Original Research Article

PREDICTING FUTURE CARBON SEQUESTRATION TRENDS IN AWKA, ANAMBRA STATE, NIGERIA USING A REGRESSION MODELLING

ABSTRACT

Aims: The purpose of the study was to use mathematical models to estimate the future effect
of the land use and land cover change (LULCC) on carbon sequestration in the Awka Capital Territory (ACT), Nigeria.

Study Design: It would be a quantitative research design that combines remote sensing and laboratory soil analysis.

Place and Duration of Study: Six communities in the Awka Capital Territory, Anambra State,
Nigeria, in a 30-year study (1993-2023).

Methodology: Walkley-Black took place whereby soil organic carbon (SOC) was established
in depths of 0-60 cm in the four-land use cover: forest, shrubs, farmlands, and built-up land. To
develop the relationship between area changes and carbon stock, Multiple Linear Regression
(MLR) were carried out along with Pearson correlation analysis to predictive model.

Results: Statistical confirmation rejected the null hypothesis, H 0 2, which provided significant correlations LULCC and carbon stock (0.62 to 0.99). The carbon stock became a near-perfect negative forecast of urbanization (-0.93 to -0.99). Predictive models of the individual communities indicate that the growth of urbanization causes a linear decline in the carbon sinks
in the region.

Conclusion: The acquired regression models are also a critical instrument that will enable the
local policymakers forecast the environmental effects of urban planning choices and emphasize
the necessity of adopting adaptive land management to alleviate climate change in the ACT.

Keywords: Regression Modelling; Carbon sequestration; Urbanization; Soil organic carbon;

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Climate mitigation; Awka.

1. INTRODUCTION

The dramatic transformation of the Earth surface in the form of land use and land cover change (LULCC) have become one of the major factors in the global environmental instability (Güneralp, 2020). Possibly the largest continental stores of organic carbon are the terrestrial ecosystems and in particular soils and vegetation. Nevertheless, the ability of these ecosystems to operate as carbon sinks is being undercut by human actions in a systematic manner. According to Sleeter *et al.* (2018), land-use and land-cover transformation has a strong impact on climate and weather as it alters the interaction between the land surface and the atmosphere with regard to the exchange of greenhouse gases (GHGs). When it comes to tropical areas, where the inherent sequestration capacity is vast, the transformation of natural landscapes into either a controlled or an engineered space is a decisive intervention to the world-carbon cycle.

Nigeria as one of the countries with the 44th position of the world in terms of emitting the greenhouse gas of carbon dioxide in the atmosphere in 2010 has a great challenge in development and environmental conservation (Samuel and Yelebe, 2015). Land-use activities in the country, most of which are deforestation, uncontrolled bush burning and intensive tillage have been the primary contributors to the global warming problems because in the past, these practices have led to a net depletion of soil organic carbon (SOC) emissions to the atmosphere (Stewart and Robinson, 2019). The efforts of the Nigerian government in the signing of the Paris Agreement, where Nigeria is determined to cut down its emissions by 20% to 45% by 2030, require an effective framework in monitoring and forecasting the trends in stock of carbon in the local and regional level (Anwadike, 2021). The Awka Capital Territory (ACT) in the Anambra State offers a successful miniature of these issues, having experienced a phase of rampant and unplanned urbanization since it was designated capital territory.

The basic issue is the transformation of high-carbon density vegetation (i.e., forests and shrublands) to low-carbon density urban surfaces. As the natural vegetation is cleared, the loss of biomass is immediate and will be offset in the long term by the degradation of soil carbon pools through soil sealing and compaction and the loss of organic matter. According to Zhang *et al.* (2020), the adaptive management of carbon sequestration requires the understanding of the impact of land use change especially in fast-developing urban centres. The change in the ecological role of a region, i.e., one of a carbon sink to a potential source of carbon is not only a change in land cover in the ACT, but an essential transition in the ecological role of the region.

Predictive modelling can be a crucial scientific avenue to these environmental changes. Although historical evaluation gives us an account of the damage done in the past, regression analysis enables the determination of how land use area and carbon storage capacity are interrelated. This is a mathematical technique that allows environmental managers to predict the future sequestration trends when different development conditions are considered. In spite of remote sensing data and the characterization of soils, the predictive mathematical frameworks specific to the ACT have been quite lacking. The majority of studies of the region have been descriptive rather than being statistically rigorous enough to represent how certain decadal shifts in the percentages of land use directly relate to the loss or gain of carbon stocks.

The gap that this research aims to fill is the creation of community-specific Multiple Linear Regression (MLR) models using thirty years of empirical data (1993-2023). Based on the association of the size of the various types of cover such as shrub, forest, farmland, and built-up with the measured carbon stocks, this research paper offers a predictive measure of the so-called adaptive management of carbon sinks. The importance of such modelling is that it converts raw data relating to the environment to intelligible data that can be applied by urban planners. As an example, looking at the almost ideal negative correlation between urbanization and carbon depletion means that it is possible to incorporate the idea of a green infrastructure as a measurable mitigation measure, as opposed to an aesthetic option.

Moreover, the paper indicates the peculiar effect of the so-called agricultural treadmill, which is observed in the territory and consists in the fact that the increase of farmland is not accompanied by the increase of the carbon in the region but it actually leads to the decrease of the latter due to soil depletion. This points to the fact that there is a need to have models that explain the quality of land use instead of the mere quantity of land. Soil degradation is about to tip over as was witnessed by Yusuf *et al.* (2019) in the Nigerian savanna. Carbon stocks in the ACT have dropped by up to 87% in some sectors, and prediction of the remaining lifespan of such sinks is a key to the resilience to the climate in the region.

With the development of these predictive trends, it is the objective of this paper to give a scientific foundation to the sustainable land-use planning in Anambra State. The models created here are used as an early-warning system, where the nature of the future carbon loss is emphasized in case the current rates of urbanization are not exercised in any way. Eventually, the study aims to address the research gap between the geospatial analysis and climate policy, that is, to provide a framework that can be duplicated in other fast- growing urbanized tropical ecosystems in sub-Saharan Africa.

2. MATERIAL AND METHODS

2.1 Study Area and Research Design Study

The study was done in the Awka Capital Territory (ACT) in the state of Anambra, south-eastern Nigeria. The area of the study is in the tropical rain forest savanna transition zone which consists of a variety of ecosystems that include forest, shrublands, grasslands and a vast agricultural land (Ossai *et al.,* 2025). Six communities were purposively chosen in order to have a representative evaluation of the various land-use dynamics; the communities used were Awgbu, Abagana, Awka, Nawgu, Urum, and Agulu (Figure 1). These sites are a range of environmental pressures, between the fast urban centre of Awka and the agriculturally intensive areas of Nawgu and Urum. The study was designed as a quantitative study, which combined the geospatial technology and field-based laboratory analysis to provide a foundation of predictive modelling (Wang *et al.,* 2016; Hossan *et al.,* 2023).

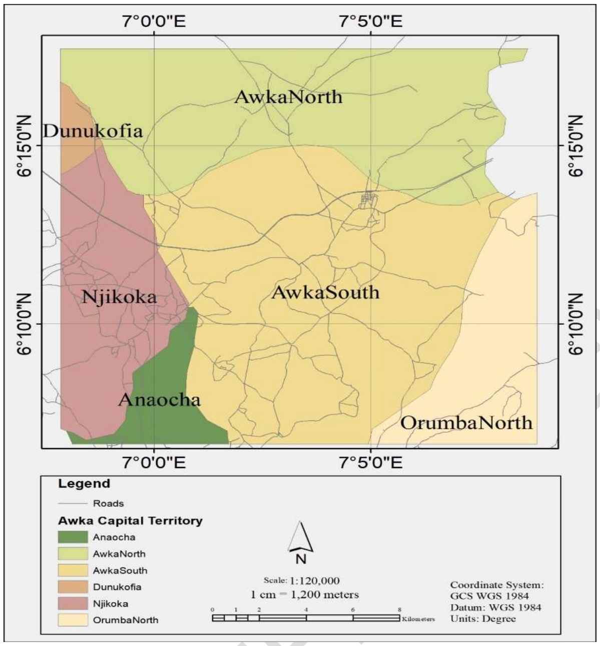

Figure 1: *Map of Anambra State showing the Local Government under Awka Capital Territory Indicating the 10km radius as depicted by UN-Habitat*

2.2 GIS and Remote Sensing Data acquisition

Multi-temporal remote sensing (Yang *et al.,* 2018) was used to determine the land use and land cover (LULC) change in a span of 30 years. Four decadal points were obtained, namely, 1993, 2003, 2013 and 2023. Landsat satellite images, namely, Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) sensors were the main sources of data (Crósta and De Souza Filho, 2009).

GIS software was used to process the imagery and put the landscape into four different categories (Eastman, 2001):

- **Forest:** Areas that are well covered by trees and possess high canopy.
- **Shrubs:** Regions where the vegetation is mainly low woody vegetation.
- **Farmlands:** It refers to land that is actively utilized in crop farming activities.
- **Built/Urban:** Areas of buildings, roads and other solid structures.

The Spatial area (SPAT) area of each category was computed (in hectares) and percentage cover computed (In every decadal interval) (Feng *et al.,* 2023). This geospatial data was used in supplying the independent variables (X) that were required during the regression modelling part of the research.

2.3 Soil Sampling and Field Techniques

Field sampling was necessary to assess the dependent variable, which is the stock of carbon. In the six communities chosen, the four LULC classes were sampled on the soil. Sampling was done in a systematic manner in order to attain spatial representativeness. The extraction of the soil was performed using the hand auger in every community in two levels, top (0 - 30 cm) and subsoil (30 - 60 cm) levels. This two-depth sampling is essential in terms of comprehending the vertical distribution of organic carbon and a complete summation of the soil organic carbon (SOC) pool (Jensen *et al.,* 2024).

Also, cores of undisturbed soils were taken at every site to identify bulk density. Bulk density is an essential physical characteristic that is necessary to translate the percentage of organic carbon that is found in the lab to a mass-based stock value (tonnes per hectare). All the samples were doubled bagged, labelled and taken to the laboratory to be processed and characterized (Okalebo *et al.,* 2022).

2.4 Laboratory Analysis of Soil Properties

The determination of Soil Organic Carbon (SOC), was the main laboratory objective. The Walkley-Black wet oxidation method was used to do this which consists of rapid titration of the soil with potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4) (Ladoni *et al.,* 2010; Mylavarapu et al., 2014). It has been known to be precise in soils of tropical nature where the level of organic matter also differs considerably depending on land-use.

Other auxiliary parameters that were obtained were:

- Bulk Density: Tested on the paraffin wax clod method whereby aggregates of dry soil are coated with paraffin wax to measure the volume through the use of displacement of water (Fariña *et al.,* 2025).
- Soil pH: The chemical environment where carbon is maintained was measured by analysing a 1:2.5 soil-water suspension using a digital pH meter (Hartemink and Barrow, 2023).
- Particle Size Distribution: It was decided to find out the texture of the soil, which is a determining factor in the retention of carbon (Liu *et al.,* 2023).

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2.5 Carbon Stocks Calculation

The mathematical expression used to compute the carbon stock of each community, land-use type and period was as follows:

$$SOC_{stock} = C \times BD \times d$$ (Tadiello *et al.,* 2020)

Where:

C = Organic percentage of carbon determined in the laboratory.
BD = Bulk density (g/cm3).
d = The soil layer depth (cm).

The 0 - 60 cm profile of the total carbon stock was a summation of the stock calculated of the 0 - 30 cm and 30 - 60 cm layer. These were the predicted values of the study which became the historical baseline of the predictive models.

2.6 Statistical and Predictive Modelling Framework

The main aim of the paper, which is the prediction of future trends, was conducted in two steps of statistical analysis with the help of SPSS version 22.0 (Rahayu *et al.,* 2024).

2.6.1 Correlation Analysis:

The Correlation analysis conducted by Pearson was used to estimate the extent and direction of the relationships between the area of LULC changes (independent variable) and the carbon stock (dependent variable). This was necessary to test out the null hypothesis (H_0) of the relationship of land use transition and sequestration potential. The correlation coefficients (r) were examined as to each category of land use in the thirty-year span.

2.6.2 Regression Modelling:

In order to create the predictive tool, Multiple Linear Regression (MLR) was used. This enabled the establishment of mathematical models of each of the six communities, by categorizing the land use. The overall expression of the linear model was:

$$Y = a + bX$$ (James *et al.,* 2023)

Where:
Y = Stock of Carbon predicted (mg/ha).
a = The intercept (constant).
b = The slope coefficient (b), which is a rate of change of carbon stock at every single unit change in land area.
X = The area of the particular land use/cover (hectares or percentage).

The models allow simulation of the future "what-if" scenario. As an illustration, the models can be used to predict the exact reduction in the carbon sequestration in the region in case urban growth is sustained at the same pace as now. The quality of these models was tested with the coefficient of determination (R^2) that indicated the degree of variation in carbon stock that was covered by the change in land cover area. The research offers a strong framework of adaptive land management in the ACT by incorporating these statistical outcomes into the geospatial trends.

3. RESULTS AND DISCUSSION

3.1 Correlation Analysis between Land Use Area and Carbon Stock

The statistical analysis of the correspondence between the land use area and the change in carbon stocks between the 30 years of study (1993 - 2023) provided strong evidence about direct influence of the landscape transformation on the sequestration capacity. Pearson correlation and the analysis of the coefficient of determination (R^2) demonstrated that the shift in the spatial extent of categories of land covers explained a significant amount of change in the overall change in the carbon stock, that is, between 38% and 98% ($R^2 = 0.38$ to 0.98). This level of explanatory power highlights the suitability of land use area as a key predictor of a regional carbon stock.

The correlation coefficients (r) of natural vegetation types - i.e. shrubs and forests- were all positive and statistically significant ($p < 0.05$) across the 6 communities. This shows it is directly linear in nature: as the size of the natural vegetation decreases so does the size of the soil organic carbon (SOC) pool, in a predictable manner.

Table 1: Pearson Correlation Coefficients (r) for Shrub and Forest Areas vs. Carbon Stock

Community	Shrub Area (r)	Forest Area (r)
Awgbu	0.98	0.99
Abagana	0.99	0.96
Awka	0.89	0.96
Nawgu	0.93	0.86
Urum	0.96	0.97
Agulu	0.62	0.98

The correlation of shrub areas in places like Awgbu and Abagana was close to near-perfection (r = 0.98 and 0.99, respectively), which argues that land cover area is nearly solely accountable in the recorded dynamics of carbon in these places. The outlier was slight in the shrub areas of Agulu (r = 0.62) wherein the lower coefficient indicates that though land area was a significant predictor, other site-specific environmental factors, possibly soil erosion or local disturbance, explain about 62 percent of the changes in the carbon stock.

3.2 Development of Predictive Regression Models.

Developing on the good correlation outcomes, mathematical equations were developed to predict future stock of carbon (Y) using the changes in the area of land use (X) as projected. These Multiple Linear Regression (MLR) models are the technical supporting component behind the adaptive management within Awka Capital Territory (ACT). With the introduction of a target land area (in hectares or as a percentage) the policymakers can now estimate the resulting potential of carbon sequestration in mg/ha.

The regression equations of Shrub areas among the various communities are as follows as the main representative equations of the ACT:

Awgbu: CS = 20.83 + 4.53 x Area
Abagana: CS = -58.83 + 5.53 x Area
Awka: CS = 51.41 + 3.93 x Area
Nawgu: CS = 86.83 + 6.41 x Area
Agulu: CS = 115.23 + 2.83 x Area

The gradient of these equations (b coefficient) provides the level of carbon sensitivity of each community. As an example the unit increase in the area of shrubs in Nawgu is predicted to increase carbon stock of the unit area by 6.41 mg/ha, and in Agulu, it is 2.83 mg/ha. Such diversities emphasize the different ecological productivity and soil retention abilities on the territory.

3.3 Urbanization as a Negative Predictor of Carbon Sequestration

The role of urbanization as an incredibly high negatively predictive factor of carbon stock can also be considered one of the most important discoveries of this research. The developmental areas of the community had a near perfect negative relationship with carbon stocks which was found to be constant in all the six communities with coefficient values of -0.93 to -0.99. Such a connection substantiates that urban growth in terms of impervious surfaces and urban infrastructure is a leading sink destroyer (Figure 1).

Table 2 Mean carbon stock and mean percentage built-up area in the entire Awka capital territory (ACT) from 1993 to 2023

Year	Mean carbon stock (mg/hect.) of built-up area in ACT	Mean percentage area of ACT occupied by built-up areas (%)
1993	271.68	9.97
2003	238.55*	21.42*
2013	206.02*	29.53
2023	49.37*	48.15*

*= significant ($p < 0.05$) when compared to the past 10 years

Only 9.97% of the ACT was built-up areas in 1993. This figure increased by 383 to 48.15 and that is astronomical (Table 2). The forecasting models indicate that this urbanization trend is the key contributor to the loss of urban soil carbon by 81.8 percent of the territorial change.

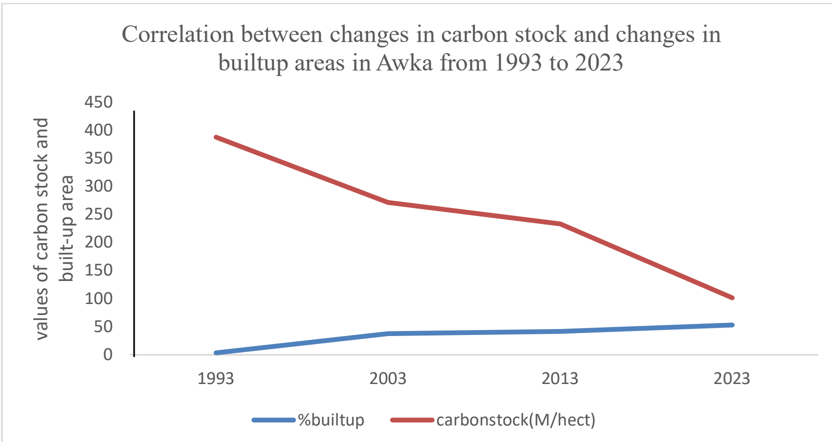

Figure 1: Correlation between changes in carbon stock and changes in built-up areas in Awka from 1993 to 2023

The statistical model of the capital city (Awka) particularly proves that with each increase in built-up density denoted substantially, the carbon sequestration potential in the region decreases linearly. This negative correlation has a statistical significance of 0.01, which gives a solid mathematical ground to include the concept of green belts and permeable urban surfaces to reduce the carbon debt that the high rate of infrastructural development has brought about.

3.4 Summary of Regional Sequestration Trends

The results show that there is a carbon collapse in a territory when the data is aggregated over all communities. In 1993, the average carbon stocks of natural land covers (Forest and Shrub) were more than 230mg/ha. The predictive models and lab findings prove that by 2023, these values have dropped to about 48mg/ha.

Table 3: Comparative Analysis of Predicted vs. Observed Carbon Stock Reductions

Land Use Category	Mean Reduction (%)	Correlation Significance	Predictive Accuracy
Forest Area	79.1%	0.001	0.96
Shrub Area	79.4%	0.005	0.88
Farmland Area	84.8%	0.001	0.95
Built-up Area	81.8%*	0.001	0.98

**Represents the decrease in the carbon density of the soil within urbanized zones.*

The similarity between the experimental laboratory results and the estimated regression model results prove that these mathematical instruments are very precise to the ACT (Table 3). The overall outcomes reveal that the land is soon to be a carbon-neutral, or even a carbon-source, in which a ratio of emitted in the land-use conversion is much higher than the sequestration ability of the left-over residual vegetation. The results of these studies give the empirical and statistical basis that is necessary to carry out the further discourse on the adaptive land management and urban policy.

4. DISCUSSION

The results of this study represent a vivid empirical example of the fact that rapid, unintended urbanization in a tropical transition zone may result in a carbon collapse. This paper has been able to quantify how Awka Capital Territory (ACT) has transformed into a major carbon source by incorporating multi-temporal remote sensing analysis with laboratory-based soil analysis and model predictions.

4.1 The Mechanism of Carbon Collapse

The breakdown of the carbon cycle has been the cause of the reduction of the Carbon dioxide levels in the planet since the commencement of the Cambrian period. The most notable conclusion is the drastic decrease in the average carbon stock of all types of land use, which dropped to an average of about 48 mg/ha in 2023 as opposed to the 230 plus in 1993. This carbon collapse is not only the consequence of the loss of biomass on the surface but a significant loss of the soil organic carbon (SOC) pool.

The fact that the Forest and Shrub carbon stocks were decreased by 79.1% and 79.4%, respectively, indicates how serious this tendency is. As soon as natural vegetation is cut down to build cities, the instant loss in photosynthetic capacity is multiplied by soil sealing, or the covering of the soil surface with impervious materials such as concrete and asphalt. This process stops the natural process of organic matter returning to the soil, basically suffocating the carbon sink in the soil.

4.2 Urbanization as the Primary "Sink Destroyer"

The statistical soundness of this research, as demonstrated by the almost negative correlation (r = -0.93 to -0.99) existing between the built-up areas and the carbon stocks, confirms the fact that urbanization is the major cause of carbon depletion in the ACT. The transformation of the built-up area of 9.97% in 1993 to 48.15% in 2023 is an astronomical increase of 383% in physical infrastructure. Such growth is a direct reflection of the 81.8 per cent decline in urban soil carbon.

These are in line with the findings of Sleeter *et al.* (2018), who reported that the conversion between land-cover changes the exchange of greenhouse gases between the land and the atmosphere. The sink destroyer effect is especially strong in the ACT as the urbanization process can be rather unplanned resulting in the highest level of soil compaction and minimum retention of green corridors. The fact that built-up areas have a high predictive value (R^2 = 0.98) implies that on every hectare of concrete poured in Awka or Abagana, there is a definite and substantial loss of sequestration potential that is mathematically assured.

4.3 The Agricultural Paradox

One such trend that is interesting and concerning is the fact that there is a 84.8% decline in carbon stocks in farmlands. Agriculture is traditionally considered as a green land use, but these findings indicate an effect of an agricultural treadmill. The growth in the A.C.T. farmland has caused a net reduction in the carbon not an increase. This is most probably because of the heavy cultivation, unregulated bush burning and the absence of regenerative processes, which deplete the soil of its organic matter. In similar cases like that of the Yusuf *et al.* (2019), agricultural land use, which is not enhanced with appropriate organic additions, results in the fast rate of soil erosion in the Nigerian savanna. In the ACT, farmlands are practically being mined of their carbon, rendering them virtually of no use as to sequestration value than are the urban areas they tend to be encircled with.

4.4 Predictive Modelling for Adaptive Management

The idea to create community-specific regression models (e.g., Awka: CS = 51.41 + 3.93 x Area) is a great improvement compared with the past descriptive work on the region. These models offer a scientific predeterminate system. Urban planners can determine the projected growth rates by plugging them into the estimation of the carbon debt of future developments. An example of this is the fact that Nawgu (6.41 mg/ha per unit area of shrub) was found to be very sensitive; hence the ecological interests of some communities in the preservation of the remaining natural covers are high.

These models (R^2 up to 0.96 for forests) are precise enough to justify the use of land area as a good proxy of carbon stock in tropical transition zones. This means that the local governments can perform monitoring with ease using geospatial data to make high-stakes decisions on carbon management without having to undergo exhaustive weekly laboratory tests.

4.5 Implications for Climate Policy in Nigeria

The targets that Nigeria has made under the Paris Agreement to lower emission by 20% - 45% by 2030 cannot be fulfilled by regulation of industries alone; it must be met with violent local land-use controls. The trend of the ACT is now towards becoming a source of carbon, the pace of carbon release by land-use conversion is much too great and the ability of the remaining 11.94% forest cover to sequester the carbon is too small.

In order to undo this, the opposing anticipator of urbanization should be alleviated by incorporation of green infrastructure. The findings imply that expanding the urban areas in permeability and gazetting the remaining part of the high carbon density forests in communities such as Awgbu and Urum are no longer aesthetic decision-making efforts but climate requirements.

Overall, the transformation of the Awka Capital Territory during the past three decades can be discussed as the warning to other developing tropical cities. The research confirms that unless something is done, the process of the carbon collapse will go on until the natural capacity of the region to control its microclimate is completely lost. The forecast models that have been given herein offer the empirical basis that is required to transform the reactive planning into proactive planning that is sensitive to carbon in urban governance.

4. CONCLUSION

Analysis of changes in the land use and land cover (LULCC) in the Awka Capital Territory (ACT) of 1993 and 2023 shows that there is an ecological shift that is critical. This paper has empirically shown that the high rate of mostly unplanned urbanization of the area has transformed the land into a weak carbon reservoir to a potential source of carbon. The combination of geospatial analysis, laboratory soil characterization and multiple regression modeling has given an overall view of the so-called carbon collapse that is being experienced in south eastern Nigeria.

The main finding of the study is that the spatial expansion of built-up areas is the most notable adverse predictor of the soil organic carbon (SOC) stocks. The territorial reduction of urban soil carbon ($r = -0.93$ to -0.99, $R^2 = 0.98$) has been directly related to the increase in impervious surfaces. The built-up density that has been increasing substantially in an area of about 10 percentage to 48 percentage of the total land area over a span of thirty years has literally killed the natural sequestration abilities of the soil.

Moreover, the paper points to another, less prominent yet no less threatening tendency in the agricultural land utilization. The observed agricultural treadmill whereby a large percentage of 84.8 of carbon stocks had been reduced despite the fact that farmland was classified under the green category is an indication of extreme soil depletion. This implies that the existing land management activities with the ACT such as intensive tillage and biomass burning cannot be aligned with the national objectives of Nigeria to have a 200% to 450%reduction in greenhouse emissions by 2030.

The localized regression equation models that have been established in this research are very crucial mathematical tools that are used in adaptive land management. The models assist urban planners by giving them a scientific basis to predict the environmental costs of future developmental projects by establishing the carbon sensitivity of other communities, including high vulnerability in Nawgu and the fact that the Awka community is rapidly being depleted.

Finally, the study makes a conclusion that the carbon-neutrality of the ACT is presently at risk. To overcome this, there has to be a change in policy- paradigm shift as a shift towards traditional "grey" infrastructure to go to a green-blue urban planning. The remaining high-density carbon forests (only 11.94% of the territory now) should not be classified as an elective environmental strategy, but a necessity of the regional climate resiliency. This paper offers the empirical and statistical platform to the gap between geospatial trends and climate policy providing a model that can be replicated with the other rapidly expanding tropical urban ecosystems in Sub-Saharan Africa.

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