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Research Article

INTEGRATION OF REMOTE SENSING DATA AND GEOGRAPHIC INFORMATION SYSTEM FOR PRECISE MAPPING OF CARBON SEQUESTRATION POTENTIAL IN FOREST

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Abstract
Accurate assessment of forest carbon sequestration potential has become increasingly important for climate change mitigation, sustainable forest management, and environmental policy development. Advances in Remote Sensing and Geographic Information System (GIS) technologies offer new opportunities to improve the precision and efficiency of carbon mapping across large and heterogeneous forest landscapes. This study aimed to examine the effectiveness of integrating remote sensing data and GIS techniques for precise mapping of carbon sequestration potential in forest ecosystems and to identify the environmental factors influencing carbon distribution patterns. A quantitative geospatial approach was employed using multisource satellite imagery, vegetation indices, biomass estimates, topographic variables, land-cover data, and field validation measurements. Spatial modeling, statistical analysis, and GIS-based overlay techniques were applied to evaluate carbon sequestration potential across the study area. Results revealed substantial spatial variation in carbon storage capacity, with high-carbon zones concentrated in dense and ecologically intact forests. Vegetation density, biomass accumulation, forest cover percentage, and topographic characteristics showed significant positive relationships with carbon sequestration estimates. Integrated modeling achieved high predictive accuracy and demonstrated strong agreement with field observations. Findings indicate that combining remote sensing and GIS technologies provides a reliable framework for identifying carbon-rich forest areas, supporting evidence-based conservation planning, improving carbon accounting practices, and strengthening climate change mitigation strategies through more accurate spatial assessment of forest carbon resources.

Keywords: Biomass Estimation, Carbon Sequestration, Forest Mapping

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INTRODUCTION

Forests play a critical role in mitigating climate change through their capacity to absorb and store atmospheric carbon dioxide. Global concerns regarding rising greenhouse gas emissions have intensified interest in understanding the carbon sequestration potential of forest ecosystems (Pascual et al., 2024; Sarkheil et al., 2025). International climate agreements and sustainable development initiatives increasingly emphasize the importance of accurately quantifying forest carbon stocks as part of broader climate mitigation strategies (Shen et al., 2025). Reliable information regarding carbon sequestration capacity is therefore essential for environmental planning, carbon accounting, and ecosystem management (Ribas-Costa et al., 2025; Shao et al., 2025).

Carbon sequestration assessment has traditionally relied on field-based forest inventories and biomass measurements. Conventional approaches provide valuable ecological information but often require substantial financial resources, labor, and time (Ouattara et al., 2025; M. Wei et al., 2025). Spatial coverage limitations further constrain the ability of traditional methods to capture the heterogeneity of forest landscapes across large geographic areas. Advancements in geospatial technologies have created opportunities to overcome these limitations through more efficient and scalable approaches (Fu et al., 2025; Wang et al., 2025).

Remote sensing technologies and Geographic Information Systems (GIS) have emerged as powerful tools for environmental monitoring and spatial analysis (Y. Wei et al., 2025). Satellite imagery, aerial observations, and geospatial databases enable researchers to evaluate forest characteristics, vegetation dynamics, biomass distribution, and land-cover changes with increasing precision (Ferreira et al., 2025; Jevšenak et al., 2024). Integration of remote sensing and GIS technologies offers the potential to generate comprehensive spatial information regarding carbon sequestration patterns while supporting evidence-based forest management and climate policy development (Schmidt et al., 2025).

Accurate mapping of forest carbon sequestration potential remains a significant scientific and practical challenge despite technological advancements in environmental monitoring (Beisekenov et al., 2025). Forest ecosystems exhibit substantial variability in species composition, canopy structure, biomass accumulation, topographic conditions, and ecological productivity (Tompalski et al., 2024). Such variability complicates efforts to develop reliable spatial models capable of representing carbon storage dynamics across diverse forest landscapes (X. Zhang et al., 2024).

Existing carbon assessment approaches frequently encounter limitations related to data resolution, methodological consistency, and spatial accuracy (Duan et al., 2025). Many studies rely on either remote sensing datasets or GIS-based spatial analyses independently, resulting in fragmented assessments that may not fully capture the complexity of carbon sequestration processes (Kafy et al., 2023). Inconsistent integration of ecological variables, environmental factors, and geospatial information often contributes to uncertainty in carbon estimation outcomes (Ali & Rahman, 2025).

Decision-makers responsible for forest conservation, climate adaptation, and carbon management require spatially explicit information that accurately identifies areas with high carbon sequestration potential (Odebiri et al., 2024; Zanguim et al., 2024). Insufficient precision in carbon mapping may lead to ineffective allocation of conservation resources, inaccurate carbon accounting, and suboptimal land management strategies. Addressing these challenges requires methodological frameworks capable of integrating diverse geospatial datasets into a coherent and reliable assessment model (Chen et al., 2025).

This study aims to develop an integrated framework that combines remote sensing data and Geographic Information System technologies to enhance the precision of forest carbon sequestration mapping (Anees et al., 2024; M. Xu et al., 2025). The proposed framework seeks to generate spatially detailed information regarding carbon storage potential while accounting for ecological and environmental variability across forested landscapes (F. Xu et al., 2025; Y. Zhang, Cheng, et al., 2025).

Research efforts focus on identifying key biophysical variables that influence carbon sequestration capacity and examining how these variables can be effectively extracted, analyzed, and integrated using geospatial technologies (N. Wei et al., 2025). Vegetation indices, land-cover characteristics, topographic conditions, biomass indicators, and environmental parameters are considered important components of the analytical framework. Integration of these variables is expected to improve the accuracy of carbon potential estimation (Abu Bakar et al., 2025).

Investigation also seeks to evaluate the effectiveness of combined remote sensing and GIS approaches in supporting forest management and climate mitigation initiatives (Sarmiento et al., 2025). Spatial outputs generated through the study are intended to provide decision-makers with actionable information for prioritizing conservation efforts, designing carbon offset programs, and monitoring ecosystem sustainability. Findings are expected to contribute to both scientific knowledge and practical environmental governance (Li et al., 2024; Suárez-Fernández et al., 2025).

Existing literature demonstrates substantial progress in the application of remote sensing technologies for biomass estimation and carbon stock assessment (Kasahun, 2025). Numerous studies have utilized satellite imagery, LiDAR data, vegetation indices, and machine learning algorithms to estimate forest carbon dynamics. Research findings consistently highlight the value of remote sensing in improving spatial coverage and reducing the costs associated with traditional field measurements (Ahmed et al., 2025; Huang et al., 2024).

Studies focusing on GIS-based carbon mapping have similarly contributed to understanding the spatial distribution of carbon resources and environmental variables (Almeida et al., 2025). GIS applications have been used to analyze land-use patterns, habitat characteristics, ecological suitability, and environmental risk factors associated with carbon sequestration (Rashid & Rafiq Kashani, 2025). Contributions from GIS research have improved the visualization and management of spatial information relevant to forest ecosystems (Chang et al., 2025).

Limited attention has been devoted to developing comprehensive frameworks that fully integrate multi-source remote sensing datasets with advanced GIS-based spatial modeling techniques for high-precision carbon sequestration mapping (Louzada et al., 2025; Y. Zhang, Zhao, et al., 2025). Existing investigations frequently emphasize either biomass estimation or spatial visualization without systematically combining both dimensions into a unified analytical model (Pizarro et al., 2025). Research examining the interaction among vegetation characteristics, environmental factors, and spatial decision-support systems remains relatively scarce. Such limitations reveal a significant knowledge gap that warrants further investigation (Garshasbi et al., 2025).

The novelty of this study lies in the development of an integrated geospatial framework that combines remote sensing-derived biophysical indicators with GIS-based spatial analysis to generate precise maps of forest carbon sequestration potential. Integration of multiple environmental variables within a unified analytical system represents an advancement beyond conventional approaches that rely on isolated datasets or single-method assessments. The framework seeks to improve both spatial accuracy and ecological relevance in carbon mapping applications.

Methodological innovation is further reflected in the incorporation of multi-layer geospatial analysis capable of simultaneously evaluating vegetation condition, biomass distribution, topographic influences, and environmental suitability factors. Such an approach provides a more comprehensive understanding of carbon sequestration dynamics than methods focused solely on forest cover or biomass estimation. Enhanced analytical precision may support more effective environmental monitoring and resource management practices.

Scientific and practical justification for the study arises from the increasing demand for reliable carbon information in climate change mitigation initiatives, sustainable forest management programs, and international carbon accounting mechanisms. Governments, conservation organizations, and environmental stakeholders require accurate spatial data to support evidence-based decision-making and policy formulation. Development of an integrated remote sensing and GIS framework contributes to these needs while advancing methodological knowledge within the fields of environmental science, geospatial analysis, and climate research.

RESEARCH METHOD

Research Design

This study employed a quantitative geospatial research design integrating remote sensing data and Geographic Information System (GIS) techniques to assess and map the carbon sequestration potential of forest ecosystems. The research adopted a spatial modeling approach that combined satellite-derived environmental information, forest biophysical characteristics, and geographic datasets to generate high-resolution carbon sequestration maps. Spatial analysis was selected because carbon storage capacity is inherently influenced by geographical variability, vegetation conditions, topographic features, and land-cover dynamics. Integration of multiple geospatial datasets enabled a comprehensive assessment of forest carbon distribution across the study area (Ma et al., 2025).

A cross-sectional environmental assessment framework was utilized to examine current carbon sequestration potential within forest landscapes. Remote sensing data were processed to extract vegetation indicators, while GIS-based spatial analyses were applied to evaluate environmental suitability and biomass-related variables. Carbon sequestration potential was estimated through the integration of normalized vegetation indices, forest cover characteristics, elevation, slope, and land-use information. Validation procedures were conducted using field observations and secondary forest inventory data to ensure the reliability and accuracy of the spatial model.

Research Target/Subject

The population of this study consisted of all forested areas located within the selected research region. Forest ecosystems characterized by varying vegetation densities, species compositions, topographic conditions, and land-cover classifications were included in the investigation. These forest areas represented diverse ecological conditions that influence carbon accumulation and sequestration processes. Spatial units within the study area served as the primary analytical population for carbon assessment (Y. Zhang, Li, et al., 2025).

The sample was determined through a stratified spatial sampling approach. Forest zones were classified into several strata based on vegetation density, land-cover type, and topographic characteristics derived from satellite imagery and GIS databases. A total of 150 spatial sampling plots were selected to represent low, moderate, and high vegetation cover categories. Ground-truth data were collected from representative sample plots to validate remote sensing outputs and estimate above-ground biomass. Sample selection ensured adequate representation of ecological variability across the forest landscape, thereby improving the accuracy of carbon sequestration estimates.

Research Procedure

Data collection commenced with the acquisition of satellite imagery, topographic datasets, forest inventory records, and land-use information from relevant governmental and environmental agencies. Image preprocessing procedures included atmospheric correction, geometric correction, cloud masking, and image enhancement to improve data quality. Vegetation indices were subsequently generated from the processed imagery to represent forest productivity and biomass conditions. GIS databases were developed by integrating environmental, ecological, and geographical variables into a unified spatial framework.

Spatial analysis was conducted using overlay techniques, weighted modeling, and suitability analysis to identify areas with varying levels of carbon sequestration potential. Carbon estimation models were developed based on relationships among vegetation indices, biomass indicators, land-cover characteristics, and environmental variables. Ground-truth observations from sample plots were used to validate model outputs through statistical accuracy assessments, including correlation and root mean square error analyses (Anees et al., 2024). Final carbon sequestration maps were classified into low, moderate, high, and very high potential categories. Interpretation of spatial patterns was subsequently performed to identify priority areas for forest conservation, carbon management, and climate change mitigation initiatives.

Instruments, and Data Collection Techniques

Research instruments consisted of both geospatial technologies and environmental datasets. Remote sensing data were acquired from multispectral satellite imagery, including Sentinel-2 and Landsat 8 platforms, which provided information regarding vegetation conditions, canopy characteristics, and land-cover distribution (F. Xu et al., 2025; Y. Zhang, Cheng, et al., 2025). Geographic Information System software was employed to process, analyze, and visualize spatial data. Digital Elevation Models (DEMs) were incorporated to extract topographic variables such as elevation and slope, which are known to influence biomass productivity and carbon storage capacity.

Vegetation indices, particularly the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI), were utilized as indicators of vegetation health and biomass potential. Forest inventory records, land-use maps, climatic data, and field measurement instruments such as Global Positioning System (GPS) devices and diameter measurement tools supported data collection and validation processes. Accuracy assessment was performed through comparison between remote sensing-derived estimates and field-based observations. Integration of these instruments facilitated the development of a robust spatial framework for evaluating forest carbon sequestration potential.

RESULTS AND DISCUSSION

Analysis of remote sensing imagery and GIS-derived environmental variables revealed substantial spatial variation in carbon sequestration potential across the forest landscape. A total of 150 sampling plots were evaluated using integrated geospatial datasets, including vegetation indices, topographic variables, land-cover classifications, and biomass estimates. Forest areas characterized by dense vegetation exhibited considerably higher carbon sequestration values than areas with sparse canopy cover. Spatial classification results indicated that 18.7% of the study area belonged to the very high carbon sequestration category, while 34.6% and 28.4% were classified as high and moderate categories, respectively. Remaining areas were categorized as low carbon sequestration zones.

Table 1. Distribution of Carbon Sequestration Potential Across Forest Areas

Category	Area (ha)	Percentage (%)
Very High	5,610	18.7
High	10,380	34.6
Moderate	8,520	28.4
Low	5,490	18.3
Total	30,000	100.0

Descriptive statistics further demonstrated significant variability among environmental indicators used in the spatial model. Mean NDVI values ranged from 0.42 in degraded forest areas to 0.87 in dense forest stands. Above-ground biomass estimates varied between 42.3 and 356.8 Mg ha^{-1}, reflecting considerable differences in vegetation productivity and carbon storage capacity. Elevation values ranged from 120 to 1,480 meters above sea level, while average slope gradients varied from 4° to 38°, indicating diverse environmental conditions influencing carbon accumulation patterns.

Spatial analysis indicated that forest areas with higher vegetation density consistently exhibited greater carbon sequestration potential. Elevated NDVI and EVI values were strongly associated with increased biomass accumulation, suggesting that vegetation productivity serves as a reliable predictor of carbon storage capacity. Dense canopy structures contributed to enhanced carbon absorption through greater photosynthetic activity and biomass development. Spatial clustering of high carbon potential areas was predominantly observed in protected and minimally disturbed forest zones.

Environmental variables also demonstrated substantial influence on carbon distribution patterns. Moderate elevations and gentle slopes supported higher vegetation productivity compared with steep and highly fragmented landscapes. Forest areas experiencing limited anthropogenic disturbance exhibited stronger carbon sequestration performance than regions affected by land-use conversion. Integration of remote sensing and GIS datasets enabled the identification of environmental gradients that would have been difficult to detect using conventional field-based approaches alone.

Carbon sequestration estimates generated through the integrated spatial model revealed an average carbon storage potential of 186.4 Mg C ha^{-1} across the study region. Dense forest zones recorded the highest mean carbon value of 289.7 Mg C ha^{-1}, while degraded forests exhibited significantly lower values averaging 74.6 Mg C ha^{-1}. Spatial heterogeneity was evident throughout the landscape, reflecting differences in ecological conditions and vegetation characteristics.

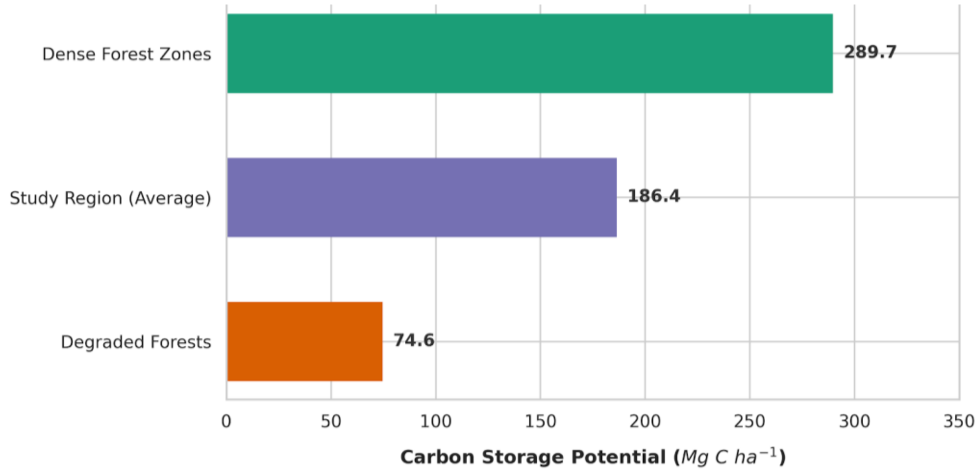

Figure 1. Carbon Sequestration Potential Across Forest Zones

Land-cover analysis demonstrated that primary forests accounted for the largest proportion of total carbon storage within the study area. Secondary forests contributed moderate carbon reserves, whereas mixed-use landscapes and disturbed forest zones exhibited substantially lower sequestration capacities. Variations in carbon potential corresponded closely with forest structure, vegetation density, and ecosystem integrity. Such findings underscore the importance of preserving mature forest ecosystems as major carbon sinks.

Inferential statistical analysis was conducted to examine the relationship between environmental variables and carbon sequestration potential. Multiple regression results indicated that NDVI, biomass density, elevation, and forest cover percentage collectively explained 78.4% of the variance in carbon sequestration estimates ($R^2 = 0.784$, $p < 0.001$). Biomass density emerged as the strongest predictor, followed by vegetation indices and forest cover characteristics.

Pearson correlation analysis revealed significant positive associations between NDVI and carbon sequestration potential ($r = 0.812$, $p < 0.001$), as well as between biomass density and carbon storage estimates ($r = 0.879$, $p < 0.001$). Negative correlations were observed between carbon sequestration and indicators of land disturbance ($r = -0.691$, $p < 0.001$). Statistical significance across these variables confirmed the robustness of the spatial model and supported the predictive capacity of integrated geospatial approaches.

Relationships among remote sensing indicators, environmental variables, and carbon sequestration potential revealed a coherent ecological pattern. Forest areas characterized by high vegetation vigor, dense canopy cover, and elevated biomass levels consistently demonstrated greater carbon storage capacity. GIS-based overlay analysis illustrated strong spatial correspondence between vegetation indices and carbon-rich zones throughout the landscape.

Topographic variables also influenced observed spatial relationships. Moderate elevations supported favorable climatic conditions for vegetation growth, resulting in higher carbon accumulation. Steep slopes and fragmented habitats displayed reduced biomass productivity and lower carbon sequestration capacity (Abu Bakar et al., 2025; N. Wei et al., 2025). Interactions among vegetation, topography, and land-use characteristics collectively shaped the spatial distribution of carbon storage potential across the forest ecosystem.

A detailed case study was conducted within a protected forest sector occupying approximately 4,500 hectares. Remote sensing analysis indicated exceptionally high vegetation density, with mean NDVI values exceeding 0.82 and above-ground biomass estimates reaching 325 Mg ha^{-1}. Carbon sequestration potential within this sector averaged 301.5 Mg C ha^{-1}, placing the majority of the area within the very high carbon category.

Field validation confirmed the reliability of remote sensing-derived estimates. Ground measurements revealed mature tree stands, complex canopy structures, and limited human disturbance. Carbon estimates obtained from field inventory data differed by only 4.8% from geospatial model predictions, indicating strong agreement between observed and modeled values. Such consistency highlights the effectiveness of integrating remote sensing and GIS technologies for carbon assessment purposes.

Findings from the case study demonstrated that protected forest management contributes significantly to long-term carbon accumulation. Dense vegetation cover, ecological stability, and limited land-use change created favorable conditions for biomass growth and carbon storage. Remote sensing indicators successfully captured these ecological characteristics and translated them into spatially explicit carbon estimates.

Model performance also benefited from the integration of multiple environmental datasets. Satellite imagery provided detailed information regarding vegetation conditions, while GIS-based analyses incorporated topographic and land-cover variables into the assessment process. Synergistic use of these technologies improved both spatial precision and ecological realism, resulting in more accurate identification of carbon-rich forest zones.

Results indicate that integration of remote sensing data and Geographic Information System technologies provides a highly effective framework for mapping forest carbon sequestration potential. Strong statistical relationships among vegetation indices, biomass estimates, and carbon storage values confirm the suitability of geospatial approaches for environmental monitoring and climate-related assessments. High predictive accuracy demonstrates the capability of integrated models to support evidence-based forest management strategies.

Spatial patterns identified through the analysis suggest that conservation of dense forest ecosystems represents a critical strategy for enhancing carbon sequestration and mitigating climate change. Precise mapping of carbon-rich areas enables policymakers and environmental managers to prioritize conservation investments, optimize carbon offset initiatives, and strengthen sustainable forest governance. Findings further demonstrate that geospatial technologies can substantially improve the efficiency and accuracy of large-scale carbon assessment programs.

Results demonstrated that the integration of remote sensing data and Geographic Information System (GIS) techniques provided a highly effective approach for identifying and mapping forest carbon sequestration potential. Spatial analysis revealed that areas characterized by dense vegetation cover and high biomass accumulation exhibited substantially greater carbon storage capacity than degraded or fragmented forest zones. These findings confirm the importance of vegetation condition as a primary determinant of carbon sequestration performance.

Statistical analysis further indicated that vegetation indices, biomass density, forest cover percentage, and topographic variables collectively explained a large proportion of the variation in carbon sequestration estimates. Strong positive relationships between NDVI values and carbon storage potential suggest that remotely sensed vegetation indicators can serve as reliable proxies for carbon assessment in forest ecosystems.

Spatial modeling identified distinct clusters of high carbon sequestration potential within protected forest regions. Areas subjected to minimal anthropogenic disturbance consistently exhibited higher carbon accumulation than landscapes experiencing land-use conversion or forest degradation. Such patterns highlight the ecological significance of forest conservation for maintaining carbon sink functions.

Validation results demonstrated strong agreement between remote sensing-based estimates and field observations. The relatively small difference between modeled and observed carbon values indicates that the integrated geospatial framework achieved a high level of accuracy. Reliability of the generated maps supports their application in forest management, climate mitigation planning, and environmental decision-making (Sarmiento et al., 2025; Suárez-Fernández et al., 2025).

Findings align with previous research emphasizing the effectiveness of remote sensing technologies for biomass estimation and carbon accounting. Numerous studies have reported significant associations between vegetation indices and carbon storage capacity, supporting the argument that satellite-derived indicators provide valuable information regarding ecosystem productivity and carbon dynamics. Consistency with these studies strengthens confidence in the applicability of remote sensing approaches across different forest environments.

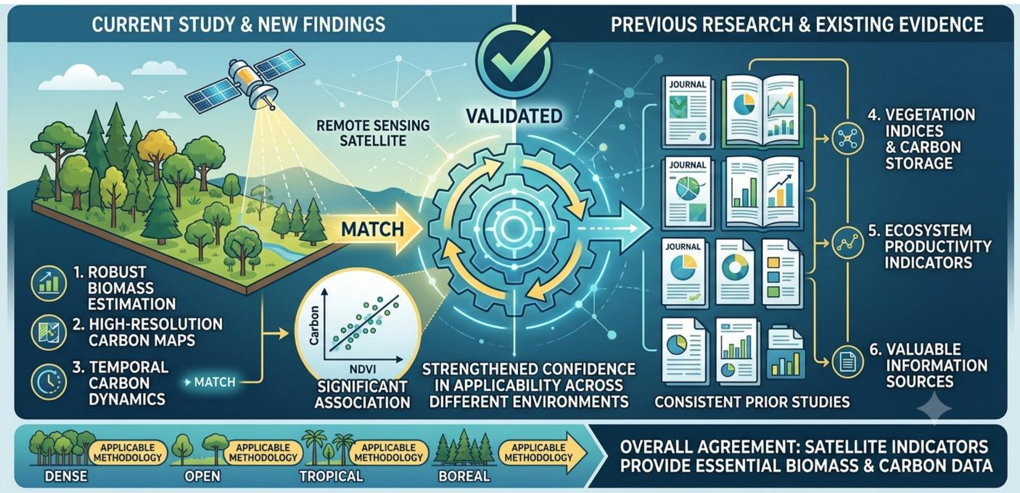

Figure 2. Aligning Finding: The Effectiveness of Remote Sensing for Forest Carbon Accounting

Results also support earlier investigations highlighting the importance of GIS as a spatial decision-support tool for environmental management. Existing literature has demonstrated that GIS facilitates the integration of multiple ecological and geographical variables, enabling more comprehensive assessments of environmental processes. The present findings reinforce this perspective by illustrating how GIS contributes to the identification of spatial carbon distribution patterns.

Differences emerge when comparing the methodological framework of this study with conventional carbon mapping approaches. Previous investigations frequently relied on either remote sensing data or GIS-based analyses independently. The present study employed a more integrated framework that simultaneously incorporated vegetation indices, biomass indicators, land-cover characteristics, and topographic variables. Such integration resulted in greater spatial precision and improved predictive performance.

Distinctive contributions are also evident in the scale and comprehensiveness of the spatial analysis. Several earlier studies focused primarily on estimating total carbon stocks without explicitly identifying areas of varying sequestration potential. Findings from the present research provide a more detailed understanding of spatial heterogeneity, thereby extending existing knowledge regarding forest carbon dynamics and landscape-level environmental management.

Findings indicate that carbon sequestration capacity is strongly influenced by ecological integrity and vegetation quality. Forest ecosystems characterized by dense canopy cover, mature vegetation structures, and limited disturbance demonstrate substantially greater capacity to store atmospheric carbon. Such evidence highlights the ecological value of maintaining healthy and resilient forest environments.

Results also indicate that environmental heterogeneity plays a significant role in determining carbon storage patterns. Variations in topography, vegetation density, and land-use conditions contribute to substantial differences in sequestration potential across the landscape. Recognition of this spatial variability is essential for developing effective carbon management strategies and climate mitigation programs.

Strong predictive relationships between geospatial indicators and carbon storage suggest that technological advances are transforming environmental assessment practices. Remote sensing and GIS technologies increasingly provide opportunities to monitor ecological conditions with greater efficiency, accuracy, and spatial coverage than traditional field-based methods. Such developments represent a significant shift in the way environmental information is generated and utilized.

Evidence generated by the study further indicates that carbon sequestration should be viewed not only as an ecological process but also as a spatial phenomenon influenced by multiple interacting environmental factors. Understanding these interactions provides valuable insights into ecosystem functioning and enhances the scientific foundation for sustainable forest governance.

Practical implications of these findings are substantial for forest conservation and climate change mitigation efforts. Accurate identification of carbon-rich areas enables policymakers to prioritize conservation investments in locations that provide the greatest environmental benefits. Spatially explicit information improves the efficiency of resource allocation and strengthens evidence-based environmental planning.

Implications extend to national and international carbon accounting initiatives. Governments increasingly require reliable estimates of carbon sequestration capacity to support greenhouse gas inventories, climate commitments, and carbon offset programs. The integrated geospatial framework developed in this study offers a valuable tool for enhancing the accuracy and transparency of such assessments.

Forest managers may also benefit from the ability to identify areas vulnerable to carbon loss. Spatial information regarding carbon distribution can support targeted restoration efforts, sustainable harvesting practices, and ecosystem monitoring programs. Improved management interventions contribute to long-term ecosystem resilience and environmental sustainability (Kasahun, 2025; Li et al., 2024).

Scientific implications are equally significant. Findings demonstrate the value of integrating remote sensing and GIS technologies within a unified analytical framework. Adoption of similar approaches may encourage future research to explore increasingly sophisticated methods for assessing ecosystem services, biodiversity conservation, and environmental change across diverse geographical contexts.

Observed patterns can largely be explained by the ecological relationship between vegetation productivity and carbon accumulation. Dense forest stands contain greater biomass and therefore store larger quantities of carbon within vegetation tissues and soil systems. Higher NDVI and EVI values reflect enhanced photosynthetic activity, which directly contributes to carbon sequestration processes.

Topographic influences provide an additional explanation for the observed spatial variability. Moderate elevations and favorable slope conditions often support greater vegetation growth through improved moisture retention, soil stability, and nutrient availability. Such environmental conditions facilitate biomass accumulation and consequently increase carbon storage potential.

Protected forest areas exhibited higher carbon sequestration capacity primarily because of reduced anthropogenic disturbance. Limited logging activities, restricted land conversion, and stronger conservation measures enable ecosystems to maintain mature vegetation structures. Preservation of ecological integrity promotes long-term carbon accumulation and enhances ecosystem stability.

Strong model performance resulted from the complementary strengths of remote sensing and GIS technologies. Remote sensing provided detailed information regarding vegetation characteristics, while GIS facilitated the integration and analysis of multiple environmental variables. Synergy between these technologies enabled a more comprehensive representation of carbon dynamics than would have been possible through isolated analytical approaches.

Future research should explore the integration of advanced remote sensing technologies such as LiDAR, hyperspectral imagery, and unmanned aerial vehicle systems. These technologies may provide higher-resolution information regarding forest structure and biomass distribution, thereby improving carbon estimation accuracy. Enhanced spatial detail would contribute to more precise environmental assessments.

Longitudinal investigations are needed to examine temporal changes in carbon sequestration potential under varying climatic and land-use conditions. Dynamic monitoring approaches could reveal trends in carbon accumulation and loss, offering valuable insights into ecosystem responses to environmental change. Such information would strengthen climate adaptation and mitigation strategies.

Expansion of the analytical framework to different ecological regions would provide opportunities to evaluate its broader applicability. Comparative studies across tropical, temperate, and boreal forests could improve understanding of regional variations in carbon sequestration dynamics. Broader geographical coverage would also enhance the generalizability of the findings.

Development of decision-support systems based on integrated geospatial technologies represents another promising direction. Incorporation of carbon sequestration maps into policy platforms and environmental management tools could facilitate real-time monitoring and evidence-based decision-making. Continued collaboration among environmental scientists, geospatial analysts, and policymakers will be essential for maximizing the practical value of future research in this field.

CONCLUSION

Findings from this study demonstrate that the integration of Remote Sensing data and Geographic Information System (GIS) technologies provides a highly accurate and spatially explicit framework for mapping forest carbon sequestration potential. Distinctive results reveal that carbon storage capacity is not uniformly distributed across forest landscapes but is strongly influenced by vegetation density, biomass accumulation, topographic conditions, and land-use characteristics. High-carbon zones were consistently associated with dense and ecologically intact forest ecosystems, while degraded and fragmented areas exhibited significantly lower sequestration capacities. Strong statistical relationships between vegetation indices, biomass variables, and carbon estimates confirm the effectiveness of geospatial indicators as reliable predictors of carbon sequestration potential. This finding extends existing knowledge by demonstrating how integrated spatial modeling can simultaneously capture ecological complexity and geographic variability, resulting in more precise carbon assessment outcomes than conventional approaches.

The principal contribution of this research lies in its methodological advancement rather than solely its conceptual perspective. Integration of multisource remote sensing datasets, GIS-based spatial analysis, and environmental modeling produced a comprehensive framework capable of identifying carbon-rich forest areas with high accuracy and operational efficiency. Such an approach offers substantial value for environmental monitoring, forest management, climate change mitigation planning, and carbon accounting initiatives. Methodological integration enables decision-makers to move beyond generalized carbon estimates toward geographically targeted conservation and restoration strategies. Scientific value of the study is reflected in its demonstration that combining geospatial technologies can significantly enhance the reliability and practical applicability of carbon sequestration assessments at landscape scales.

Several limitations should be acknowledged when interpreting the findings. Carbon sequestration estimates were derived primarily from remotely sensed indicators and selected field validation plots, which may not fully capture temporal fluctuations in biomass dynamics or long-term ecosystem changes. Environmental factors such as climate variability, species composition, soil carbon dynamics, and disturbance regimes were not incorporated in equal detail within the spatial model. Future research should integrate advanced technologies such as LiDAR, hyperspectral imagery, machine learning algorithms, and long-term ecological monitoring data to improve predictive precision. Comparative investigations across diverse forest ecosystems and climatic regions would further strengthen model generalizability and contribute to the development of more robust carbon assessment frameworks for global climate governance and sustainable forest management.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used Google Gemini to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Abu Bakar, N. A., Omar, H., Abdul Maulud, K. N., Muhammad Nor, S. M., Muhmad Kamarulzaman, A. M., Mohan, M., & Wan Mohd Jaafar, W. S. (2025). Development of a new mangrove integrity index (MII) using multi-sensor remote sensing approaches. Ecological Indicators, 181, 114421. https://doi.org/https://doi.org/10.1016/j.ecolind.2025.114421

Ahmed, M. M. M., Prikaziuk, E., Laub, M., Klaasse, A. L., & Ellerbroek, L. E. (2025). A novel approach to mapping and monitoring land carbon sinks by combining remote sensing and biogeochemical modeling: A case study in Burkina Faso. Ecological Informatics, 90, 103174. https://doi.org/https://doi.org/10.1016/j.ecoinf.2025.103174

Ali, Y., & Rahman, M. M. (2025). Quantifying forest stocking changes in Sundarbans mangrove using remote sensing data. Science of Remote Sensing, 11, 100181. https://doi.org/https://doi.org/10.1016/j.srs.2024.100181

Almeida, B., Monteiro, L., Tiengo, R., Gil, A., & Cabral, P. (2025). Spatially explicit assessment of carbon storage and sequestration in forest ecosystems. Remote Sensing Applications: Society and Environment, 38, 101544. https://doi.org/https://doi.org/10.1016/j.rsase.2025.101544

Anees, S. A., Mehmood, K., Khan, W. R., Sajjad, M., Alahmadi, T. A., Alharbi, S. A., & Luo, M. (2024). Integration of machine learning and remote sensing for above ground biomass estimation through Landsat-9 and field data in temperate forests of the Himalayan region. Ecological Informatics, 82, 102732. https://doi.org/https://doi.org/10.1016/j.ecoinf.2024.102732

Beisekenov, N., Banakinaou, W., Ajayi, A. D., Hasegawa, H., & Tadao, A. (2025). Remote sensing-based soil organic carbon monitoring using advanced machine learning techniques under conservation agriculture systems. Smart Agricultural Technology, 11, 101036. https://doi.org/https://doi.org/10.1016/j.atech.2025.101036

Chang, J., Shao, Z., Wang, J., Mao, Z., Cheng, T., Xu, X., & Zhuang, Q. (2025). Estimation of carbon sequestration capacity of urban green infrastructure by fusing multi-source remote sensing data. International Journal of Applied Earth Observation and Geoinformation, 141, 104643. https://doi.org/https://doi.org/10.1016/j.jag.2025.104643

Chen, M., Dong, W., Yu, H., Woodhouse, I. H., Ryan, C. M., Liu, H., Georgiou, S., & Mitchard, E. T. A. (2025). Multimodal deep learning enables forest height mapping from patchy spaceborne LiDAR using SAR and passive optical satellite data. International Journal of Applied Earth Observation and Geoinformation, 143, 104814. https://doi.org/https://doi.org/10.1016/j.jag.2025.104814

Duan, M., Sanchez-Azofeifa, A., Abdulmajeed, M., Turner, D., Buckingham, K., Odari, A., Mtwana, J., Kipkoech, S., & Kasraee, N. (2025). Aboveground Carbon Estimation in a Mangrove Ecosystem Using UAV-Based Remote Sensing and Machine Learning. Ecological Indicators, 178, 113950. https://doi.org/https://doi.org/10.1016/j.ecolind.2025.113950

Ferreira, M. P., Almeida, D. R. A., Lima, I. D., Molin, P. G., dos Santos, D. R., Oliveira, R. A. A. C., Brancalion, P. H. S., Rodrigues, R. R., & Viani, R. A. G. (2025). Liana removal alters canopy chemistry more than structure in tropical seasonal forests: Insights from UAV-borne hyperspectral and LiDAR data. Ecological Indicators, 181, 114468. https://doi.org/https://doi.org/10.1016/j.ecolind.2025.114468

Fu, H., Zhao, H., Liu, G., Zhang, Y., Huangfu, X., & Jiang, J. (2025). Forest aboveground carbon storage estimation and uncertainty analysis by coupled multi-source remote sensing data in Liaoning Province. Ecological Indicators, 176, 113729. https://doi.org/https://doi.org/10.1016/j.ecolind.2025.113729

Garshasbi, F., Ashournejad, Q., & Ghalenoei, N. (2025). A comparative assessment of remote sensing based land cover products for economic valuation of ecosystem services of Hyrcanian forests. Advances in Space Research, 75(6), 4552–4574. https://doi.org/https://doi.org/10.1016/j.asr.2024.12.064

Huang, C., Xie, L., Chen, W., Lin, Y., Wu, Y., Li, P., Chen, W., Yang, W., & Deng, J. (2024). Remote-sensing extraction and carbon emission reduction benefit assessment for centralized photovoltaic power plants in Agrivoltaic systems. Applied Energy, 370, 123585. https://doi.org/https://doi.org/10.1016/j.apenergy.2024.123585

Jevšenak, J., Klisz, M., Mašek, J., Čada, V., Janda, P., Svoboda, M., Vostarek, O., Treml, V., van der Maaten, E., Popa, A., Popa, I., van der Maaten-Theunissen, M., Zlatanov, T., Scharnweber, T., Ahlgrimm, S., Stolz, J., Sochová, I., Roibu, C.-C., Pretzsch, H., … Buras, A. (2024). Incorporating high-resolution climate, remote sensing and topographic data to map annual forest growth in central and eastern Europe. Science of The Total Environment, 913, 169692. https://doi.org/https://doi.org/10.1016/j.scitotenv.2023.169692

Kafy, A.- Al, Saha, M., Fattah, M. A., Rahman, M. T., Duti, B. M., Rahaman, Z. A., Bakshi, A., Kalaivani, S., Nafiz Rahaman, S., & Sattar, G. S. (2023). Integrating forest cover change and carbon storage dynamics: Leveraging Google Earth Engine and InVEST model to inform conservation in hilly regions. Ecological Indicators, 152, 110374. https://doi.org/https://doi.org/10.1016/j.ecolind.2023.110374

Kasahun, M. (2025). Quantifying deforestation drivers through multi-temporal LULC analysis and population-forest correlation modeling: A case study of Dara Woreda, Ethiopia. Environmental Challenges, 19, 101163. https://doi.org/https://doi.org/10.1016/j.envc.2025.101163

Li, H., Hiroshima, T., Li, X., Hayashi, M., & Kato, T. (2024). High-resolution mapping of forest structure and carbon stock using multi-source remote sensing data in Japan. Remote Sensing of Environment, 312, 114322. https://doi.org/https://doi.org/10.1016/j.rse.2024.114322

Louzada, R. O., Bergier, I., Bolfe, É. L., & Barbedo, J. G. A. (2025). Integrating GIS and remote sensing for soil attributes mapping in degraded pastures of the Brazilian Cerrado. Soil Advances, 3, 100044. https://doi.org/https://doi.org/10.1016/j.soilad.2025.100044

Ma, S., Xia, J., Wang, C., Zhao, Z., Zou, F., Zhang, M., Luan, G., Li, C., Tu, X., & Li, L. (2025). Forest aboveground biomass retrieval integrating ICESat-2, Landsat-8, and environmental factors. Ecological Informatics, 89, 103194. https://doi.org/https://doi.org/10.1016/j.ecoinf.2025.103194

Odebiri, O., Mutanga, O., Odindi, J., Slotow, R., Mafongoya, P., Lottering, R., Naicker, R., Nyasha Matongera, T., & Mngadi, M. (2024). Remote sensing of depth-induced variations in soil organic carbon stocks distribution within different vegetated landscapes. CATENA, 243, 108216. https://doi.org/https://doi.org/10.1016/j.catena.2024.108216

Ouattara, B., Thiel, M., Forkuor, G., Mouillot, F., Laris, P., Tondoh, E. J., & Sponholz, B. (2025). Fire Impacts, vegetation Recovery, and environmental drivers in West African savannas (2014–2023): A High-Resolution remote sensing assessment. International Journal of Applied Earth Observation and Geoinformation, 143, 104783. https://doi.org/https://doi.org/10.1016/j.jag.2025.104783

Pascual, A., Grau-Neira, A., Morales-Santana, E., Cereceda-Espinoza, F., Pérez-Quezada, J., Cárdenas Martínez, A., & Fuentes-Castillo, T. (2024). Old-growth mapping in Patagonia's evergreen forests must integrate GEDI data to overcome NFI data limitations and to effectively support biodiversity conservation. Forest Ecology and Management, 568, 122059. https://doi.org/https://doi.org/10.1016/j.foreco.2024.122059

Pizarro, S., Requena-Rojas, E., Barboza, E., Peña-Elme, E., Arias-Arredondo, A., & Ccopi, D. (2025). Ecological and carcinogenic risk assessment of potentially toxic elements in rangelands and croplands around Lake Junin (Peru): Integrating remote sensing, machine learning, and land cover segmentation. Science of The Total Environment, 999, 180327. https://doi.org/https://doi.org/10.1016/j.scitotenv.2025.180327

Rashid, I., & Rafiq Kashani, S. D. (2025). Forest dynamics and above-ground forest biomass changes utilizing Google Earth Engine, machine learning, and field-based observations in the Kashmir Himalaya, India. Environmental and Sustainability Indicators, 27, 100759. https://doi.org/https://doi.org/10.1016/j.indic.2025.100759

Ribas-Costa, V. A., Trlica, A., & Gastón, A. (2025). Integrating regional forest productivity maps with supplemental data to optimize forest management priority: A case study in Ibiza (Spain). Journal of Environmental Management, 381, 125221. https://doi.org/https://doi.org/10.1016/j.jenvman.2025.125221

Sarkheil, H., Rostamian, E., Rahbari, S., & Lak, R. (2025). Developing a novel ecological fuzzy forest health index (FFHI) for Standardizing forest-smart mining using remote sensing techniques. Environmental and Sustainability Indicators, 26, 100700. https://doi.org/https://doi.org/10.1016/j.indic.2025.100700

Sarmiento, R. T., Abella, P. Y., Handayan, S. M. B., Madelo, J. M., Mercado, J. A., & Palaso, R. L. (2025). Potential impacts of industrial tree plantation encroachment on tree species diversity and carbon storage in the riparian zones of Andanan Watershed Forest Reserve, Philippines. One Ecosystem, 10. https://doi.org/https://doi.org/10.3897/oneeco.10.e135722

Schmidt, H. E., Osorio Leyton, J., Noa Yarasca, E., Popescu, S. C., Jones, J. J., Wied, J. P., & Wu, X. (2025). A novel approach to field data augmentation with remote sensing and machine learning in rangelands. Ecological Informatics, 90, 103353. https://doi.org/https://doi.org/10.1016/j.ecoinf.2025.103353

Shao, T., Qian, F., Wang, S., Jiang, Z., Liu, H., Lal, R., & Han, W. (2025). Spatial prediction and dynamic change of soil organic carbon using remote sensing variables as auxiliary information in wavy plain, Northeast China. Soil and Tillage Research, 254, 106759. https://doi.org/https://doi.org/10.1016/j.still.2025.106759

Shen, F., Haseeb, M., Tahir, Z., Mahmood, S. A., & Tariq, A. (2025). Reimagining land use policies: Carbon trade-offs between urbanization and ecological restoration. Land Use Policy, 158, 107770. https://doi.org/https://doi.org/10.1016/j.landusepol.2025.107770

Suárez-Fernández, G. E., Martínez-Sánchez, J., & Arias, P. (2025). Enhancing carbon stock estimation in forests: Integrating multi-data predictors with random forest method. Ecological Informatics, 86, 102997. https://doi.org/https://doi.org/10.1016/j.ecoinf.2025.102997

Tompalski, P., Wulder, M. A., White, J. C., Hermosilla, T., Riofrío, J., & Kurz, W. A. (2024). Developing aboveground biomass yield curves for dominant boreal tree species from time series remote sensing data. Forest Ecology and Management, 561, 121894. https://doi.org/https://doi.org/10.1016/j.foreco.2024.121894

Wang, C., Luo, C., Meng, X., Wang, C., & Liu, H. (2025). Intelligent mapping paradigm to overcome systematic bias in remote sensing SOC estimation: A case study of the black soil region in China and the United States. ISPRS Journal of Photogrammetry and Remote Sensing, 230, 644–660. https://doi.org/https://doi.org/10.1016/j.isprsjprs.2025.10.002

Wei, M., Zhao, Y., Xu, J., Du, H., Li, X., & Mao, F. (2025). Phenology-explicit remote sensing estimation of V25cmax spatiotemporal dynamics and uncertainty in Moso bamboo forests. Ecological Indicators, 181, 114469. https://doi.org/https://doi.org/10.1016/j.ecolind.2025.114469

Wei, N., Lin, Y., & Zheng, H. (2025). Prediction of the flood distribution caused by returning cropland to forest based on Generative Adversarial Network and multi-source remote sensing data. International Journal of Applied Earth Observation and Geoinformation, 143, 104790. https://doi.org/https://doi.org/10.1016/j.jag.2025.104790

Wei, Y., Chen, Y., Wang, J., Yu, P., Xu, L., Zhang, C., Shen, H., Liu, Y., & Zhang, G. (2025). Mapping soil organic carbon in fragmented agricultural landscapes: The efficacy and interpretability of multi-category remote sensing variables. Journal of Integrative Agriculture, 24(11), 4395–4414. https://doi.org/https://doi.org/10.1016/j.jia.2025.02.049

Xu, F., Yan, Q., & Ding, Z. (2025). A study on perception of urban green space carbon sequestration based on biotope classification: a case study of the Urban Forest in Shanghai. Trees, Forests and People, 22, 101047. https://doi.org/https://doi.org/10.1016/j.tfp.2025.101047

Xu, M., Tian, J., Tian, Q., Huang, F., He, S., Zhang, Z., & Li, X. (2025). Optimizing remote sensing methods for forest stand density estimation in mountainous areas: a UAV-sentinel-2 synergy. Ecological Indicators, 179, 114247. https://doi.org/https://doi.org/10.1016/j.ecolind.2025.114247

Zanguim, T. G. H., Delanot, T. N. A., Kaam, R., Bondoro, H. O., Odjimbaye, N.-A., Awazi, N. P., & Tchamba, M. N. (2024). Inventory of timber and non-timber forest products through remote sensing and mapping: The example of bamboo resources in chad. Advances in Bamboo Science, 9, 100118. https://doi.org/https://doi.org/10.1016/j.bamboo.2024.100118

Zhang, X., Jia, W., Lu, S., & He, J. (2024). Ecological assessment and driver analysis of high vegetation cover areas based on new remote sensing index. Ecological Informatics, 82, 102786. https://doi.org/https://doi.org/10.1016/j.ecoinf.2024.102786

Zhang, Y., Cheng, K., Yang, Z., Chen, Y., Yang, H., Ren, Y., Wan, J., & Guo, Q. (2025). Spatio-temporal dynamics of future aboveground carbon stocks in natural forests of China. Forest Ecosystems, 13, 100293. https://doi.org/https://doi.org/10.1016/j.fecs.2025.100293

Zhang, Y., Li, X., Zhang, R., Cheng, L., Jia, M., Zhao, C., Guo, X., Zeng, H., Yu, W., Shi, Q., & Wang, Z. (2025). A robust and efficient approach to estimating the age of secondary mangrove forests employing time-series Landsat images and the CCDC model. International Journal of Applied Earth Observation and Geoinformation, 143, 104789. https://doi.org/https://doi.org/10.1016/j.jag.2025.104789

Zhang, Y., Zhao, B., Yang, W., Sui, L., Yang, G., Wei, Z., Yang, C., Du, H., Qu, P., & Yu, S. (2025). Optimization of remote sensing estimation model for biomass of rubber plantations from the perspective of multi-source feature fusion. Trees, Forests and People, 21, 100969. https://doi.org/https://doi.org/10.1016/j.tfp.2025.100969