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ASSESSMENT OF LAND-COVER CHANGES AND CARBON SEQUESTRATION POTENTIALS OF TREE SPECIES IN J4 SECTION OF OMO FOREST RESERVE, OGUN STATE, NIGERIA

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ABSTRACT

We evaluated carbon stock accumulation on potential of tree species in five forest-types in Omo Forest Reserve of western Nigeria. This included four forest plantations and a natural forest of mixed species. The reserve was stratified into *Gmelina arborea*, *Tectona grandis*, *Pinus carebeae* and *Nauclea diderrichii* plantations as well as natural forest. Each forest-type was assessed using circular plot method. Plot points were pre-determined using remote sensing. For each point, two circular plots were established, the main plot with a radius of 12.61 m (500 m^2) and the subplot with a radius of 5.64 m (100 m^2). In each plot, tree Dbh and height were measured for trees with Dbh $\geqslant$10 cm, while only trees with Dbh <10 cm but >2 cm (i.e. 2 cm $\leqslant$ Dbh < 10 cm) were considered in the sub-plot. Soil samples were also collected at 10 locations with 2 each in the north, south, east, west and at the plot centre, in each forest-type. The samples were analysed to obtain soil organic carbon. Above- and below-ground biomass and carbon stocks were estimated using the appropriate allometries formulated for the tropics. All empirical relationships were included in the existing allometries with Dbh and height as predictors. Landsat images of the reserve in 1991, 2000, 2014 and 2019 were processed and analysed to assess forest degradation. The results revealed that 23-year-old *Pinus caribaea* plantation sequestered more carbon (35.78±2.73 tons/ha) than 35-year-old *Gmelina arborea* (18.96±1.82 tons/ha), 43-year-old *Tectona grandis* (17.75±2.13 tons/ha) and 43-year-old *Nauclea diderrichii* (17.36±1.87 tons/ha) plantations and natural forest (21.98±2.38 tons/ha). The study showed that stand density influences carbon stock accumulation of forest. It was observed that individual stems of *Pinus caribaea* were better carbon accumulators than *Gmelina arborea*, *Tectona gransdis* and *Nauclea diderrichii*. The same trend was observed for CO_2 captures as *Pinus caribaea* captured 131.31±10.02 tons/ha with *Nauclea diderrichii* the least, having a value of 63.71±6.9 tons/ha.

Keywords: Biomass, Carbon stock, Degradation, Forest-type, Stand density

INTRODUCTION

According to Ostadhashemi *et al.* (2014), the world's forests stored an estimate of 289 Gt of carbon in their biomass. However, this value has previously been reported to shrink by 0.5 Gt annually in five years, between 2005 and 2010 due, largely, to forest disappearance (FAO, 2010). In the context of climate change, special attention is given to carbon, which is seen as a major constituent of greenhouse gas emissions (Liu *et al.*, 2014). Forests account for 48% of the total storage capacity of carbon by global terrestrial ecosystems (Watson *et al.*, 2000; IPCC, 2001). Trees, the major components of forest, absorb large amounts of atmospheric carbon dioxide (CO_2) through photosynthesis, and forests return an almost equal amount to the atmosphere by auto- and heterotrophic respirations (Folega *et al.*, 2010).

The main carbon pool in tropical forest ecosystems consists of the living biomass of trees, understorey vegetation, dead mass of litter, woody debris and soil organic matter (Kumar and Sharma, 2015). Kumar and Sharma (2015) observed that carbon stored in the Above-Ground Biomass (AGB) of trees is the largest pool. Quantifying AGB and Below-Ground Biomass (BGB) carbon is a critical step in estimating carbon stocks and fluxes from tropical forests. The major environmental concern today is the increase of carbon dioxide in the atmosphere and its potential effect on climate, considered as global warming. However, a small fraction of carbon remaining in forests continuously accumulates in vegetation, detritus, and soil. Thus, undisturbed forest ecosystems have been viewed as important global carbon sinks (Lorenz and Lal, 2009).

Forests remain a reservoir of carbon (FAO, 2003; 2008) due to their good capacity to store carbon from the atmosphere (Ullah and Amin, 2012). However, in the face of current anthropogenic activities and relentless efforts by people to survive, lots of forests have been lost, especially in the tropics. To that end, afforestation and enrichment planting have long been suggested as viable options in addressing high rates of forest losses in order to boost carbon base or reservoir. Photosynthesis in plants converts carbon dioxide (CO_2) to biomass, thereby reducing the carbon in the atmosphere and stores it in plant tissues, above and below ground (Ahmedin *et al*., 2013). The biomass produced is mainly stored as AGB, BGB, dead wood, litter and soil organic matter in the forest ecosystem (Cienciala *et al*., 2010).

Forest ecosystems are very important in the global carbon cycle as they sequester close to 80% and 40% of all above- and below-ground terrestrial organic carbon, respectively (IPCC, 2001), and they are directly influenced by deforestation and forest degradation (Gibbs *et al*., 2010). According to Vashum and Jayakumar (2012), Haghparast *et al.* (2013), carbon sequestration could reduce CO_2 emission by up to 55% by 2100, and this would have great influence on greenhouse gas contribution to climate pattern of the world. Quantification of carbon stock potential of any ecosystem is challenging, however, it is crucial for sustainability and for making decision for a safe environment.

Hence, periodic evaluation of the amount of carbon stored in the forest ecosystem is a means of determining the CO_2 emission due to deforestation and degradation (Vashum and Jayakumar, 2012). Information on AGB and BGB carbon in Omo Forest Reserve, one of the remaining protected areas in Nigeria is too inadequate to evolve sustainable forest management strategies. Besides, potential and adequacy of a non-destructive carbon assessment method has not been employed in the area. Although some reported anthropogenic activities in the reserve were rumoured to have diminished the extents and values of the reserve, no appreciable efforts have hitherto been made to put the causal factors in prespectives. Moreover, the impacts these may have had on biodiversity in the reserve remains unknown and also the capacity of the different forest-types in the area to sequester carbon. Therefore, we assessed total biomass carbon sequestered by the reserve to aid sustainable management practices.

MATERIALS AND METHODS

The study area was the J4 Section of Omo Forest Reserve (OFR), which is located between latitudes 6°35' and 7°05'N and longitudes 4°19' and 4°40'E in Ijebu East and North Local Government Areas of Ogun State in western Nigeria (Figure 1). It covers an area of about 130,500 ha, and bounded with other three important forest reserves in the west of the country. The rainy season in OFR usually commences in March with mean annual rainfall range of about 1600 to 2000 mm and two peaks in June and September. The temperature ranges from 32.15 °C to 21.40 °C with a minimum relative humidity of 76.34% (Adebisi, 2004). The vegetation of the reserve is a moist semi-deciduous rainforest. Most of the forests are disturbed with a substantial part converted to monoculture plantations of *Gmelina arborea* in a programme assisted by loans from the World Bank and the African Development Bank to provide material for a pulp mill in the early 1990s. For effective management, the reserve was sub-divided into four areas viz: J1, J3, J4 and J6. These sub-divisions were apportioned to enclave dwellers in isolated villages or camps. Estimated human population in the area is between 20,000 and 25,000. Farming, fishing, hunting and non-timber forest products (NTFPs) gathering are the predominant occupations for the majority of the enclaves.

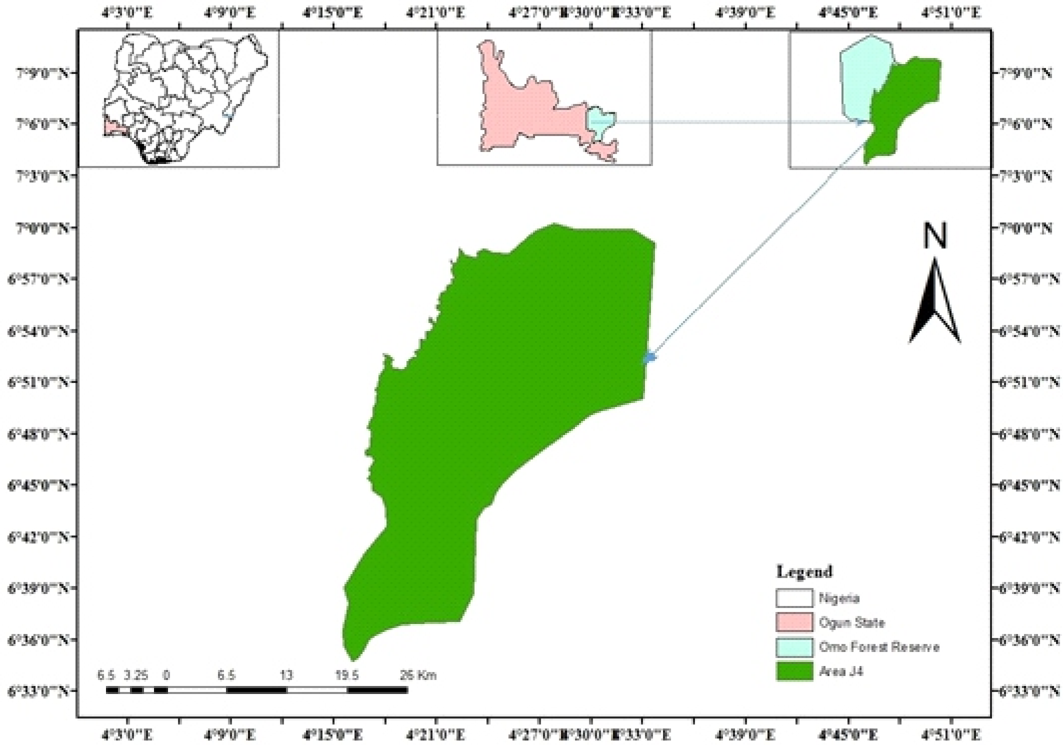

Figure 1: Map of the Study Area

With the exception of the 640 ha Strict Nature Reserve, now a Biosphere Reserve at the centre, most of the forest are disturbed with a substantial parts converted to forest plantations, especially of, but not limited to, exotic tree species such as *Gmelina arborea*, *Tectona grandis* and *Pinus caribaea*. The topography of the sites varies widely from nearly flat to rolling hills. About 80% of the sites are well-drained into the watershed of River *Omo*, which is the major river that traverses the reserve. The uneven topography is characterized by numerous small hills, which are dissected by tributaries of the *Omo*, *Shasha* and *Oluwa* Rivers. This unevenness has been attributed to past geological events (Ojo, 2004). The area was once composed of sedimentary rocks, probably sandstone, of varying coarseness. A period of volcanic activity in the past heated these rocks to such an extent that they became viscous and flowed.

Data Collection

For the field data, stratified random sampling technique was adopted for the study. Five forest-types including natural forest, *Gmelina arborea*, *Tectona grandis*, *Pinus carebeae* and *Nauclea diderrichii* plantations within the reserve were distinguished. Each forest-type was assessed using circular plot method. Plot points were pre-determined using remote sensing. For each point, two circular plots were established, the main plot with a radius of 12.61 m (500 m^2) and the subplot (within the main plot) with a radius of 5.64 m (100 m^2). After locating each point, the centre was marked with GPS before the inventory measurements. In each plot, diameter at breast height (Dbh) and height were measured using diameter tape and Spiegel Relaskop. In the main plot, all trees with Dbh $\geqslant$ 10 cm were measured while only trees with Dbh < 10 cm but >2 cm (i.e. 2 cm $\leqslant$ Dbh < 10 cm) were considered. To ensure accurate placement of the sample plot, GPS receiver was used to locate plot centres as situated on the map. Landsat images of 1991, 2002, 2014 and 2019 were acquired from the US Geological Survey (USGS)'s Earth Explorer. The images were processed and analyzed using iso-cluster unsupervised classification in ArcGIS 10.5, mainly to ascertain possible forest carbon pool in the area. The major dominant land-cover types within the reserve were assessed during ground-truthing to enhance image classification. The images were then reclassified into four land-cover types, viz: closed forest, degraded forest, buil-up area and bare land.

Soil Sampling

Soil samples were collected at 10 locations (i.e. 2 each from north, south, east, west and centre) in each of the forest-types. The samples were taken at 0-15 and 15-30 cm depths since most of carbon are concentrated within 0 to 30 cm of soil depths. The soil samples were collected following standard practices for sample collections. A total of 300 samples were collected, air-dried and bulked into 50 composite samples for further laboratory analyses.

Data Analysis

Measured trees were grouped into diameter classes as: sapling (i.e. 5 ⩽ Dbh < 10 cm), the pole size tree (10-25 cm) and the standard size trees (Dbh ⩾ 25 cm). To estimate other tree components, biomass equations for tree species growing in the tropics were used. All empirical relationships were included in the existing allometric equations with Dbh and height as the predictors, either singly, or in combinations. Estimation of tree biomass, carbon stock, soil carbon stock were done for each of the forest-types as given in the subsequent sections.

Estimation of Biomass and Carbon Stock

Above-ground Biomass

The above-ground biomass (AGB) for each of the forest strata were estimated from the allometric equation by Brown (1997), using field measurements of Dbh and height of individual trees that make up each stratum of the forest. The AGB for each of the forest-types was then multiplied by its extent, as follows:

$$ABG_{land-cover} = \sum \exp\{^{-3.1141 + 0.9719 \ln \left(Dbh_{land-cover} \times H_{land-cover}\right)}\} \quad (1)$$

Therefore, the total AGB of each forest-type was calculated using:

$$ABG_{total} = ABG_{forest-type} \times \text{Area of forest type} \quad (2)$$

Below-ground Biomass

Below-ground biomass was estimated from AGB, as developed by Ponce-Hernandez (2004) for a non-destructive approach, which depends on below-ground biomass values for vegetation as 20% of the above-ground biomass:

$$BGB = 20\% \times AGB \quad (3)$$

Where: BGB = below-ground biomass;
AGB = above-ground biomass;
exp. = exponential function;
ln = natural logarithm;
Dbh = diameter at breast height.

Soil Carbon Stock

The total organic carbon (TOC) matters were determined using the Walkley-Black method (PeRie and Ouimet, 2008). Soil carbon stock was computed for each of the forest-types by multiplying the concentration of total carbon by bulk density and the corresponding depth at which the sampling was collected, as proposed by Kauffman *et al.* (2012), taking into account that soil carbon is concentrated between 0 and 30 cm depth.

$$SC = bd \times sd \times \%Carbon \quad (4)$$

Where: SC = soil carbon (mg/ha); bd = bulk density (g/cm^3); sd = soil depth (cm).

$$SC_{0-15\ cm}\ of\ forest\ type = \sum TOC \times depth \times bulk\ density \quad (5)$$

$$SC_{15-30\ cm}\ of\ forest\ type = \sum TOC \times depth \times bulk\ density \quad (6)$$

$$Total\ Soil\ Carbon = SC_{0-15\ cm} + SC_{15-30\ cm} \quad (7)$$

The sum total of all the biomass obtained from the three pools (i.e. AGB, BGB and SOC) were calculated and the carbon stock was obtained using Ponce-Hernandez's (2004), as modified:

$$\text{Carbon stock in standing tree} = \text{Total biomass} \times \%\ \text{Carbon} \quad (8)$$

$$\text{Total carbon stock} = AG_{carbon\ stcok} + BG_{carbon\ stock} \quad (9)$$

$$\text{Total carbon} = AG_{carbon\ stcok} + BG_{carbon\ stock} + Soil_{carbon} \quad (10)$$

$$CO_2 = Total\ Carbon\ Stock \times 3.67 \quad (11)$$

Trend analysis

$$\Delta LC = L2 - L1 \quad (12)$$

Rate of change

$$R_t = \left((L2 - L1)\ X\ \frac{1}{L1\ X\ t}\right) X\ 100 \quad (13)$$

Where: = ΔLC change in land cover; L_1 (ha) = final year; L_2 (ha) = initial year; t (year) = periodic interval.

Classification Accuracy Assessment

The overall accuracy of land-use/land-cover classification was done by creating a confusion matrix in ArcMap 10.4 using ground reference points obtained during ground-truthing, and following these steps:
Spatial Analyst Tools ▶ Extraction ▶ Extract Multi Values to Points ▶ Input point features (input the Ground-truth GPS points collected on the field) ▶ Input raster (input the classified raster) ▶ Ok ▶ done.

The attribute table was then exported (in dBASE format) for further analysis of the confusion matrix to determine classification accuracy and Kappa Coefficient. A total of 400 ground-truthed points (locations) were used for accuracy assessment of the land-use/land-cover classification. A total of 400 points were also created in the classified image of the study area to generate the cell array for confusion matrix table. This was carried out by dividing the total correctly-classified pixels by the total number of pixels in the confusion matrix following Liu *et al.* (2007), Enaruvbe and Atedhor (2015), Rwanga and Ndambuki (2017). Overall classification accuracy was determined by:

$$Y = \frac{\sum_{i=1}^{n} x_i}{\sum_{j=1}^{N} X_j} \times 100 \quad (14)$$

Where: *Y = overall accuracy;* $\sum_{i=1}^{n} x_i$ *= sum of the correct points; Xj =* $\sum_{j=1}^{N} x_i$ *= total number of all points.*

Other statistics used for accuracy assessment included sensitivity (producer's accuracy), specificity, commission error, omission error, users' accuracy and Kappa's coefficient (K) as given in the subsequent equations.

$$\text{Producer's Accuracy} = \frac{w}{w + x} \quad (15)$$

$$\text{User's Accuracy} = \frac{y}{y + z} \quad (16)$$

$$\text{Specificity} = \frac{z}{x + z} \quad (17)$$

$$\text{Commission Error} = 1 - \text{Specificity} \quad (18)$$

$$\text{Ommission Error} = 1 - \text{Producer's Error} \quad (19)$$

Where: w = number of times a classification agreed with the observed value; x = number of times a point was classified as 'a' when it was observed to not be 'a'; y = number of times a point was not classified as 'a' when it was observed to be 'a'; z = number of times a point was not classified as 'a' when it was not observed to be 'a'. Kappa's coefficient measures perfect agreement between prediction and reality or classification results and the real observation, as is the case in this study. It was computed as:

$$K = \frac{N\sum_{i=1}^{n} x_{ij} - \sum_{ij=1}^{r}(x_{ij} + Xx_{+1})}{N^2\sum_{ij=1}^{r}(x_{ij}Xx_{+1})} \quad (20)$$

Where: r = number of rows and columns in error matrix; N = total number of observations (pixels); x_{ij} = observations in the ith row and jth column; x_{+1} = marginal total of the ith row; and x_{+1} = marginal total of the jth column.

Kappa Coefficient ranges between 0 and 1. A Kappa coefficient of 1 implies perfect agreement, while any value nearing zero means that the agreement between prediction and reality or between classification and real observation is no better than that due to chance. Kappa statistic is categorized as reproduced by Rwanga and Ndambuki (2017), and shown in table 1.

Table 1: Rating Criteria for Kappa Statistics

SN	Kappa statistic	Strength of agreement
1	<0.0	Poor
2	0-0.2	Slight
3	0.21-0.4	Fair
4	0.41-0.6	Moderate
5	0.61-0.8	Substantial
6	0.81-1.0	Almost perfect

Source: Rwanga and Ndambuki (2017)

RESULTS

Five forest-types including *Gmelina arborea*, *Pinus caribeae*, *Nauclea diderrichii*, *Tectona grandis* plantations and natural forest were distinguished within the reserve. Figure 2 shows the tree diameter classes within the forest-types. Most of the trees encountered fell in the Dbh class of 10-25 cm. In the *Gmelina arborea* plantation, there were 165 trees/ha in the diameter class of <10 cm and 298 trees/ha in the diameter class 10-25 cm with 100 trees/ha in ⩾ 25 cm. *Pinus caribaea* has 491 trees/ha in 10-25 cm class with 370 trees/ha in Dbh class > 25 cm. In *Nauclea diderrichii* plantation, 239 trees/ha were in the Dbh class of between 10 and 25 cm, and 207 trees/ha in the above 25 cm. There were 172, 212, and 186 trees/ha of *Tectona grandis* in the diameter classes of <10 cm, 10-25 cm and ⩾ 25 cm, respectively. The natural forest had only 119, 296 and 141 trees/ha in the diameter classes of < 10 cm, 10-25 cm and >25 cm, respectively.

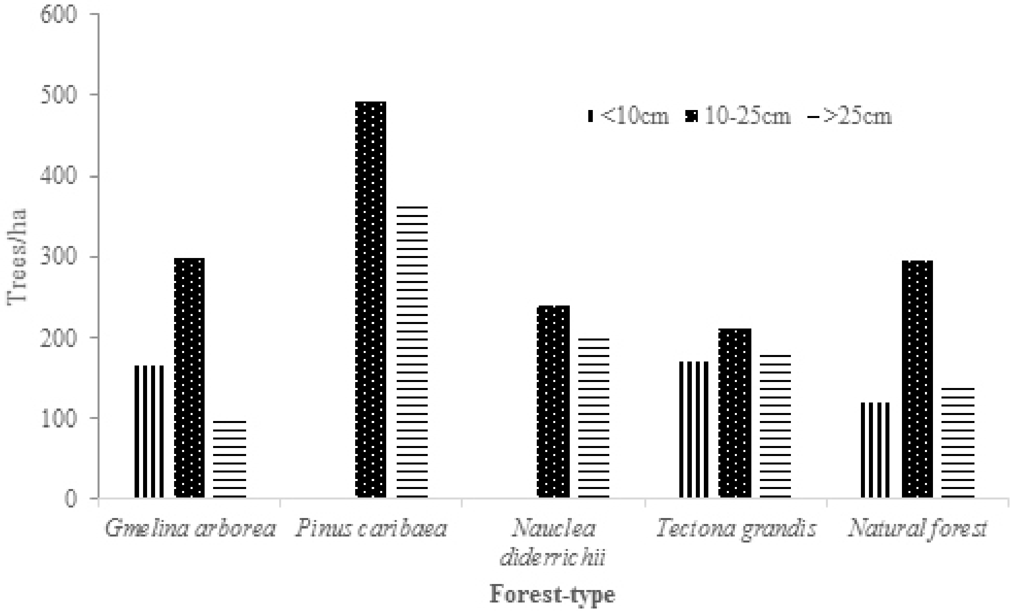

Figure 2: Tree Diameter Classes

Table 2 presents the stand-level tree growth characteristics in the study area. The mean Dbh ranged between 12.65 ± 3.6 and 34.59 ± 7.9 cm for the five forest-types. Mean height values were between 9.0 ± 4.0 m in *Tectona grandis* plantation and 29.75 ± 7.5 m in the natural forest. In terms of stand density, *Pinus caribaea* was highest with 861 trees/ha and 55.73 m^2/ha in basal area. *Nauclea diderrichii* plantation was least-densed with 446 trees/ha.

Table 2: Stand-level Tree Growth Characteristics in J4 Omo Forest Reserve

Forest type	Age (yr)	Dbh (cm)	Height (m)	N/ha	BA (m^2/ha)	V (m^3/ha)
Gmelina arborea	35	12.65 ± 3.6	19.0 ± 6.6	563	51.29	11.80
Pinus caribaea	23	24.30 ± 12.8	21.1 ± 1.8	861	55.73	12.60
Nauclea diderrichii	43	25.27 ± 10.1	15.3 ± 5.7	446	18.65	4.24
Tectona grandis	43	13.05 ± 4.6	9.0 ± 4.1	570	50.25	11.79
Natural forest	-	34.59 ± 7.9	29 ± 7.5	556	17.50	4.41

Abbreviations: Dbh - diameter at breast height; N - number of trees; BA - basal area; V - stem volume

Above- and Below-ground Biomass and Carbon Stocks in J4 Section of OFR

The above- and below-ground biomass, and carbon stocks estimated across the five forest-types within the reserve are presented in table 3. Results revealed that *Pinus caribaea* has an average of 57.45 ± 4.99 tons/ha of above ground biomass. This was followed by the natural forest with 33.41 ± 0.78 tons/ha. *Nauclea diderrichii* was least in terms of the above-ground biomass with 27.37 ± 2.12 tons/ha. Similar trend was observed with respect to below-ground biomass with *Pinus caribaea* having the highest of 11.49 ± 1.0 tons/ha and *Nauclea diderrichii* the least with 5.47 ± 0.42 tons/ha. In terms of carbon stocks in the five forest-types, *Pinus caribaea* has 28.73 ± 2.49 tons/ha and *Nauclea diderrichii* was least with 13.68 ± 1.06 tons/ha in above-ground carbon stock. The results for the below-ground carbon stock was not so different in that *Pinus caribaea* was highest with 5.74 ± 0.50 tons/ha and least in *Nauclea diderrichii* (2.74 ± 0.21 tons/ha). With regards to the total tree carbon stock, *Pinus caribaea* sequestered 34.47 ± 2.99 tons/ha, which was the highest among the forest-types. The least values of carbon was obtained under *Nauclea diderrichii* plantation (16.42 ± 1.27 tons/ha), which is not too far from what was obtained in *Tectona grandis* plantation. The result further revealed that *Pinus caribaea* significantly differed from the four other forest-types in terms of tree above- and below-ground biomass and carbon stocks (Table 3). At the individual tree level, a stem of *Pinus caribaea* sequestered 0.442 ± 0.04 ton of carbon, which was the highest among the tree species studied with least amount of carbon (0.322 ± 0.04 ton/tree) sequestered by *Tectona grandis* stem (Table 4).

Table 3: Mean Separation (LSD) for Tree Biomass and Carbon Stocks in Five Forest-types

Forest type	AGB (tons/ha)	BGB (tons/ha)	AGCS (tons/ha)	BGCS (tons/ha)	TTCS (tons/ha)
Gmelina arborea	30.60±4.03^{a}	6.12±0.81^{a}	15.30±2.02^{a}	3.06±0.40^{a}	18.36±2.42^{a}
Pinus caribaea	57.45±4.99^{b}	11.49±1.0^{b}	28.73±2.49^{b}	5.74±0.50^{b}	34.47±2.99^{b}
Nauclea diderrichii	27.37±2.12^{a}	5.47±0.42^{a}	13.68±1.06^{a}	2.74±0.21^{a}	16.42±1.27^{a}
Tectona grandis	27.92±3.50^{a}	5.59±0.70^{a}	13.96±1.75^{a}	2.79±0.35^{a}	16.74±2.10^{a}
Natural forest	33.41±0.78^{a}	6.68±0.16^{a}	16.71±0.39^{a}	3.34±0.08^{a}	20.05±0.47^{a}

N.B.: means with the same alphabet as superscripts under each column are not significantly different.

Abbreviations: AGB - above-ground biomass - below-ground biomass; AGCS - above-ground carbon stock; BGCS - below-ground carbon stock; TTCS - total tree carbon stock

Table 4: Average Carbon Sequestered by the Individual Stems in the Five Forest-types

Forest types	Age (yr)	N/ha	TTCS (tons/ha)	MTCS (ton)
Gmelina arborea	35	563	18.36 ± 2.42	0.360 ± 0.05
Pinus caribaea	23	861	34.47 ± 2.99	0.442 ± 0.04
Nauclea diderrichii	43	446	16.42 ± 1.27	0.400 ± 0.03
Tectona grandis	43	570	16.74 ± 2.10	0.322 ± 0.04
Natural forest	-	556	20.05 ± 0.47	0.393 ± 0.01

Abbreviation: N - number of trees; TTCS - total tree carbon stock; MTCS - mean individual tree carbon stock

Soil Carbon Stock in J4 Section of OFR

The estimates of the soil carbon stock for the five forest-types in J4 Section of Omo Forest Reserve are shown in table 5. At the depth of 0-15cm, natural forest has the highest amount of 0.9669 ton/ha, followed by *Pinus caribaea* (0.6983 ton/ha), *Tectona grandis* (0.5417 tons/ha), *Gmelina arborea* (0.2708 ton/ha), and *Nauclea diderrichii* plantation has the least with 0.2255 ton/ha. Similarly, at soil depth of 15-30 cm, natural forest was highest in terms of carbon stock with 0.9669 ton/ha, followed by *Pinus caribaea* (0.6089 ton/ha), *Tectona grandis* (0.4696 ton/ha), *Nauclea diderrichii* (0.3932 ton/ha). However, *Gmelina arborea* had the least at this soil depth with 0.3274 ton/ha.

Table 5: Estimates of Soil Carbon Stock in the Five Forest-types

Forest type	Soil carbon 0-15 cm depth (tons/ha)	Soil carbon 15-30 cm depth (tons/ha)	Total soil carbon (tons/ha)
Gmelina arborea	0.2708	0.3274	0.5982
Pinus caribaea	0.6983	0.6089	1.3072
Nauclea diderrichi	0.2255	0.3932	0.6187
Tectona grandis	0.5417	0.4696	1.0113
Natural forest	0.9669	0.9669	1.0113

Total Carbon Stock in J4 Section of OFR

The estimates of the total organic carbon in the five forest-types in J4 Section of Omo Forest Reserve are presented in table 6. The result revealed that *Pinus caribaea* plantation sequestered the highest amount of carbon among all the forest-types with an estimate of 35.78 ± 2.73 tons/ha. This is followed by natural forest (21.98 ± 2.38 tons/ha) and *Gmelina arborea* (18.96 ± 1.82 tons/ha). The *Nauclea diderrichii* plantation sequestered the least amount of carbon with 17.36 ± 1.87 tons/ha. The result further revealed that *Pinus caribaea* absorbed 131.31± 10.02 tons/ha of CO_2 (Table 6). This is followed by natural forest (80.67 ± 8.7 tons/ha), *Gmelina arborea* (69.58 ± 6.7 tons/ha), with *Nauclea diderrichii* having the least CO_2-capturing capacity (63.71 ± 6.9 tons/has of atmospheric carbon).

Table 6: Estimated Total Carbon Stocks Per Hectares of the Forest types

Forest types	Age (yr)	TCS (tons/ha)	CO_2 (tons/ha)
Gmelina arborea	35	18.96 ± 1.82	69.58 ± 6.7
Pinus caribaea	23	35.78 ± 2.73	131.31 ± 10.02
Nauclea diderrichii	43	17.36 ± 1.87	63.71 ± 6.9
Tectona grandis	43	17.75 ± 2.13	65.14 ± 7.8
Natural forest	-	21.98 ± 2.38	80.67 ± 8.7
Mean		22.37 ± 7.71	82.1 ± 28.3

Land-cover Classes in the J4 Section of Omo Forest Reserve

The four land-use/land-cover (LULC) types distinguished in the study area are presented in table 7. They were closed forest, degraded forest, built-up areas and bare land. The spatial extents of land-cover types in the forest reserve between 1991 and 2019 are presented in table 8.

Table 7: Description of the Land Covers

LULC	Description
Closed-canopy forest	This is a forest with closed canopy, either natural or forest plantation.
Degraded forest	This include forest lands with open canopy, where Taungya farming (agroforestry) is being practiced with trees of open-canopy cover.
Built-up area	An area covered with houses, offices or other building structures, which decreases during a period of time, and may later increase inintensity over some period(s).
Bare land	This is an area of land with no vegetation, or abandoned farmland that has not been regenerated.

Abbrevation: LULC - land use/land cover

Table 8: The Spatial Extent of LULC Between 1991 and 2018

LULC	Area (ha)				Area (%)			
	1991	2002	2014	2019	1991	2002	2014	2019
Closed forest	51705.54	52297.92	44997.57	52547.13	65.4	66.1	56.9	66.4
Degraded forest	15892.29	12827.88	13364.64	7275.15	20.1	16.2	16.9	9.2
Built-up area	7154.28	10610.73	7524.45	9290.88	9.0	13.4	9.5	11.7
Bare land	4366.44	3381.93	13231.71	10006.29	5.5	4.3	16.7	12.6
Total	79118.55	79118.46	79118.37	79119.45	100	100	100	100

Abbrevation: LULC - land use/land cover

In 1991 (Figure 3), closed-canopy forest occupied 51705.54 ha (65%) of the reserved land with the degraded forest covering 15892.29 ha (20%). The built-up areas occupied 7154.28 ha (9%) at the time with bare land being the least with just 4366.44 ha (6%). In 2002, closed-canopy forest increase to 52297.92 ha (66%), degraded forest decreased to 12827.88 ha (16%). Built-up area, however increased by 5% to 10610.73 ha (14% of the land area). Nevertheless, bare-land declined by 2% due to regeneration and agroforestry interventions in form of Taungya farming to 3381.93 ha, which was 4% of the total area (Figure 4). In 2014, the closed-canopy forest declined by 11% of its value in 2002 to 44997.57 ha (57% of the total area), degraded forest increased by 13% of the previous area to 13364.64 ha (i.e 17% of the area in that year). In the same vein, bare land increased by 13% to 13231.71 ha during this period (Figure 5).

In 2019, however, closed-canopy forest increased by 9% to 52547.13 ha (66% of the area) with degraded forest shrinking by 8% of the previous value in 2014 to 7275.15 ha resulting from the agroforestry plots closing their canopies, thereby increasing the closed-forest size. Bare land also declined by 4% within the period (2014 to 2019) to 10006.29 ha (13% of the area). Built-up area, however, increased by 3% to 9290.88 ha (Figure 6).

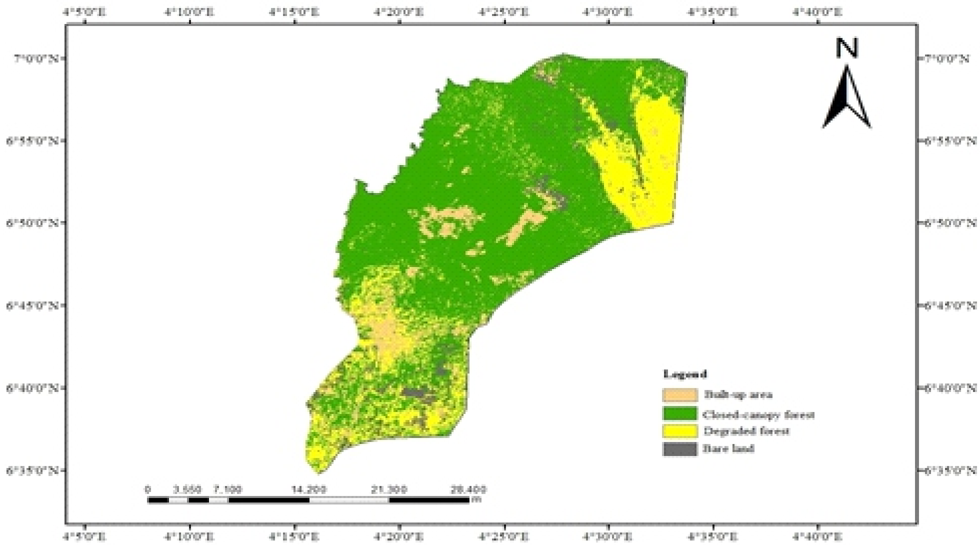

Figure 3: Land-cover Change in J4 Section of OFR in 1991

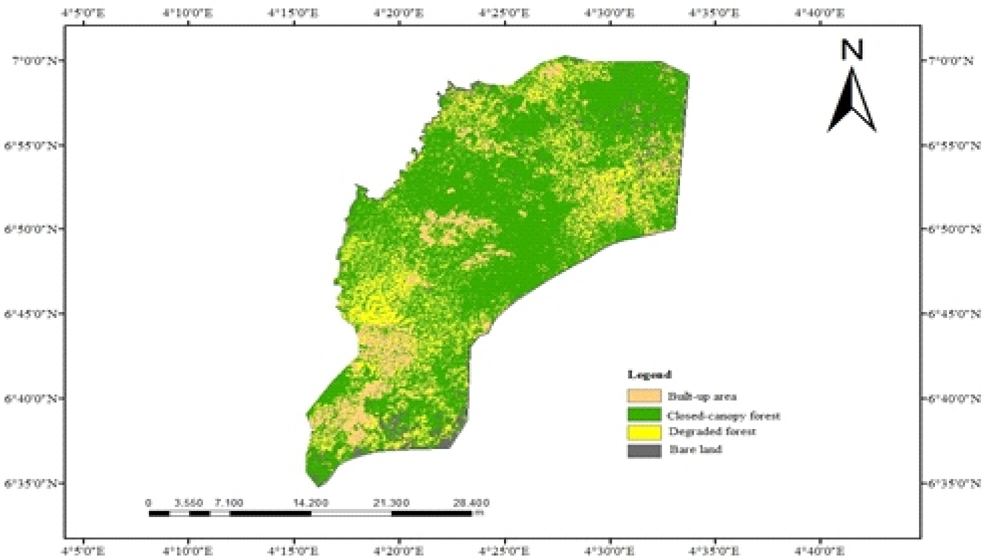

Figure 4: Land-cover Change in J4 Section of OFR in 2002

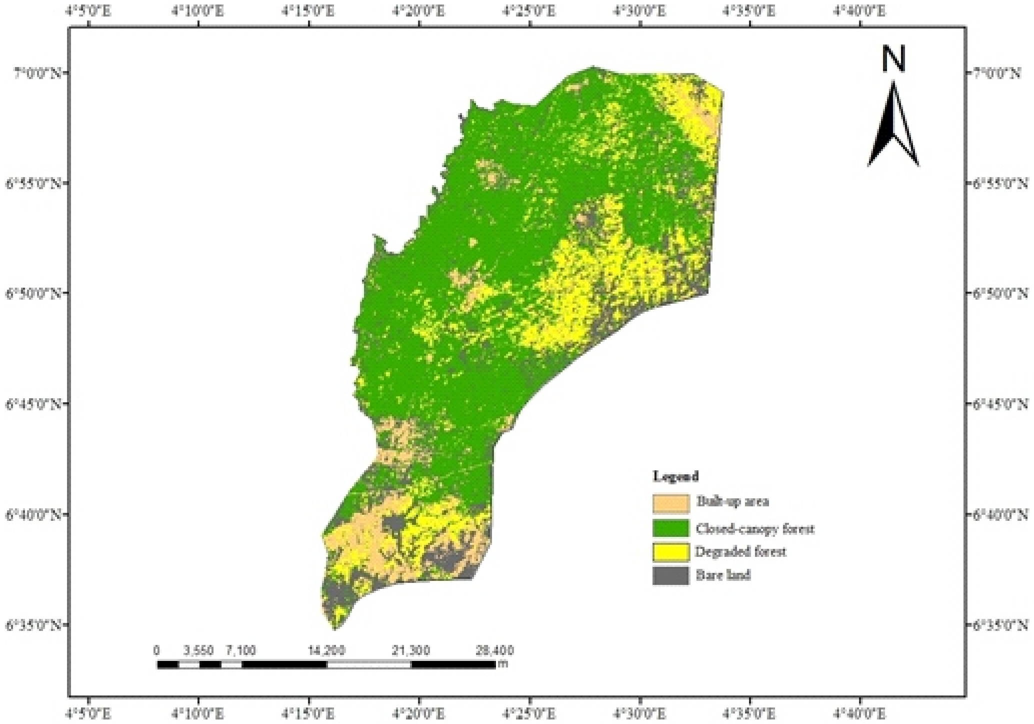

Figure 5: Land-cover Change in J4 Section of OFR in 2014

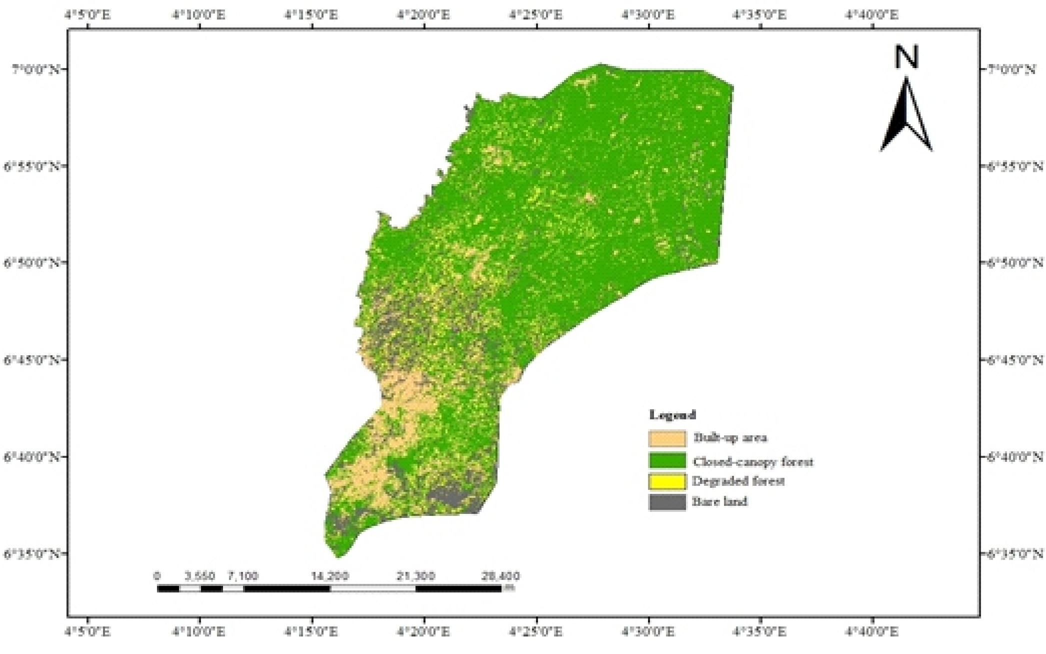

Figure 6: Land-cover Change in J4 Section of OFR in 2019

Land-cover Change Trends Between 1991 and 2019

The trend analysis of the forest reserve revealed a change in size of land covers over the 28-year period (Table 9). Closed-canopy forest increased by 1% while degraded forest lost about 11% of its original extent within the period. One per cent of which was added to the closed-canopy forest with about 10% lost to other forms of conversion like road building and residential areas.

Table 9: LULC Change Trend Between 1991 and 2019

LULC	Change (ha)			% Change		
	1991-2002	2002-2014	2014-2019	1991-2002	2002-2014	2014-2019
Built-up area	3456.45	-3086.28	1766.43	4.4	-3.9	2.2
Close Forest	592.38	-7300.35	7549.56	0.7	-9.2	9.5
Degraded forest	-3064.41	536.76	-6089.49	-3.9	0.7	-7.7
Bare Land	-984.51	9849.78	-3225.42	-1.2	12.4	-4.1

Abbrevation: LULC - land use/land cover

The result of classification accuracy assessment is presented in table 10. The overall accuracy of the classification was 86.5%. Producer's accuracies ranged between 0.9329 and 0.9716 while user's accuracies were between 0.6976 and 0.9379. This statistic is more relevant, and measures the classification actual utility in the field (Rwanga and Ndambuki, 2017). The overall Kappa's coefficient obtained for this study was 0.87.

Table 10: Classification Accuracy Assessment Results

LULC Classification	Category-wise accuracy statistics					
	Specificity	CE	OE	UA	PA	Kappa coefficient
Built-up area	0.9837	0.0163	0.0015	0.6976	0.9583	0.901
Closed Forest	0.9735	0.0265	0.0029	0.8723	0.9716	0.861
Degraded Forest	0.9537	0.0463	0.0081	0.7951	0.9329	0.842
Bare Land	0.9712	0.0288	0.0029	0.9379	0.9671	0.876
Mean	0.9705	0.02948	0.0039	0.8257	0.9575	0.87

Abbrevation: LULC - land use/land cover ; CE - commission error; OE - omission error; UA - user's accuracy; PA - producer's accuracy; Overall accuracy = **86.5%**

DISCUSSION

The results revealed that species differences and stand density significantly influenced the amount of carbon sequestered among the five forest-types with *Pinus caribaea* plantation having more net total biomass and carbon stock and *Nuclea diderrichii* plantation sequestering the least amount of carbon in the area. This corroborates Guo *et al.* (2010), who noted the profound influence of plant density on the accumulation of carbon in any forest. However, age does not seem to have much effect on biomass and carbon stock among species as 23-year-old *Pinus caribaea* sequestered almost twice the amount sequestered by 35-year-old *Gmelina arborea,* and more than double of the estimates for 43-year-old *Nauclea diderrichii* and *Tectona grandis* plantations as well as the tree-level carbon stocks. The four plantation species were planted at the same spacing of 2.5 × 2.5 m, and unthinned. Nevertheless, within-species variations at later growth stages are possible since same species tends to accumulate more biomass and carbon stocks.

As reported by Kohl *et al.* (2017), some tropical tree species may accumulate up to 50 percent of their final carbon stock in the last quarter of their lifetime. This is also in consonance with the finding of Idiege *et al.* (2013), who reported higher biomass accumulation for *Gmelina arborea* at later growth stages. Whereas, this may not be so for pine species, whose rates of carbon stock accumulation were better at early stage of development (Zhang *et al.*, 2019).

However, it has been noted that decline in forest biomass is attributed to the mortality or loss of large trees within the stand, which must have caused changes in stand density and structure. In effect, it did not imply that carbon accumulation decline has to do with the individual tree growth, or stand structure but a reduction in stand density due to mortality (Xu *et al*., 2012). This impacted the total forest biomass and carbon stock negatively. In the present study, three stand density parameters, which affected biomass and carbon stock accumulations and distributions were trees, basal area and stem volume per hectare. Although it has been reported that litters and biomass accumulations in pine plantation are expected to be smaller with correspondingly less organic matter (Robert *et al*., 2002), in the present study, soil carbon stock was highest under pine plantation. It is possible that stand density contributed positively to the amount of litter, and consequently, organic matter. This may also be due to the activities of arbuscular mycorrhiza. According to Okonji *et al*. (2018), arbuscular mycorrhiza directly improve important soil properties for plant growth, and also contribute remarkably to soil organic matter by increasing microbial population and activities. At lesser density, however, natural forest was richer than *Gmelina arborea* plantation in terms of soil carbon stock, probably due to richer concentration of tree species with better accumulation of organic matter in natural forest compared to a monoculture plantation of *Gmelina arborea*.

The result of change detection and forest-cover analysis showed that anthropogenic activities impacted negatively on the forest reserve. However, the closed forest increased between the period by 1%. Azeez *et al*. (2017) noted great contributions of taungya system of farming to forest regeneration in Oso Forest Reserve of Oyo State. A similar case may have played out in the study area. Izekor and Ajobi (2016) have also noted the importance of taungya farming in enhancing forest regeneration while contributing immensely to the income base of the practicing farmers in Edo State. The finding of this study is also in consonance with the finding of Chamshama *et al*. (1992), who reported that taungya system impacted tree survival positively. However, taungya farming has been reported to fail in some places in Nigeria for lack of government support and necessary incentives (Ehiagbonare, 2006).

The gain in closed-canopy forest was not commensurable to the loss of degraded or secondary forest to bare land by 10.9% and built-up areas to the tune of 2.7% and 7.1%, respectively due to encroachments by local communities around the reserve, who farmed within the forest reserve. The continued farming in the area has left most part of the secondary forest badly degraded and almost non-existent. It appears that as population increases, which were seen in form of increment in number of built structures in the area, the more land was needed, and the more the secondary forest disappeared. Basnyat (2009) noted the negative impacts of demographic changes, especially population growth, wood and housing demands on forest degradation and eventual deforestation. This is in line with the observations by Mmom and Mbee (2013), who noted the negative effects of population growth and infrastural developments on forest extent. Forests, in developing world with high poverty rate, hardly thrive in atmosphere of geometric population increases, as people continued to turn to forests and forest lands for virtually every need.

CONCLUSION

This study has shown that carbon sequestration in the reserve is dependent upon tree species composition and less-inflenced by ages among the forest-types. However, we found that stand density has great contribution to tree biomass and carbon stock accumulations with direct consequences on soil carbon stock. At the age of 23 years, an individual stem of *Pinus caribaea* could accumulate 9.5% more of carbon than a 43-year-old stem of *Nauclea diderrichii*, 18.6% more than a 35-year-old stem of *Gmelina arborea* and 11.1% more than a 43-year-old stem of *Tectona grandis*. There was an addition of about 1% to the closed-canopy forest within the period probably due to some interventions like afforestation and artificial regeneration. Therefore, further positive interventions to encourage forest regeneration in the reserve is advocated. This would enhance more carbon sink. For future plantation establishments, and when choices are to be made among tree species, especially in the tropics, *Pinus caribaea* could be a best choice for its ability and potential to sequester more carbon, as observed in this study.

The study showed that the use of allometries for carbon stock estimation is adequate, and this presents an opportunity for a non-destructive analysis of carbon in order to prevent further depletion of a badly-degraded ecosystem. Hence, non-destructive approach is advisable at all times, particularly during carbon studies since reliable estimate of carbon stock is possible without cutting down trees. With this in mind, there is urgent need for regeneration and enrichment planting in the reserve for improving the carbon stocks.

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