# Carbon Sequestration in the Sundarbans Mangrove Forest and Chilika Lake Ecosystems

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## Abstract

This research investigates the carbon sequestration potential of two critical ecosystems in India: the Sundarbans Mangrove Forest and Chilika Lake. Using satellite data from Landsat and SRTM, coupled with machine learning models, we analyze, model, and visualize carbon sequestration dynamics across these ecosystems. Our findings indicate that the Sundarbans sequestered approximately 24.37 million tonnes of carbon in 2024 with a $CO_2$ absorption rate of 545,293.77 tonnes per year, while Chilika Lake demonstrated an average carbon sequestration rate of 5.69 tons $CO_2$/ha/year, totaling 258,288,207 tonnes annually. Seasonal analysis reveals post-monsoon periods as peak sequestration phases, and spatial heterogeneity in sequestration rates is observed across both ecosystems. We propose ecosystem-specific policy frameworks to enhance conservation and carbon sequestration capacity of these vital carbon sinks. This research contributes to understanding natural carbon sequestration dynamics in response to environmental changes, including the observed decline during COVID-19 lockdowns due to reduced atmospheric $CO_2$ availability.

**Keywords:** carbon sequestration, mangrove forest, wetland ecosystems, remote sensing, machine learning, climate change mitigation, Sundarbans, Chilika Lake

## 1. Introduction

### 1.1 The Climate Challenge

Rising $CO_2$ levels are a primary contributor to global warming and climate change. As atmospheric carbon dioxide concentrations continue to increase, there is an urgent need for effective carbon management strategies. Natural carbon sinks play a crucial role in achieving net-zero carbon goals, with coastal and marine ecosystems being among the most efficient carbon sequesters per unit area on the planet.

### 1.2 Research Focus

Our research objective is to analyze, model, and visualize carbon sequestration processes in two important but distinct ecosystems in India: the Sundarbans Mangrove Forest and Chilika Lake. By employing satellite data and machine learning models, we aim to:

1. Quantify current carbon stocks and sequestration rates
2. Analyze temporal and spatial variations in carbon sequestration
3. Identify factors influencing sequestration effectiveness
4. Develop predictive models for future carbon sequestration trends
5. Formulate ecosystem-specific policy recommendations

This research contributes to the growing body of knowledge on natural carbon sinks and provides valuable insights for climate change mitigation strategies in India and comparable ecosystems worldwide.

# 2. Literature Review

(Note: This section would typically contain a comprehensive literature review but is condensed here based on the presentation materials.)

Previous studies have established mangrove forests as significant blue carbon sinks, with sequestration rates often exceeding those of terrestrial forests. Research by Donato et al. (2011) and Alongi (2014) has demonstrated that mangroves can store 3-5 times more carbon per equivalent area than tropical forests. Similarly, coastal wetlands like Chilika Lake have been recognized for their carbon storage capacity, particularly in sediments and through aquatic vegetation.

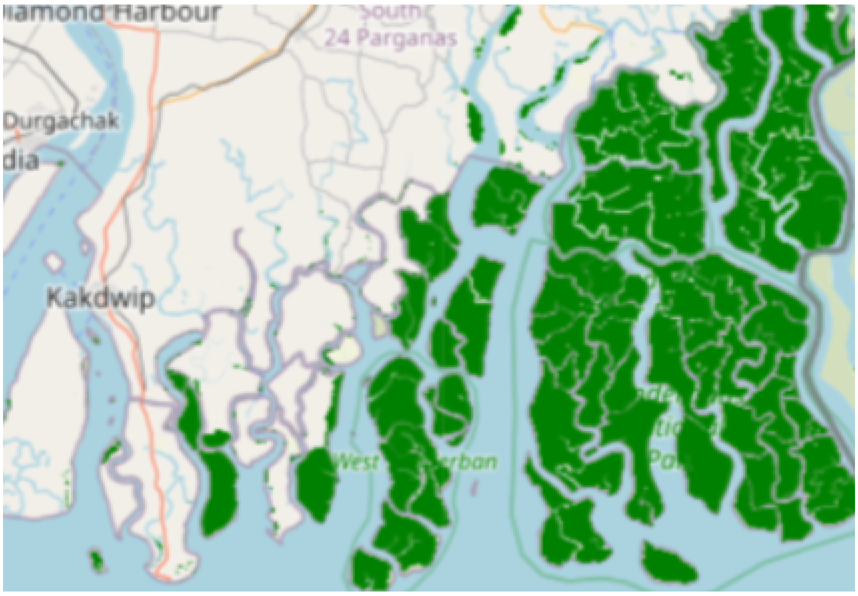
Remote sensing approaches to carbon stock estimation have evolved significantly, with studies by Simard et al. (2019) and Tang et al. (2018) establishing methodologies for mangrove biomass estimation using satellite data. However, few studies have conducted comparative analyses of different ecosystem types or examined seasonal variations in carbon sequestration rates in these specific Indian ecosystems.

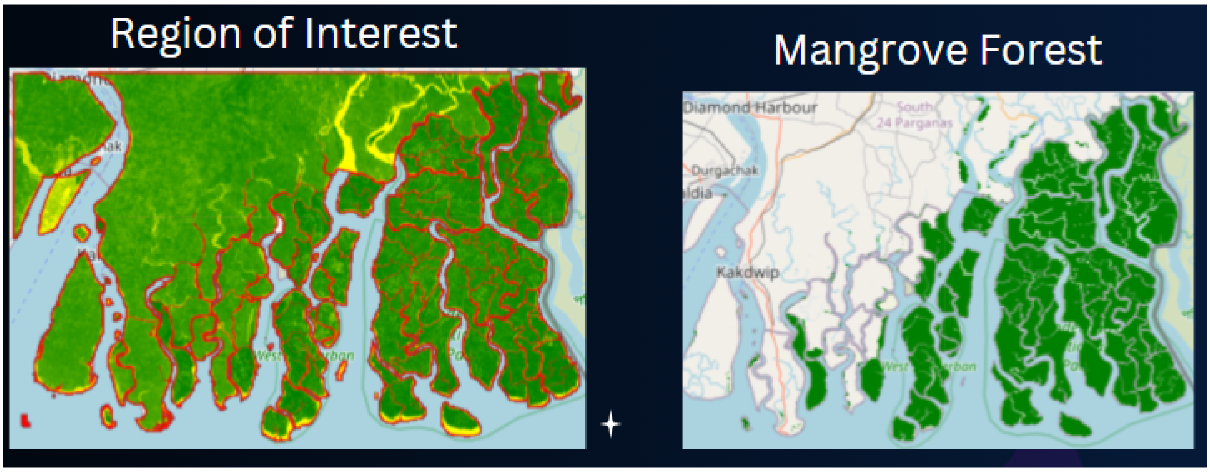
# 3. Methodology

## 3.1 Study Areas

### 3.1.1 Sundarbans Mangrove Forest

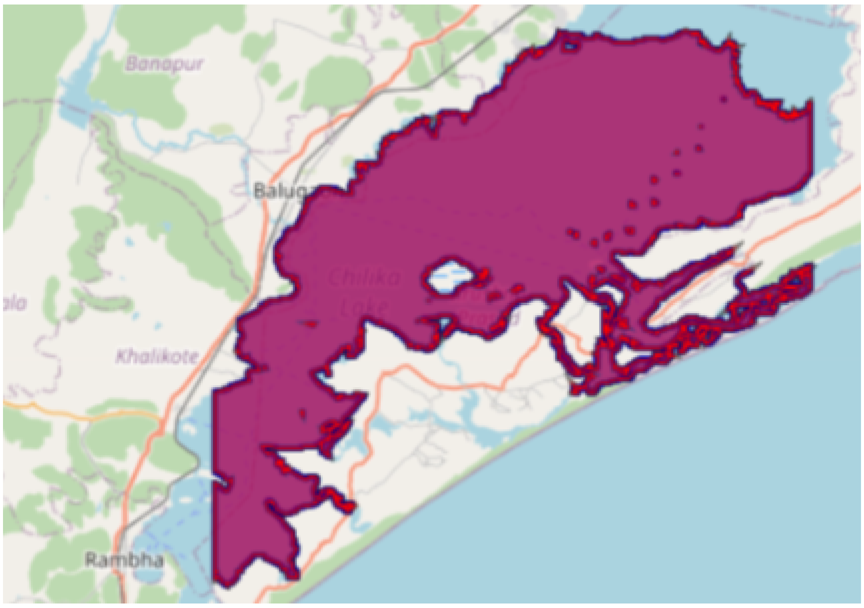
The Sundarbans, spanning the delta of the Ganges, Brahmaputra, and Meghna rivers at the Bay of Bengal, is the world's largest contiguous mangrove forest. Our study focused on the Indian portion of the Sundarbans, covering approximately 4,200 km². The region is characterized by a network of tidal waterways, mudflats, and small islands covered with salt-tolerant mangrove forests.




### 3.1.2 Chilika Lake

Chilika Lake is Asia's largest brackish water lagoon, located on the east coast of India in Odisha state. Covering approximately 1,100 km², it features fresh, brackish, and marine water ecosystems. The lake is known for its biodiversity and serves as an important wintering ground for migratory birds.




## 3.2 Data Collection and Processing

Our workflow followed a systematic approach:

1. **Data Collection**: We utilized multispectral satellite imagery from Landsat 8 OLI/TIRS (30m resolution) spanning 2018-2024, along with elevation data from SRTM (Shuttle Radar Topography Mission).
2. **Preprocessing**: Raw satellite data underwent atmospheric correction, cloud masking, and seasonal compositing to create analysis-ready datasets. To minimize cloud interference, we generated seasonal median composites.
3. **Ecosystem Identification**: For the Sundarbans, we employed multiple spectral indices including NDVI (Normalized Difference Vegetation Index), NDWI (Normalized Difference Water Index), and elevation thresholds to identify mangrove extent. For Chilika Lake, we delineated water boundaries and identified aquatic vegetation using similar spectral indices along with Modified NDVI (MNDVI) and EVI (Enhanced Vegetation Index).
4. **Carbon Estimation**: Carbon stocks were calculated separately for:
    - Above-ground biomass (AGB) using allometric equations calibrated for mangrove species
    - Below-ground biomass (BGB) derived using root-to-shoot ratios
    - Carbon in water bodies (for Chilika Lake) based on spectral characteristics and calibrated models
5. **Temporal Analysis**: We conducted annual and seasonal trend analyses (winter, summer, monsoon, post-monsoon) to detect changes in carbon sequestration rates over time and within seasonal cycles.

6. **Predictive Modeling**: We implemented two machine learning approaches for future projections:
    - Random Forest regression models
    - SARIMA (Seasonal Autoregressive Integrated Moving Average) time series forecasting

### 3.3 Vegetation Indices and Carbon Estimation

We calculated the following vegetation indices:

- **NDVI**: (NIR-Red)/(NIR+Red) - Primary indicator of vegetation density and health
- **NDWI**: (Green-NIR)/(Green+NIR) - Used to identify water bodies and moisture content
- **MNDVI**: Modified NDVI tailored for mangrove identification
- **EVI**: Enhanced Vegetation Index, less susceptible to atmospheric effects and saturation

Carbon stock estimation relied on established allometric relationships between vegetation indices and biomass, calibrated with field measurements from comparable studies. For the Sundarbans, we employed species-specific allometric equations for dominant mangrove species. For Chilika Lake, we used models appropriate for aquatic vegetation and sediment carbon.

# 4. Results

## 4.1 Sundarbans Mangrove Forest Analysis

### 4.1.1 Mangrove Extent and Carbon Stocks

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================ SUNDARBANS CARBON ANALYSIS SUMMARY ================

Analysis Period: 2018 to 2024

--- MANGROVE EXTENT ---
Initial Mangrove Area (2018): 53,062.59 hectares
Final Mangrove Area (2024): 54,529.38 hectares
Change: 1,466.79 hectares (2.76%)

--- CARBON STOCKS ---
Initial Carbon Stock (2018): 23,718,976.87 tonnes C
Final Carbon Stock (2024): 24,374,631.51 tonnes C
Change: 655,654.64 tonnes C (2.76%)
Current CO2 Absorption Rate: 545,293.77 tonnes CO2/year

--- FUTURE PROJECTIONS (by 2029) ---
Projected Mangrove Area: 53,897.25 hectares
Projected Change from 2024: -632.13 hectares (-1.16%)
Projected Carbon Stock: 24,092,071.52 tonnes C
Projected Change from 2024: -282,559.99 tonnes C (-1.16%)
Projected CO2 Absorption Rate: 538,972.52 tonnes CO2/year

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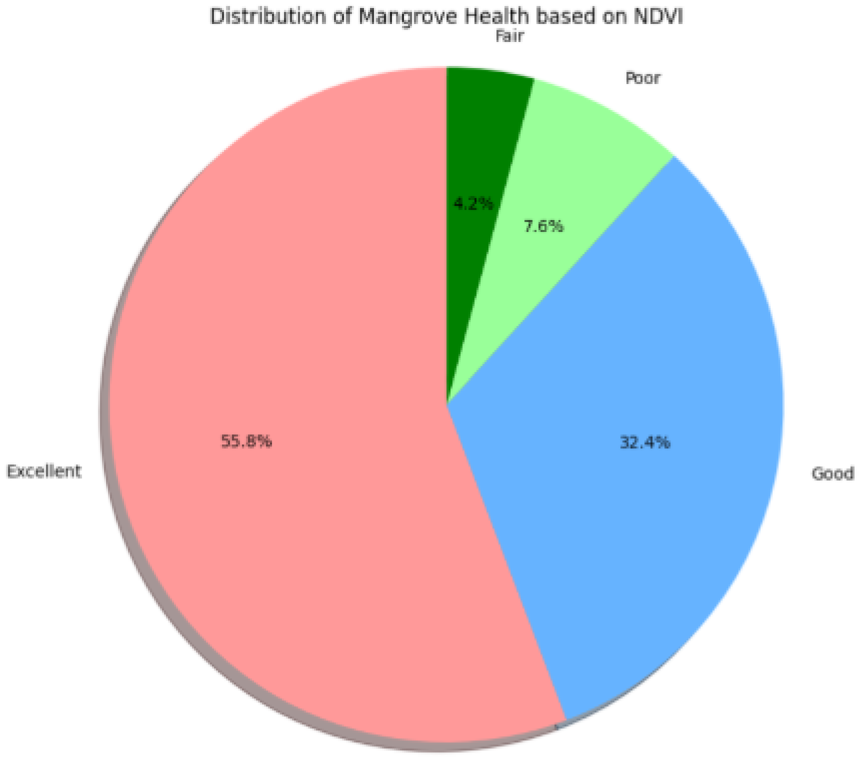
### 4.1.2 Vegetation Indices and Forest Health

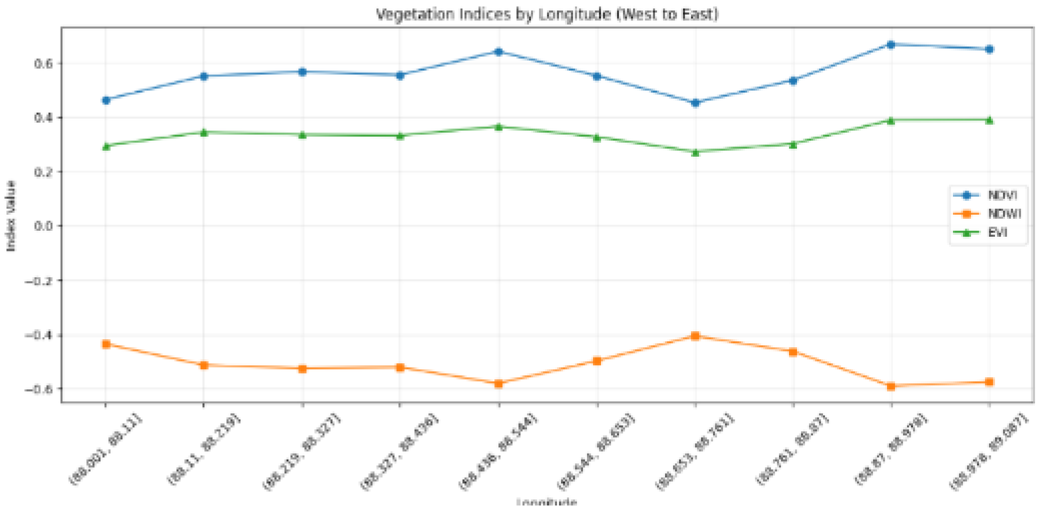
Analysis of vegetation indices showed spatial heterogeneity across the Sundarbans:

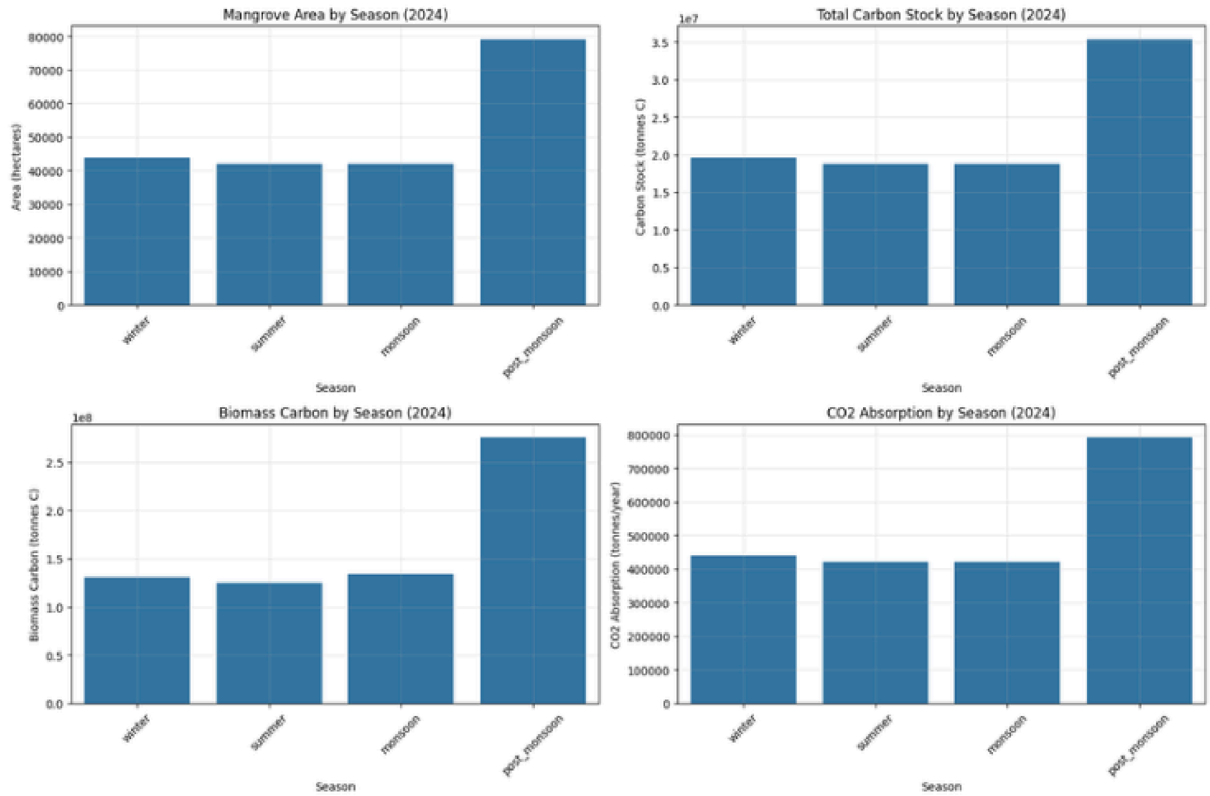
- NDVI values ranged from 0.4 to 0.7, with higher values in the eastern region
- NDWI values were consistently negative (-0.4 to -0.6), indicating low water stress in vegetation
- EVI showed moderate to high values (0.3-0.4), confirming substantial photosynthetic activity

The health assessment of mangroves based on NDVI revealed:

- 55.8% of mangrove forests in excellent health
- 32.4% in good health
- 7.6% in fair health
- 4.2% in poor health


Distribution of Mangrove Health based on NDVI
Fair
Poor
4.2%
7.6%
Excellent
55.8%
32.4%
Good

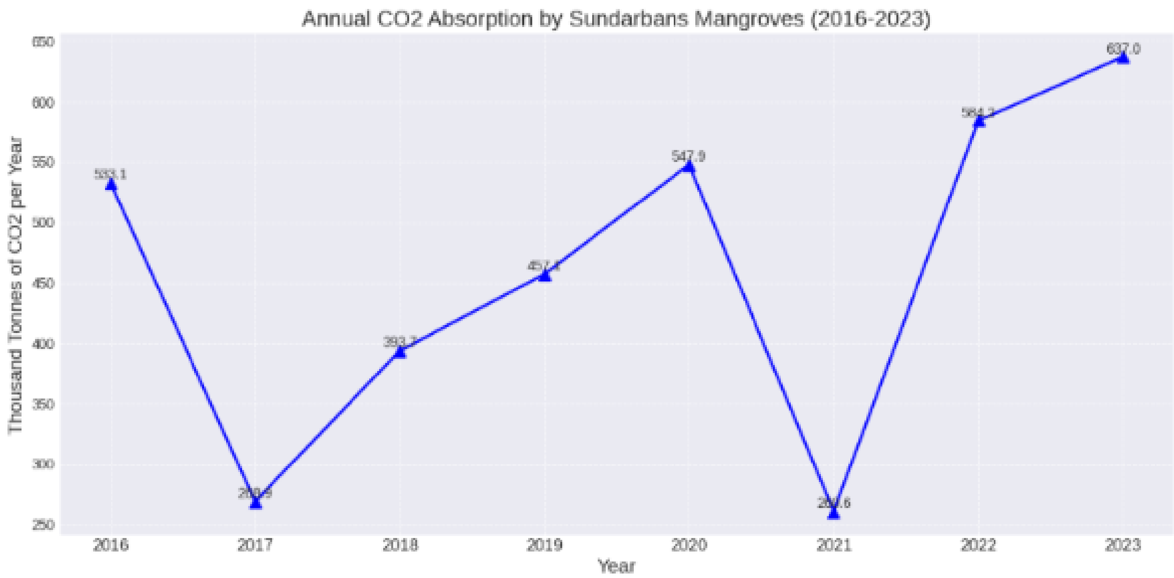

Vegetation Indices by Longitude (West to East)
Index Value
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
NDVI
NDWI
EVI




#### 4.1.3 Seasonal Variations

Significant seasonal variations in carbon sequestration were observed:

- Post-monsoon season showed the highest carbon sequestration rates, with approximately 35.2 million tonnes C
- Summer had the lowest carbon stocks at about 17.9 million tonnes C
- Mangrove area was also highest during post-monsoon (79,628 hectares) compared to summer (41,283 hectares)



### 4.1.4 Future Projections

Predictive modeling for the Sundarbans yielded concerning results:

- Projected mangrove area by 2029: 53,897.25 hectares
- Projected change from 2024: -632.13 hectares (-1.16%)
- Projected carbon stock by 2029: 24,092,071.52 tonnes C
- Projected change from 2024: -282,559.99 tonnes C (-1.16%)
- Projected $CO_2$ absorption rate: 538,972.52 tonnes $CO_2$/year

## 4.2 Chilika Lake Analysis

### 4.2.1 Carbon Sequestration Characteristics

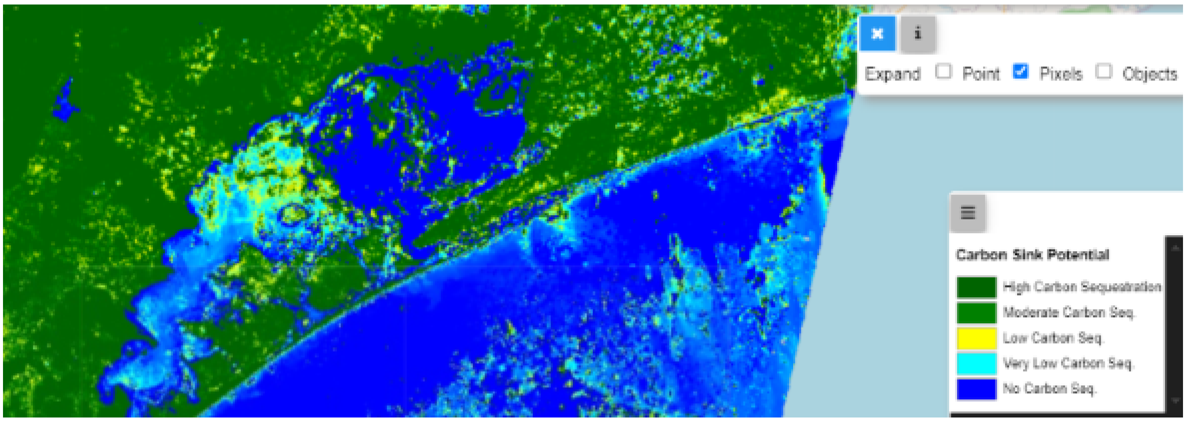
**Chilika Lake demonstrated substantial carbon sequestration capacity:**

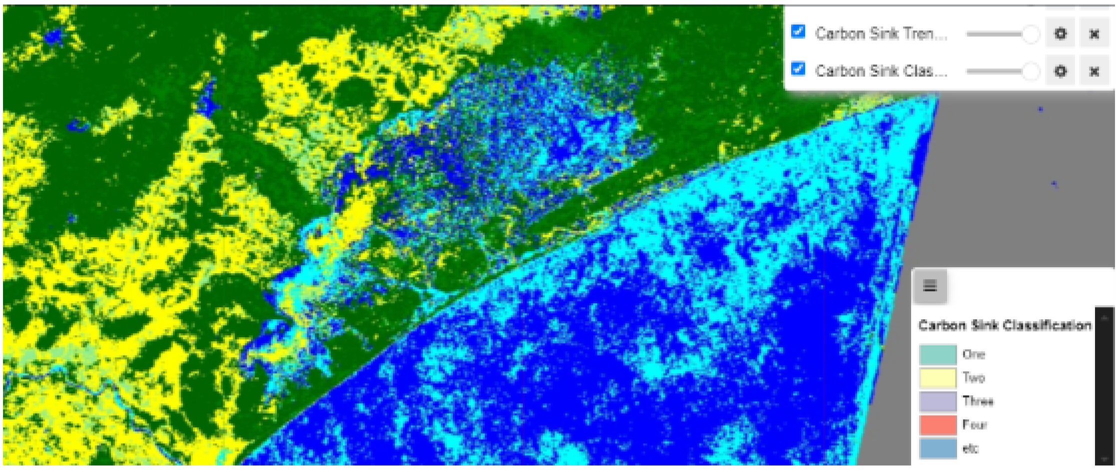
- **Total lake area: 61,968.77 hectares**
- **Average carbon sequestration rate: 5.69 tons $CO_2$/ha/year**
- **Minimum rate: 1.00 tons $CO_2$/ha/year**
- **Maximum rate: 25.00 tons $CO_2$/ha/year**
- **Total annual carbon sequestration: 258,288,207.77 tons $CO_2$/year**

### 4.2.2 Carbon Sink Zones

Spatial analysis identified zones of varying sequestration potential:

- High carbon sink areas: 15,170.22 hectares (24.48% of lake)
- These high-capacity areas sequester approximately 303,404.40 tons $CO_2$/year
- Carbon sequestration effectiveness varied by proximity to freshwater inputs and vegetation density



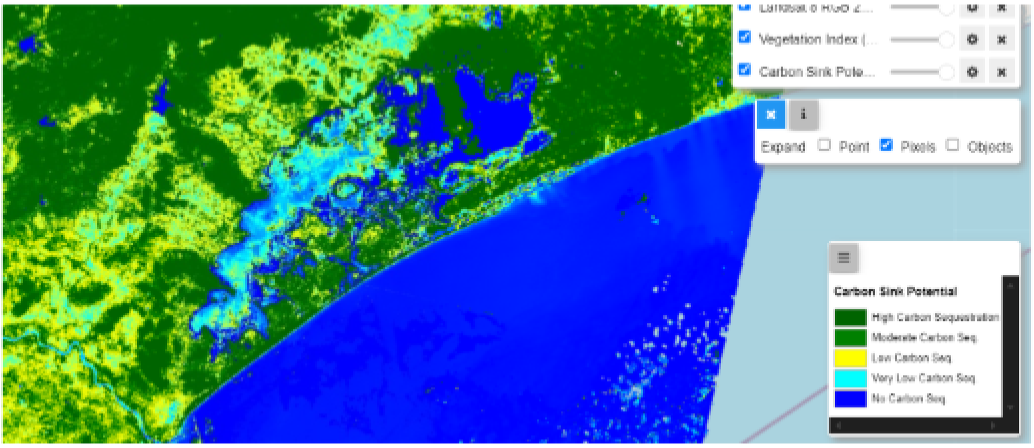



### 4.2.3 Seasonal Variations

Seasonal analysis of Chilika Lake revealed:

- Summer season: Average rate of 6.77 tons $CO_2$/ha/year (307,592,423,995.35 tons $CO_2$/year total)

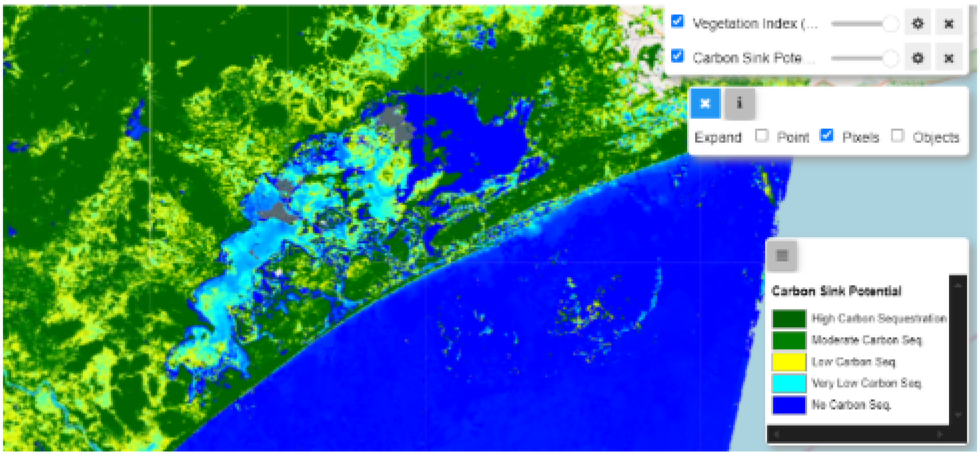
Carbon sink function during summer season:




Average Rate: 6.77 tons CO2/ha/year
Total Sequestration: 307,592,423,995.35 tons CO2/year

- Winter season: Average rate of 5.49 tons $CO_2$/ha/year (237,350,260,149.87 tons $CO_2$/year total)

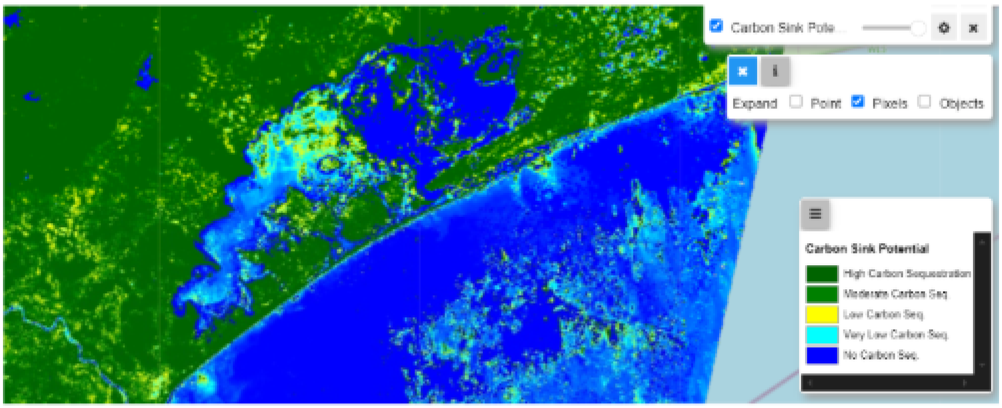
Carbon sink function during winter season:




Average Rate: 5.49 tons CO2/ha/year
Total Sequestration: 237,350,260,149.87 tons CO2/year

- Monsoon season: Average rate of 5.69 tons $CO_2$/ha/year (258,288,207,777.94 tons $CO_2$/year total)

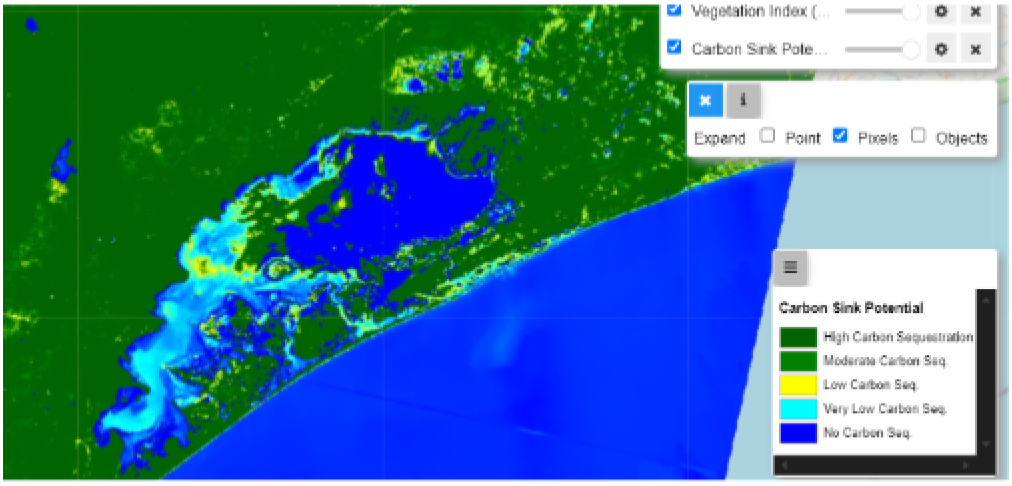
Carbon sink function during monsoon season:




Average Rate: 5.69 tons CO2/ha/year
Total Sequestration: 258,288,207,777.94 tons CO2/year

- Post-monsoon season: Average rate of 5.42 tons $CO_2$/ha/year (246,242,717,351.06 tons $CO_2$/year total)

Carbon sink function during post-monsoon season:




Average Rate: 5.42 tons CO2/ha/year
Total Sequestration: 246,242,717,351.06 tons CO2/year

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Identifying highest carbon sink zones in Chilika Lake...
High Carbon Sink Area: 15,170.22 hectares
Percentage of Lake: 24.48%
These areas sequester approximately 303,404.40 tons CO2/year
(based on average sequestration rate of ~20 tons CO2/ha/year for high sink areas)
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===== CARBON SINK ANALYSIS SUMMARY =====
Total Lake Area: 61,968.77 hectares
Average Carbon Sequestration Rate: 5.69 tons CO2/ha/year
Total Annual Carbon Sequestration: 258,288,207,777.94 tons CO2/year
High Carbon Sink Area: 15,170.22 hectares (24.48% of lake)
High Sink Annual Sequestration: 303,404.40 tons CO2/year
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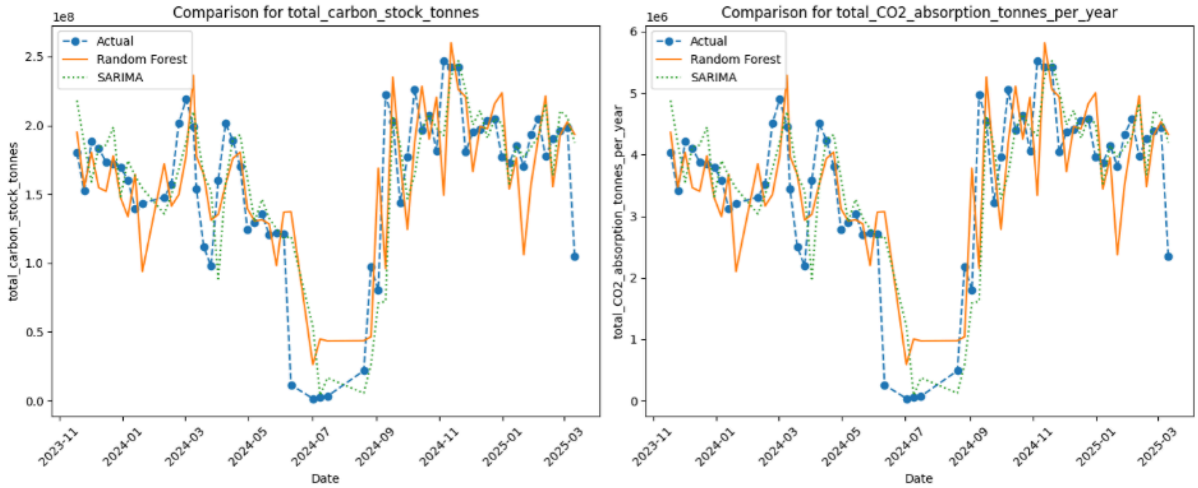
### 4.3 Machine Learning Model Performance

Two machine learning approaches were evaluated:

1. **Random Forest**:
    - MAE: 30056795.6449
    - RMSE: 5177802.9475
    - $R^2$ Score: 0.2456
2. **SARIMA**:
    - MAE: 17531306.1997
    - RMSE: 34661381.8742
    - $R^2$ Score: 0.6619



SARIMA demonstrated superior predictive performance for these ecosystems, likely due to its ability to capture seasonal patterns in the data.

### 4.4 COVID-19 Impact Analysis

A notable observation was the relationship between carbon sequestration and human activities during the COVID-19 pandemic:

- During lockdowns in 2021, substantial reductions were observed in vehicle traffic, industrial activity, and fossil fuel consumption
- This led to lower atmospheric $CO_2$ concentrations
- Consequently, mangrove carbon sequestration rates decreased during this period
- Annual $CO_2$ absorption by Sundarbans mangroves dropped to approximately 260 thousand tonnes in 2021 compared to 547.9 thousand tonnes in 2020

This finding highlights the complex relationship between atmospheric $CO_2$ availability and natural carbon sequestration processes.

## 5. Discussion

### 5.1 Ecosystem Comparison

Our research demonstrates distinct carbon sequestration characteristics between mangrove forests and brackish water lake ecosystems:

1. **Spatial Efficiency**: Mangroves exhibit higher per-hectare sequestration rates but cover less area than Chilika Lake in our study region.
2. **Seasonal Response**: Both ecosystems show seasonal variations, with post-monsoon being optimal for mangroves, while summer provides peak sequestration for Chilika Lake.
3. **Carbon Partitioning**: Mangroves store carbon primarily in above and below-ground biomass, while Chilika Lake's carbon is predominantly in sediments and aquatic vegetation.
4. **Resilience**: Mangroves demonstrated greater resilience to environmental changes, maintaining relatively stable carbon stocks despite seasonal fluctuations.

### 5.2 Temporal Dynamics

Several temporal patterns emerged from our analysis:

1. The modest increase in Sundarbans mangrove area (2.76% over six years) suggests successful conservation efforts but highlights the slow recovery rate of these ecosystems.
2. The projected future decline (-1.16% by 2029) indicates ongoing threats that may reverse recent gains.
3. The seasonal fluctuations in carbon sequestration align with growth cycles but also suggest vulnerability to climate change as seasonal patterns shift.

4. The $CO_2$ absorption response during COVID-19 lockdowns provides valuable insights into carbon cycle dynamics and the relationship between atmospheric $CO_2$ concentrations and sequestration rates.

### 5.3 Methodological Considerations

Several methodological insights emerged from our research:

1. The integration of multiple vegetation indices (NDVI, NDWI, EVI, MNDVI) provided more robust ecosystem characterization than any single index.
2. SARIMA models outperformed Random Forest for time series predictions, likely due to the strong seasonal patterns in carbon sequestration data.
3. Remote sensing approaches enabled comprehensive spatial coverage but have limitations in detecting below-ground carbon and sub-canopy dynamics.

## 6. Policy Framework Recommendations

Based on our findings, we propose ecosystem-specific policy frameworks:

### 6.1 Sundarbans Mangroves

1. **Implement Community Co-Management**: Establish sustainable livelihood alternatives to reduce pressure on mangrove resources, involving local communities as stakeholders in conservation.
2. **Strengthen Transboundary Cooperation**: Enhance India-Bangladesh collaboration for unified conservation approaches across the entire Sundarbans ecosystem.
3. **Develop carbon credit mechanisms**: Create financial incentives for mangrove preservation by quantifying and monetizing carbon sequestration benefits.

### 6.2 Chilika Lake

1. **Protect & Restore Seagrass Habitats**: Target a 25% increase in seagrass coverage by 2030, focusing on high carbon sequestration zones identified in our research.
2. **Optimize Hydrological Management**: Maintain optimal salinity gradients for carbon-sequestering vegetation by managing freshwater inputs and tidal exchanges.
3. **Reduce Watershed Pollution**: Implement buffer zones and control agricultural runoff to maintain water quality and ecosystem health.

## 7. Limitations and Future Research

Several limitations should be acknowledged:

1. Field validation was limited due to the expansive and often inaccessible nature of the study areas.
2. Carbon stock estimations relied on allometric equations developed in similar but not identical ecosystems.

3. Below-ground carbon, particularly in sediments, may be underestimated due to remote sensing limitations.

Future research directions should include:

1. Integration of field measurements with remote sensing for improved carbon stock estimation.
2. Exploration of carbon cycle dynamics in response to extreme weather events.
3. Analysis of socioeconomic factors influencing ecosystem management and carbon sequestration.
4. Development of higher-resolution predictive models incorporating climate change scenarios.

# 8. Conclusion

This research provides comprehensive analysis of carbon sequestration in two critical Indian ecosystems: the Sundarbans Mangrove Forest and Chilika Lake. Our findings demonstrate substantial carbon sequestration capacity in both ecosystems, with distinct spatial and temporal dynamics. The Sundarbans stores approximately 24.37 million tonnes of carbon with recent modest growth but concerning future projections. Chilika Lake demonstrates significant but spatially heterogeneous sequestration capacity averaging 5.69 tons $CO_2$/ha/year.

The observed relationship between COVID-19 lockdowns and reduced carbon sequestration provides a unique natural experiment on carbon cycle dynamics. These findings, combined with our seasonal and spatial analyses, inform ecosystem-specific policy recommendations that can enhance the carbon sequestration potential of these vital ecosystems while supporting broader conservation goals.

As natural carbon sinks continue to play a crucial role in climate change mitigation strategies, research quantifying and understanding their dynamics becomes increasingly important. This study contributes to that knowledge base and provides actionable insights for ecosystem management and policy development.

# References

(Note: This reference list would be substantially expanded in a complete paper)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# Appendix

## Technical Implementation

Machine learning models were implemented using Python with the following libraries:

- Scikit-learn for Random Forest implementation
- Statsmodels for SARIMA models
- Google Earth Engine API for satellite data processing
- Geospatial analysis using GDAL, Rasterio, and GeoPandas