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Carbon Storage and Environmental Determinants in a Tropical Rainforest Landscape

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Abstract

Tropical ecosystems sequester vast amounts of carbon but remain much varied across different landscapes. In order to provide estimates on carbon storage for the ecosystem and show the role of forest structure and environmental factors in determining aboveground and soil carbon of a rainforest landscape, forest inventory was conducted across 30 forest plots. Each of the plots measured 50 m × 50 m and was used to identify and measure tree species ≥ 10 cm diameter at breast height (DBH measured at 130cm). Soil samples were collected for up to 30 cm deep at the four edges and then the middle of each plot, bulked for analysis and tested in the laboratory. Aboveground carbon estimates ranged from 8.18 - 91.29 t/ha across the ecosystem and were similar with carbon storage in tropical landscapes. With variations in stem density, basal area and structure across the region, much of the carbon capacity across the ecosystem was much varied ($F (29, 2127) = 3.794$, $p = 0.000$). Environmental variables (mainly edaphic variables) were not positively correlated with soil carbon and did not largely determine its storage and variation. The need to reduce disturbances (which are a main driver of disparity in biomass carbon storage) across the region and across tropical ecosystems was advocated as a pathway to enhancing higher carbon sequestration.

Keywords

Climate Change, Conservation, Degradation, Land Use Change, Tropical Ecosystem

1. Introduction

Tropical landscapes and ecosystems are useful for modulating global biogeochemical cycles, and storing vast amounts of carbon [1] [2]. This understanding has been given attention within international assessments (such as Intergovernmental Panel on Climate Change (IPCC), United Nations Framework Convention on Climate Change (UNFCCC)) and measures are being put in place to ensure that carbon emissions from terrestrial ecosystems are managed. With such initiatives, research and inquiry surrounding carbon cycle/ sequestration and its importance in global climatic system have been promoted across the tropics, with much emphasis on Amazonia and the Congo forest due to their global importance [3]. These efforts have become necessary especially because environmental changes (due to changing climatic system and land use changes) have become global concerns threatening our planet. Addressing such environmental concerns appropriately will require concerted efforts and availability of requisite information and data. Quantifying the contribution of ecosystems (especially, tropical ecosystems) to global carbon store and climate change mitigation are quite imperative and among the foremost steps to achieving such aim. While it is known that tropical forests store 40 - 50 percent of terrestrial vegetation carbon [4], patterns of spatial variation in the carbon stocks remain poorly understood [5].

Carbon estimates in above and below ground vary across ecosystems and landscapes, and are to a large extent determined by environmental factors. Being predictors of the ecology of ecosystems, environmental factors influence the presence, absence and abundance of species in a landscape and then its capacity to store carbon (wood specific gravity). The understanding of environmental predictors of carbon and their tree stature will indeed help in prioritising data collection for future assessments [6] and guide conservation efforts. Equally, there is a need to understand the variations in soil carbon across landscapes and elucidate the determinants of variations and patterns. Other (environmental) factors such as the elevation and soil chemical parameters relate and determine the carbon capacity of the soil and needs to be equally understood. Indeed edaphic (environmental) variables no doubt explain variations in aboveground carbon as well [7] [8], but have altogether not been given much attention in literature. Promoting such understanding are topical concerns especially as environmental degradation seems to be increasing at both landscape and regional scales; and hence the need to document reliable baselines and provide insights that could guide restoration initiatives.

Across much of the tropical landscapes such as Nigeria, baseline information on their carbon storage and capacities that will help address climate change concerns are lacking for many of the ecosystems at regional and local scales. While the subject of carbon storage is beginning to evolve across Nigeria, much of the work utilizes only satellite imageries for the work (such as [9] [10] [11]) without baseline ecological data needed to produce reliable estimates especially at ecosystem levels. Ecological data is however needed for such estimates as it is used for calibration and validation of remote sensing methods and models that international policies are based on [2]. Baseline information on the ecology-carbon nexus, determinants and patterns are much needed for ecosystems so as to be able to effectively address their climate change concerns and design ecosystem specific reliable policies for their conservation. This work is hence focused on providing insights on this for the rainforest ecosystem in south east Nigeria where there is paucity of data on the subject. It will elucidate the aboveground and soil carbon estimates for a rainforest zone, show the variations and contribution of forest structure to aboveground carbon and the extent to which environmental factors—mainly the edaphic variables, determines the carbon pool of the ecosystem.

2. Materials and Methods

2.1. Study Area

The area for the research is a part of South East Nigeria (**Figure 1**). The climate is characterized by a humid tropical, tropical wet and dry, and marked with rainy and dry seasons. It has a high annual rainfall which ranges from 1400 mm in the North to 2500 mm in the South, and a mean monthly temperature of 27.6˚C. Geology of the region comprises of ancient Cretaceous delta, with the Nkporo shale, the Mamu formation, the Ajali sandstone and the Nsukka formation as its main deposits [12]. The natural vegetations in this region are mainly the rainforest ecosystem with relicts of the savanna ecotone in some part of the region. The zone experiences about 3 dry months in its northern zone and 1 - 2

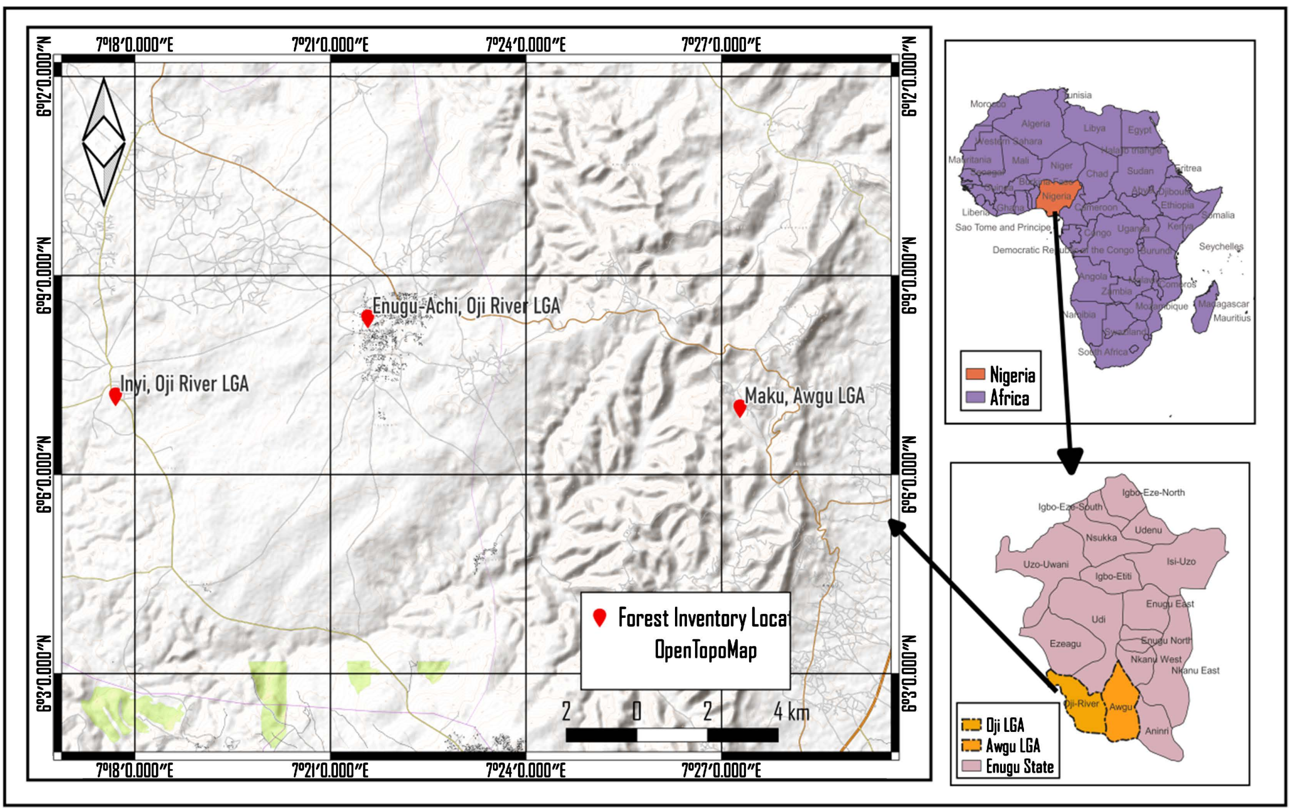

Figure 1. Map of the study area with the map of Nigeria and Africa inset.

dry months in the south; making it much humid and with sufficient rainfall.

Forest inventory was done in Maku town, Awgu Local government area, Enugu state, Enugu-Achi and Inyi towns, both in Oji river local government area of Enugu state. This location is characterized by a gradient of high elevation with hilly features and low elevation and rugged terrain in some other areas. The forest in the area is extensive and relatively undisturbed—mainly due to the hilly terrain, very poor accessibility of the forests and their distant locations from human dwelling units.

2.2. Data Collection and Analysis

To be able to estimate aboveground and soil carbon across a rainforest ecosystem zone, 30 forest plots was set up randomly across 6 forest sites within the 3 locations. Each of the plots measured 50 m × 50 m and had intervals of not less than a hectare between the plots in each location. Tree species ≥ 10 cm diameter at breast height (DBH measured at 130 cm) were identified and measured. DBH or girth tape was used to measure the tree stems while a rangefinder was used to measure the heights. Species identification followed the taxonomy of Nigerian plants [13] and The Plant List [14]. Soil samples were collected for up to 30 cm deep at the four edges and then the middle of each plot and bulked for analysis. The samples were analyzed for carbon (C), N, pH, P, exchangeable aluminium (Al), exchangeable cations namely, Ca, K, Mg, Na and CEC which was used in the determination of base saturation.

Organic carbon was derived with Walkey-Blacks titration method [15] after which the Van Bemmelan factor was used to calculate the organic matter. Exchangeable aluminium (Al) and exchangeable cations, namely calcium (Ca), magnesium (Mg), sodium (Na) and potassium (K), were derived following Allen *et al.* [16]. Summer and Miller [17] was employed for CEC determination; Semi-micro kjedahls distillation method [18] was used to get the nitrogen while pH employed the H2O and 0.1 M KCl methods of Rowell [19].

Above ground carbon (AGC) was estimated with Chave *et al.* [20] pantropical equation as follows:

$$\text{AGB} = 0.0673 \times \left(\rho \text{D}^2 \text{H}\right)^{0.976} \tag{1}$$

where AGB is the above ground biomass; ρ is the wood specific gravity (WSG; $g \cdot cm^{-3}$); D is the diameter at breast height (DBH; cm) and H is the height (m).

Edaphic variables that correlated with soil carbon were verified with Pearson correlation analysis. Furthermore, analysis of variance was conducted to verify if there were significant variations in soil carbon across the locations. Generalised linear models (GLM) were used to investigate the influence of predictor variables on above ground carbon (AGC). Pearson correlation was equally used to verify which variables that had higher correlation and influenced above ground carbon. Partial correlation was done to check the reliability of the test. Carbon stocks were analyzed per plot with Equation (1) and variations across the plots analyzed with analysis of variance (ANOVA). Variations in the contribution of different forest structural classes to AGC were verified with a Kruskal Wallis test. Forest structural classes were categorized as: small (<20 cm dbh), medium (20 - 40 cm dbh), large (40 - 60 cm dbh) and largest (>60 cm dbh).

3. Results

Aboveground carbon varied across the plots. Analysis of variance at 0.05 significant level showed the variation (F (29, 2127) = 3.794, $p = 0.000$) (**Table 1**).

Contributions to the carbon estimate based on the different species (according to their wood specific gravities) were varied. *Spathodea campanulata* recorded the least contribution (0.232 g/cm^3) to AGC as a species, while *Rhizophora racemosa* had the highest contribution of 0.959 (g/cm^3). Kruskal-Wallis test showed that there was a statistically significant difference in the carbon stored by the trees according to the different forest structural classes, X^2 (3) = 1308.735, p = 0.000; with a mean rank of 719.06 for small (<20), 1614.69 for medium (20 - 40), 2055.21 for large (40 - 60) and 2127.23 for largest (>60).

Though the number of species was more with the lower structural classes, mean ranks were found to be more in higher structural classes (**Table 2**)

Amount of carbon contributed by the different structural classes are quite varied. 20 - 40 cm structural class recorded the highest amount of carbon (109.39 t). This was followed by 40 - 60 cm category, <20 cm category and >60 cm class, with 85.39, 57.45 and 38.77 tons respectively (**Figure 2**).

Generalised linear models (GLM) showed that WSG had significant contribution to the above ground carbon (t = 106.433, p < 0.05, AIC = −2287.571) as well as DBH (t = 5224.339, p < 0.05, AIC = −2287.571). Basal area of the trees (DBH) had more significant contribution to AGC than the WSG though. Results of the Pearson correlation analysis (r) (**Table 3**) showed that aboveground carbon (t)

Table 1. ANOVA for Carbon per plot.

Carbon (t)	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	7.34	29	0.253	3.794	0.000
Within Groups	141.909	2127	0.067		
Total	149.249	2156			

Table 2. Distribution of the forest structural classes, frequency of species occurrence and mean rank.

Forest structural class (cm)	Frequency of species occurrence	Mean rank
Small (<20)	1366	719.06
Medium (20 - 40)	641	1614.69
Large (40 - 60)	124	2055.21
Largest (>60)	26	2127.23

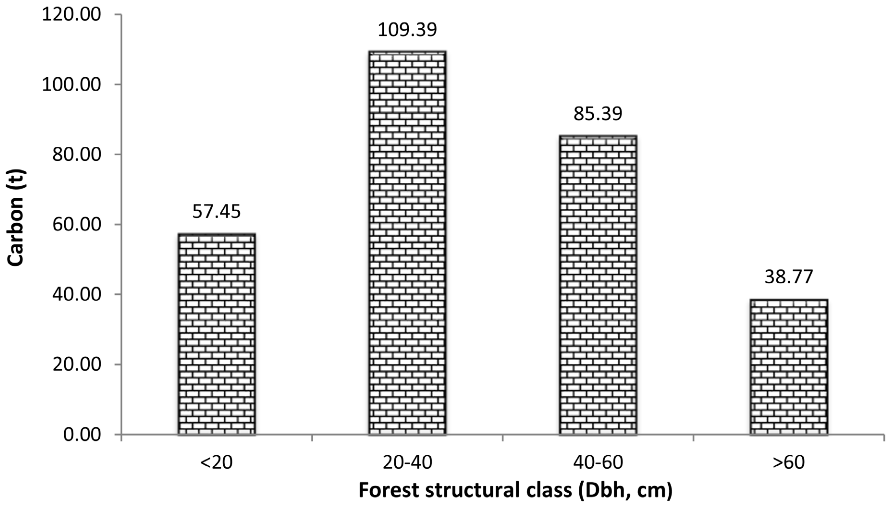

Figure 2. Total amount of carbon per forest structural class (Dbh, cm).

Table 3. Correlation between Carbon (t) and other variables.

	WSG	DBH (cm)	H (m)	Elevation (m)
Carbon (t)	−0.032	0.833*	0.556*	0.024

*Correlation is significant at the 0.05 level (2-tailed).

had significantly high and positive linear association with diameter at breast height (DBH, r = 0.833) and tree total height (H, r = 0.556) respectively.

Soil carbon varied across the plots and ranged from 5.27% - 9.38% across the plots. Correlation analysis indicated that % soil carbon content had significantly low and negative linear relationship with Iron ppm, Aluminum ppm, Magnesium cmol/kg, Magnesium ppm, pH, Manganese ppm, with r values of −0.470, 0.331, −0.319, −0.318, −0.306 and −0.270 respectively (**Table 4**).

Analysis of variance result showed that percentage soil carbon content varied across the plots: (F (29, 30) = 56.527, p = 0.000; **Table 5**).

4. Discussion

The ecosystem was seen to store much carbon in its biomass; 8.18 - 91.29 t/ha across the ecosystem. Such ample amounts of carbon are characteristic of tropical ecosystems [2; 5] and reinforce the strategic role the ecosystem plays in climate change mitigation. While this is the case, there were much variations in the capacity of the landscape to store carbon (F (29, 2127) = 3.794, p = 0.000; **Table 1**) across the different plots. With varying stand structure and configurations of the plots (such as its densities and canopies) the total amount of carbon in its biomass will be varied. Gradients in AGC are mainly associated with the tree densities, as well as tree canopy cover [21] that differs across landscapes. Tree densities vary according to site history, soil condition, tree species and size class, age of the forest and the forest community [22]. Since ecosystems are varied at different spatial scales and at local scales, their tree densities are expected to be

Table 4. Pearson's correlation for soil carbon content.

	% Carbon content
pH	−0.306*
Chloride mg/kg	0.092
Phosphorus abs	−0.119
Phosphorus conc.	−0.131
Magnesium ppm	−0.318*
Sodium ppm	−0.02
Manganese ppm	−0.270*
Iron ppm	−0.470*
Potassium ppm	0.056
Calcium ppm	−0.121
Aluminum ppm	0.331*
Calcium cmol/kg	−0.125
Magnesiumcmol/kg	−0.319*
Potassiumcmol/kg	0.057
CEC cmol/kg	−0.176
% Nitrogen	0.222
% sand	−0.037
% Clay	0.036
% Silt	0.017
% loss of ignition	0.103

*Correlation is significant at the 0.05 level (2-tailed).

Table 5. Partial correlation analysis of carbon with the variables

Variable	**% Carbon**
pH	−0.276
Chloride mg/kg	0.126
Phosphorus mg/kg	−0.178
Magnesium ppm	−0.304
Sodium ppm	−0.061
Manganese ppm	−0.232
Iron ppm	−0.406
Potassium ppm	−0.012
Calcium ppm	−0.141
Aluminium ppm	0.274

Continued

Calcium cmol/kg	−0.136
Magnesium cmol/kg	−0.302
Potassium cmol/kg	−0.012
CEC cmol/kg	−0.254
% Nitrogen	0.263
% Sand	−0.066
% Clay	0.069
% Silt	0.027
% loss of ignition	0.104
% Organic matter	−0.145

Table 6. ANOVA for soil carbon content.

% Carbon content	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	108.926	29	3.756	56.527	0.000
Within Groups	1.993	30	0.066		
Total	110.919	59			

much varied. Hence, with stand densities of 168 stems to 484 stems per hectare across the region, plots with more stem densities are inclined to have higher biomass capacities than those with lesser stem densities. While stem densities largely determines the capacity at which biomass carbon store is determined (following the frequencies of stems per location), the basal areas of the stems however shows the capacity of each stem to store carbon.

Basal area of trees is a measure of tree density and important in assessing the capacity of trees to render vital services (such as carbon storage or timber). It ranged between 5.522 - 22.489 $m^2 \cdot h^{-1}$ across the region, and contributed to much of the variation in carbon store in the ecosystem. It showed a more significant contribution and correlation to carbon than any other variable according to the GLM ($t = 5224.339$, $p < 0.05$, $AIC = -2287.571$) and Pearson correlation analysis (**Table 3**), respectively. Variations in basal area exist across and within ecosystems due to differences in age structure, species composition, altitudinal variations, successional stages and intensity of disturbance [23] [24]. While other factors are mostly inherent and are processes that ecosystems undergo, disturbances (especially anthropogenically induced ones) are exogenous and quite debilitating to ecosystems than other factors. Disturbances (through logging, fragmentation and generally from land use changes) are responsible for the loss of carbon to the atmosphere (carbon sources) and reduction of the capacity of ecosystems to store carbon (carbon sink). With tropical ecosystem loss and changes increasing in scale [25] such that global carbon cycles are affected greatly [26] [27], there is need to not only increase conservation efforts in forested landscapes, but equally review land use change policies more critically.

The structure of trees in the ecosystem were quite varied, as is common with similar tropical landscapes [28] and largely determined the carbon estimates. Trees with medium structural ranges (20 - 40 cm) recorded the highest amount of carbon (**Figure 2**); and in effect had more carbon than the smallest structural range with more trees (**Table 2**), but only slightly higher (in carbon estimates) than the large structural range which had far lesser number of trees than it (**Figure 2**, **Table 2**). Mean rank for carbon were found to be highest in the largest stem sizes and decreased with decrease in stem sizes accordingly (**Table 2**). Though bigger structural classes did not record the highest amount of AGC due to their fewer tree stands, their mean rank were higher (and decreased as their structural classes reduced); and thus showed their higher capacity for storing carbon than the smaller stem sizes. Forest landscapes where large stem sizes are the dominant features and very few smaller trees stems coexisting with it, are features normally found in mature, undisturbed or climax vegetation. It is hence imperative that conservation efforts are targeted and promoted on such landscapes as they have much potential in providing ecosystem services (carbon storage). Locations with such features across tropical ecosystems are quite few in number (considering the magnitude of forest loss in the region) and where they exist, they are however threatened by forest loss and degradation; as seen in the Amazon [29]. Efforts that would reduce such threats across the study area and the bulk of tropical ecosystems are advocated.

Soil carbon storage is a vital biogeochemical process that is inherent in ecosystems. With as much as 60% of total tropical carbon stored below ground in the soil [30], it serves important roles similar to aboveground carbon storage in ecosystems. Percentage soil carbon per hectare ranged from 17.78% - 37.54% across the region and was much varied across the plots: (F (29, 30) = 56.527, p = 0.000; **Table 6**). While these variations exists across the region, % soil carbon content had significantly low and negative linear relationships with other variables (**Table 4**); thus showing weak relationships with and contributions from edaphic variables. Soil carbon capacities are mainly driven by the quantity and quality of plant inputs [31] [32] in the terrain; and hence differ according to the variations in plant compositions in the landscape than from edaphic inputs. Such understanding will indeed help to promote tree species that have suitable interplay of soil physicochemical properties and can enhance better carbon sequestration across different spatial scales.

5. Conclusion

Aboveground carbon estimates for the region were ample and similar to other tropical forest zones. It was varied across the region based on basal area/structure and tree density; and showed the extent to which disturbances could determine carbon estimates of landscapes. Soil carbon was equally varied in the region, but was not associated with edaphic variables. Suitable conservation and management strategies that would enhance better carbon storage in the biomass and better soil-plant enhancements are advocated.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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