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Harnessing mangrove ecosystems for CO_2 sequestration: Insights from remote sensing and GIS technologies

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ABSTRACT

Mangrove ecosystems are among the most efficient natural carbon sinks, which are critical in mitigating climate change through their exceptional CO_2 sequestration capabilities in both biomass and sediments. However, these ecosystems face mounting pressures from urbanization, deforestation and climate-induced changes, which threaten their carbon storage potential and contribute to significant emissions. This review explores the pivotal role of Remote Sensing (RS) and Geographic Information System (GIS) technologies in assessing and enhancing the management of mangrove CO_2 sequestration. Advancements such as high-resolution satellite imagery, LiDAR, Machine learning models and vegetation indices have revolutionized the accuracy of mangrove carbon stock mapping and monitoring. Additionally, the review highlights the challenges and limitations associated with existing methodologies, including data gaps and modelling uncertainties and outlines future research directions. By integrating innovative technologies with ground-based measurements and community-based conservation strategies, this review underscores the urgent need to preserve and restore mangroves to maximize their carbon sequestration potential and support global climate resilience.

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INTRODUCTION

In recent years, the world has become increasingly aware of the environmental challenges posed by global warming and climate change, along with their significant implications.

Global warming is closely linked to the rise in greenhouse gas emissions from both natural and human-made sources (Fagorite *et al.*, 2023) which absorbs long-wavelength infrared energy (heat) from the Earth, trapping the escaping solar radiation and causing excessive heating of the planet (Aminu *et al.*, 2017; Anderson *et al.*, 2016; MacDowell *et al.*, 2010). Since the Industrial Revolution, there has been a substantial increase in the concentration of carbon dioxide (CO_2) and other greenhouse gases, primarily due to the escalating use of fossil fuels (Nanda *et al.*, 2016). According to the annual report from NOAA's Global Monitoring Lab, the global average atmospheric carbon dioxide level reached a new record high of 419.3 parts per million (ppm) in 2023. Owing to this, carbon capture and sequestration (CCS) has been proposed and recommended as a technologically proven mitigation option to reduce concentration of CO_2 in the atmosphere (Cao *et al.*, 2020; Kalam *et al.*, 2021a; Zhan *et al.*, 2021). CO_2 sequestration involves capturing the excess CO_2 from the atmosphere and storing it for the long term (Kalam *et al.*, 2021a, 2021b). Biological CO_2 sequestration is the most effective means to reduce the atmospheric carbon dioxide. This includes the role played by thallophytes, cryptogams and higher plants. Mangrove forests are exceptionally productive, with carbon production rates comparable to tropical humid forests. They allocate more carbon belowground, resulting in higher below- to above-ground carbon mass ratios compared to terrestrial trees (Alongi, 2012; Song *et al.*, 2023).

In recent years, the application of remote sensing (RS) and Geographical Information systems (GIS) has revolutionized our understanding of mangrove carbon storage. This review explores the potential of mangroves as CO_2 sinks and delves into how advanced RS and GIS technologies enable us to monitor, quantify, and manage these ecosystems effectively. By integrating ecological knowledge with advanced spatial technologies, we can improve our approaches to climate mitigation and sustainable coastal management.

Mangrove ecosystem

Mangrove ecosystems are intertidal areas found in tropical and subtropical regions, roughly between 30° N and 30° S latitude, spanning 147,359 km² across 118 countries worldwide (Bunting *et al.*, 2022). They are unique as the only forests located where land meets the sea, often found along sheltered coastlines with low wave energy, such as in shallow lagoons, river, deltas and estuaries and is home to various species (Naidoo, 2023). The mangrove ecosystem comprises key components including the forest, soil, and marine systems.

Mangrove soils are intricate and heterogenous, formed from sediment carried by rivers and seas (Hossain and Nuruddin, 2016) and consists of silt and clay mixed with organic matter and salts, often appearing dark grey in colour (Huergo *et al.*, 2018) with nutrient availability varying significantly across different sites (Faridah-Hanum *et al.*, 2019).

Significance of mangrove ecosystem

Mangroves are often found in areas with dense human populations because they offer numerous ecosystem services (Liu *et al.*, 2021). The total annual economic value of mangrove ecosystem services worldwide is estimated to be $2.7 trillion, with each hectare contributing approximately $1,940 per year (Barbier, 2016). Mangroves support biodiversity and fisheries by contributing to marine food webs through detrital energy flow. Their ecosystem services related to climate change mitigation and adaptation include protecting shore lines from natural disasters like storm surges and sea level rise (Barbier, 2016; Kulkarni *et al.*, 2018; Spalding, 2024). They play a significant role in transporting carbon and nutrients to adjacent coastal areas or the ocean via the biogeochemical cycle (Deng *et al.*, 2021).

Mangroves as blue carbon system

Mangroves, as part of blue carbon systems, play a crucial role in mitigating climate change by sequestrating excess atmospheric carbon (Hilmi *et al.*, 2021). The concept of blue carbon was introduced in 2009 through an assessment report involving collaboration among the United Nations Environment Programme (UNEP), the Food and Agriculture Organization (FAO), and the Intergovernmental Oceanographic Commission of UNESCO (IOC/ UNESCO). This concept highlighted the essential role of coastal ecosystems, including salt marshes, mangroves, and seagrass meadows, in reducing emissions by absorbing carbon (Alongi, 2020).

The International Union for Conservation of Nature (IUCN) conducted a thorough assessment to evaluate the carbon management potential of various coastal habitats, including mangrove forests. The assessment concluded that these habitats are crucial for several reasons, particularly due to their significant capacity for carbon management (Laffoley 2009) despite their relatively small geographic coverage, the sediments and soils in these ecosystems sequester more carbon than terrestrial ecosystems because they emit fewer greenhouse gases such as methane (CH_4) and CO_2.

Objectives of this review are:

1. To explore mangrove potential for CO_2 Sequestration with RS and GIS Technologies.
2. To explore emerging trends and research directions in the field of mangrove CO_2 sequestration.
3. To highlight the role of mangroves in climate change mitigation.

Role of mangrove ecosystem in co_2 sequestration

Mangrove forests, as unique woody plants, plays a crucial role in sequestrating significant amounts of CO_2 from the atmosphere. Their net primary production rate rivals that of tropical rainforests. The periodic tidal flooding contributes to a more substantial and stable soil carbon pool compared to other forest ecosystems. On a global scale, mangrove sediments exhibit a high carbon burial rate, averaging 1.74 Mg C ha^{-1} $year^{-1}$ (Alongi, 2012). The efficiency of mangrove ecosystems in sequestering atmospheric CO_2 varies significantly, primarily due to differences in dominant species. The composition of mangrove communities affects both biomass and soil organic carbon (SOC) stocks on regional and global scales (Atwood *et al.*, 2017; Xin *et al.*, 2018). Notably, carbon stocks in vegetation can differ by over 30 times among different mangrove species (Xin *et al.*, 2018).

While global efforts are focused on mangrove afforestation and restoration to restore natural ecosystems (Qin *et al.*, 2021; Romañach *et al.*, 2018), the unintended growth of non-native species in coastal wetlands has altered vegetation communities (Soper *et al.*, 2019). A global meta-analysis indicates that areas invaded by exotic species may have higher carbon pools compared to unvegetated mudflats, although there are no significant differences in carbon stocks between non- native and native species (Davidson *et al.*, 2018).

Mechanism of CO_2 sequestration in mangroves

Mangroves are highly efficient ecosystems for capturing and storing CO_2 through several mechanisms. A key method by which they sequester carbon is via photosynthesis, where they transform CO_2 into biomass, including leaves, branches and roots. Their unique adaptations to saline environment and ability to thrive in tidal zones enhance this process, enabling them to absorb organic materials carried in by tidal waters (Martin Zimmer n.d.).

The extensive root systems of mangrove play a crucial role in trapping sediments and organic matter. These roots slow down water flow, allowing for the deposition of carbon-rich materials that settle and become buried in the anaerobic conditions of the sediment. This slow decomposition process significantly reduces the release of CO_2 back into the atmosphere, allowing mangrove sediments to store carbon for many decades or even centuries (Alongi, 2012).

Mangroves are recognized for their exceptional productivity, often capturing carbon at rates that can be four times higher than those of land-based forests (Goldberg *et al.*, 2020). A large amount of the carbon stored in these ecosystems is located in below-ground biomass, which consists of dead roots and organic matter in the soil. Besides this, older mangrove forests generally have higher rates of carbon fixation and accumulation because their root systems are well-developed and their biomass is greater as their capacity to sequester carbon continues to enhance (Spalding, 2024).

Factors affecting CO_2 sequestration

Mangrove carbon sequestration is significantly affected by various climatic factors such as temperature and precipitation, as well as stand age, tidal elevation, and specific soil and forest characteristics like soil P^H, salinity and tree height. These elements can be challenging to evaluate comprehensively in a single study (Osland *et al.*, 2018; Sasmito *et al.*, 2019; Walcker *et al.*, 2018). Generally, mangroves in tropical regions with hot and humid climates are more effective at sequestrating carbon (Osland *et al.*, 2018). However, the impact of these climatic factors on carbon storage can vary depending on the mangrove species. For instance, thermophilic stenotopic species, thermophilic eurytopic species and winter- resistant eurytopic species tend to thrive and sequester more carbon in suitable climatic conditions (Wu *et al.*, 2018). Rather than this, Human activities have greatly diminished the carbon sequestration capabilities of mangrove ecosystems, leading to significant reductions in their carbon storage. Urbanization, agriculture and aquaculture have caused extensive degradation and loss of mangrove forests results a decrease in carbon storage.

Remote sensing and GIS technology

RS and GIS are essential tools in environmental studies, offering valuable insights and applications for managing natural resources and assessing environmental changes.

Principles of RS and GIS

RS involves collecting data about Earth's surface using satellite or aerial imagery. This technology captures various environmental parameters, enabling the monitoring of changes such as deforestation, urban expansion and climate variations. GIS is a system that allows for the storage, analysis and visualization of spatial data. It integrates diverse datasets, facilitating the examination of relationships among different environmental factors (Kumar, 2013).

RS Data collecting technologies in mangrove studies

Traditional and advanced technologies for RS data collection in mangrove studies are picturized in the Fig. 1.

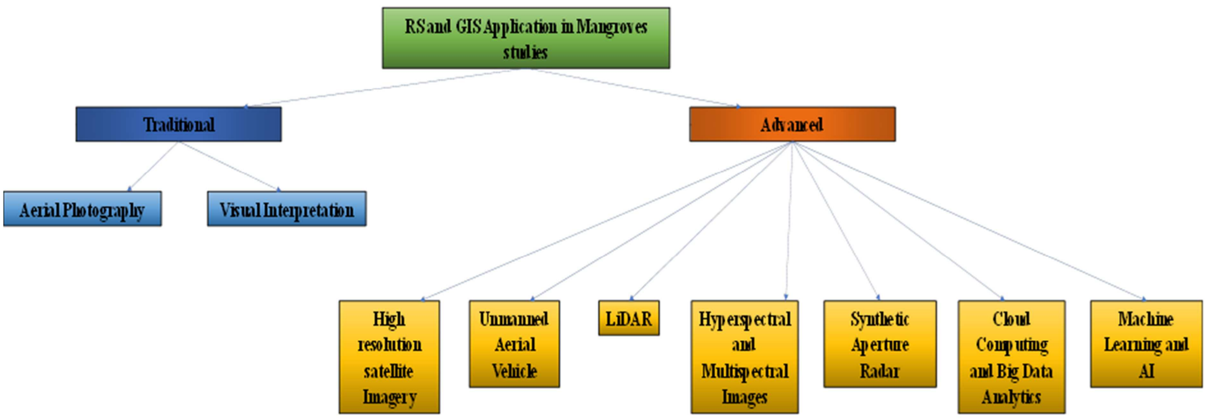

Fig. 1. Application of RS and GIS in mangrove studies

RS techniques play a crucial role in evaluating mangrove studies by offering insights into ecosystem dynamics and changes. Traditional methods like aerial Photography and visual interpretation (VI) have been extensively used in mangrove studies (Heenkenda *et al.*, 2014). Aerial photography involves capturing high-resolution images from aircraft, making it effective for examining smaller areas with detailed classification, while VI depends on human expertise to interpret and categorize image elemnts. Advances in technology now allow for enhanced mangrove monitoring through satellite imagery (such as Landsat ETM$^+$ and Sentinel-2), drones, LiDAR, hyperspectral and multispectral imaging, Synthetic Aperture Radar (SAR), along with cloud computing, big data analytics, and AI-driven image processing. These newer methods build upon traditional approaches, providing a more accurate and in-depth analysis of mangrove ecosystem over time (Vasquez *et al.*, 2024).

RS and GIS technologies for carbon sequestration assessment and mangrove biomass estimation

RS and GIS application for carbon sequestration are well explained by (Giri, 2017). The major steps involved are:

Carbon sequestration quantification and estimation

Estimating carbon sequestration potential involves spatially tailored models that consider climate conditions, management practices, ecosystem diversity, species types, and local community roles. This process begins by defining the study region's environmental conditions and then collecting remote sensing data via satellites or drones. GIS is then used to prepare, manage and integrate spatial and attribute data layers, allowing researchers to apply specialized models for carbon stock estimation. Each case may vary based on unique local conditions, making model adjustment and field validation essential for accuracy. This approach allows for flexible and tailored carbon sequestration analysis, leading to more dependable results.

RS and GIS integration for spatial analysis

Remote sensing provides geo-referenced data over broad areas that can be effectively integrated with GIS for comprehensive spatial analysis. Initially, diverse RS platforms capture information on landcover, vegetation and ecosystems. GIS then processed and manages these data sets, combining them with additional data for enriched analysis. With GIS, researchers can classify ecosystem types, conduct land-use analysis, and model scenarios, making it possible to assess carbon sequestration and other spatial patterns. When combined with decision support systems (DSS), RS and GIS provide powerful tools for guiding ecosystem management and carbon strategy decisions.

Landsat TM for above-ground biomass estimation

Landsat Thematic Mapper ™ data is extensively used to assess above-ground biomass, especially in younger forests where it is more effective than in older, mature forests. This involves capturing Landsat imagery and using texture analysis to differentiate forest types. Biomass estimation models are developed using Landsat's spectral and spatial data to calculate biomass across large areas, with field data serving as validation to ensure accuracy. This method illustrates the utility of satellite imagery in estimating forest biomass on a landscape scale, which is especially valuable for regional analysis.

LiDAR for biomass and carbon stock measurement

LiDAR (Light Detection and Ranging) technology enables accurate measurement of above-ground biomass in various forests by analyzing canopy structure. LiDAR systems emit laser pulses that penetrate the canopy and capture data on forest height and structure, which can be correlated with on-ground biomass measurements. A universal equation relating canopy structure to biomass can be developed for diverse biomes, enabling biomass estimation across forest types. High-resolution, 3D LiDAR scans can even capture individual tree structures for detailed carbon stock estimation, making it highly effective for mixed and coniferous forests and a reliable approach for large-scale biomass assessments.

Carbon sequestration in semi-arid grasslands using SPOT-vegetation data

In semi-arid landscapes, SPOT-vegetation satellite data can be combined with field data to estimate carbon sequestration potential across vast areas. Using the Montecito algorithm, satellite data is merged with field biomass inventories to calculate Gross Primary Production (GPPP), Net Primary Production (NPP), and Net Ecosystem Prduction (NEP), capturing carbon storage differences across various vegetation types. This model highlights carbon storage variations based on each vegetation type's productivity, with higher productivity observed in grasslands in regions with more rainfall. This approach allows for detailed carbon stock mapping in difficult-to-access ecosystems.

Mapping forest carbon stocks using RS and GIS

Large-scale estimation of forest carbon stocks combines RS data with GIS to assess forest features like height, density, type, and leaf area index. These parameters, which correlate closely with biomass, are measured through RS and combined with forest and soil data in GIS to provide accurate estimates of carbon storage, providing a visual representation of carbon storage across a landscape. This approach supports regional and national carbon stock assessments, aiding in management and policy decisions to boost carbon sequestration efforts.

Case studies of RS and GIS integration

The case studies in this review investigate the use of RS and GIS for CO_2 sequestration (Table 1). This table details the methodologies, key findings, challenges and limitations of various global studies 2014 to 2024. It offers a comprehensive overview of how different regions and research teams have utilized these technologies to enhance carbon sequestration, emphasizing the progress, challenges and areas for improvement in this field over the past decade.

Future directions in mangrove conservation and CO_2 sequestration

As the urgency to address climate change escalates, the strategic role of mangrove ecosystems in CO_2 sequestration becomes increasingly vital. The integration of RS and GIS technologies will be crucial in enhancing our understanding and management. Future advancements in these technologies are expected to provide more precise and comprehensive data on mangrove health, biomass, and carbon stocks. Emerging tools such as high-resolution satellite imagery, drone surveillance and machine learning algorithms will significantly improve our ability to monitor changes in mangrove ecosystems over time. Enhanced predictive models utilizing RS data can forecast the impacts of climate change and human activities on mangrove health and carbon storage potential, allowing for proactive management strategies that prioritize conservation areas most at risk. Effective policy frameworks will also be essential for the sustainable management of mangrove ecosystems. In the future, countries should aim to integrate mangrove conservation into their Nationally Determined Contributions (NDCs) under the Paris Agreement. This integration not only enhances carbon sequestration efforts but also promotes biodiversity and coastal protection.

Additionally, developing robust carbon markets that value blue carbon ecosystems can incentivize conservation and restoration efforts. By assigning economic value to the carbon sequestration potential of mangroves, stakeholders can mobilize resources for ecosystem restoration projects, making financial investments more attractive.

Community involvement will play a pivotal role in the success of mangrove conservation initiatives. Future strategies should emphasize engaging local communities in the planning and execution of restoration projects, leveraging traditional ecological knowledge to ensure that interventions are both culturally appropriate and ecologically effective. Furthermore, raising awareness about the importance of mangroves for climate mitigation among the importance of mangroves for climate mitigation among local populations can foster stewardship and encourage sustainable practices that protect these vital ecosystems.

Table 1. Case studies of RS and GIS integration in CO_2 sequestration

Sl	Location	Methodology	Key findings	Key challenges	Limitation	References
1	Gujarat, India	Carbon sequestration estimation using regional data and remote sensing methods.	Sequestration rate varies by mangrove species and age. High carbon sequestration in older mangrove areas.	Challenges in measuring exact species composition, Variability in carbon sequestration rates across different mangrove types.	Need for more detailed, region-specific studies, Reliance on coarse-resolution satellite data.	(Pandey, 2013)
2	Thane creek, Mumbai	Allometric models, GIS, CHN analysis for carbon content estimation, ground-based measurements	Carbon stock in Avicennia marina stands is 39.72 t/ha and methodology is then validated by ground truthing and GIS mapping.	Inaccurate ground-based measurements may influence carbon stock estimation, Limited spatial analysis due to regional constraints.	Potential errors in allometric equations affecting biomass estimates. Inconsistent data collection methods leading to discrepanies	(Patil *et al.*, 2014)
3	Puttalam Lagoon, Srilanka	Estimation of carbon sequestration and storage impacts using historical and remote sensing data.	Net carbon loss of 191,584 tC, 75.5% of which was from mangrove conversion.	Significant loss of mangrove ecosystem services, including carbon storage.	Dependence on historical imagery may not fully capture real-time dynamics, Carbon loss estimates rely on assumptions from previous studies.	(Bournazel *et al.*, 2015)
4	South China Sea (Oligo-Miocene)	Palaeogeographic reconstructions, palaeotidal modelling, facies analysis, stratigraphics studies.	Elevated tidal ranges, tectonic subsidence and sediment supply optimized mangrove carbon burial, contributing 4,000 Gt to long-term lithospheric carbon storage.	Complex interplay of tectonics, sea level changes, sedimentation and tidal dynamics, quantifying long-term carbon contributions with accuracy.	Reconstruction limitation due to gaps in stratigraphic records, uncertainity in modelling historical tidal dynamics and sedimentation processes.	(Collins *et al.*, 2017)
5	Northern Ecuador	RS and GIS integrated with field measurements	7.74 million tons of carbon, high in Rhizophora stands.	Deforestion, need for local allometric equations.	Limited global relevance, non-region-specific models	(Hamilton and Friess, 2018)
6	Perancak Estuary, Bali, Indonesia	NDVI relationship with Above Ground Biomass (AGB) and Below Ground Biomass8(BGB). Carbon conversion factor:0.47.	Total Biomass: 47.20 ± 25.03 ton/ha, Total carbon stock: 22.18 ± 11.76 tonC/ha, CO_2 sequestration: 81.41 ± 43.18 tonC/ha.	NDVI sensitivity to canopy parameters, Limited capture of structural complexity and species specific reflectance.	NDVI fails to capture tree height and wood density. Field validation required for accuracy.	(Hastuti, 2017)
7	Mangrove Bay, North-west Australia	Combined LiDAR data and Landsat 8 OLI with mangrove allometric equations to derive height, biomass, and C stocks; spatial statistics used to analyze spatial herogeneity	Mangrove Bay showed significant spatial variability in biomass (70 mg/ha) and C Stocks (45 Mg C/ha), with hotspots near hydrological features, highlighting the importance of fine-scale, scalable methods for carbon accounting and sampling.	Semi-arids conditions, salinity gradients, tidal influences shape mangrove growth, but limited data on hydrology and sampling biases challenge accurate biomass and carbon stock assessment.	The study's omission of salinity and tidal flux measurements limits understanding of their impact on mangrove growth, with site- specific findings and field data focused on accessible areas, reducing generalizability to broader mangrove ecosystems.	(Hickey *et al.*, 2018)

8	Global (with focus on Indonesia, Brazil, Malaysia, Papua New Guinea)	Quantification of annual mangrove carbon stocks (2000-2012) at global, national and subnational levels; calculation of carbon emissions from deforestation.	Global mangroves stored 4.19 Pg C in 2012, with 2.96 Pg in soils and 1.23 Pg in biomass, while 2 % of the stock was lost between with 2.96 Pg in soils and 1.23 Pg in biomass, while 2 % of the stock was lost between 2000-2012, resulting in 316,996,250 T CO_2 emissions.	High rates of deforestation leading to carbon emissions, Difficulty in precise quantification due to spatial and temporal variability.	Study limited to 2000-2012 perios; doesn't account for more recent changes, Limited focus on regional variations beyond key countries.	(Inoue, 2019)
9	Negombo estuary, Srilanka	GIS analysis, satellite image interpretation, ground truthing.	Mangrove store 499.45 Mg C/ha, sea level rise could reduce carbon sink by 11.32 Mg C ha^{-1} y^{-1}.	Vulnerability to sea level rise and local factors like predation, water quality.	Reduced mangrove extent; limited long-term data.	(Perera *et al.*, 2018)
10	Bangladesh	Literature Survey	In 2000, global mangrove area was estimated at 130,420 km^2 with aboveground biomass of 1.908 Pg and a carbon stock of 0.725 Pg C, utilizing high- resolution geospatial data, allometric models based on canopy height, and parallel computing 120 CPUs.	High data and computation demands, Discrepancies in spatial resolution and data sources, Variability in allometric models.	Lack of consistent and representative field data, Uncertainity in biomass models affecting reliability.	(Majumder *et al.*, 2019)
11	Mangrove National Nature Reserves of South China	Ecosystem Carbon Storage (ECS) based on Vegetation biomass and soil organic carbon (SOC)	ECS varies by location, with landward mangroves storing more carbon than seaward ones, influenced by temperature and precipitation, while global warming promotes mangrove migration to higher latitudes, increasing ECS and mitigating sea level rise.	SOC storage is undersimated due to depth limitations, and ECS variation across hydro-geomorphic setting requires more investigation, with limited data and varying methodologies affecting comparisons and vulnerabilities to extreme weather and sea level rise.	SOC and ECS estimates in mangroves are underestimated due to limited soil depth analysis, sedimentation data, and site-specific factor, with weak biomass correlations and insufficient insights into long-term climate impacts and sea- level rise resilience.	(Wang *et al.*, 2019)
12	South coast of NSW, Australia	Raster- based spatial analysis integrating biophysical and socio-economic data.	Identified blue carbon hotspots for conservation and restoration, including fossil carbon areas.	Socio-economic factors not fully assessed; land-use changes affect carbon 3storage.	Qualitative approach, lacks high-resolution data on carbon storage and flux.	(Rogers *et al.*, 2019)
13	Global (Systematic Review)	Review of 478 data points from peer-reviewed literature on LULC impacts on mangrove carbon stocks and soil GHG effluxes	Significant biomass (82% ± 35%) and soil (54% ± 13%) carbon loss due to LULC; no significant effect on soil GHG effluxes; regeneration leads to biomass recovery after ~40 years, but soil carbon recovery is slower	Variability of LULC impacts based on time, type, geography and climate; challenges in quantifying soil carbon recovery.	Lack of clear patterns in soil carbon recovery post-biomass regeneration; long-term study required.	(Sasmito *et al.*, 2019)

14	Western Coast, Central Mexico	Landsat classification (1986,2001,2017), Cellular Automata Markov chain for future modelling, InVEST for carbon estimation.	Exposed soils increased by 65%, Ecological footprint and Total Domestic Footprint decreased, carbon stock dropped from 362.9 TgC in 1986 to 336.2 TgC in 2017.	Accuracy assessment and predicting future land-use changes.	Model assumptions and uncertainity in long term projections	(Hernández-Guzmán *et al.*, 2019)
15	Gowatr Bay, Gulf of Oman	A field study from 2017-18 quantified biomass and carbon stock across various components of mangroves, with measurements taken seasonally at three stations and extrapolated to the total mangrove area, including statistical analysis for seasonal and spatial variations.	The Gowtr mangrove store significant carbon, with seasonal biomass and soil carbon values showing strong positive correlations, and a total carbon stock of approximately 43.9 to 44.2 Kt C (approximately 161.13 to 162.102 Kt CO_2).	Biomass and carbon stock showed no significant seasonal variations ($P>0.05$), but significant spatial variations ($P<0.05$), highlighting the impact of site-specific factors on carbon storage.	Limited to three stations; broader geographic coverage could improve extrapolation accuracy, No long-term temporal data for carbon trends.	(Savari, 2020)
16	Kunhimanga lam,Kannur, Kerala	Field data collection (species ID, GPS, Photographs), satellite imagery analysis (NDVI), biomass calculation using allometric equations	Estimated total carbon content: 12.67 tonnes from26.67 tonnes biomass. High-class vegetation contributed 70.6% of the carbon.	Vector -raster mismatches during biomass calculation, NDVI sensitivity to atmospheric conditions, Limited temporal analysis (Single satellite image)	Limited data due to inaccessible areas, Missing height data for more accurate biomass estimation, Single snapshot satellite image limits temporal analysis.	(Bindu *et al.*, 2020)
17	Colombo, Srilanka	Field measurements, NDVI stratification	High carbon stocks in aboveground (13.79-66.49 tC/ha) and belowground biomass (2.47- 10.12 tC/ha) due to Annona glabra, with lower stocks linked to fewer invasive species and lower diameter at breast height levels	Invasive alien species dominance and urban development pressures disrupts native ecosystems.	Lower BGB carbon than other wetlands, Limited exploration of Invasive alien species.	(Dayathilake *et al.*, 2020)
18	Mangroves in Indonesia	RS analysis, spatial modelling and carbon flux estimation of CO_2 emissions.	Mangrove management reduces CO_2 emissions and lowers air temperature, with significant ecological and climate benefits.	Limited consideration of diverse stressors(Pollution, invasive species), Limited temporal data on long-term effects.	Lack of consideration for other ecological stressors like invasive species and pollution, Model assumptions may not fully capture all environmental variables.	(Sumarmi *et al.*, 2021)
19	Australia	Machine learning (62-72% accuracy) to map soil carbon stocks in vegetated coastal	Total soil carbon stock in Australia VCEs: 951 Tg(±65 Tg). Future projections show 19% of mangrove/ tidal	Predicting changes in carbon stocks due to climate change (RCP scenarios); understanding regional variability	Accuracy limited to 62-72%; projections depend on climatic model uncertainties; site-specific data not included; results may	(Young *et al.*, 2021)

		ecosystems (VCEs) using geospatial data (topography, climate, geomorphology and anthropogenic impacts.)	marshes may gain C stocks, 38% may lose, while 56% pf seagrass areas may increase.	and environmental suitability for C stock retention.	not generalize globally	
20	Central Coastal Bangladesh	Carbon storage estimation using InVEST model. Three future scenarios: Bussiness-as-usual, Econimic Development, Ecological protection-afforestation.	Plantation forests increased by 984.9 km² (1988-2018), boosting carbon storage by 3.30 Tg C, with future projectings (2018-2041) showing the highest carbon gain (+ 3.77 Tg C) and 225.7 km² mangrove restoration under the EPA scenario.	Trade-offs between ecological restoration and food security. Population growth leading to land conversion for agriculture and settlements. Natural erosion and accretion processes.	LULC projections are dependent on assumptions for BAU, ED and EPA scenarios. Limited precision in predicting natural processes like sea-level rise and erosion. Simplified carbon density estimates for different land covers.	(Hoque *et al.*, 2021)
21	Southwestern The Gambia	Satellite imagery and GIS techniques; pixel-based supervised LULC classification using Random Forest Algorithm; integration with InVEST carbon storage and Sequestration.	From 1985-2020, forest cover loss of 22,408 ha (18%) led to 21,824 metric tons of carbon emissions valued at USD 521, 526, 899, 830. The forest carbon stock is estimated at ~421,344 metric tons.	Drivers: deforestation, urbanization, real estate, climate change, migration and timber extraction, weak enforcement of forestry laws, governance issues, unclear land ownership and corruption.	There are data gaps in land ownership and ecosystem services, with limited forest monitoring capacity and uncertainties in scaling recommendations across different regions.	(Dampha, 2021)
22	Arunachal Pradesh, India	Field data, Landsat OLI VIs (SAVI, ARVI, NDVI), stepwise regression, CO2FIX model	Dense forest has highest AGB (332.28 t/ha); land-use change leads to significant carbon loss (e.g., dense forest to Jhum 84%).	Terrain complexity, atmospheric and soil reflectance effects on VI predictions.	Short study period, limited sample locations, model underestimation of carbon stock.	(Das *et al.*, 2021)
23	San Juan Bay Estuary, Puerto Rico	Radiometric dating, dendrometers, interpolation and vegetation data analyses.	High carbon burial rates in urbanized areas (469 g m² y⁻¹) contrast with the estuary- wide mean (188 g m² y⁻¹), impacted by urbanization and hydrology.	Urbanization impacts soil fertility and hydrology, GHG emissions offset sequestration.	Focused on shallow soil layers(18-30 cm), Spatial variability due to human activity.	(Wigand *et al.*, 2021)
24	Tubli Bay, Bahrain	High- resolution satellite imagery (Worldview-3, IKNOS) is used, GIS- based spatial analysis and carbon sequestration modelling.	Mangrove cover decreased by 95% from 1967 to 2020. Carbon stock loss:85%, Mangroves turned from carbon sink to carbon source, emitting 109 Gg CO_2e	Historical data inconsistencies, High anthropogenic pressures (urbanization, land reclamation), Variability in carbon stock estimation due to site-specific factors.	Inconsistent historical data availability, limiting long term trend analysis, variability in carbon estimates due to different methodologies, Land reclamation continues to threaten mangroves.	(Aljenaid *et al.*, 2022)
25	Santos and Sao Vincente, Brazil	InVEST coastal Blue carbon model, historical land cover data from MapBiomas,	Increase in mangrove extent and carbon stocks between 1988 and 2018. Projections show growth in	Historical data inaccuracies (MapBiomas), soil carbon modelled, not directly	Inaccurate historical land cover data, Model's assumptions of constant sequestration rate	(Rosa *et al.*, 2022)

		soil carbon modelling.	sequestration potential if conserved.	measured, Limited capture of rapid urbanization.	oversimplifies complex ecological processes.	
26	Northeast India	Combined field inventory and Landsat OLI-derived vegetation indices (NDVI, SAVI, ARVI), Stepwise multilinear regression for AGB modelling, Empirical model (CO_2 FIX) for future carbon stock simulation.	Predicted AGB ranged from 14.32 to 185.92 Mg/ha with a combined VI model achieving R^2= 0.79 and RMSE= 51.04 Mg/ha, showing carbon stock variation across landuses, highest in tropical forests(182.31 Mg/ha) and lowest in agricultural lands (61.36 Mg/ha) and CO_2Fix simulation indicating an increasing trend of carbon stock.	Challenges include accessibility issues, satellite data inconsistencies, data accuracy, scenario sensitivity, and model calibration and validation across diverse land use types.	Complex terrain affects surface reflectance and VI accuracy, High saturation in NDVI for areas with high AGB, use of low-resolution satellite data impacts precision.	(Bordoloi *et al.*, 2022)
27	Eastern Coastal Zone, Bangladesh	Carbon storage estimated using InVEST model (above ground, below ground, dead organic matter and soil carbon densities).	Trees out of forest (TOF) increased threefold, boosting carbon storage by 9.01 TgC, while declines in agricultural and hill vegetation reduced it by 7.98 TgC, resulting in a net regional increase of 1.27 Tg C influenced by anthropogenic and natural LULC changes.	Seasonal variations in coastal LULC create challenges for accurate classification. Balancing TOF expansion with food security and ecosystem preservation. Managing socio-environmental impacts of shrimp farming and salt aquaculture.	Carbon estimates are approximations, lacking seasonal fluctuation and localized carbon density data. InVEST model limitations in quantifying waterbodies and undeveloped land.	(Islam *et al.*, 2022)
28	Khuran Mangrove, Iran (Persian Gulf)	Cores retrived from 32 stations, radiocarbon dating used to estimate sediment accretion and C sequestration rates over 18 centuries.	Khuran mangrove store 16.79 Tg C, with 98.8% in soils, sequestering 8967 Mg C/year, driven by high organic C content from phytoplankton, sedimentation and sea-level rise, comparable to tropical mangroves despite desert conditions.	Difficult to assess the impact of salinity and tidal flux accurately. Limited data on the role of phytoplankton and their long-term impacts on C sequestration. Potential biases due to variation in sedimentation rates and vegetation types.	Study area limited in small scale, Limited validation of RS data. Study doesn't account for other environmental variable like tidal flux and salinity.	(Hamzeh and Lahijani, 2022)
29	Viti Levu Island, Fiji	RS data acquisition (Landsat 7-8), CA-ANN modelling, InVEST model	Deforestation from 2000-2020, projected loss by 2040, carbon loss of 7.337 Mt C (2000-2020), economic loss of USD 1369.38 million.	Impact of natural disasters, limited local carbon data.	Overestimated carbon stock in 2020, lack of field data for accurate carbon estimation.	(Avtar *et al.*, 2022)
30	Hainan Island, China	Field surveys, Sentinel-2 imagery, Structural Equation Modelling (SEM) analysis.	Total Carbon stock: 703,181 Mg C; soil nitrogen and species diversity are key drivers.	Regional variability, need for integrated approaches.	Results specific to Hainan Island only.	(Meng *et al.*, 2022)

31	Iran	Field sampling at 10 stations, GIS-based satellite image processing (<1 m resolution Google Earth), Soil organic carbon (SOC) and biomass carbon assessment (AGB and BGB)	Top 1 m soil C stock: 108 Mg C/ha (total: 220,867 MgC). Biomass C : 361,000 MgC (69% AGB, 31% (BGB), Total stored carbon : 537 GgC (~1.97 Tg CO_2 equivalent). Deforestation could release 1.33 Tg CO_2.	High-energy coastal conditions reduce fine sediment deposition, competition between R. mucronate and A. marina alters habitat composition, Climate stressors (temperature, salinity, freshwater shortage) threaten persistence.	GHW mangroves, sensitive to climate change and dominated by coarse sediments, face declining organic retention and potential habitat loss by 2070.	(Hamzeh and Azizi, 2023)
32	Hainan Island, China	Carbon storage evaluation using ArcGIS and InVEST models.	Build-up land expansion and forest land degradation were primary drivers of carbon density reduction. Under ecological priority scenarios (2030), carbon storage increased by 1.34 ×10⁵ t, contrasting with declines in baseline and development priority scenarios.	Managing trade-offs between development and ecological preservation. Limited data availability for high-resolution temporal changes.	Limited consideration of socio-economic and policy factors affecting land use. Possible oversimplification of ecological processes in carbon storage modelling.	(Gong *et al.*, 2023)
33	Mae Moh Mine, Thailand	Landsat 8 OLI RS, GIS, NDVI analysis and Multispectral-UAV integration for high-resolution carbon sequestration assessment.	Peak carbon sequestration in 2022: 331.28± 11.89kt CO_2 e (baseline:126.53 kt CO_2 e). Correlation with rainfall and reforestation success.	The COVID-19 pandemic disrupted monitoring and development, while droughts, such as in 2019, reduced reforestation productivity, Operational constraints and natural factors (e.g., precipitation variability).	Uncertainity in satellite imagery due to atmospheric conditions and cloud cover, Limited spatial resolution.	(Somprasong *et al.*, 2023)
34	Lubul Kertang and Pulau Sembilan , North Sumatra, Indonesia	Field measurements and allometric equations, Comparison of AGB between oil palm/ coconut plantations and mangrove ecosystems, UAV photogrammetry, in situ biomass measurement, mapping of restored mangroves.	Mangrove conversion to oil palm and coconut plantations drastically reduces aboveground biomass (AGB) and carbon stocks (AGC), with mangroves having 10-12 times higher carbon stocks. Restoration efforts can recover AGB and AGC to natural levels within 25-40 years, supported by RS technologies for national carbon sink goals.	UAV technology limitations and site-specific uncertainties affect AGB variability, especially with different species and forest ages. Recovery of carbon stocks in mangrove takes 25-40 years and comparison challenges arise due to variability in management practices.	UAVs provide high-resolution data but face challenges at larger scales and limited area coverage. Comparisons of carbon stocks challenges at larger scales and limited area coverage. Comparisons of carbon stocks across different land uses are hindered by varying soil conditions and management practices, requiring further development for broader applicability.	(Basyuni *et al.*, 2023)

35	South Africa	National estimates of total carbon storage, CO2 emissions, and restoration potential using historical data and ecosystem assessments	Mangroves store the highest carbon per unit area, followed by salt marshes and seagrasses. Since 1930, 6500 ha of blue carbon ecosystems have been lost, releasing 1086 Gg C, with potential restoration of 3998 ha capable of removing 14,845 tCO2e annually.	Abiotic pressures such as flow modification, reduced water quality, and artificial breaching affect ecosystems, with limited understanding of their impact on carbon dynamics and resilience. Further research is needed to grasp these effects fully.	Small spatial extent of blue carbon ecosystems limits broader impact, Lack of high-resolution, long-term national data on carbon storage and sequestration rates.	(Raw *et al.*, 2023)
36	Thane Creek, Maharashtra	Allometry, Allometry-Remote Sensing Integration	Above-ground biomass: 84.83 Mg ha−1 (Allometry), 111.31 Mg ha−1 (Integrated); Total carbon: 116.58 Mg C ha−1 (Allometry), 127.89 Mg C ha−1 (Integrated)	Biomass estimation accuracy, data integration	RMSE of 6.21 Mg ha−1 indicates some estimation error.	(Singh *et al.*, 2023)
37	China	InVEST model's carbon storage module, Data inputs: Species proportions, above- and below-ground biomass, and soil carbon from previous studies.	Total storage: 2.11×10^6 tons, Major contributors: Guangdong (7.35×10^5 t), Guangxi (6.47×10^5 t), and Hainan (5.09×10^5 t), Decline in storage from south to north due to species and biomass differences.	Sea-level rise accelerating (3.4 mm/year from 2019–2021).	Biomass estimates depend on prior studies, which may not reflect current conditions.	(Li *et al.*, 2023)
38	Pacific coastal zone of Nariño	Random Forest model with 28 soil profiles (2 m depth) and 16 predictor variables and Comparison with global SOC models and field data	Mean SOCstock is 270.32 ± 52.75 t C ha−1, influenced by depth, CEC, pH, and sand. Regional data reveals global models overestimate SOC, with higher SOC at depth due to reduced decomposition in anoxic soils.	Global models overestimate SOC due to insufficient localized data and inconsistent predictions. Integrating regional datasets is essential to improve accuracy and understand deep soil carbon stabilization.	Limited sampling and exclusion of carbon below 2 m hinder accurate estimates, with global predictions lacking regional variability and deeper reservoir data.	(Moreno Muñoz *et al.*, 2024)
39	Red Sea Coast, Egypt	Field sampling, sediment core collection, laboratory analysis for organic carbon, Landsat 9 NDVI-based biomass estimation	Low organic carbon (OC) stocks in sediments (54.49–86.00 MgC/ha), low carbon sequestration rate (11.94–18.02 g C m−2/year). Sediment is the main OC pool. CO2 emissions from mangroves are negligible.	Low precipitation, desert conditions, limited riverine input.	OC content and CSR values are low compared to global averages; study is region-specific.	(Youssef *et al.*, 2024)
40	Cox's Bazar, Bangladesh	Landsat and MODIS imagery, InVEST model, Cellular Automata-Artificial Neural Network, statistical analysis	Daytime LST increased by 3.57°C, nighttime LST decreased slightly; CSC reduced in high areas; projections to 2041 show further LST increase	Managing urbanization and climate change impacts on coastal ecosystems	Uncertainty in future projections, model limitations in complex ecosystems	(Kafy *et al.*, 2024)

Future research should focus on several key areas to enhance our understanding of mangrove ecosystems. Establishing long-term monitoring programmes to assess changes in mangrove carbon stocks over time will provide critical data for understanding their role in global carbon cycles. Additionally, investigating the carbon sequestration potential of different mangrove species is most effective under varying environmental conditions, guiding reforestation efforts. Research should also continue to explore how urbanization, agriculture and other human activities impact mangrove ecosystems and their ability to sequester carbon, as understanding these dynamics is crucial for developing effective mitigation strategies.

CONCLUSION

Based on extensive review it is concluded that RS and GIS technologies have revolutionized the assessment, monitoring and management of mangrove ecosystems and improved understanding of their distribution, carbon stocks and stressors. Through meticulous review, it has been found that RS and GIS integration in carbon sequestration is reported to demonstrate drastic variation in specific geographical locations. The predominant methodologies employed in these case studies include satellite imagery analysis for land-use changes and vegetation indices, alongside carbon stock modelling using tools like InVEST and CO_2 FIX.

Few studies have been identified certain locations were prone to excessive mangrove degradation. However, these studies faced many challenges like data limitations, methodological inconsistencies and environmental complexities demand continued innovation. Addressing gaps in high-resolution satellite data, regional allometric equations and soil organic carbon assessments is vital for enhancing model accuracy. Further exploration of the impacts of invasive species, sedimentation dynamics and long-term climate stressors is also needed. Future efforts should integrate RS and GIS tools with ground-based measurements, innovative modelling and community engagement. Internal collaboration and standardized methodologies should be implemented for effective conservation strategies, maximizing the ecological and climatic benefits of mangroves.

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