policy directions.

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