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Assessing Spatio-Temporal Variability of Seagrass Blue Carbon Stock: An Integrated Field-Satellite Approach in Palk Bay, India

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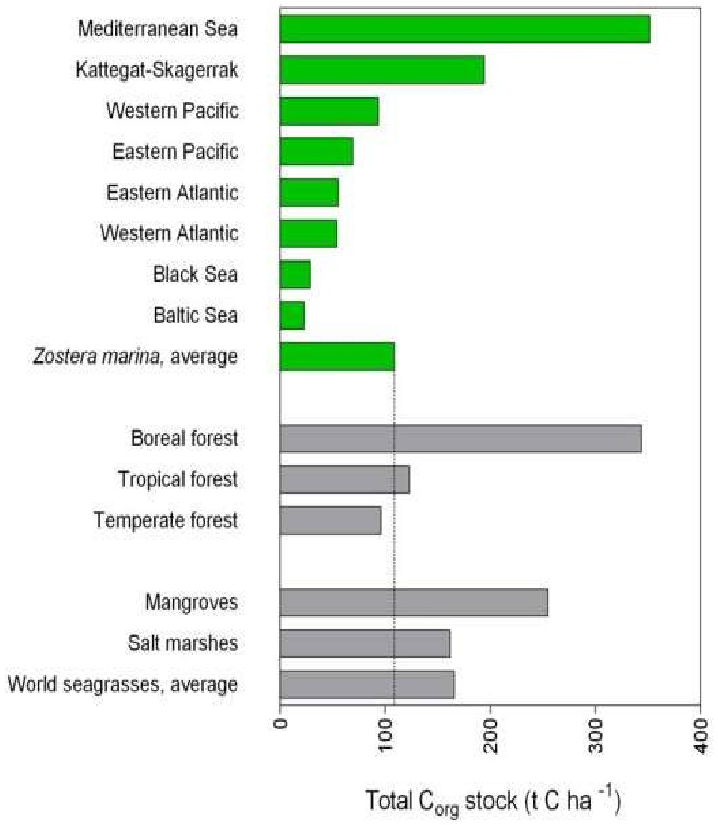
Introduction

- **Seagrass ecosystems sequester and store disproportionately large amounts of carbon relative to their spatial extent.**
- **Their pronounced sensitivity to climate variability and human disturbances necessitate timely and reliable monitoring of associated ecosystem dynamics.**
- **Conventional field measurements are laborious, spatially limited and often impractical for sustained monitoring whereas, satellite-derived observations can enable continuous, large-scale assessment of blue carbon dynamics in vulnerable ecosystems such as seagrass meadows.**
- **This urges for the development of regional remote sensing algorithms using satellite data to continuously monitor the blue carbon dynamics in vulnerable ecosystems such as seagrasses.**



Knowledge Gaps

Non-Viable Monitoring
Developed and validated a cost-effective, integrated field-satellite methodology for regional-scale mapping of seagrass AGB and carbon stock in Palk Bay[1].

Lack of Regional Algorithms
Established seasonal empirical models specific to Palk Bay, achieving strong validation metrics

Role of Habitat Connectivity
Demonstrated the novel finding that the association of coral reefs significantly increases the total organic carbon stock and sequestration capacity of seagrass meadows compared to seagrass-alone habitats.

Spatial Planning Tools
Developed the first total carbon stock atlas for the Palk Bay region and incorporated outputs into a WebGIS application for immediate decision support and management actions

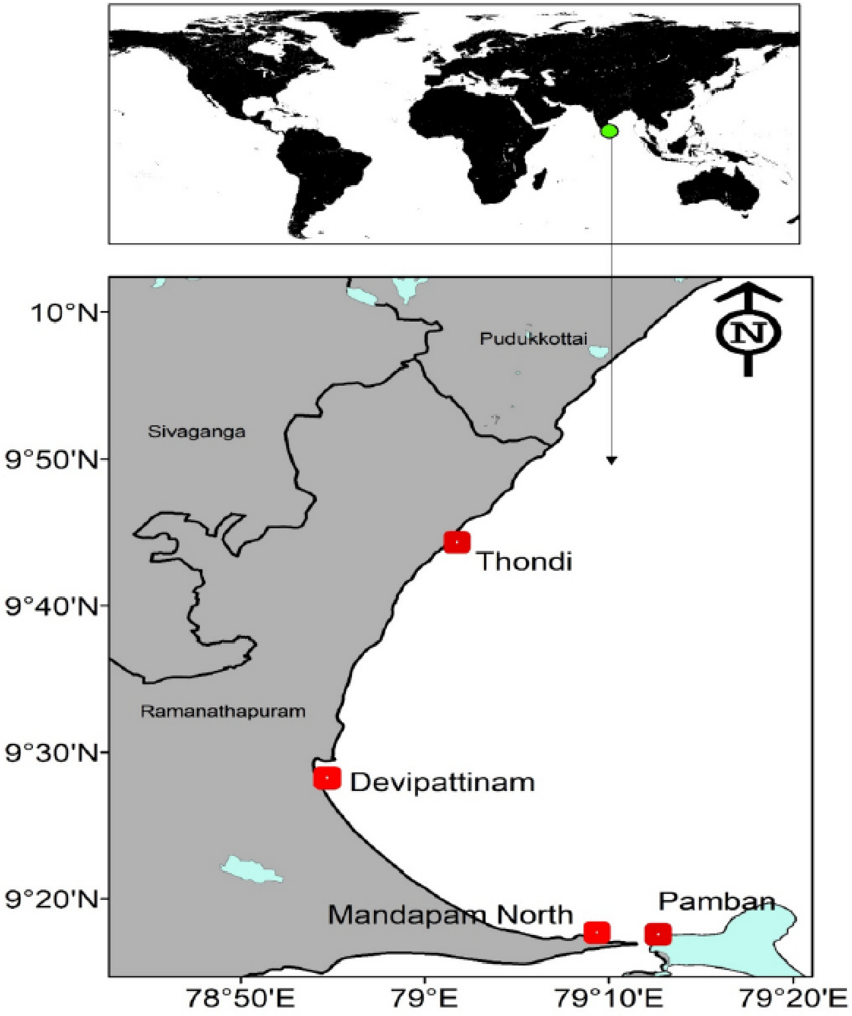
Key objectives

Objectives (Key Focal areas):

Assess status and spatio-temporal changes in sediment organic carbon content between habitats.

Derive algorithms to enable satellite-based monitoring of organic carbon dynamics in seagrass ecosystem.

Study area and methodology



Field Survey Design

- Monthly surveys conducted from January 2022 to December 2023.
- Two permanent monitoring stations identified:
    - Pamban – Seagrass-only (SG) habitat
    - Mandapam – Seagrass–Coral Reef (SG–CR) associated habitat
- Additional sampling performed along Thondi & Devipattinam transects in Palk Bay.
- These extra stations used for validation of satellite-derived biomass and carbon stock.

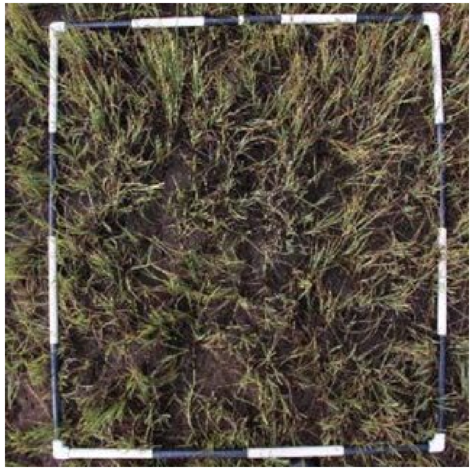
methodology

Field Sampling & Laboratory Analysis

- Seagrass biomass collected (1 sq.m quadrats)

  Above-ground biomass (AGB)

  Below-ground biomass (BGB)
- Water and sediment samples
- Sediment samples collected using PVC core (30cm length 10cm diameter) and sub-sampled
- Sediment organic carbon (LOI method)
- Seasonal variability of sediment carbon stock assessed across all sampling locations.



Remote Sensing Data Acquisition & Pre-processing

- Satellite imagery used:

Sentinel-2 MSI

Landsat series

- Temporal coverage: 2015–2023
- Processing workflow:

Atmospheric correction

Water-column correction

Generation of median reflectance composites

Supervised classification using extracted spectral signatures

- Annual and seasonal seagrass cover maps derived from processed imagery.

methodology

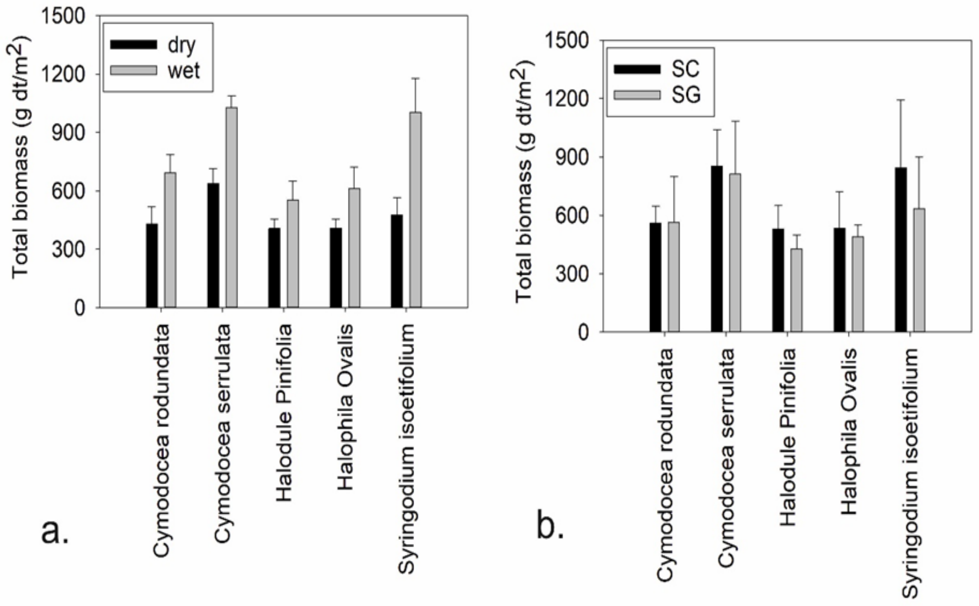
NDVI–Biomass Model Development

- NDVI computed for all satellite scenes.
- Field-collected ground-truth (GT) points for seagrass and non-seagrass are overlaid to extract corresponding NDVI values.
- A series of NDVI thresholds (e.g., 0.0–0.6) is tested. For each threshold, GT pixels are classified as Seagrass (NDVI ≥ T) or Non-Seagrass (NDVI < T).
- Confusion matrix, sensitivity, and Youden's J.
- The NDVI value that maximizes Youden's J is selected as the optimal seagrass mapping threshold.
- Empirical relationship used to estimate AGB from NDVI.
- Additional ground truth points used for statistical validation.

Results

Seasonal Variability

- Permanent benthic surveys showed significant seasonal variation in total seagrass biomass ($F(1,38) = 29.495$, $p < 0.001$).
- Wet season biomass was highest (778.29 ± 227.06 g dwt/m^2), compared to dry season.



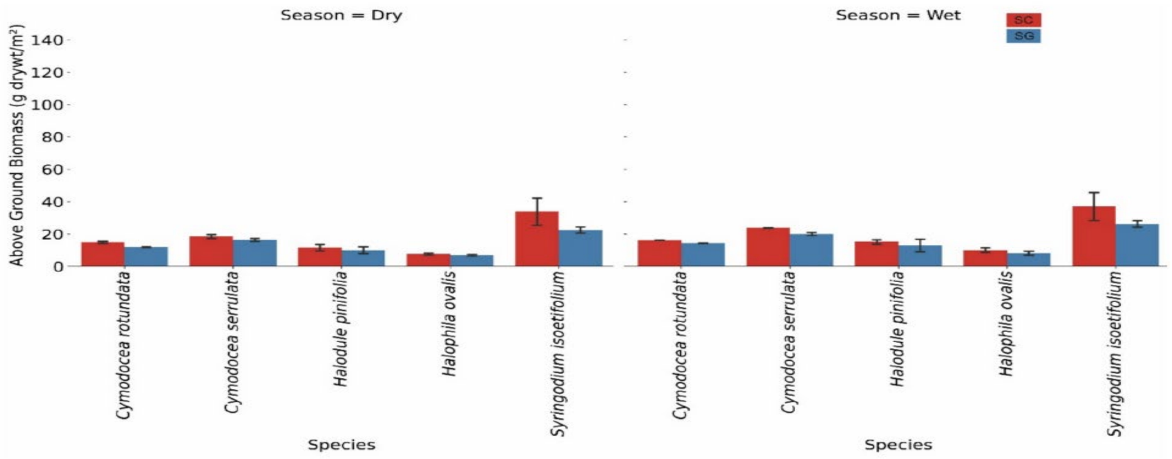
Species-wise Biomass Patterns

- Dry season: Highest biomass: *Cymodocea serrulata* (638.75 ± 74.54 g dwt/m^2); Lowest biomass: *Halophila ovalis* (409 ± 45.35 g dwt/m^2)
- Wet season: Highest biomass: *Cymodocea serrulata* (1027.5 ± 60.21 g dwt/m^2);Lowest biomass: *Halodule pinifolia* (553.5 ± 96.24 g dwt/m^2)
- Significant inter-species variability in biomass: ($F(1,4) = 21.32$, $p < 0.001$).
- Biomass also varied within species between seasons: ($F(1,4) = 5.25$, $p = 0.003$).

Habitat-class Comparison

- Biomass comparison between Seagrass (SG) and Seagrass–Coral Reef (SC) habitats showed no significant difference ($F(1,1) = 1.47$, $p = 0.24$).
- Indicates that coral reef association does not significantly influence seagrass cover or biomass (Fig. b).

Results



Above-Ground Biomass (AGB) – Seasonal & Habitat Variability

- Higher AGB in SC than SG in both seasons, but not statistically significant.
- Dry season:

  SC = 17.33 ± 9.94 g dwt/m²

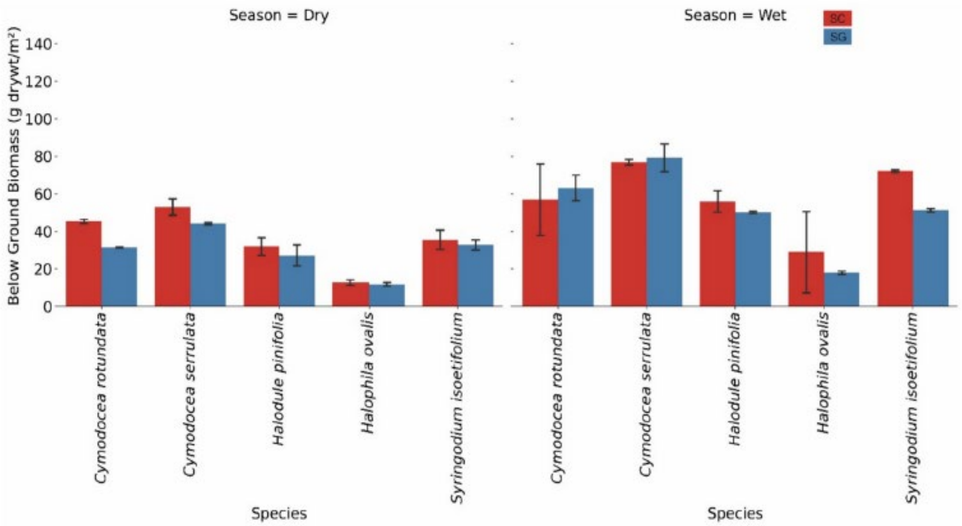
  SG = 13.56 ± 5.81 g dwt/m²

  No significant difference ($Z = 0.45$, $p = 0.48$)
- Wet season:

  SC = 20.46 ± 10.29 g dwt/m²

  SG = 16.38 ± 6.72 g dwt/m²

  No significant difference ($Z = –0.83$, $p = 0.41$)



Below-Ground Biomass (BGB)

- BGB consistently higher in SC areas than SG areas across both seasons.. (p>0.05)
- Dry season:

  SC = 35.71 ± 14.62 g dwt/m²

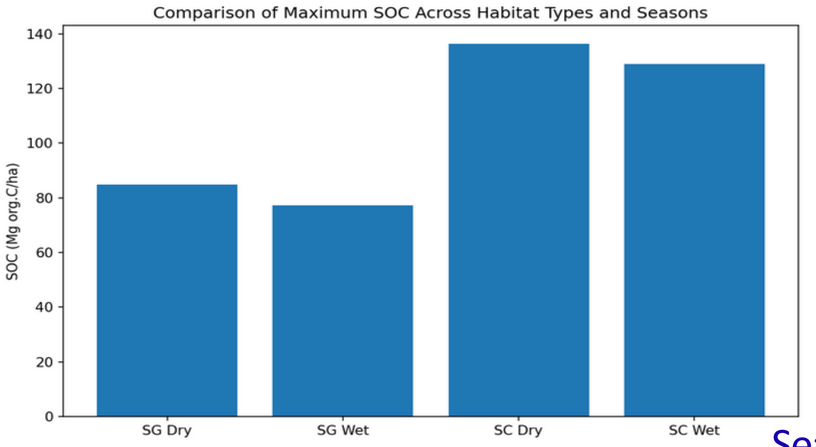
  SG = 29.48 ± 11.23 g dwt/m²
- Wet season:

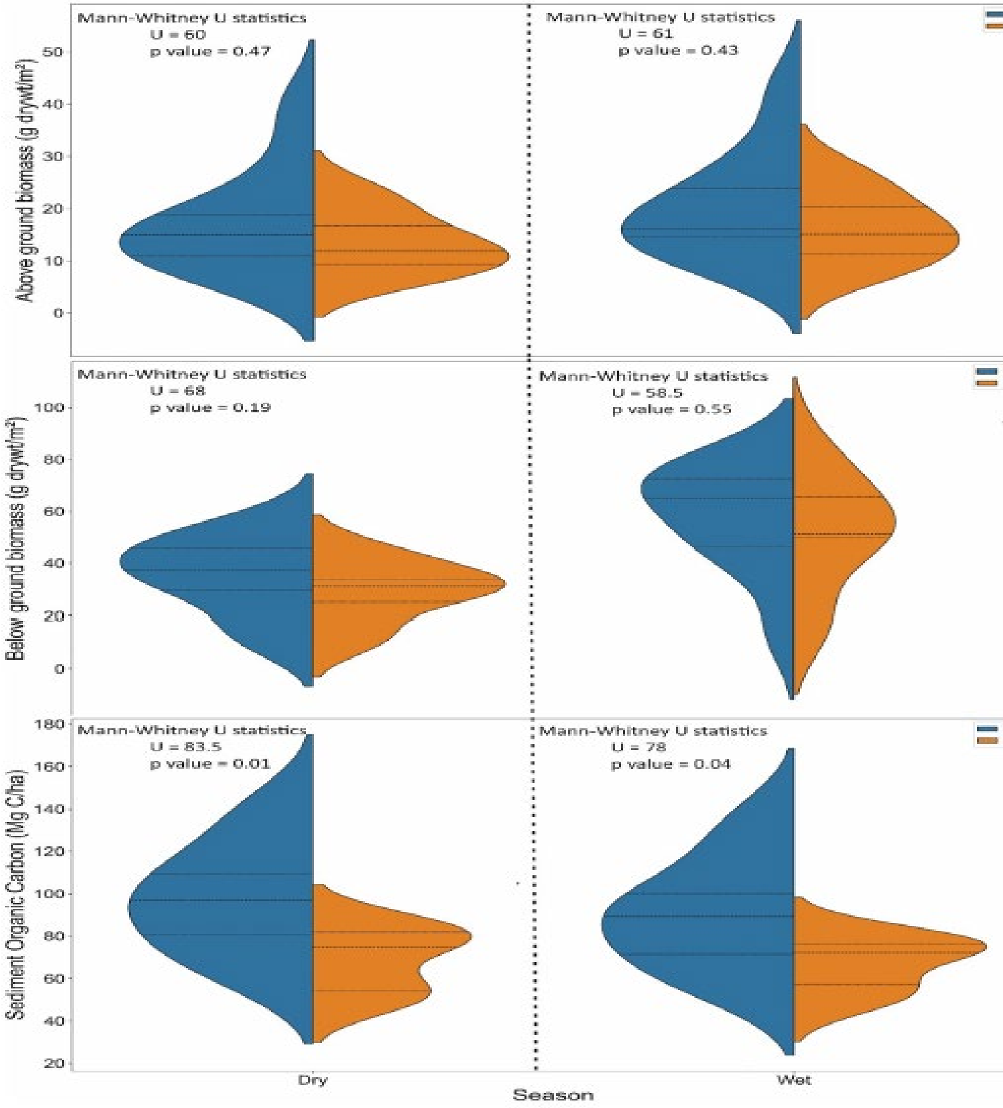
  SC = 58.16 ± 20.21 g dwt/m²

  SG = 52.36 ± 21.51 g dwt/m²

Results

Sediment Organic Carbon (SOC) – Species-Level Variability at different habitats





Seagrass areas

- **Dry season**

Highest SOC: *Cymodocea rotundata*
84.79 ± 1.37 mg org. C/ha
Lowest SOC: *Halophila ovalis*
51 ± 3.32 mg org. C/ha

- **Wet season**

Highest SOC: *Cymodocea serrulata*
77.28 ± 7.13 mg org. C/ha
Lowest SOC: *Halophila ovalis*
48.8 ± 3.61 mg org. C/ha

Seagrass-coral reef areas

- **Dry season**

Highest SOC: *Syringodium isoetifolium*
136.22 ± 8.38 mg org. C/ha
Lowest SOC: *Halophila ovalis*
64.3 ± 3.19 mg org. C/ha

- Wet season

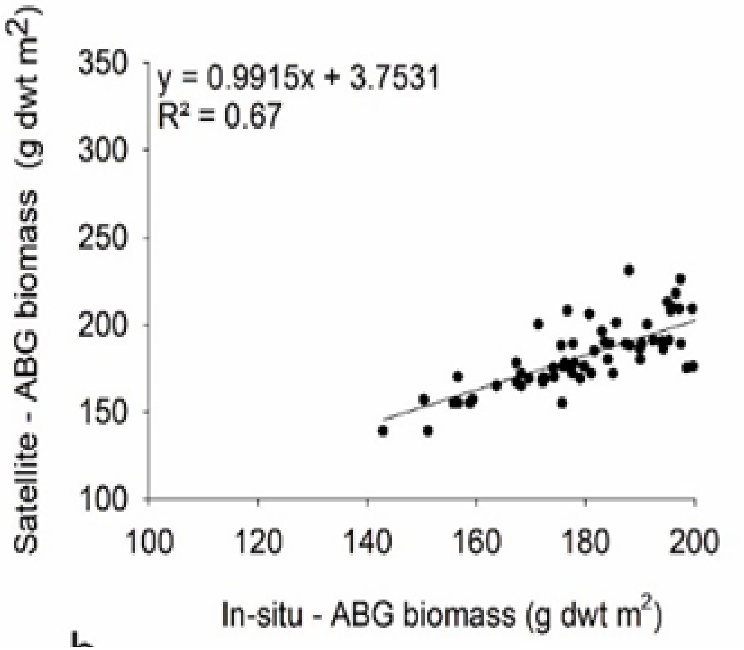
Highest SOC: *Syringodium isoetifolium*
129 ± 9.5 mg org. C/ha
Lowest SOC: *Halophila ovalis*
58.8 ± 3.43 mg org. C/ha

Results

- The linear regression analysis evidenced strong linear relationship between total soil organic carbon stock (mg C org m-3) and seagrass AGB during the dry and wet seasons.

For dry season ---- Total carbon stock = 0.0075*AGB - 0.29 [r2 = 0.74, p<0.05]
For wet season ---- Total carbon stock = 0.0032*AGB + 0.098 [r2 = 0.82, p<0.05]

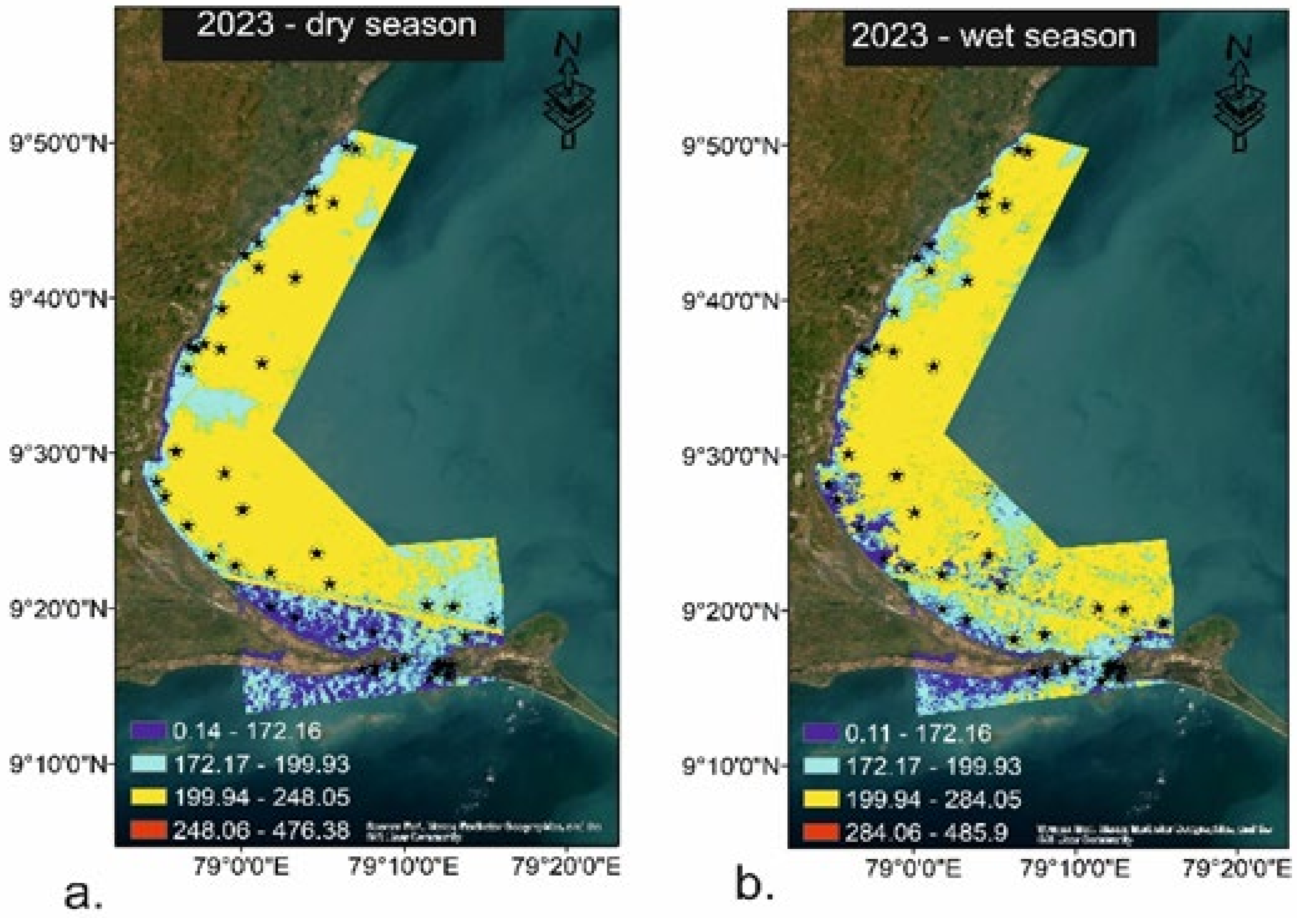
- Further analysis also showed that there is no variability in the relationship between total soil organic carbon and seagrass AGB for different seagrass species.



- The NDVI generated from the satellite image was then used with the *in-situ* seagrass AGB from the fixed monitoring sites to derive an empirical model to map spatial seagrass AGB and were validated with the seagrass biomass collected from the stations other than the fixed monitoring sites

Y = 558.13*NDVI + 129.15 [r2 = 0.8, p<0.05]

Results



Above-Ground Biomass (AGB) Mapping

- Satellite-derived AGB maps showed similar spatial patterns and biomass ranges as field observations.

Seasonal trends matched field data:

- Higher AGB in wet season
- Lower AGB in dry season

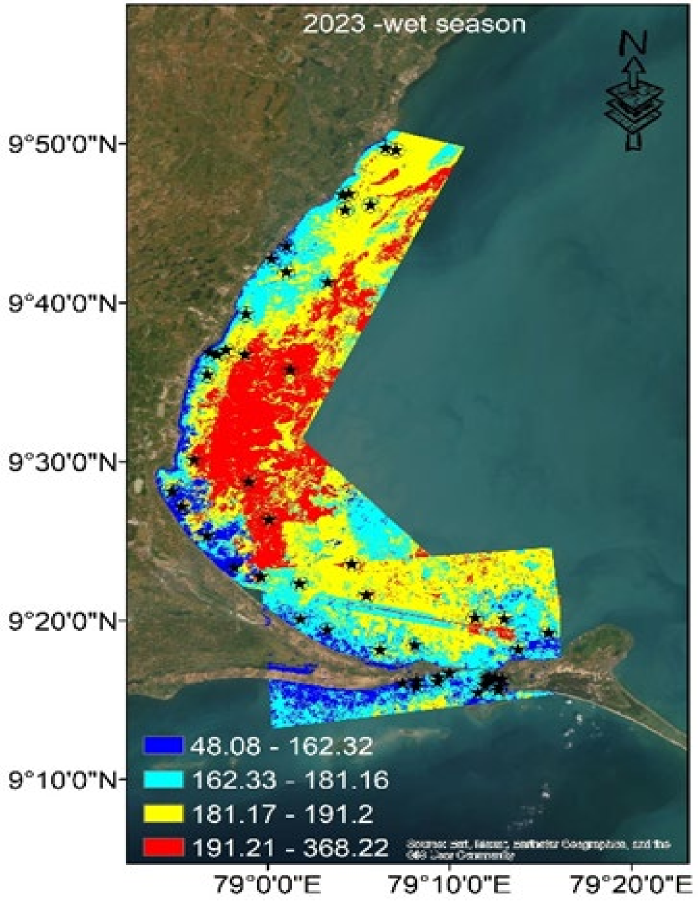
Match-up validation with 51 independent field points confirmed strong agreement:
$R^2 = 0.67$, $p < 0.05$ (statistically significant)

- Demonstrates high reliability of the empirical AGB model for Palk Bay.

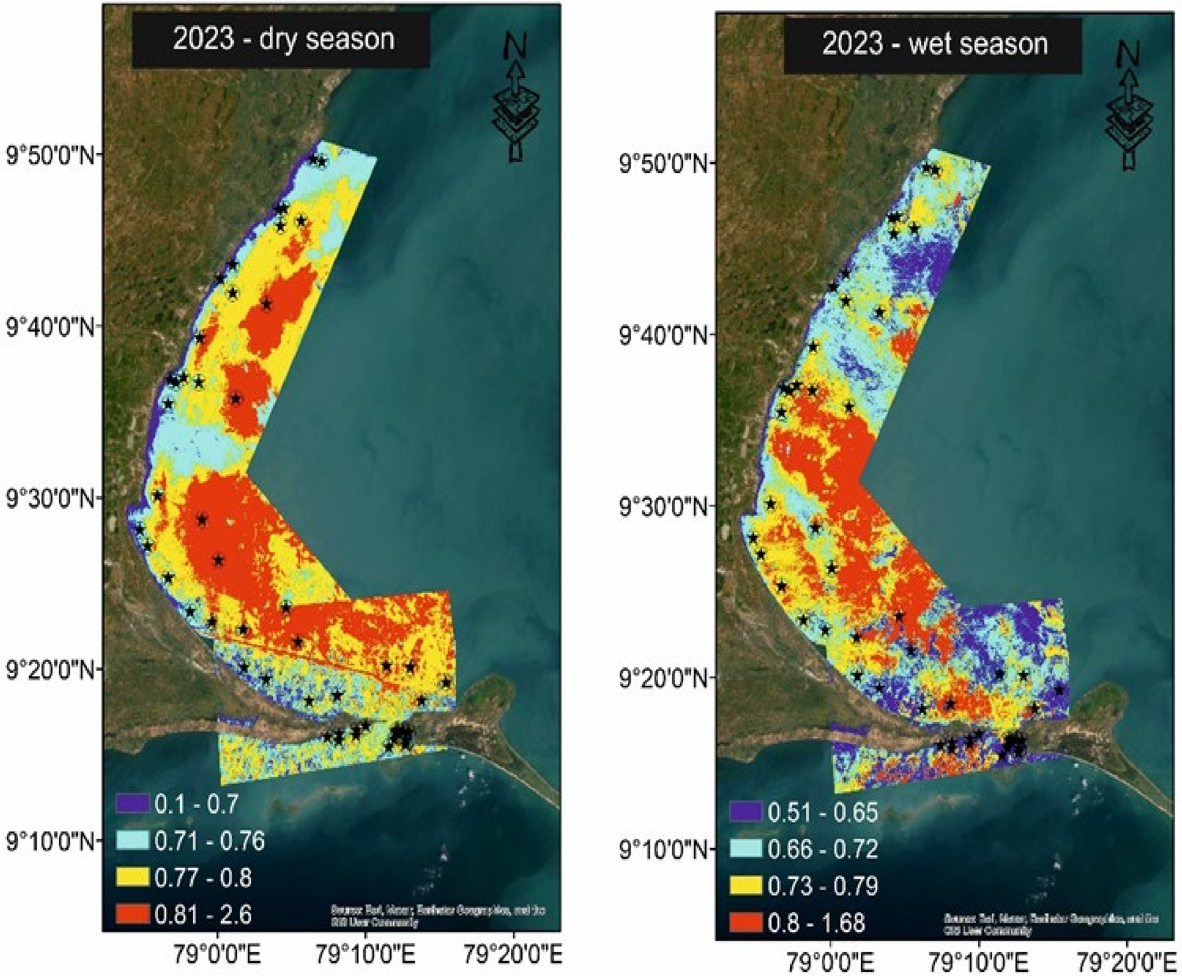
Results

Below-Ground Biomass (BGB) Mapping attempted

- BGB mapping attempted using satellite data for the 2023 wet season.
- Field BGB range: 285–628 g dwt/m²
- Satellite-derived BGB range: 48–368 g dwt/m²
- Satellite estimates show consistent underestimation of actual BGB.
- Due to low accuracy, BGB modelling was not used further for carbon stock computation.



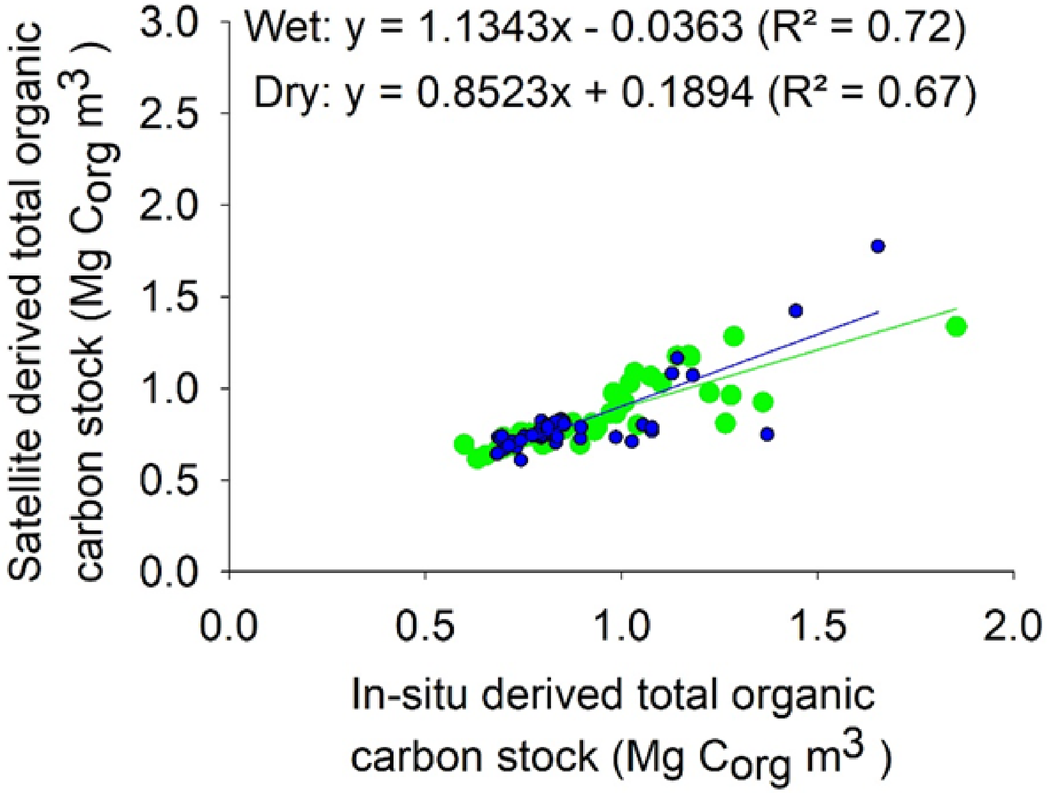
Results



Total Organic Carbon Stock Mapping

- Since BGB could not be modelled accurately, total organic carbon stock was estimated using satellite-derived AGB
- Equations 1 & 2 (for dry and wet seasons).
- Carbon stock maps produced for 2022 and 2023 (wet & dry seasons).
- Seasonal pattern clearly captured:
- Higher carbon stock in dry season
- Lower carbon stock in wet season (consistent with field observations)

Results



Validation of Carbon Stock Maps

- Match-up analysis showed good agreement between satellite-derived and in-situ carbon stock:
  Dry season: $R^2 = 0.67$, $p < 0.05$
  Wet season: $R^2 = 0.72$, $p < 0.05$
- Confirms reliable capability of AGB-based empirical models for regional carbon stock assessment.

- Established a novel relationship showing that coral reef association significant improves the overall blue carbon dynamics and storage capability of the seagra ecosystem
- Showcase the need for an integrated conservation of coral reefs and seagrass in the region for improved ecosystem services.
- Established and validated simple seasonal models that link AGB to total carbo stock, improving upon existing methods for large-area assessment

Future priorities

Immediate

Rollout Carbon Stock Atlas for Management: Fully deploy the WebGIS application showing the Palk Bay Carbon Stock Atlas to stakeholders to enable immediate identification of geospatial areas requiring management intervention for restoration and improved carbon sequestration capability.

Intermediate

Collaborate with government agencies to establish a national seagrass carbon monitoring program utilizing the validated Palk Bay statistical models to develop a total carbon stock inventory for coastal habitats across India, and concurrently dedicate research to refining the satellite estimation of Below-Ground Biomass (BGB).

Long-term

Support the transition of validated regional carbon stock data and the WebGIS framework into national Blue Carbon accounting and policy frameworks to facilitate carbon credit calculation and to advocate for the long-term protected status and investment in critical seagrass ecosystems

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