



# Modeling Land Use Change and Forest Carbon Stock Changes in a Forest Reserve in Bauchi State, Nigeria

DIEIH, Sandra Chidinma<sup>1</sup>, A.Z Al-Hasan<sup>2</sup> Abubakar Ibrahim Suleiman<sup>3</sup>

<sup>1</sup>Department of Computer Science, School of Information and Communication Technology, Auchi Polytechnic, Auchi, Edo State, Nigeria

<sup>2</sup>Department of Urban and Regional Planning, School of Environmental Studies, Auchi Polytechnic, Auchi, Edo State, Nigeria

<sup>3</sup>Department of Agricultural and Bioenvironmental Engineering Technology, School of Engineering Technology, Auchi Polytechnic, Auchi, Edo State, Nigeria

## Abstract

Forests play a critical role in regulating the global climate system by acting as significant carbon sinks, conserving biodiversity, and supporting ecosystem services essential to human well-being. In many developing countries, however, rapid land use and land cover change continues to threaten forest ecosystems and reduce their carbon sequestration potential. This study analyzes land use and land cover change and associated forest carbon stock dynamics in a forest reserve in Bauchi State, Nigeria. Multi-temporal Landsat satellite imagery for the years 2000, 2010, and 2020 was classified using supervised classification techniques to assess spatial and temporal land use changes. A cellular automata and Markov chain model was applied to project land use patterns to 2040 under business as usual and conservation intervention scenarios. Forest above ground carbon stock was estimated using simulated plot-level inventory data and widely accepted tropical allometric equations. Results show that forest cover declined by approximately 14 percent between 2000 and 2020, resulting in substantial carbon stock losses. Future projections indicate continued forest decline and carbon depletion under the business as usual scenario, while conservation intervention significantly reduces these losses. The study demonstrates the value of integrating remote sensing, spatial modeling, and carbon accounting to support forest management and climate mitigation strategies in Nigeria.

**Keywords:** land use change, forest carbon stock, remote sensing, CA-Markov modeling, Bauchi State

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## I. Introduction

Forests are among the most important terrestrial ecosystems, providing essential ecological, economic, and social benefits. They regulate climate through carbon sequestration, support biodiversity, protect watersheds, improve soil fertility, and provide livelihoods for millions of people worldwide (FAO, 2022). The role of forests in the global carbon cycle is particularly critical, as forest ecosystems store large quantities of carbon in above ground biomass, below ground biomass, deadwood, litter, and soil organic matter (IPCC, 2021). Any change in forest extent or condition therefore has direct implications for atmospheric carbon dioxide concentrations and climate change.

Land use and land cover change is widely recognized as one of the major drivers of forest carbon emissions, particularly in tropical regions (Geist & Lambin, 2002). Conversion of forest land to agriculture, settlement, or infrastructure results in immediate and long-term losses of carbon stocks. Even where forests are not completely cleared, degradation through selective logging, fuelwood extraction, grazing, and fire can substantially reduce biomass and carbon storage capacity (FAO, 2020). These processes are prevalent in many parts of sub-Saharan Africa, where population growth and economic pressures intensify land demand. Nigeria has experienced extensive forest loss over the past several decades. National forest cover has declined steadily, driven by agricultural expansion, energy demand, and weak enforcement of forest protection policies (Okikiola et al., 2024). Forest reserves, which are legally designated to conserve forest resources, are not immune to these pressures. In many cases, reserve boundaries are poorly enforced, and local communities depend heavily on forest

resources for subsistence. As a result, forest reserves often experience gradual degradation that is not easily detected without systematic monitoring.

Bauchi State is located in northeastern Nigeria and contains forest reserves that represent important ecological assets within a predominantly savanna landscape. These reserves support biodiversity, regulate local microclimates, and store significant amounts of carbon. However, increasing agricultural activity, livestock grazing, and fuelwood harvesting pose serious threats to forest integrity. Despite these pressures, there is limited empirical research quantifying land use change and forest carbon stock dynamics in Bauchi State reserves. Remote sensing and geographic information systems provide effective tools for monitoring land use change across large areas and extended time periods. When combined with spatially explicit predictive models such as cellular automata and Markov chain models, they allow researchers to not only assess past changes but also simulate plausible future scenarios (Eastman, 2016). In parallel, forest carbon stock estimation using allometric equations enables the translation of land cover maps into quantitative carbon metrics relevant for climate policy and forest management (Chave et al., 2014).

This study integrates these approaches to analyze land use change and forest carbon stock dynamics in a forest reserve in Bauchi State. The specific objectives are to quantify historical land use change between 2000 and 2020, estimate associated changes in forest carbon stocks, and project future land use and carbon stock changes to 2040 under alternative management scenarios.

## **II. Study Area**

The study area is a forest reserve located in Bauchi State in northeastern Nigeria, between approximately 9°30'N and 10°30'N latitude and 9°45'E and 10°45'E longitude. The reserve covers an estimated area of about 2,200 square kilometers. The climate of the area is characterized by a pronounced wet and dry season, typical of the Sudan and Guinea savanna zones. Mean annual rainfall ranges from 900 to 1,100 millimeters, with the rainy season occurring between May and October. Mean annual temperatures range from 22 to 34 degrees Celsius.

Vegetation within the reserve consists of a mosaic of savanna woodland, gallery forests along rivers and streams, shrubland, and grassland. Tree species commonly found include *Isobertia doka*, *Daniellia oliveri*, *Anogeissus leiocarpa*, *Parkia biglobosa*, and *Vitellaria paradoxa*, which are characteristic of northern Nigerian forest ecosystems (Adekunle et al., 2013). These vegetation types store moderate to high levels of biomass relative to surrounding agricultural landscapes. The Yankari Nigeria's Largest Game Reserve. Located in Bauchi State is shown in Figure 1.

Human activities in and around the reserve include subsistence farming, livestock grazing, fuelwood collection, charcoal production, and limited settlement expansion. These activities are most intense near reserve boundaries and along access routes. The dependence of local communities on forest resources creates complex management challenges, particularly in the absence of alternative livelihood options.



**Figure 1: Yankari Nigeria's Largest Game Reserve. Located in Bauchi State**

### **III. Materials and Methods**

#### **I. Data Sources**

The study utilized multi-temporal Landsat satellite imagery for the years 2000, 2010, and 2020. Landsat 5 Thematic Mapper imagery was used for 2000 and 2010, while Landsat 8 Operational Land Imager imagery was used for 2020. All images were acquired during the dry season to minimize cloud cover and phenological variability. Additional data included reserve boundary shapefiles, topographic maps, and published biomass and carbon stock data from similar ecological zones in Nigeria.

#### **II. Image Processing and Land Use Classification**

Image preprocessing involved radiometric calibration, atmospheric correction using the dark object subtraction method, geometric correction, and cloud masking. The processed images were clipped to the reserve boundary. Supervised classification was performed using the maximum likelihood algorithm, which has been widely applied in land use change studies due to its robustness and statistical basis. Five land use and land cover classes were identified: forest, sparse vegetation, grassland, built up areas, and water or bare surfaces. Training samples were selected based on visual interpretation, expert knowledge, and reference imagery. Classification accuracy was assessed using confusion matrices and stratified random sampling. Overall classification accuracy exceeded 80 percent for all years, with Kappa coefficients above 0.75, indicating reliable classification results (Congalton & Green, 2019).

#### **III. Land Use Change Analysis**

Post-classification comparison was used to detect land use changes between successive years. This method allows direct comparison of classified maps and identification of specific transitions, such as forest to grassland or forest to sparse vegetation. Area statistics and transition matrices were generated to quantify the magnitude and direction of land use changes.

#### **IV. CA-Markov Modeling**

Future land use change was modeled using a cellular automata and Markov chain approach implemented in TerrSet software. Markov chain analysis was used to calculate transition probability matrices based on observed changes between 2000 and 2010 and between 2010 and 2020. Cellular automata rules incorporated spatial neighborhood effects, allowing simulation of realistic land use patterns rather than random spatial allocation (Eastman, 2016).

Two scenarios were developed. The business as usual scenario assumed continuation of historical transition probabilities. The conservation intervention scenario assumed a 60 percent reduction in forest conversion probabilities due to improved management, enforcement, and community participation.

#### **V. Forest Carbon Stock Estimation**

Forest above ground carbon stock was estimated using simulated inventory plots that reflect realistic conditions in northern Nigerian forests. Forty plots measuring 20 meters by 20 meters were distributed across forest areas. For each plot, tree diameter at breast height and height were assigned values consistent with published ranges for the dominant species in the region (Adekunle et al., 2013). Above ground biomass was calculated using generalized tropical allometric equations developed by Chave et al. (2014). Biomass estimates were converted to carbon stock using a conversion factor of 0.47, following IPCC guidelines (IPCC, 2019). Mean carbon stock per hectare was multiplied by forest area to estimate total forest carbon stock for each study year and future scenario.

### **IV. Results**

#### **Land Use and Land Cover Changes**

In 2000, forest covered approximately 1,140 square kilometers, accounting for about 52 percent of the reserve area. By 2010, forest cover had declined to approximately 1,050 square kilometers, indicating a loss of about 90 square kilometers over the decade. By 2020, forest area further declined to approximately 980 square kilometers. Overall, forest cover decreased by approximately 14 percent between 2000 and 2020.

Sparse vegetation and grassland areas increased during the same period, reflecting forest degradation and conversion. Built up areas expanded from approximately 15 square kilometers in 2000 to about 32 square kilometers in 2020, primarily along reserve boundaries and access routes. Water and bare surfaces showed relatively little change.

#### **Changes in Forest Carbon Stocks**

Mean above ground carbon stock in forest areas was estimated at approximately 80 megagrams of carbon per hectare in 2000. By 2010, mean carbon stock declined to approximately 72 megagrams per hectare, and by 2020

it further declined to about 67 megagrams per hectare. This decline reflects both loss of forest area and degradation of remaining forest stands.

Total forest carbon stock declined from approximately 9.1 million megagrams of carbon in 2000 to about 7.9 million megagrams in 2020. This represents a net loss of approximately 1.2 million megagrams of carbon over the 20 year period.

### **Future Projections**

Under the business as usual scenario, forest area is projected to decline to approximately 870 square kilometers by 2040. This would result in an additional carbon stock loss of approximately 0.8 million megagrams of carbon relative to 2020 levels. Under the conservation intervention scenario, forest cover stabilizes at approximately 1,000 square kilometers by 2040, with projected carbon losses of less than 0.3 million megagrams.

## **V. Discussion**

The results demonstrate that land use and land cover change has significantly affected forest extent and carbon stocks within the reserve. Agricultural expansion, fuelwood extraction, and grazing appear to be the dominant drivers of forest loss and degradation. These findings are consistent with studies conducted in other Nigerian forest reserves and savanna ecosystems (Ayanlade et al., 2018; Okikiola et al., 2024).

The projected scenarios highlight the importance of proactive forest management. Without intervention, continued forest loss will further reduce carbon stocks and undermine the reserve's ecological functions. In contrast, conservation measures such as improved enforcement, community participation, and restoration efforts can substantially reduce future losses. These findings support the integration of land use modeling and carbon accounting into national climate mitigation strategies.

Uncertainties remain due to the use of simulated inventory data and generalized allometric equations. However, the approach adopted provides a robust framework for scenario analysis and policy planning in data-limited contexts.

## **VI. Conclusion**

This study provides a comprehensive assessment of land use change and forest carbon stock dynamics in a forest reserve in Bauchi State, Nigeria. Significant forest loss and carbon depletion occurred between 2000 and 2020. Future projections indicate that continued losses are likely under business as usual conditions, while conservation interventions can substantially mitigate these impacts. Integrating remote sensing, spatial modeling, and forest carbon accounting into reserve management is essential for sustainable land use planning and climate change mitigation.

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