The geospatial modelling of carbon sequestration in Oluwa Forest, Ondo State, Nigeria

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ABSTRACT
The study assessed the amount of carbon being sequestrated in the Ondo State Afforestation Project in Oluwa Forest, south-west of Nigeria, with the view to determine the above ground biomass (AGB) and belowground biomass (BGB), estimate the total carbon content and evaluate the CO₂ sequestered. Geospatial techniques and the non-destructive field observation method were used. The results showed that a total of 359 megatons of CO₂ was estimated to have been sequestrated using the non-destructive field measurements. In addition, the rate of change in land use land cover between 1984 and 2015 was determined. A geospatial database derived from field measurements was developed to monitor carbon content of the forest.

Introduction
Carbon sequestration (CS) refers to the storage of carbon in a stable form through direct and indirect fixation of atmospheric carbon dioxide (Van Beek, 2010). Photosynthesis in plants converts carbon dioxide (CO₂) 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 aboveground biomass (AGB), below ground biomass (BGB), dead wood, litter and soil organic matter in the forest ecosystem (Cienciala, Seufert, Blujdea, Grassi, & Exnerová, 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 the IPCC Special Report on CO₂ Capture and Storage, CO₂ sequestration could provide an emission reduction of CO₂ until 2100 of up to 55% which is known for its potential influence as a greenhouse gas to climate pattern of the world (Haghtparast, Delbari, & Kulkarni, 2013) and (Vashum & Jayakumar, 2012). The quantification of CS potential of various ecosystems is a challenge (Jeyanny, Balasundram, & Husni, 2011). Thus, assessing the amount of carbon stored in the forest ecosystem periodically is a means of determining the CO₂ emitted into the atmosphere due to deforestation and degradation (Vashum & Jayakumar, 2012).

According to (Bajracharya, 2008), every 2 cm³ growth in forest wood gives rise to one ton of carbon captured in the air. The Kyoto Protocol is a major global instrument to mitigating the adverse effect of CO₂ and other greenhouse gases. The protocol is an international legal framework that enables industrialized countries to comply with the reduction of greenhouse gases emitted from 2008 to 2012 for sustainable development. Forests create a carbon reservoir of increased AGB through increased forest cover and by increased proportion of soil organic carbon content (Banskota, Karky, & Skutsch, 2007). The estimation of forest biomass involves field measurement and remote sensing–GIS methods. The field measurement can be through a destructive approach which involves harvesting and measuring the oven-dried weight of the different tree components of the harvested tree, as against a non-destructive approach where individual trees are estimated by considering the physical characteristics of the trees like shape, height and diameter at breast height (DBH) measurements, volume and bulk density for developing a predictive model. The latter approach does not involve felling of tree especially in areas with protected tree species where tree cutting may not be feasible. However, while the field measurement method is most accurate, it becomes more challenging for large area estimation where it is a strenuous, expensive, time-consuming and destructive approach. As a result, remote sensing provides a synoptic means of obtaining geospatial information for inaccessible areas for monitoring vegetation, land use land cover (LULC) change (Vashum & Jayakumar, 2012).
Cortés, Girotto, and Margulis (2014) explained the use of Landsat imagery, Aster Global Digital Elevation Model data and field measurements in estimating the AGB of forests. The use of band ratio indices such as the Normalized Differential Vegetation Index (NDVI) in taking advantage of the discriminating power of infrared band ratios on vegetation provides a direct measure for estimating biomass (Ponce-Hernandez, 2004). There are a few existing estimations of forest biomass carbon stocks in Nigeria, from that in Effan Forest Reserve, north-western Nigeria (Abubakar, Abdulkadir, Jibrin, & Abubakar, 2014) to the study in Ile-Ife, south-western Nigeria (Odwe, Rofiat, & Ogunsanwo, 2012) and a general overview of carbon fluxes in five forest zones in Nigeria from 1990 to year 2000 (Momodu, Siyanbola, Pelemo, Obioh, & Adesina, 2011). Momodu et al. (2011) carried out an estimation of the carbon fluxes in the forest zones of Nigeria from 1990 to 1995, with extrapolation up to year 2000. The report established that of the five categories of forest life zones, lowland rainforest occupies close to 80% of the land area and contributes about 84% to the total carbon stock in the forest zones of Nigeria in year 2000. Total carbon stored was estimated to be 2.55 TgC in 2000, the estimated value of 2.84 TgC in 1990. Houghton (2005) estimated that 90% of the world’s terrestrial carbon is sequestered in forests, which makes about 3.6 billion hectares (28%) of the land area. The influence of forests ecosystem on climate change is not well quantified and is often disregarded. The overall CO\(_2\) source/sink dynamics of forests is of great consideration as trees grow, die and decay. Also, human influences on forests (inefficient management) can further affect CO\(_2\) sequestered (Nowak, Greenfield, Hoehn, & Lapoint, 2013). Thus, adequate information should be available to better understand the consequences of anthropogenic activities in our forest ecosystem.

The purpose of this research is to estimate the AGB and BGB in the study area, determine the total carbon content and evaluate the CO\(_2\) sequestered. The questions this research addressed are: what is the total amount of AGB and BGB estimated in the study area between 1984 and 2015?; what is the percentage change in the LULC during the periods under consideration? and is there a pattern in the biomass distribution across the study area? This paper, therefore, assessed the rate of change in LULC between 1984 and 2015 and develops a geospatial database for monitoring carbon content in the study area.

### Methods

#### Study area

The study area is located on the north-western part of the Oluwa Forest, in Lisagbede Village, Odigbo LGA in Ondo State. Having an area of approximately 24,100 ha, it lies between 4°38′30″E, 6°43′50″N and 4°33′50″E, 6°39′8″N and is bounded in the north by the river Oni flowing into Oke-Igbo in Ondo State, in the south by Lagos – Benin expressway, the river Oluwa in the east and in the west by Omo Forest Reserve in Ogun state. The topography is between 137 m southward and 277 m towards the northern part of the forest and is gently undulating with a well-drained soil and outcrops of rocks of a basement complex of Precambrian era in some parts of the reserve (Omolade & Akinwolere, 2012). The rainfall pattern of the area is bimodal in nature and characterized with heavy downpour in September and October with annual rainfall ranging between 1500 and 2200 mm as reported by Onyekwelu, Mosandl, and Stimm (2006) and Omo & Akinwolere (2012). The study area (path 190, row 055) on Landsat Worldwide Reference System (WRS-2) archive is shown in Figure 1.

#### Field data

##### Sampling design

As recommended by Pouyat, Groffman, Yesilonis, and Hernandez (2002) and Okunade and Okunade (2007), to be in line with recommended practice, 10 random sample plots of 20 m × 20 m (from office-reconnaissance survey) were located in the field using a Garmin GPS. According to MacDicken (1997), the use of GPS receivers enables efficient and accurate placement of the plots. In each of the plots, all trees with DBH (i.e. diameter at 1.3m) exceeding 5 cm were measured with a 50 m tape and their heights measured with a distometer. For each plot, field sketch on the accessibility of the plot, the DBH and the heights of trees including the photograph of the plot were recorded. All field measurements were carried out in the month of March 2015.

##### Classification system

Tree major dominant tree-specie groups namely Tectona grandis, Gmelina arborea and indigenous species (such as Mahogany, Obeche and Opepe) were observed in the forest reserve. These were used as ground-truth parameters for the image classification as adopted by Abubakar et al. (2014). Trees were grouped in diameter classes as: sampling, i.e. younger tree class with DBH below 40 cm, the pole size tree with DBH ranging from 40 to 80 cm and the standard size trees with DBH above 80 cm. Smaller trees <5 cm DBH were not considered since they contribute a relatively small quantity of biomass (Brown, Gillespie, & Lugo, 1989). It is worthy of mentioning that replantation of T. grandis was carried out in the years 1989, 1986 and 1996 in some parts of the forest.
Soil sampling

Soil samples were randomly collected at the centre of each plot at depths of 0–15 and 15–30 cm, respectively, since the highest proportion of the total root is within the first 30 cm of the soil surface (Jackson et al., 1996; Bohm, 1979). About two-thirds of the carbon in terrestrial ecosystems comes from soil organic carbon (Eswaran, Van Den Berg, & Reich, 1993). As a result, the soil samples were carefully collected since it forms the major component of the result, thereby preventing the top-layer soil from falling to the lower samples according to best practices.

Data preparation

Estimation of biomass and carbon stock

AGB for the tree species strata was estimated from measured DBH and tree height using a generalized tree biomass regression equation for the specific precipitation zone (Brown, 1997):

\[ y = e^{(-3.1141 + 0.9719 \ln(DBH + H))}, \]

where \( y \) is the AGB in kg; DBH, diameter at breast height in cm; \( H \) is the height of tree in meter and this was converted to ton ha\(^{-1} \) by multiplying with 0.001.

The regression equation of Brown et al. (1989) and Brown (1997) with \( r^2 = 0.97 \) was adopted. The criteria for using this model are that the trees parameter has a DBH > 5 cm, the study area is in the moist tropical forest with a rainfall pattern in the range 1500 < rainfall < 4000 mm. This study area is located in the moist tropical forest and has an annual rainfall range of 1700 to 2200 mm (Onyekwelu et al., 2006).

In summary, the total AGB of trees per sampled plots was multiplied by the number of trees per plot. Then, the biomass from all sampled plots per class was added to represent the biomass for each class (Table 1).

Land cover area estimation was obtained from the supervised classification of Landsat imagery of 2015 using field observations as training classes for spectral signatures which were subsequently used for upscaling the biomass from plot to the entire land cover types.

Above ground biomass. The AGB, \( y \) for each of the forest strata was estimated from the regression equation (Brown, 1997) using field measurements of DBH and height of individual trees that make up each stratum of the forest.

The AGB for the entire stand was then multiplied by the land cover area estimation.

\[
y_{\text{landcover}} = \sum e^{(-3.1141 + 0.9719 \ln(DBH_{\text{landcover}} + H_{\text{landcover}}))},
\]

Total AGB of each landcover \( y_{\text{TOTAL}} \) = \( y_{\text{landcover}} \times \text{Area of landcover} \).

Below ground biomass. BGB is estimated from AGB. According to Ponce-Hernandez, (2004) a non-destructive approach depends on belowground biomass values for vegetation as 20% of the aboveground biomass.

Below ground biomass = 20% × above ground biomass

i.e.

\[
BGB = 20\% \times AGB.
\]
Soil carbon stock.. The total organic carbon (TOC) of soil matter was determined by collecting soil samples from the sub-plot within the main sample plots (Table 13) using the Walkley–Black method (Périé and Ouimet, 2008). A total of 20 samples at 0–15 and 15–30 cm were collected and for TOC (%Carbon). Soil carbon stock was computed by multiplying the concentration of total C by bulk density and the corresponding depth at which the sampling was done.

\[
\text{Soil carbon} = \text{bulk density \left( g/cm}^3 \right) \times \text{soil depth interval (cm)} \times \% \text{Carbon},
\]

(3)

\[
\text{Soil carbon}_{0\text{–}15\text{ cm} \text{of land cover}} = \sum \text{TOC} \times \text{Depth} \times \text{Bulk Density},
\]

\[
\text{Soil carbon}_{15\text{–}30 \text{ cm} \text{of land cover}} = \sum \text{TOC} \times \text{Depth} \times \text{Bulk Density}.
\]

Carbon stock estimation. The sum total of all the biomass obtained from the three pools considered which are AGB, BGB and SOC was calculated and the carbon stock was obtained using Equation (4). According to Ponce-Hernandez (2004), total carbon stock can be calculated from

\[
\text{Carbon stock in standing tree} = \text{Total biomass} \times \% \text{ Carbon},
\]

(4)

Total carbon stock = AG carbon stock + BG carbon stock = AG carbon stock + carbon belowground biomass + carbon stock in soil.

LULC change

In ERDAS Imagine 2014 software, a false colour composite (band 754) of the downloaded Landsat imagery (1984, 1991, 2002, 2010 and 2015) was carried out. The false colour composite enables vegetation to be detected readily on the imagery. The area of interest was defined and the training sites for the supervised classification extracted using the maximum likelihood algorithm. The imageries acquired were of the same season, which was between December and January. The ground-truth data (see the section "Field data") was also incorporated as criteria for change detection. In line with Anderson, Hardy, Roach, and Witmer (1976) classification scheme, the study area was categorized into six classes for the classification based on spectral responses of the ground-truth features. The signature separability showing the statistical distance between signatures which determines how distinct the spectral signatures of features are to one another was also done. An accuracy assessment was, however, carried out for the classification (Tables 2 and 3). From the results of the supervised classification, post-classification change differencing technique described by Lu, Mausel, Brondízio, and Moran (2004) and Mas (1999) was used in assessing changes in land use/land cover within the study area.

Accuracy assessment

The overall accuracy for the 2015 classification was obtained as 89.17%, while the overall kappa coefficient was 0.8223. The accuracy totals for the same year are shown in Table 2, while the corresponding conditional kappa for each of the categories is shown in Table 3.

Normalized Difference Vegetation Index

The surface reflectance imagery was downloaded from USGS webpage (http://espa.cr.usgs.gov) by placing an order for each of the surface reflectance data of the imagery used except for 2002 and 2010 which were not available. The NDVI was carried out using both the top of atmosphere (TOA) reflectance from the raw Landsat imagery and that from the surface reflectance in order to compare both the results.

Table 1. Biomass area estimates.

| Year | Forest stand | Gmelina arborea | Natural forest | Tectona grandis | Total |
|------|--------------|----------------|----------------|----------------|-------|
| 1984 | Area (Ha)    | 2479           | 16,207         | 88,392         | 104,599|
|      | Biomass (ton)| 369,852        | 68,738         |                | 438,588|
| 1991 | Area (Ha)    | 9162           | 9455           | 5371           | 15,688|
|      | Biomass (ton)| 209,073        | 192,949        | 122,584        | 524,606|
| 2002 | Area (Ha)    | 10,939         | 5949           | 6578           | 23,466|
|      | Biomass (ton)| 249,621        | 135,751        | 150,112        | 535,484|
| 2010 | Area (Ha)    | 4935           | 7406           | 11,652         | 23,993|
|      | Biomass (ton)| 112,620        | 168,997        | 265,903        | 547,520|
| 2015 | Area (Ha)    | 116            | 13,955         | 5,783          | 19,854|
|      | Biomass (ton)| 2649           | 318,456        | 131,977        | 453,082|

Image processing

Five Landsat scenes were acquired on 11 December 1984, 5 January 1991, 3 January 2002, 11 December 2010 and 15 January 2015 (path/row: 190/55) from the US Geological Survey (USGS) Earth Explorer website.
Geospatial database for monitoring carbon content

The biomass distribution map of 2015 (as a reference biomass regime for other years) was done in ArcMap 10.1 (Figure 14) using the inverse distance weight interpolation technique in the Spatial Analyst tools from the ground-truth (sample plots) measurements as adopted by Abubakar et al. (2014). However, to monitor the biomass distributions and carbon contents over the years, NDVI of the Landsat imageries of 1984, 1991, 2002, 2010 and 2015 was used as explained by Klemas and Pieterse (2015), that AGB is usually evaluated using one of several vegetation indices. The most common index used is the NDVI, which is the ratio of the difference between the Red and Near Infrared reflectance and their sum. NDVI indicates how healthy the leaves are and can be related to plant biomass and also its carbon content.

Results

Tree height-DBH

The height and DBH of the trees measured are shown in Table 4.

Soil organic content

The result of the soil organic content derived from TOC analysis using the Walkley–Black method is shown in Tables 5 and 6.

Tables 3 and 4 show the soil organic carbon at different soil horizon and the proportion of soil organic carbon in the forest stand, respectively, with the degraded forest having 46.7% of the entire SOC, while the natural forest has 6.7%, which is the lowest organic carbon content in soil.

Table 5 shows that T. grandis has the overall highest biomass of 101,016.92 ton/ha followed by the natural forest with 90,743.729 ton/ha then 3240.115 ton/ha for degraded forest and 396.647 ton/ha for G. arborea which has the lowest total biomass.

Field-based measurements

About 760 trees measured had their DBH between 13 and 245 cm. The DBH was categorized into classes similar to that adopted by Abubakar et al. (2014). Figure 2 shows the distribution of the tree stand density with T. grandis having trees within the sapling, pole and standard sizes, while G. arborea has between sapling and pole sizes. The natural forest has between pole and the largest standard sizes with the degraded forest only within pole sizes.

Allometric equation

The allometric equation of Brown (1997) was applied to field measurements to estimate the AGB for the sample plots. The equation was found to exhibit a positive correlation of $R^2 = 1$ as shown in Figure 3.
Figure 4 shows a high logarithmic relationship and not a linear relationship between AGB and the product of the square of DBH and height ($D^2H$).

**Other allometric equations from field measurements relationships**

Figures 4 and 5 show the relationships between the logarithmic functions of height, DBH and AGB. A positive correlation of $R^2 = 0.8228$ for lnH – lnDBH graph and $R^2 = 0.8084$ for lnAGB – lnH graph was found.

Other strong relationships which exist between field-measured height and diameter are polynomial in nature.

It was established from the field measurement that height is strongly correlated with the AGB, having $R^2 = 0.8084$.

**Total AGB**

The AGB from all the forest stands ($T. grandis$, G. arborea, indigenous species and degraded forest) was added to represent the biomass for the entire forest.

Total AGB = $\gamma_{Tectona grandis} + \gamma_{Gmelina arborea}$

+ $\gamma_{Indigenous} + \gamma_{Degraded}$

= 84, 177, 547 + 330, 521 + 75, 618.541 + 2, 699.73

= 162, 826, 343 ton

**Total BGB**

The BGB is estimated from AGB as 20% of the AGB (see the section “Below ground biomass”).

Total BGB = $0.2 \times 162, 826.343 = 32, 565.269 ton.

**Soil carbon**

The organic carbon of soil samples collected at 0–15 and 15–30 cm depth was determined by multiplying the concentration of total C by bulk density and the corresponding depth at which the sampling was done.

Soil carbon (Mg/ha) = %Carbon

$\times$ soil depth interval (cm)

$\times$ bulk density (g/cm$^3$),

Unit bulk density = Unit weighted sample

$\div$ Unit volume of sample

= $\frac{10g}{20 \text{ cm}^3} = 0.5 \text{ g cm}^{-3}$.

The bulk density was determined from the unit weight and volume of the soil sample.

Soil carbon at 0 – 15 cm for each forest stand

= $\sum$ %TOC $\times$ depth $\times$ bulk density,
Soil carbon at 15 – 30 cm for each forest stand = $\sum \%\text{TOC} \times \text{depth} \times \text{bulk density}$,

Soil carbon = $\%C \times 15 \text{ cm} \times 0.5 \text{ g cm}^{-3} = \text{kg} \times 0.001 = \text{ton}$,

Soil carbon of each forest stand = Soil carbon at 0 – 15 cm + soil carbon at 15 – 30 cm

The soil carbon from the top/surface soil (0 cm) to depth of 15 cm was added to the soil carbon up to 30 cm. The total soil carbon was then added for all the forest stands.

Total soil carbon = Soil carbon extent$_{Tectona grandis}$ + soil carbon extent$_{Gmelina arborea}$ + soil carbon extent$_{natural forest}$ + soil carbon extent$_{degraded forest}$

Total soil carbon = $3.861 + 0.0218 + 1.480 + 0.434 = 5.797 \text{ ton}$,

Total soil carbon = 5.797 ton.

**Total carbon stock**

The total carbon stock was estimated as the total stock of carbon in the ecosystem, including above ground and below ground stock. The constituents of the below ground stock are the carbon content in roots and all BGB and the carbon in the soil.

The total below ground carbon stock is the addition of both carbon in forest floors and litters and those beneath the soil.

Total below ground carbon stock = BGB carbon + soil carbon = $16,282.6343 \text{ ton} + 5.797 \text{ ton}$ = $16,288.431 \text{ ton}$.  

(5)

The above ground carbon stock was used as 50% of the AGB for converting forest AGB to carbon stock (IPCC, 2003; Ponce-Hernandez, 2004).

AGB carbon stock = $162,826.343 \times 0.5$

= $81,413.1715 \text{ ton}$.

The total carbon stock for the study area was estimated as the summation of the total above ground carbon stock and the total below ground carbon stock.

Total carbon stock = AGB carbon stock + TBGB carbon stock

= $81,413.1715 \text{ ton} + 16,288.431 \text{ ton}$

= $97,701.6031 \text{ ton}$

(6)

**Carbon dioxide (CO$_2$) sequestered**

The total carbon stock can be converted to CO$_2$ by multiplying carbon stock by 3.67 which is the ratio of the molecular weights between CO$_2$and carbon (Kauffman & Donato, 2012).

CO$_2$ = Total carbon stock $\times 3.67$

(7)

CO$_2$ = $97,701.603 \times 3.67$ = $358,564.883 \text{ ton}$.

The total carbon sequestered by the forest reserve is estimated to be 359 megaton of carbon.

**LULC change**

Tables 2 and 3 show the accuracy assessment result, and the LULC changes are illustrated in Tables 7–10, and Table 14 including Figure 6.
Figure 3. Allometric regression equation on field measurements.

Figure 4. Logarithmic relationship between height and DBH.

Figure 5. Logarithmic relationship between aboveground biomass and height.
Table 7. Land use land cover area.

| Land use land cover | 1984   | 1991    | 2002    | 2010    | 2015    |
|---------------------|--------|---------|---------|---------|---------|
|                     | Area (Ha) |         | Area (Ha) |         | Area (Ha) |
| Built-up            | 2500.035 | 1207.990 | 740.028  | 186.964 | 432.878 |
| Gmelina arborea     | 2479.137 | 9161.847 | 10.938.711 | 4935.161 | 116.066 |
| Natural forest      | 16207.351 | 8455.265 | 5948.792 | 7405.639 | 13955.108 |
| Tectona grandis     | 3012.196 | 5371.798 | 6578.097 | 11625.176 | 5783.411 |
| Wetland             | –       | –       | –       | –       | 15.998  |
| Deforested          | –       | –       | –       | –       | 3908.475 |
| Grand total         | 24198.718 | 24196.900 | 24205.628 | 24198.718 | 24195.983 |

Biomass map

Figure 3 shows the biomass distribution map of the study area obtained from ground-based plot-level measurement as used by Goswami, Verma, and Kaushal (2014) and Abubakar et al. (2014) for the current biomass variation.

Normalized Difference Vegetation Index

The NDVI for the years 1984–2015 using the digital numbers directly from the imagery is shown in Figures 7–9. The years 1984 and 1991 have NDVI values which range from 0.377 to 0.345, indicating a reduction in biomass while in 1991 and 2002, there was an increase from 0.345 to 0.408; and between 2002 and 2010 an increase from 0.408 to 0.513 was observed. However, between 2010 and 2015 a huge decrease from 0.513 to 0.360 was observed when compared to the trends observed from 1984 to 2010.

It was observed that the NDVI for the years 1984–1991 using surface reflectance varied between 0.278–0.570 and −0.120 to 0.083 compared to using the TOA reflectance (digital number) which varied between 0.084–0.377 and 0.055–0.345 (Figures 7 and 10), indicating an increase in biomass as confirmed by the LULC change. While, the NDVI values using the digital numbers for 2015 range between 0.058 and 0.390 compared to 2015 NDVI values from surface reflectance between −0.174 and 0.141 (Figures 9 and 10), which is still in the theoretical range of −1 to 1 for NDVI. This shows that the NDVI was not affected by the surface reflectance in the study area, which although compensates for the adverse effects of the atmosphere from clouds, atmospheric aerosol, gases, etc. However, this was further proved by carrying out the NDVI for the entire Landsat scene, which was in the range of −1 to 1 as shown in Figure 10.

Predicting biomass and carbon content

The biomass database trend extracted from the three vegetative land cover (natural forest, G. arborea and T. grandis) shows the variation from 1984 to 2015. G. arborea and T. grandis give a decrease in biomass and in turn carbon content from 2002 and 2010, respectively; while, the afforested species are steadily replaced by the natural forest as illustrated in Figure 11.

Tables 1 and 11 show the biomass estimates and database obtained using the forest stands of 2015 field measurements as reference on the imagers for the various epochs. Land cover area for each of the forest stand was multiplied by the stands plot measurement biomass per unit area.

Discussion

To estimate the AGB and BGB in the study area, determine the total carbon content and evaluate the carbon dioxide (CO₂) sequestered, a total of 760 trees were measured on field. The DBH of all the trees measured ranges from 26 to 130 cm. The smallest tree category by
size (DBH) was below 40 cm having an average stand density of 612.5 DBH/ha, the next in size is the pole size trees with the DBH ranging from 40 to 80 cm having an average stand density of 497.5 DBH/ha and the standard
tree with the DBH greater than 80 cm having an average tree stand density of 790 DBH/ha as shown in Tables 4 and 5. The natural forest has the highest number of trees of 208 also with the biggest DBH of 197 and 52 cm standard size and pole size categories, respectively, due to its diversity in tree species. Ebuy, Lokombe, Ponette, Sonwa, and Picard (2011) explained the difficulty in estimating heterogeneous or mixed-species forest stand, hence the reason for adopting (Brown, 1997) pan-topical allometric model which gave a positive correlation of 1 between the field measurements and the biomass. We observed a linear relationship between the logarithmic functions of the DBH and AGB with $R^2 = 0.9375$ (Figure 12), while the relationship between DBH and height is non-linear (Figure 4). As stated earlier, DBH had a stronger correlation with biomass compared to the tree heights, which agrees with both Brown et al. (1989) and Chave et al. (2004). Odiwe et al. (2012) also used the Brown et al. (1989) allometric model in estimating the carbon stock in topsoil, standing floor litter and AGB in T. grandis plantation 10 years after establishment in Ile-Ife, south-western Nigeria.

Degraded forest (originally T. grandis plantation) was found to have the highest soil organic carbon of 46.7%. The total AGB for the study area (163 Mg ton/ha) shown in Table 12 was smaller compared with

Figure 9. NDVI for 2015 (using top of atmosphere (TOA) reflectance).

Figure 10. Landsat-derived NDVI (using surface reflectance).
Brown et al. (1989) assertion that AGB for undisturbed tropical forests of Asia and the world to be an average of 215 and 192 Mg/ha, respectively. The total aboveground carbon stock estimated was 81 Mg tons of carbon, while the total belowground carbon stock was 16 Mg tons of carbon with soil carbon of 5.797 tons (see the sections “Soil carbon” and “Total carbon stock”).

A total of 359 Mg ton/ha of CO$_2$ was estimated to have been sequestered in the area. This value, though considering varying area extent, is higher compared to the values of carbon stock recorded in Ile-Ife (28.18 ton/ha) and in other regions of Africa reported by Odiwe et al. (2012) that the cocoa agroforestry in South Cameroon has 152 Mg ton/ha, while oil palm and rubber plantations in Cameroun both have 66–88 and 248–264 Mg ton/ha, respectively. Based on the 2015 supervised classification, the area extent of land use is in the order of natural forest > T. grandis > degraded forest > G. Figure 11. Biomass estimates between 1984 and 2015.

Table 11. Plot biomass database estimate of 2015.

| Plot | Easting (mE) | Point (mN) | H (m) | lnH | D (cm) | lnD | n | lnD2H | AGB (ton) | TOC % | BGB (ton) | Above ground carbon (ton) | Below ground carbon (ton) | Total carbon (ton) | Total CO$_2$ (ton) |
|------|--------------|------------|-------|-----|--------|-----|---|-------|---------|-------|----------|-------------------------|------------------------|----------------|---------------------|
| Plot1 | 675,803.250  | 768,972.850 | 20.531 | 3.022 | 182.000 | 5.204 | 39 | 13.430 | 20.712 | 16 | 4.142 | 10.356 | 20.142 | 30.499 | 111.929 |
| Plot2 | 673,696.230  | 771,454.960 | 17.640 | 2.870 | 127.000 | 4.844 | 81 | 12.559 | 8.880 | 16 | 1.776 | 4.434 | 17.774 | 22.216 | 81.533 |
| Plot3 | 679,595.720  | 769,663.050 | 17.708 | 3.166 | 167.000 | 5.118 | 78 | 13.402 | 20.153 | 14 | 4.031 | 10.077 | 18.031 | 28.107 | 103.153 |
| Plot4 | 674,967.180  | 757,490.460 | 17.278 | 2.849 | 84.000 | 4.431 | 78 | 11.711 | 3.897 | 14 | 0.779 | 1.948 | 14.779 | 16.728 | 61.391 |
| Plot5 | 677,823.030  | 753,258.570 | 16.370 | 2.795 | 337.000 | 5.820 | 208 | 14.436 | 55.043 | 14 | 11.009 | 27.522 | 25.009 | 52.530 | 192.786 |
| Plot6 | 679,929.360  | 752,786.530 | 16.911 | 2.828 | 140.000 | 4.942 | 22 | 12.711 | 10.301 | 16 | 2.060 | 5.150 | 18.060 | 23.211 | 85.182 |
| Plot7 | 675,727.910  | 748,120.570 | 15.720 | 2.755 | 86.000 | 4.454 | 30 | 11.664 | 3.721 | 15 | 0.744 | 1.861 | 15.744 | 17.605 | 64.610 |
| Plot8 | 677,594.190  | 750,021.410 | 22.300 | 3.105 | 80.000 | 4.382 | 84 | 11.869 | 4.542 | 15 | 0.908 | 2.271 | 15.908 | 18.179 | 66.717 |
| Plot9 | 672,578.310  | 765,758.730 | 32.453 | 3.480 | 86.000 | 4.454 | 136 | 12.388 | 7.527 | 9 | 1.505 | 3.764 | 10.505 | 14.269 | 52.367 |
| Plot10| 671,360.210  | 744,972.300 | 23.615 | 3.162 | 115.000 | 4.745 | 42 | 12.652 | 9.722 | 14 | 1.944 | 4.861 | 15.944 | 20.805 | 76.355 |

(Brown et al., 1989)
In assessing the rate of change in LULC between 1984 and 2015, a decrease of 1292 Ha, a rate of 51.68% and 7752 Ha at the rate of 47.83% in bare-ground/built-up area and natural forest, respectively, was observed between 1984 and 1991. Contrarily, both G. arborea and T. grandis increased in area by 6683 Ha at the rate of 269.56% and 2360 Ha at the rate of 78.33%. Between 1991 and 2002, the area of both built-up and natural forest further reduced by 468 Ha at the rate of 38.74% and 2506 Ha at 29.64%. However, G. arborea and T. grandis increased by 1777 Ha at the rate of 19.39% and 1206 Ha at the rate of 22.46%, respectively.

Between 2002 and 2010, G. arborea began its areal reduction to 4935 Ha in 2010 compared to 10,939 Ha observed in 2002, a rate of 54.88%. As a result of this, there was a corresponding expanse in the area covered by the natural forest. It increased by 24.49%, from the 5949 Ha observed in 2002 to 7406 Ha in 2010. At the same time, the decrease in the built-up area/bare ground persisted with 187 Ha observed in 2010, compared to the 740 Ha observed in 2002. There was on the other hand an increase in T. grandis. Its area cover at this time was observed to be 11,652 Ha, a further increase of 77.14%. The drastic reduction of the G. arborea could be as a result of the heavy and indiscriminate logging activities.

Similarly, between 2010 and 2015, G. arborea experienced a further reduction of 97.65% whereas T. grandis reduced by 50.37%. Whereas, the built-up area/bare ground increased by 131.53%, while the natural forest further increased by 88.44%. It is evident from the last 5 years under consideration that the rate at which the forest was degraded is quite alarming. This may be due to the World Bank withdrawing its support from the afforestation project in 1998, thus ending any reforestation or planting efforts. In addition, by this time, the presence of dead trees and logged woods in several places coupled with the non-stop entries of lumber vehicles into the forest and their exits from it is an evidence of disproportionate exploitation of these timbers (USAID, 2008). Afterwards, this setback made the forest a means of revenue for the Ondo State Government.

Finally, in order to develop a geospatial database for monitoring carbon content in the study area, NDVI (Figure 15) was used in estimating biomass and the biomass graphical pattern which shows the vegetation cover in Figure 13, and both T. grandis and G. arborea show a steady decline in biomass from 2002 to 2015. We can clearly deduce that, if factors such as deforestation are not controlled, the CS capability of the study area may continue to reduce. (Ponce-Hernandez (2004), Yin, Udelhoven, Fensholt, Pflugmacher, and Hostert (2012) and Klemas and Pieterse (2015) explained that the use of band ratio indices such as NDVI exploits the discriminating power of the infrared band ratios of chlorophyll activity in vegetation; however, the strength in the relationships may vary with tree structure and state of health of the vegetation and other environmental parameters.

**Conclusion**

It can be concluded that forests help maintain conditions that make life possible, from regional hydrological cycles to global climate changes and

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**Table 12.** Percentage of soil organic carbon for the forest stands.

| Plot | Forest stand | 0-15 cm | 15-30 cm | Total (cm) | Percentage (%) |
|------|--------------|---------|----------|------------|----------------|
| 1    | Tectona grandis | 31.91   | 38.29    | 70.20      | 33.126         |
| 2    | Gmelina arborea | 15.25   | 13.44    | 28.69      | 13.538         |
| 3    | Degraded forest | 6.60    | 8.21     | 98.89      | 46.664         |
| 4    | Natural forest | 7.79    | 6.35     | 14.14      | 6.672          |

| Total | 211.92   | 100 |

However, between 2002 and 2010, G. arborea of 13,955.108, 5783.411, 3908.475 and 116.066 ha, respectively.

In assessing the rate of change in LULC between 1984 and 2015, a decrease of 1292 Ha, a rate of 51.68% and 7752 Ha at the rate of 47.83% in bare-ground/built-up area and natural forest, respectively, was observed between 1984 and 1991. Contrarily, both G. arborea and T. grandis increased in area by 6683 Ha at the rate of 269.56% and 2360 Ha at the rate of 78.33%.

Between 1991 and 2002, the area of both built-up and natural forest further reduced by 468 Ha at the rate of 38.74% and 2506 Ha at 29.64%. However, G. arborea and T. grandis increased by 1777 Ha at the rate of 19.39% and 1206 Ha at the rate of 22.46%, respectively.

**Figure 12.** Logarithmic relationship between aboveground biomass and DBH.

**Figure 13.** Percentage of soil organic carbon for the forest stands.

| Plot | Forest stand | 0-15 cm | 15-30 cm | Total (cm) | Percentage (%) |
|------|--------------|---------|----------|------------|----------------|
| 1    | Tectona grandis | 31.91   | 38.29    | 70.20      | 33.126         |
| 2    | Gmelina arborea | 15.25   | 13.44    | 28.69      | 13.538         |
| 3    | Degraded forest | 6.60    | 8.21     | 98.89      | 46.664         |
| 4    | Natural forest | 7.79    | 6.35     | 14.14      | 6.672          |

| Total | 211.92   | 100 |
that the existence of deforestation, degradation and poor forest management practices has been proved in the study area. This research has been able to estimate a total of 162,826 ton/ha of AGB, 32,571 ton/haBGB, total carbon stock of 97,701.603 ton/ha and 358,564.883 ton/ha of carbon dioxide sequestered by the study area. Also, change in LULC carried out between 1984 and 2015, which was confirmed by the NDVI, revealed that the forest is drastically losing its greenness and carbon storage capacity to uncontrolled logging and forest degradation.

Furthermore, the deforestation, degradation and poor forest management practices have been proved in the study area. The Oluwa Forest might be one of the tropical rainforests projected by Urquhart, Walter, David, & Chris (2007), to disappear within the next 100 years. In mitigating against this, both constant field data as well as remote sensing data should be deployed in assessing the carbon sequestered by the study area, since, to our knowledge, this may be the first CS project in Ondo State Afforestation Project (OSAP-OA1), Oluwa Forest which supports other researches advocacy on the need to carry out more biomass estimation and CS projects in Africa especially, since the continent is a huge consuming one and fast developing, thus the consequences of our anthropogenic activities should be scientifically assessed.

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Figure 14. Biomass distribution map.

Figure 15. Landsat-derived NDVI (from digital numbers) for the entire scene (path 190/row 55).
Disclosure statement
No potential conflict of interest was reported by the authors.

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