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Anthropogenic Impacts on Carbon Sequestration Dynamics in the Borgu and Zugurma Sectors of Kainji Lake National Park, Nigeria

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Received: 04-15-2025 **Revised:** 05-22-2025 **Accepted:** 05-30-2025

Citation: Mamman, S., Muhammad, M., Aishetu, A., & Odekunle, M. (2025). Anthropogenic impacts on carbon sequestration dynamics in the Borgu and Zugurma sectors of Kainji lake national park, Nigeria. *Oppor Chall. Sustain.*, *4*(2), 98-109. https://doi.org/10.56578/ocs040203.

Abstract: The influence of anthropogenic activities on carbon sequestration within the Borgu and Zugurma sectors of Kainji Lake National Park, Niger State, Nigeria, was quantitatively assessed using a multidisciplinary approach. Forest carbon stocks were estimated across land use types through biometric forest inventory techniques, direct biomass sampling, and subsequent laboratory analyses. Variations in ecological parameters and carbon distribution were statistically evaluated using analysis of variance (ANOVA) and Student's t-test. Results revealed significant spatial heterogeneity between the two sectors. Borgu exhibited a higher mean tree density (142 trees ha^{-1}) and canopy cover (48%) compared to Zugurma (74 trees ha^{-1}; 22%), indicative of greater vegetation structural integrity. Species diversity, measured using the Shannon-Wiener index, was also higher in Borgu (H' = 2.96) than in Zugurma (H' = 1.84). Major anthropogenic drivers—including logging, deforestation, and livestock grazing—were identified, with recorded activity intensities reaching 94% in Borgu and 75.5% in Zugurma. Temporal analysis of carbon stock distribution from 1990 to 2040 demonstrated a projected decline exceeding 75% in zones with initially very high carbon storage, primarily attributable to continued land degradation. The degradation of forest structure and reduction in biomass suggest a substantial loss in the park's carbon sink capacity and associated ecosystem services. These findings underscore the urgent need for ecologically informed land-use strategies, including targeted reforestation, conservation of carbon-dense and ecologically dominant tree species, and the enforcement of sustainable land management policies. Such interventions are essential for restoring carbon sequestration potential and safeguarding biodiversity in West African savannah ecosystems.

Keywords: Anthropogenic disturbance; Effects; Carbon sequestration; Savannah ecosystem; Species diversity

1. Introduction

Forests and protected areas such as national parks are vital carbon sinks that play a critical role in mitigating climate change by absorbing atmospheric carbon dioxide (CO_2) through the process of carbon sequestration. Kainji Lake National Park, comprising the Borgu and Zugurma sectors, is one of Nigeria's most significant conservation areas. However, recent years have witnessed an increasing pressure on these ecosystems due to anthropogenic activities, threatening their ecological integrity and capacity to sequester carbon. Anthropogenic activities such as illegal logging, poaching, overgrazing, encroachment for agriculture, bush burning, and uncontrolled tourism have been identified as major drivers of forest degradation in and around the park (Adeyemi & Aderibigbe, 2024). These actions not only contribute to biodiversity loss but also result in the reduction of above-ground biomass (AGB) and soil organic carbon-key components of terrestrial carbon pools (Hussein et al., 2021). The Borgu and Zugurma sectors differ ecologically in the degree of human encroachment, with the Zugurma sector facing greater degradation due to less surveillance and accessibility (Oyamakin & Adebayo, 2022). Such activities accelerate deforestation and land degradation, which consequently reduce the carbon sequestration capacity of these ecosystems (Jibrin et al., 2018). Moreover, the growing population in surrounding communities, coupled with weak enforcement of conservation laws, exacerbates unsustainable land-use practices (Adeyemi & Ibrahim, 2020). As carbon sequestration is crucial for climate change mitigation and maintaining ecosystem services, assessing how these human-induced activities affect carbon storage in Kainji Lake National Park has become a research priority. Remote sensing (RS) and Geographic Information Systems (GIS) techniques, coupled with biomass estimation models, have become effective tools for monitoring vegetation changes and estimating carbon stocks in forest reserves and national parks in Nigeria (Ajayi et al., 2024; Onyeizugbe & Nnodu, 2021). Despite these advancements, there remains a research gap in localized assessments of carbon sequestration changes due to anthropogenic pressures, especially in ecologically diverse areas like Kainji Lake National Park.

Across the globe, most nations have designated parts of their land for conservation purposes, reflecting a shared commitment to preserving biodiversity. As of 2010, the World Database on Protected Areas (WDPA) recorded over 130,000 officially recognized protected sites—a number that continues to rise with growing global awareness (United Nations Environment Programme-World Conservation Monitoring Centre, 2010). These protected areas play a crucial role in national and international strategies aimed at halting biodiversity loss. They serve not only as reservoirs of genetic diversity but also as preserved landscapes that hold cultural, spiritual, and ecological significance (Nolte et al., 2013). Governments and organizations increasingly invest in their establishment and management, recognizing their contribution to ecological stability, tourism, research, and climate resilience. Despite these efforts, over 12% of the world's terrestrial land is currently protected, yet biodiversity decline persists at a concerning rate (Pelemo et al., 2018). This paradox has led to a growing emphasis on evaluating how effectively these areas are managed, prompting more robust assessment frameworks and conservation accountability mechanisms. The major reason for the creation of national parks is to ensure and secure most areas from degradation of excessive exploitation by inhabitants within the zone (Osunsina et al., 2019)

Our planet supports an immense variety of life forms, each possessing unique genetic traits and existing in complex relationships with one another and their environments. This intricate web of life forms the foundation of biodiversity. As Earth's fundamental biological asset, biodiversity holds immense ecological, cultural, and economic value, offering vital resources and development opportunities for societies worldwide. It includes diversity within species (genetic diversity), between species (species diversity), and between ecosystems (ecosystem diversity), and these include the diversity of flora or fauna. The diversity of plant and animal life plays a crucial role in ecosystems worldwide, whether in undisturbed areas like national parks and nature reserves or human-managed environments such as agricultural lands, plantations, and urban green spaces. This biological variety underpins many ecosystem services essential to human well-being. However, accurately measuring biodiversity remains challenging, even with current technologies and datasets. Detailed assessments are still necessary to understand how species diversity is evolving and to identify both its causes and ecological consequences.

To monitor biodiversity, scientists rely on ecological indicators such as species counts within defined areas which help capture patterns in diversity. These indicators are vital tools for environmental evaluation and serve to guide policy decisions with accessible, evidence-based insights. Life is present in nearly every part of the planet from soil to ocean, from forests to urban environments, but its full extent is often underestimated due to the small size, brief life cycles, or hidden nature of many organisms. Taxonomic classification, particularly of visible fauna and flora, remains the most recognized way of documenting biodiversity. Yet, it is estimated that only 1.7 to 2 million of an estimated 5 to 30 million species have been formally described (Millennium Ecosystem Assessment, 2005), highlighting the urgent need for more comprehensive inventories. Despite increasing research on forest degradation, localized assessments of how anthropogenic pressures influence carbon sequestration at the park sector level remain scarce. This study aims to fill this gap by evaluating and comparing carbon stock dynamics in the Borgu and Zugurma sectors of Kainji Lake National Park, with a focus on quantifying sector-specific degradation and proposing tailored restoration interventions.

2. Methodology

The study employed a combination of geospatial techniques and allometric models to assess the spatial and temporal dynamics of carbon stock across the Borgu and Zugurma sectors of Kainji Lake National Park. Multi-temporal satellite imagery from 1990, 2014, 2024, and projected 2040 was acquired and analyzed using RS and GIS tools for land use/land cover (LULC) classification. Supervised classification was used to map vegetation cover, which was further stratified into carbon stock classes. Field data on tree species were collected using standard sampling plots with a plot size of 20 m × 20 m (0.04 ha) and a total of 50 plots distributed across vegetation strata in both sectors. The equation proposed by Agboola et al. (2021) was chosen due to its validation for Nigerian moist tropical forest conditions and compatibility with the dominant tree species encountered in the study area. AGB was calculated using a species-specific allometric equation: $AGB = 0.0673 \times (\rho \times D^2 \times H)^{\wedge}0.976$, where ρ is the wood density (g/cm³), D is the diameter at breast height (cm), and H is the tree height (m).

To estimate carbon stock, AGB values were multiplied by the default conversion factor of 0.47, as recommended in the 2006 guidelines of the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change IPCC., 2006), reflecting the carbon content in dry biomass. Spatial extrapolation of these estimates across various land cover types was achieved using GIS-based overlay techniques. Temporal changes in carbon stock were evaluated by comparing classified land cover maps across different years and analyzing the results using statistical summaries. Anthropogenic activities influencing forest degradation were identified through structured questionnaires distributed to community stakeholders, and their responses were statistically analyzed using SPSS to determine the frequency and spread of disturbances. The combined use of field measurements, satellite imagery interpretation, and statistical tools allows for a comprehensive assessment of how human-induced pressures have altered carbon storage within the park's protected landscapes.

AGB for the tree species strata was estimated from measured diameter at breast height and tree height using a generalized tree biomass regression equation for the specific precipitation zone (Eneji et al., 2014):

$$y = e^{(-3.1141+0.9719 In(DBH \times H)} \tag{1}$$

where, y is the AGB (kg), DBH is the diameter at breast height (cm), and H is the height of the tree (m). AGB values were converted to tons per hectare (t/ha) by multiplying by 0.001, with a coefficient of determination (r^2) of 0.97. AGB for the entire stand was multiplied by the land cover area estimation.

$$y = e^{(-3.1141+0.9719 In(DBH \times H)} \tag{2}$$

Total AGB for each land cover type was obtained using the equation:

$$y_{landcover} = \sum e^{(-3.1141+0.9719 In(DBH_{landcover} \times H_{landcover})} \tag{3}$$

Below-ground biomass (BGB) was estimated from AGB. According to Ajayi et al. (2024), a non-destructive approach depends on BGB values for vegetation as 20% of AGB. The equation is as follows:

$$BGB = 20\% \times AGB \tag{4}$$

while BGB was estimated using a default ratio (20% of AGB), soil organic carbon was inferred from organic matter measurements in soil samples. However, it was not included in the total carbon pool calculation due to limited depth-specific sampling.

The land use types within the national park are characterized by distinct plant communities, including savanna woodland, riparian forest, scrubland, and grassland. For each vegetation type, key structural parameters were recorded, such as tree height, diameter at breast height, basal area, carbon stock, and overall biomass. Carbon stock estimates were derived from five principal carbon pools: AGB, below-ground roots, undergrowth vegetation, litter, and dead wood. Each carbon pool was measured using appropriate field techniques—biomass sampling and allometric equations for above-ground trees, allometric models for root biomass, clip plot sampling for undergrowth, and standard procedures for quantifying litter and coarse woody debris.

3. Results and Discussion

3.1 Ecological Composition of the Kainji Lake National Park

The vegetation structure, species composition, and overall ecological integrity of Kainji Lake National Park differ noticeably between the Borgu and Zugurma sectors.

Guinea savanna woodland predominates in the Borgu sector, featuring thick tree cover, stratified vegetation layers, and a relatively well-preserved ecosystem largely attributed to consistent conservation efforts and protective measures. Field observations and vegetation sampling revealed the presence of key tree species such as *Vitellaria paradoxa, Isoberlinia doka, Daniellia oliveri, Terminalia avicennioides*, and *Parkia biglobosa*. The mean tree density was recorded at 142 trees ha^{-1}, with an average canopy cover of 48%, indicating a moderately closed woodland structure. Species diversity indices show a Shannon-Wiener index (H') of 2.96, suggesting high species richness and evenness in the tree community. The Shannon-Wiener index reflects both the richness (number) and evenness (distribution) of species in a community. A higher value indicates a more balanced and diverse ecosystem, which is generally more resilient to disturbance. Understory vegetation included a mixture of shrubs and grasses like *Andropogon gayanus, Hyparrhenia rufa*, and *Loudetia simplex.* The sector also supports a wide range of fauna, including duikers, kob, patas monkeys, baboons, and an array of bird species, indicating good habitat quality. Soil samples from the Borgu sector showed moderate to high organic matter content (1.8-2.5%) and loamy texture, further supporting its vegetation structure. Human activities in the Borgu sector were generally limited and mostly confined to the buffer zones, contributing to the area's relatively undisturbed ecological condition. This aligns with the observations by Adebayo & Halidu (2019), who documented high bird species diversity and an intact tree canopy dominated by *Vitellaria paradoxa, Isoberlinia doka*, and *Daniellia oliveri*. Similarly, Bassey et al. (2025) reported that the Borgu sector offers critical habitat for large herbivores and primates, attributing this to the well-maintained vegetation and reduced levels of human interference, which support frequent wildlife sightings. Table 1. shows the ecological composition in the Borgu and Zugurma sectors.

Table 1. Ecological composition in Borgu and Zugurma sectors

Ecological Parameter	Borgu Sector	Zugurma Sector
Dominant vegetation type	Guinea savanna woodland	Open woodland and derived savanna
Tree species present	*Vitellaria paradoxa*, *Isoberlinia doka*, *Daniellia oliveri*, and *Parkia biglobosa*	*Combretum* spp., *Albizia zygia*, *Anogeissus leiocarpa*, and *Lannea acida*
Mean tree density (trees ha^{-1})	142	74
Average canopy cover (%)	48%	22%
Species diversity index (H')	2.96	1.84
Common grasses and shrubs	*Andropogon gayanus* and *Hyparrhenia rufa*	*Pennisetum pedicellatum* and *Imperata cylindrica*
Soil organic matter (%)	1.8-2.5%	1.2-1.5%
Signs of human disturbance	Low (limited to buffer zones)	High (grazing, logging, poaching, and farming)
Wildlife observation	Frequent (e.g., duikers, kobra, and monkeys)	Sparse (monkeys, antelope, and snakes)

In contrast, the Zugurma sector displayed signs of ecological degradation with a predominance of open woodland, derived savanna, and grassland mosaics. Dominant tree species included *Combretum* spp., *Anogeissus leiocarpa*, *Lannea acida*, and *Albizia zygia*, though at much lower densities compared to Borgu. The mean tree density was 74 trees ha^{-1}, and canopy cover was estimated at 22%, indicating a more open and fragmented landscape. Species diversity was lower, with a Shannon-Wiener index (H') of 1.84, reflecting the impact of ongoing anthropogenic pressures such as grazing, farming, and bush burning. The Shannon-Wiener index reflects both the richness (number) and evenness (distribution) of species in a community. A higher value indicates a more balanced and diverse ecosystem, which is generally more resilient to disturbance.

Herbaceous cover was more pronounced, with dominant grasses including *Pennisetum pedicellatum*, *Brachiaria* spp., and *Imperata cylindrica*. Invasive species were also recorded, particularly in disturbed patches. Soil quality in Zugurma was poorer, with lower organic matter (1.2-1.5%) and signs of compaction and erosion in areas of heavy livestock use. Wildlife sightings were significantly reduced, and indirect evidence (tracks and droppings) indicated sparse populations of antelopes and monkeys. Poaching and cattle encroachment were evident in several transects, contributing to habitat disturbance. Bassey et al. (2025) conducted an anthropogenic pressure assessment in Kainji Lake National Park and identified Zugurma as the most degraded sector due to illegal grazing, logging, farming, and poaching. Their work reported low tree density, high fragmentation, and poor soil structure. This corroborates the research of Meijaard et al. (2022) who found lower mammal populations in Zugurma compared to Borgu, attributing this to degraded habitat conditions and human conflict zones. This supports field observations of limited wildlife presence in the Zugurma sector.

3.2 Anthropogenic Activities Within and Around the Park

The results indicate a significant impact of human activities on the Borgu sector of the national park. These activities, including logging (94%), deforestation (91%), resource exploitation (89%), transportation infrastructure (86%), and mining (82%), suggest widespread environmental degradation, potentially threatening the park's biodiversity and carbon sequestration potential. Logging is a major contributor to forest degradation in the Borgu sector, with 94% of the park experiencing its effects. Illegal and unsustainable logging leads to habitat loss, reduces forest cover, and decreases carbon sequestration. The removal of trees affects the park's ability to store carbon, ultimately contributing to increased atmospheric CO_2 levels. Additionally, logging disrupts the natural ecosystem, threatening wildlife species that depend on the forest for shelter and food. This is in line with the findings of Hussein et al. (2021) who revealed that illegal logging destroys the habitat for fauna and flora organisms in arid desert environs. Table 2. shows the anthropogenic activities in the Borgu sector.

Deforestation, recorded at 91%, is one of the most significant anthropogenic pressures in the park. This activity is often driven by agricultural expansion, settlement development, and illegal timber harvesting. The loss of trees not only reduces the park's biomass and carbon stock but also leads to soil erosion, loss of biodiversity, and changes in microclimatic conditions. The high percentage of deforestation suggests a severe threat to the park's ecological balance, requiring urgent conservation measures. Akosim et al. (2010) identified deforestation as a key anthropogenic activity occurring in communities surrounding Kainji Lake National Park, posing significant challenges to ongoing conservation efforts. Among the various forms of disturbances, resource exploitation stands out as the most widespread, accounting for 89% of reported cases. This includes unsustainable harvesting of non-timber forest products, poaching, and the collection of medicinal plants. Such activities hinder natural forest regeneration and place native plant and animal species at risk. Additionally, persistent overuse of forest resources contributes to soil degradation and weakens the park's capacity to adapt to the impacts of climate change.

Table 2. Anthropogenic activities in the Borgu sector

Anthropogenic Activities	Frequency	Percentage
Farming around the park	18	9.0
Logging	168	84.0
Grazing	63	31.5
Settlement	19	9.5
Deforestation	178	89.0
Resource exploitation	182	91.0
Transportation infrastructure	180	90.0
Tourism and recreation	112	56.0
Mining	164	82.0

The development of transportation infrastructure, such as roads and pathways, affects 86% of the park. Road construction leads to habitat fragmentation, making it easier for illegal loggers and poachers to access previously undisturbed areas. Additionally, infrastructure development often results in increased human settlements near the park, further intensifying anthropogenic pressures like waste generation and land encroachment. Roads also facilitate the movement of invasive species, which can outcompete native flora and fauna.

Mining activities, impacting 82% of the park, contribute to deforestation, soil degradation, and water pollution. Mining operations often involve land clearing, which reduces vegetation cover and exposes soil to erosion. The use of chemicals in mining can contaminate water bodies, negatively affecting aquatic life and the availability of clean water for both wildlife and nearby communities. Additionally, mining leads to the displacement of species and alters the natural landscape, reducing the park's ecological integrity. This substantiates the findings of Dada et al. (2024), which show that resource exploitation, including activities like illegal grazing, has been documented in the Borgu sector. Research indicates that livestock activities, such as trampling and lopping, lead to vegetation degradation and soil exposure, contributing to environmental degradation within the park. In many regions, anthropogenic pressures interact and compound rather than occur in isolation. For example, logging not only removes critical tree cover but also creates access routes that facilitate the encroachment of livestock herders. This sequential disturbance intensifies soil compaction, disrupts natural regeneration, and exacerbates vegetation loss. Such cumulative impacts accelerate ecosystem degradation at a rate and scale that surpasses the additive effects of individual activities, leading to long-term ecological instability and loss of biodiversity.

Findings from the Zugurma sector indicate considerable human-induced pressures on the ecosystem. Key disturbances include logging (73%), grazing (75.5%), deforestation (71%), resource extraction (63.5%), and tourism-related activities (73.5%). These factors collectively drive habitat fragmentation, diminish species diversity, and impair the area's ability to store carbon, posing serious long-term threats to ecological stability and climate regulation.

Table 3. Anthropogenic activities in the Zugurma sector

Anthropogenic Activities	Frequency	Percentage
Farming around the park	48	24.0
Logging	146	73.0
Grazing	151	75.5
Settlement	49	24.5
Deforestation	142	71.0
Resource exploitation	127	63.5
Transportation infrastructure	123	61.5
Tourism and recreation	147	73.5
Mining	115	57.5

Similar to the Borgu sector, logging is a major contributor to forest degradation in the Zugurma sector, with 73% of the park impacted by tree felling for timber and fuelwood. The removal of trees reduces forest cover, disrupts wildlife habitats, and decreases the park's ability to store carbon. Unsustainable logging also affects soil stability, leading to erosion and reduced water retention capacity in the forest. If not controlled, it could result in forest fragmentation, making the area more vulnerable to further environmental degradation. This is in line with the findings of Hussein et al. (2021) who revealed that illegal logging destroys the habitat for fauna and flora organisms in arid desert environs. Furthermore, at 75.5%, grazing is a significant human activity affecting the park. Uncontrolled livestock grazing leads to overgrazing, which depletes vegetation, compacts soil, and reduces biodiversity. Trampling by livestock disrupts natural plant regeneration, while competition for forage impacts herbivorous wildlife. Additionally, conflicts between herders and wildlife can arise, increasing the risk of human-wildlife conflicts and further stressing the park's ecosystem. Over time, persistent grazing could turn once-forested areas into degraded landscapes with limited ecological value. Binlinla et al. (2019) showed that over-grazing is a major activity in and around the protected areas which hinders forest conservation. Table 3. shows the anthropogenic activities in the Zugurma sector.

Deforestation, recorded at 71%, is driven by agricultural expansion, fuelwood collection, and land clearing for settlements. The loss of tree cover contributes to habitat destruction and reduces the park's ability to regulate local climate conditions. Deforestation also impacts the hydrological cycle, leading to decreased water availability for both wildlife and nearby human communities. Furthermore, it increases carbon emissions, as trees that would have stored carbon are removed and often burned, contributing to global climate change. This observation is consistent with the findings of Akosim et al. (2010), who reported that deforestation remains a predominant activity in the communities surrounding Kainji Lake National Park, posing a significant challenge to the park's conservation initiatives.

Resource exploitation, at 63.5%, includes activities such as hunting, poaching, and the extraction of medicinal plants and non-timber forest products. This threatens biodiversity, particularly endangered species that rely on the park for survival. Overharvesting of plants and animals disrupts food chains and alters ecological balances. If not managed, resource exploitation can lead to species decline and the eventual loss of key ecosystem services that support both wildlife and human communities. Tourism and recreation, impacting 73.5% of the park, can have both positive and negative effects. While eco-tourism can provide revenue for conservation, unregulated tourism leads to habitat disturbance, pollution, and increased human activities within sensitive areas. The construction of tourism infrastructure can contribute to deforestation, and an influx of visitors may result in littering, noise pollution, and disruption of wildlife behaviors. Sustainable tourism management is necessary to balance economic benefits with environmental protection. In many areas, anthropogenic pressures overlap. For instance, logging opens up forest areas, which are then easily accessed by herders for grazing, amplifying soil compaction and vegetation loss. These compounded effects accelerate ecosystem degradation beyond the sum of individual impacts. The higher degradation in Zugurma is attributed to its remoteness, weaker enforcement, and easier accessibility by surrounding communities. Limited park infrastructure and fewer patrols enable illegal activities to persist unchecked compared to the better-managed Borgu sector.

3.3 Analysis of Temporal Dynamics of Carbon Storage

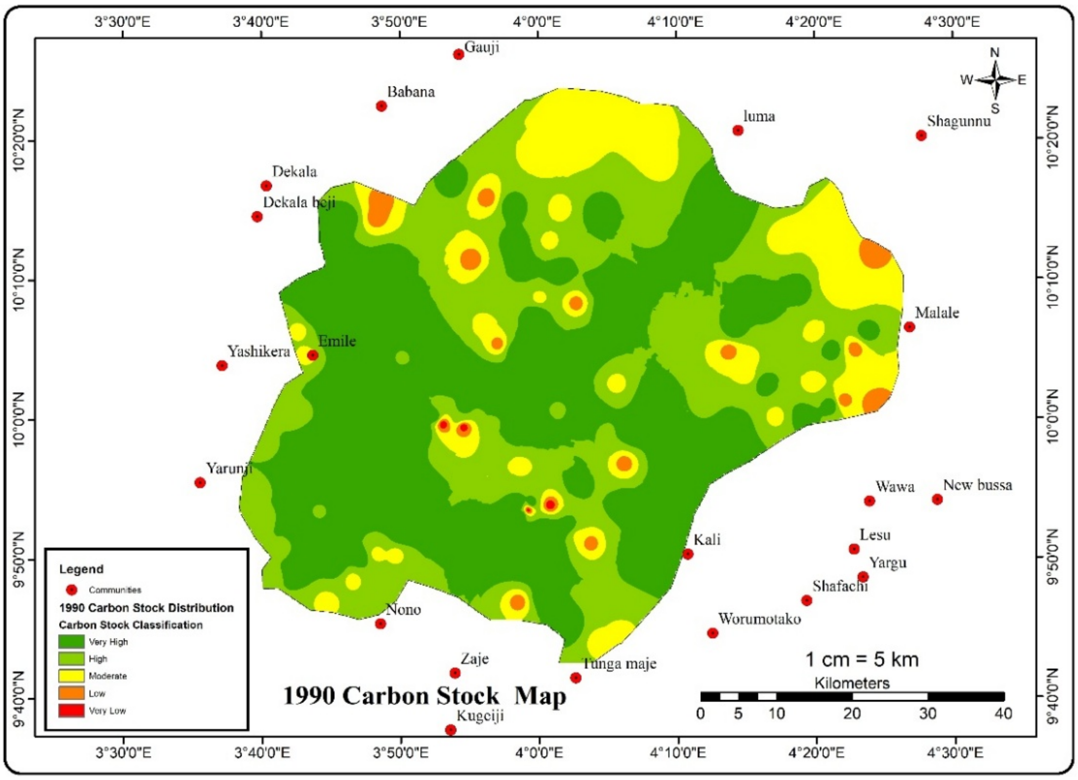


Figure 1. Spatio-temporal distribution of carbon stock in the Borgu sector (1990)

The spatio-temporal analysis of carbon stock in the Borgu and Zugurma sectors between 1990 and 2040 reveals clear patterns of vegetation degradation and biomass decline, largely driven by anthropogenic pressures. In 1990, both sectors recorded substantially high to very high carbon stock levels. Borgu had 41.7% high and 20% very high carbon stock, predominantly in its central and southern regions, while Zugurma had a higher concentration, with 40.51% very high and 24.13% high carbon stock, mostly located in the eastern and central areas. These zones correspond to dense forest cover and relatively undisturbed ecosystems. Figures 1 and 2 show the spatio-temporal distribution of carbon stock in the Borgu and Zugunma sectors in 1990, respectively.

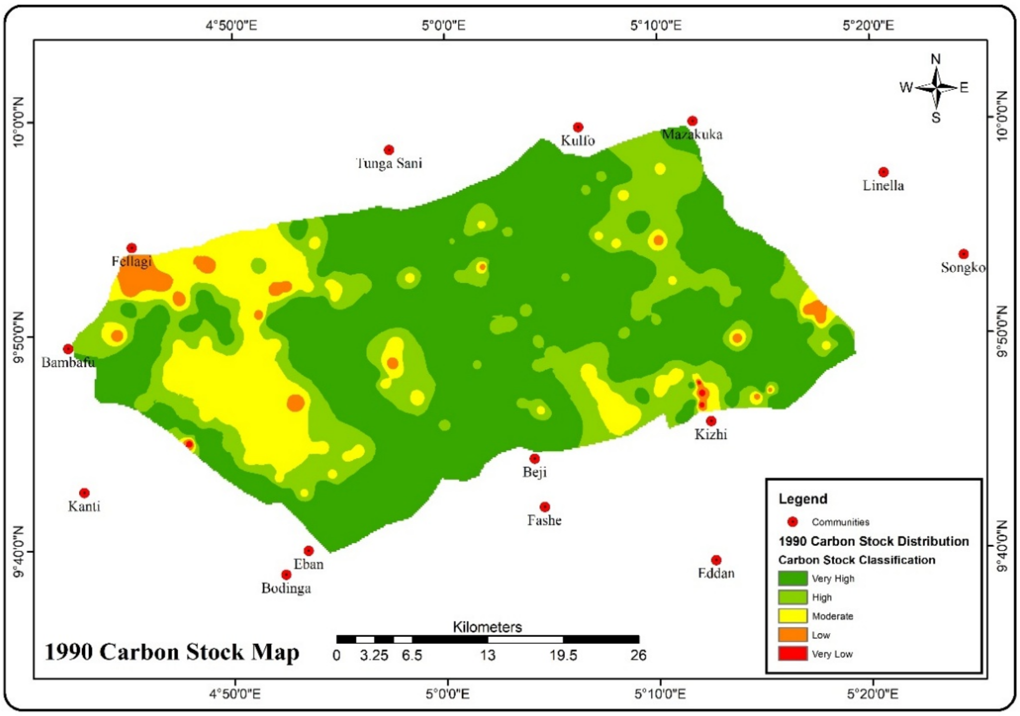
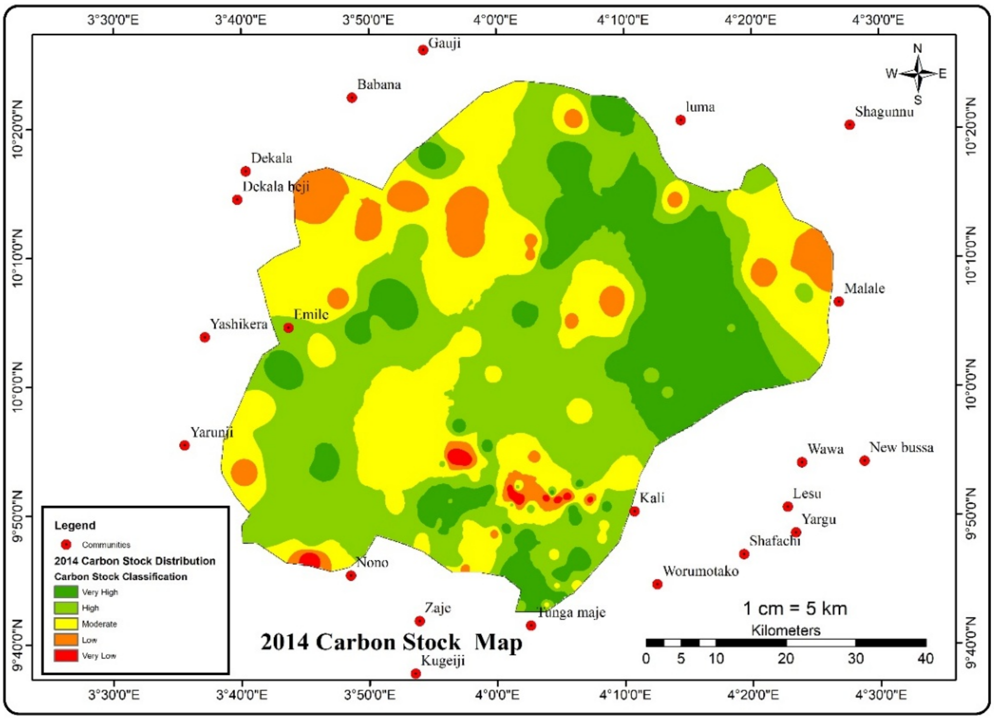


Figure 2. Spatio-temporal distribution of carbon stock in the Zugunma sector (1990)



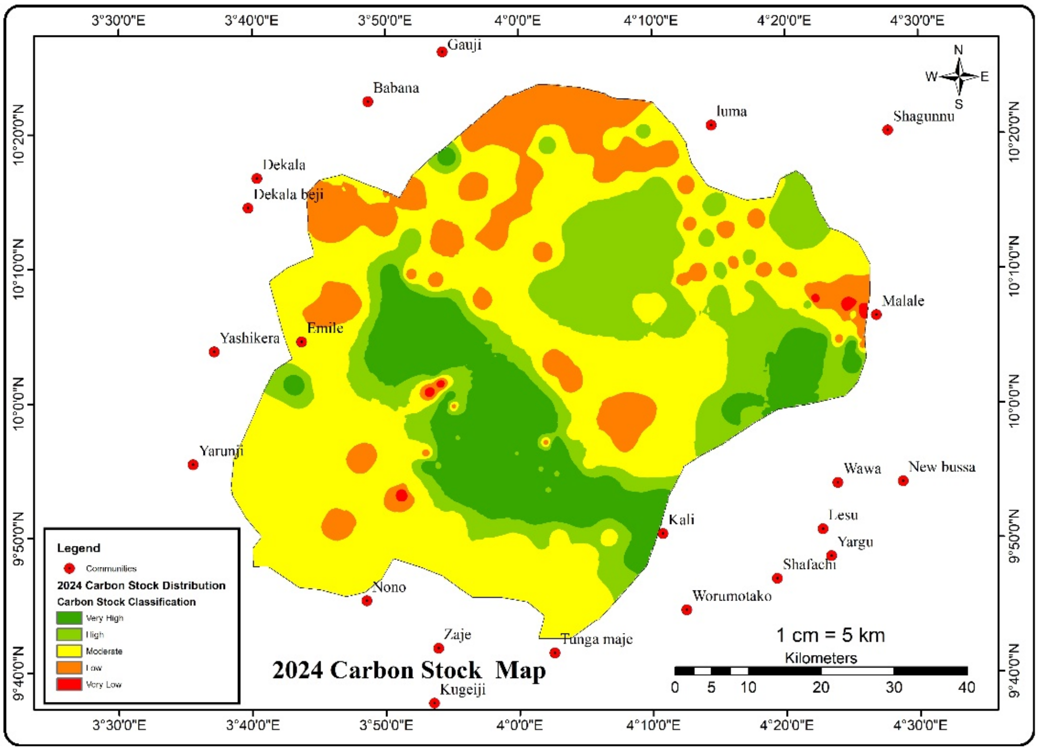
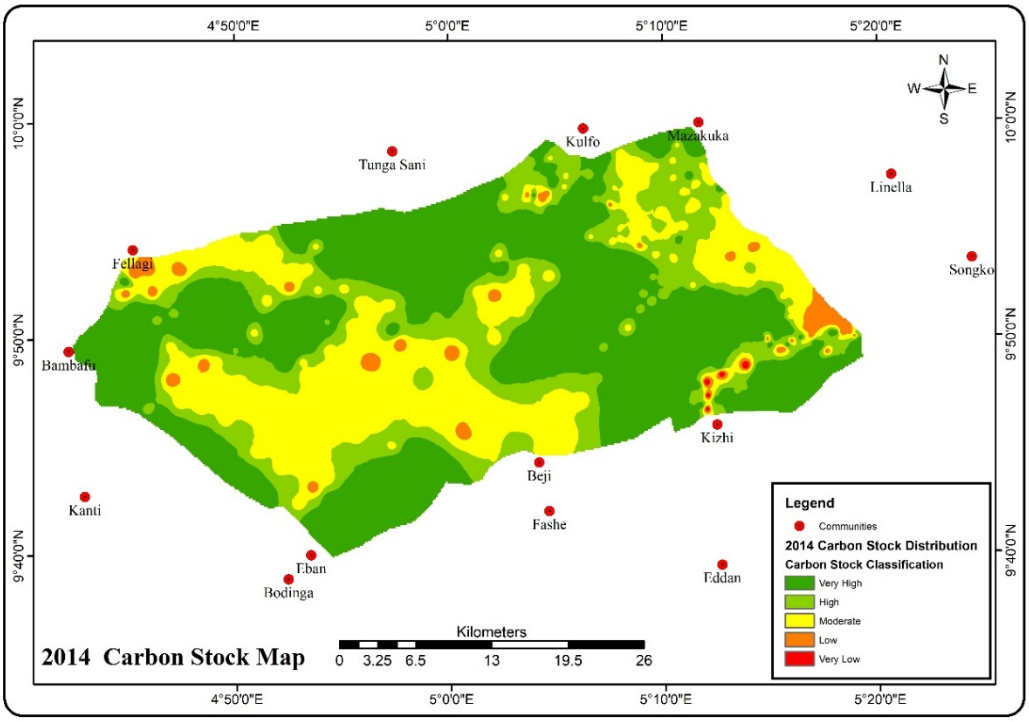


Figure 3. Spatio-temporal distribution of carbon stock in the Borgu sector (2014 and 2024)



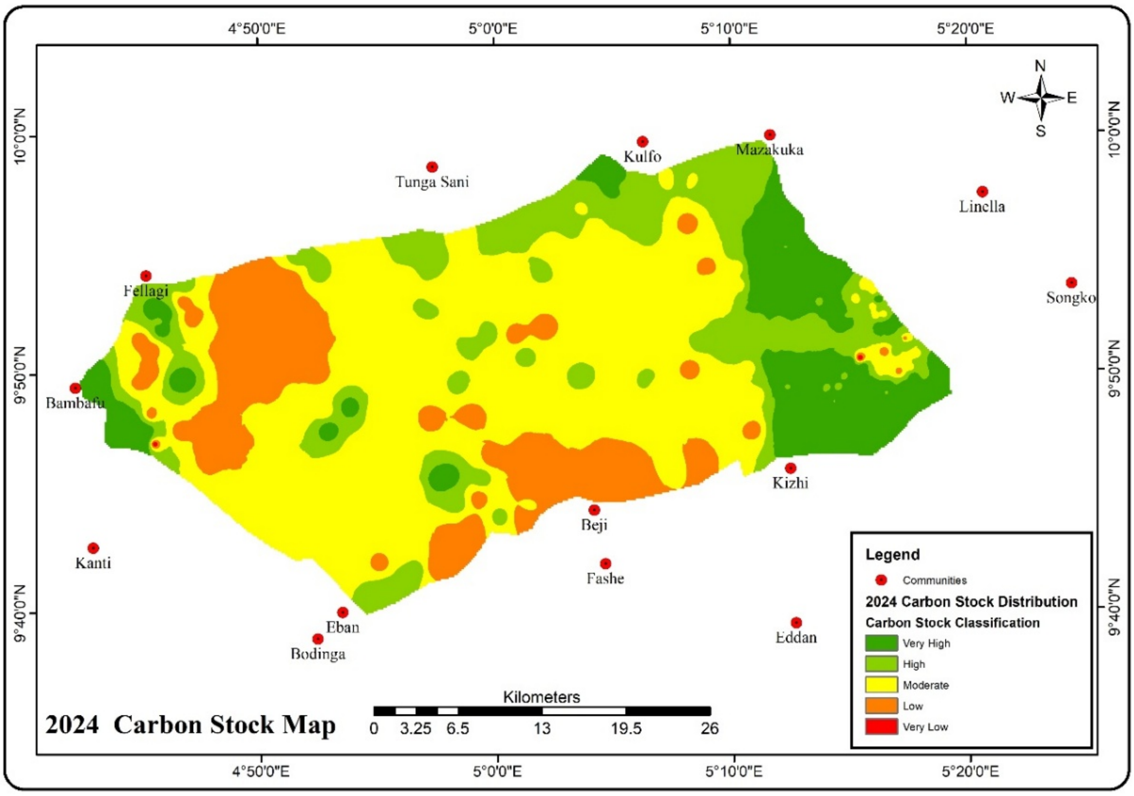


Figure 4. Spatio-temporal distribution of carbon stock in the Zugunma sector (2014 and 2024)

By 2014, the decline in carbon stock was evident in both sectors. Borgu's very high stock reduced to 14.3%, while Zugurma's dropped to 37.7%. Moderate and low categories expanded, particularly in degraded peripheral areas. Carbon-dense areas have become progressively more affected by human-induced disturbances, particularly deforestation, unauthorized logging, and bush burning. The trend continued in 2024, where very high stock in Borgu fell further to 8.6% and in Zugurma to 11.6%, with corresponding increases in low and very low carbon areas. Borgu experienced more fragmentation in its central zones, whereas Zugurma faced widespread degradation across the north and west. The significant reduction in carbon stock implies diminished carbon sink capacity, contributing to increased atmospheric CO_2 and amplifying both local microclimatic changes and broader climate instability. Loss of tree cover also affects regional rainfall patterns and exacerbates land surface temperature rise.

Figures 3 and 4 show the spatio-temporal distribution of carbon stock in the Borgu and Zugunma sectors in 2014 and 2024. The 2040 projections were based on linear extrapolation of observed degradation trends from classified satellite imagery. While they offer a useful foresight scenario, uncertainties arise from unpredictable socio-political interventions, natural regeneration potential, and policy shifts. Hence, the projections represent a worst-case degradation trajectory if current trends persist. Projections for 2040 show that Borgu's very high carbon stock is expected to decline to 4.3%, and Zugurma's to 8.34%, reflecting over 75% loss of original high-density carbon zones. The rise in low and very low carbon stock categories in Borgu (47.1%) and Zugurma (35.59%) signals an ecological tipping point. However, Zugurma shows slight improvements in moderate zones due to re-growth potential in less-accessed zones, suggesting that targeted interventions may yield recovery. Overall, Zugurma initially held more carbon-rich biomass but experienced sharper degradation due to weaker protection and accessibility challenges. Borgu, while better managed, shows consistent fragmentation and biomass loss. This comparative trend underscores the urgent need for spatially informed conservation, afforestation, and land-use policies, particularly in buffer zones and transition areas identified through mapping. Figures 5 and 6 show the spatio-temporal distribution of carbon stock in the Borgu and Zugunma sectors in 2040.

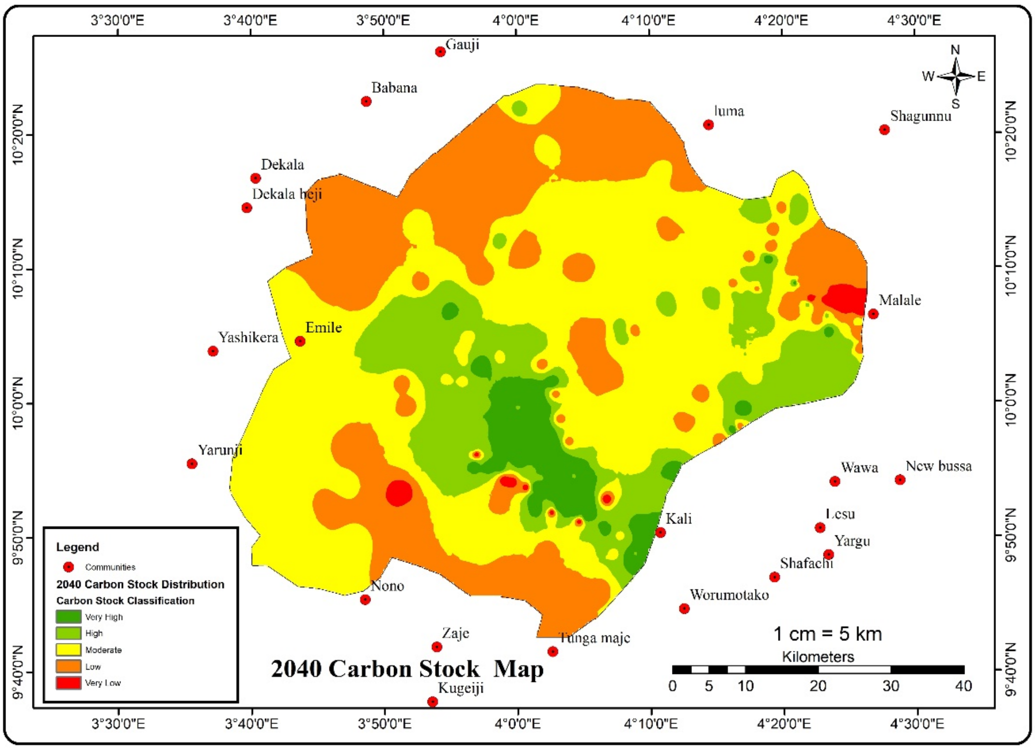


Figure 5. Spatio-temporal distribution of carbon stock in the Borgu sector (2040)

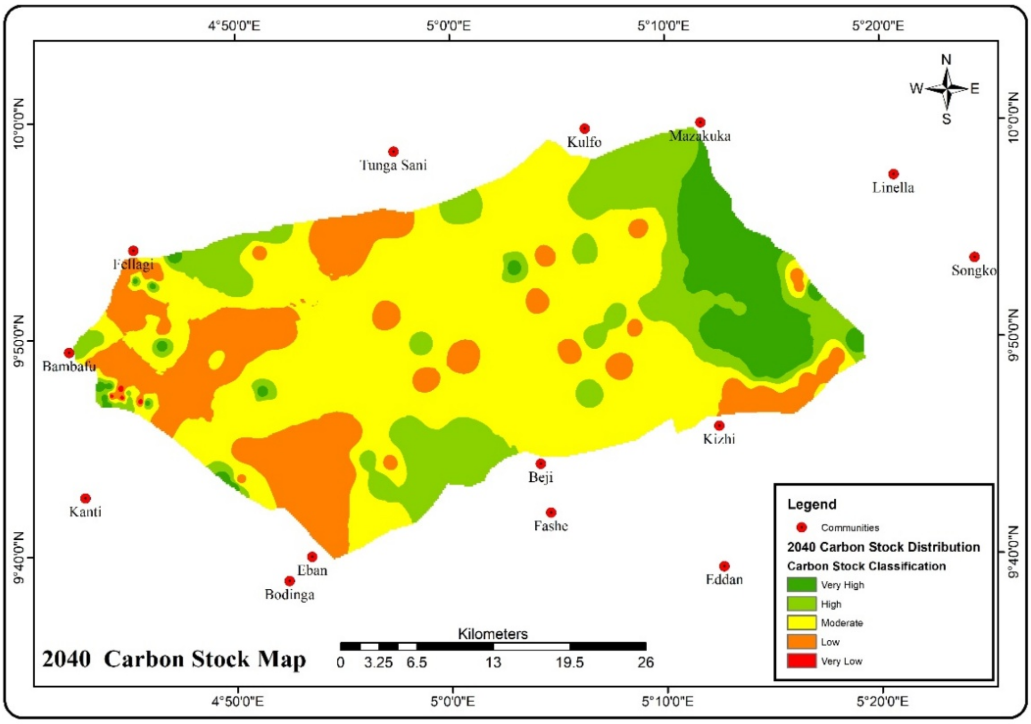


Figure 6. Spatio-temporal distribution of carbon stock in the Zugunma sector (2040)

4. Conclusions and Recommendations

The analysis of anthropogenic activities in the Borgu and Zugurma sectors reveals a significant and progressive decline in carbon stock across both sectors of Kainji Lake National Park from 1990 to 2040, driven largely by anthropogenic pressures such as deforestation, farming, bush burning, and illegal logging. While both sectors initially possessed substantial high and very high carbon stock, spatial analyses show a marked reduction in these zones, particularly in Zugurma, where surveillance and protection are weaker. The projected trends for 2040 indicate a critical shift toward low and very low carbon stock classes, threatening the park's role as a carbon sink and its ecological integrity. These findings underscore the urgency of implementing targeted mitigation strategies to restore and sustain the park's carbon sequestration potential. Future studies should incorporate long-term monitoring of biomass change using high-resolution imagery and investigate socio-economic drivers behind park encroachment. Participatory mapping and livelihood surveys can help in designing inclusive conservation strategies.

Therefore, it is recommended that restoration in Zugurma should prioritize fast-growing native species like *Combretum molle* and *Anogeissus leiocarpa*, which are resilient to grazing pressure. For Borgu, enrichment planting with *Vitellaria paradoxa* and *Isoberlinia doka* can help restore canopy structure. Assisted natural regeneration and community-led nursery programs are also encouraged. Policy recommendations include establishing community-based forest monitoring groups, increasing park ranger capacity, and enforcing conservation bylaws through participatory approaches. Engagement with local leaders and sustainable livelihood programs will enhance compliance.

Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgements

The authors gratefully acknowledge the support of the Kainji Lake National Park authorities and rangers for granting access to the study areas. Appreciation also goes to the local communities and field assistants who contributed to data gathering and logistics.

Conflicts of Interest

The authors declare no conflict of interest.

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