

Comparative assessment of sediment carbon storage and greenhouse gas dynamics in degraded mangroves and saltmarsh ecosystems of the Sundarban, India

Sujit Kumar Nayak

contactsujit98@gmail.com

ICAR-National Rice Research Institute (NRRI)

Ramanuj Bhattacharyya

University of Agricultural Sciences

Soumya Ranjan Padhy

ICAR-National Rice Research Institute (NRRI)

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Abstract

Coastal wetlands, including mangrove and saltmarsh systems, provide essential ecosystem services such as coastal protection, biodiversity conservation, and carbon sequestration. However, increasing anthropogenic activities and habitat loss can alter their carbon-storage potential and greenhouse gases (GHGs) emissions. Therefore, this study comparatively assessed soil organic carbon (SOC) storage and GHGs fluxes across degraded mangrove and saltmarsh ecosystems at three different sites on Sagar Island, Sundarban, India. SOC was quantified across a 0-100 cm sediment profile comprising five depth intervals, while ecosystem-level GHGs fluxes and inorganic nitrogen pools were assessed across the study sites. Mangrove sediments exhibited progressive enrichment of SOC with depth, whereas saltmarsh sediments showed surface-enriched SOC followed by declining concentrations toward 100 cm. Consequently, 0-100 cm SOC stocks were substantially higher in mangroves (99.89-107.15 Mg C ha⁻¹) than in saltmarshes (67.35-79.42 Mg C ha⁻¹). This contrasting vertical SOC distribution revealed distinct carbon-storage strategies, with mangroves retaining higher carbon in deeper sediment horizons and saltmarshes exhibiting surface-dominated carbon storage and higher active carbon turnover. Saltmarshes showed higher CO₂ (156.7-194.4 mg m⁻² h⁻¹) and N₂O (89.8-95.3 µg m⁻² h⁻¹) fluxes, whereas mangroves exhibited higher CH₄ fluxes (0.348-0.422 mg m⁻² h⁻¹). The divergent GHGs fluxes highlight distinct ecosystem controls over coastal carbon cycling, with SOC storage representing accumulated carbon retention and GHGs fluxes reflecting active biogeochemical turnover. These findings demonstrate the contrasting carbon-storage and GHGs-regulation functions of degraded mangrove and saltmarsh ecosystems and provide a basis for integrating blue-carbon conservation with GHGs management in tropical coastal landscapes.

1. Introduction

Coastal wetlands, particularly mangrove forests and tidal saltmarshes, are among the most effective natural ecosystems for carbon sequestration and long-term carbon storage (Guo et al., 2025; Zheng et al., 2026). Their capacity to accumulate organic matter within waterlogged sediments makes them important components of nature-based climate mitigation, while their vegetation and sediment systems provide multiple ecosystem services, including coastal protection, biodiversity conservation and nutrient regulation (Kaviarasan et al., 2025; Nayak et al., 2025). Blue-carbon ecosystems can bury carbon at rates substantially higher (18-1713 g C m⁻² yr⁻¹) than many terrestrial ecosystems (0.7–13.1 g C m⁻² yr⁻¹) and retain considerable carbon within sediment over millennial timescales (McLeod et al., 2011; James et al., 2025; Kristensen et al., 2025). Mangrove ecosystems are especially important because a large proportion of their ecosystem carbon is retained belowground within sediment, where organic matter accumulation is influenced by vegetation productivity, root-derived inputs, sedimentation, hydrology and preservation processes (Coppo et al., 2026).

The carbon-storage function of coastal wetlands is strongly influenced by anthropogenic disturbance and ecosystem degradation (Feng et al., 2026; Nayak et al., 2025). Mangrove degradation can reduce

vegetation structural complexity, litter production and belowground organic-matter inputs, thereby altering sediment carbon accumulation and carbon cycling (Dinakarkumar et al., 2026). Recent work from the Sundarban has demonstrated substantial spatial variation in carbon storage among degraded mangrove systems and has emphasized the importance of anthropogenic pressure, proximity to human settlements and ecosystem condition for identifying conservation and restoration priorities (Nayak et al., 2025; Karim et al., 2026; Mondal et al., 2026). Degraded mangroves therefore represent an important environmental-management concern because changes in vegetation condition can modify both carbon retention and the exchange of greenhouse gases between coastal sediments and the atmosphere (Duan et al., 2025; Kandauda et al., 2026).

Mangrove and saltmarsh ecosystems can exhibit distinct patterns of sediment carbon accumulation because their vegetation structure, belowground productivity, tidal position, sediment characteristics and organic-matter inputs differ (Liu et al., 2026; Han et al., 2025). Comparative evidence from southeastern coastal Bangladesh demonstrates higher 0-100 cm SOC storage in mangroves than adjacent saltmarshes, with habitat type significantly influencing total sediment carbon stocks (Hossain et al., 2026). The same study identified strong relationships between sediment texture and SOC, highlighting the role of clay and silt fractions in organic-carbon retention (Hossain et al., 2026). Recent comparative research further demonstrates that hydroperiod, mineral inputs, salinity and sediment accretion history can generate substantial variability in SOC storage among coastal wetland habitats (Nayak et al., 2025). Such habitat-specific differences become particularly important when SOC is evaluated along deeper sediment profiles, because surface carbon inputs, belowground production, burial and subsequent transformation can generate contrasting vertical carbon distributions.

The vertical distribution of SOC provides an important perspective for understanding long-term carbon retention in coastal sediments (Spivak et al., 2019; Fu et al., 2021; Park et al., 2026). Mangrove systems receive substantial belowground carbon inputs through root production, rhizodeposition and root turnover, while waterlogged and reducing conditions can favor organic-matter preservation within deeper sediment horizons (Candry et al., 2023; Padmakumar et al., 2024; Queiroz et al., 2026). Saltmarshes, in contrast, can exhibit strong surface organic-matter inputs associated with vegetation and tidal deposition, with carbon distribution influenced by sedimentation, root systems and mineral interactions (Cahoon et al., 2021; Granse et al., 2024; Liu et al., 2026; Yu et al., 2026). Comparative studies have documented substantial carbon storage across 0-100 cm profiles in both mangrove and saltmarsh sediments, while also emphasizing the importance of sediment depth and geomorphological setting when comparing ecosystem carbon stocks (Brown et al., 2016; Yan et al., 2024; Hossain et al., 2026). The depth-resolved assessment of SOC therefore provides a stronger representation of sediment carbon reservoirs than surface measurements alone.

Carbon storage also interacts with greenhouse-gas production through complex biogeochemical processes (Nayak et al., 2025). The CO₂ flux represents active carbon mineralization and respiration, whereas SOC represents an accumulated carbon reservoir (Ren et al., 2025). Consequently, ecosystems with higher SOC storage can exhibit lower instantaneous CO₂ flux when a greater proportion of stored

carbon remains protected within deeper sediments (Ke et al., 2025; Stolpmann et al., 2025; Schile et al., 2017; Queirós et al., 2019; Cavan et al., 2024). Coastal methane dynamics are influenced by substrate availability together with salinity, redox conditions, sulfate reduction and methane oxidation (Wallenius et al., 2021; Wang et al., 2024; Lee et al., 2025; Kumar et al., 2026). Previous work in Sundarban mangrove sediments has emphasized the importance of fluctuating redox conditions, sulfate-reducing processes and methanotrophic pathways in regulating CH₄ emissions (Padhy et al., 2021). However, N₂O represents an additional dimension of coastal greenhouse-gas regulation, with production influenced by inorganic nitrogen availability and coupled nitrification-denitrification under spatially variable oxic and anoxic conditions (Nayak et al., 2025).

The Sundarban provides an important natural setting for examining these ecosystem contrasts because its intertidal landscapes contain degraded mangrove habitats alongside saltmarsh environments exposed to contrasting tidal and anthropogenic conditions (Mondal et al., 2026). Previous Sundarban research has established the importance of site-specific carbon assessment for conservation and restoration planning, particularly across gradients of human pressure and estuarine influence (Nayak et al., 2025). Comparative assessments integrating depth-resolved sediment carbon storage with ecosystem-level CH₄, N₂O, and CO₂ fluxes remain valuable for understanding the role of alternative coastal vegetation systems in regulating carbon retention and greenhouse-gas exchange.

The present investigation was undertaken to address the knowledge gap in comparative carbon storage and greenhouse-gas dynamics among the degraded mangrove and saltmarsh ecosystems of the Sundarban, India. The study aimed to quantify sediment organic carbon storage across the 0-100 cm sediment profile and assess ecosystem-level CH₄, N₂O, and CO₂ fluxes together with inorganic nitrogen pools across three sites on Sagar Island, with the objective of generating site-specific information to support blue-carbon conservation and integrated greenhouse-gas management in coastal ecosystems. The findings provide a scientifically robust basis for strengthening ecosystem-specific blue-carbon conservation, greenhouse-gas mitigation and restoration planning in degraded tropical coastal landscapes, with direct relevance to sustainable environmental management of the Sundarban.

2. Materials and methods

2.1 Study area and site characterization

The study was conducted in the Sundarban, a tidally influenced deltaic system located on the eastern coast of India within the Ganga-Brahmaputra-Meghna delta. The region is characterized by extensive mangrove vegetation, intertidal wetlands, tidal creeks and estuarine environments. The Sundarban experiences a tropical monsoonal climate, with annual precipitation ranging from approximately 150 to 200 cm. Seasonal maximum and minimum temperatures range from 25–35°C and 12–24°C, respectively (Samanta et al., 2021), while tidal amplitude across the Sundarban estuarine system generally ranges from approximately 3.5 to 4 m (Ghosh et al., 2015).

Three representative locations on Sagar Island were selected for comparative assessment of degraded mangrove and saltmarsh ecosystems and were designated as Site I, Site II and Site III (Fig. 1). The three sites represented contrasting anthropogenic and environmental conditions. Site I was located relatively far from human settlements (> 1.5 km), experienced low population pressure (< 200 persons km^{-2}), and was characterized by comparatively low anthropogenic pressure and mangrove-resource dependence. Site II was located close to human settlements (500 m–1.5 km), experienced high population pressure (> 500 persons km^{-2}), and was subjected to high anthropogenic interaction associated with agriculture, aquaculture, settlements and jetties. Site III was situated very close to human settlements (< 500 m), experienced high population pressure (945 persons km^{-2}), and represented a highly anthropogenically influenced coastal setting (Mondal et al., 2013).

The dominant mangrove communities varied among the study sites. Site I was characterized by *Avicennia alba*, *A. officinalis*, *Bruguiera gymnorhiza*, *A. marina* and *Sonneratia apetala*, whereas Site II was dominated by *A. alba*, *A. officinalis* and *B. gymnorhiza*. Site III primarily comprised *A. alba* and *A. officinalis*. Plant density was 561 ± 14.1 , 344 ± 7.8 and 361 ± 15.7 trees ha^{-1} at Sites I, II and III, respectively. Based on the integrated site characteristics, Site I represented a comparatively low-degradation condition, whereas Sites II and III represented highly degraded mangrove conditions.

The three locations occurred within a semidiurnal tidal regime and were influenced by tidal creeks and fluvio-tidal sediment deposition. Site I experienced comparatively lower flood and cyclone vulnerability, whereas Sites II and III were characterized by greater hazard exposure. Reported crop-land damage during hazards reached 57.35% at Site II and 76.05% at Site III, while 54.02% of the population at Site III was reported to have been affected by flood/cyclone events (Mondal et al., 2013). Soil erosion was estimated at $3\text{--}6$ t $\text{ha}^{-1} \text{yr}^{-1}$ at Site I and > 9 t $\text{ha}^{-1} \text{yr}^{-1}$ at Site II, whereas a site-specific erosion value was unavailable for Site III. The integrated environmental, anthropogenic, vegetation and hydrological characteristics of the three sites are presented in Table 1.

Table 1

Site-specific environmental, anthropogenic, vegetation and hydrological characteristics of the mangrove and saltmarsh ecology in Sagar Island, Sundarban, India.

Parameter	Site I	Site II	Site III
Distance from human settlement	Far (> 1.5 km)	Close (500 m-1.5 km)	Very close (< 500 m)
Population pressure (persons km ⁻²)	Low (< 200)	High (> 500)	High (945)
Human-mangrove interaction	Agriculture, aquaculture, settlements, small industries, jetties	Agriculture, aquaculture, settlements, jetties	Limited agriculture and scattered human activities
Main livelihood/activities	Fishing 50%, eco-tourism 30%, agriculture 20%	Agriculture 50%, industry 30%, fishing 20%	Primary-sector population 69.86%
Mangrove-resource dependence	Low	Very high	Moderate
Degradation classification	Low	High	High
Dominant mangrove community	<i>Avicennia alba</i> <i>Avicennia officinalis</i> <i>Bruguiera gymnorhiza</i> <i>Avicennia marina</i> <i>Sonneratia apetala</i>	<i>Avicennia alba</i> <i>Avicennia officinalis</i> <i>Bruguiera gymnorhiza</i>	<i>Avicennia alba</i> <i>Avicennia officinalis</i>
Plant density (trees ha ⁻¹)	561 ± 14.1	344 ± 7.8	361 ± 15.7
Soil erosion	3–6 t ha ⁻¹ yr ⁻¹	> 9 t ha ⁻¹ yr ⁻¹	Site-specific value not established
Tidal regime	Semidiurnal tidal system	Semidiurnal tidal system	Semidiurnal tidal system
Tidal-creek influence	Present	Present	Strongly relevant
Coastal setting	Fluvio-tidal deposition	Fluvio-tidal deposition	Tidal creek environment
Flood/cyclone exposure	Lower relative vulnerability	High vulnerability	High: 54.02% population affected by reported flood/cyclone events
[Note: Soil erosion, population pressure, canopy structural conditions, anthropogenic activities, and associated environmental descriptors were interpreted based on field observations and supporting regional studies (Nayak et al., 2025; Mondal, 2013)]			

Parameter	Site I	Site II	Site III
Crop-land damage during hazards	Not reported	57.35%	76.05%
Overall anthropogenic pressure	Low	Very high	Very high
[Note: Soil erosion, population pressure, canopy structural conditions, anthropogenic activities, and associated environmental descriptors were interpreted based on field observations and supporting regional studies (Nayak et al., 2025; Mondal, 2013)]			

2.2 Experimental design

A comparative field-sampling design was employed to evaluate differences between degraded mangrove and saltmarsh ecosystems across the three study sites. The experimental framework consisted of two ecosystem types (mangroves and saltmarsh) distributed across three locations (Site I, Site II and Site III), resulting in six site-vegetation combinations. At each site, three independent sampling replicates were maintained for each vegetation type. The sampling locations were spatially separated within the respective ecosystem to capture local spatial variability in sediment characteristics and greenhouse-gas exchange. The same site-vegetation framework was maintained for sediment collection and ecosystem-level GHGs measurements, allowing direct comparison between mangrove and saltmarsh environments across the three locations.

2.3 Soil sampling and sediment collection

Sediment samples were collected from five depth intervals: 0–15, 15–30, 30–45, 45–60 and 60–100 cm, representing the complete 0-100 cm sediment profile. Three replicate samples were collected from each depth interval at each site and vegetation type. A stainless-steel soil auger was used for sediment collection. The collected sediments were carefully transferred into clean sampling containers, labelled according to site, vegetation type and depth, and transported to the laboratory for further analysis. Samples intended for physicochemical and SOC analyses were processed following standard laboratory procedures. The depth-resolved sampling design enabled characterization of vertical changes in bulk density and SOC concentration and estimation of SOC storage within each sediment interval and cumulatively across the 0-100 cm sediment profile.

2.4 Measurement of soil pH, electrical conductivity and salinity

Soil pH was determined using a portable multi-parameter tester (PCSTEST35-01×441,506; Eutech Instruments, Singapore). Electrical conductivity (EC) and salinity were measured using a conductivity/salinity meter (CONWP 15003K; Eutech Instruments, Singapore). The instruments were calibrated before measurement according to the manufacturer's recommended procedures. Soil pH, EC and salinity were determined for the collected sediment samples to characterize the physicochemical environment of the mangrove and saltmarsh ecosystems.

2.5 Determination of soil bulk density

Bulk density was determined for each sediment depth interval and expressed as g cm^{-3} . The oven-dried mass of sediment was related to the known volume of the collected sample. Bulk-density values were subsequently used for calculating depth-specific SOC stocks together with sediment depth and SOC concentration.

2.6 Estimation of soil organic carbon

Soil organic carbon was estimated following the Walkley and Black (1934) method. Sediment samples from each depth interval were processed for SOC determination, and the results were expressed as percentage of dry soil mass. The depth-specific SOC values were used together with bulk density and sediment-layer thickness to estimate SOC stock for each depth interval following the approach described by Kauffman and Donato (2012). The SOC stock was calculated using:

$$SOC \left(\text{Mg C ha}^{-1} \right) = BD \left(\text{g cm}^{-3} \right) \times \text{depth interval (cm)} \times OC \left(\% \right)$$

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Where, BD represents bulk density (g cm^{-3}), D represents sediment depth (cm), and SOC represents organic carbon concentration (%). The resulting SOC stock was expressed as Mg C ha^{-1} .

SOC stocks were calculated independently for the 0–15, 15–30, 30–45, 45–60 and 60–100 cm intervals. The SOC stocks of the individual depth intervals were subsequently summed to obtain the cumulative SOC stock to 100 cm depth for each replicate.

2.7 Determination of soil inorganic nitrogen fractions

Soil inorganic nitrogen was assessed as ammonium-N ($\text{NH}_4^+\text{-N}$) and nitrate-N ($\text{NO}_3^-\text{-N}$). Ammonium-N was determined using the Nesslerization method, whereas nitrate-N was determined using the 2,4-phenol disulphonic acid method following Jackson (1973). The concentrations were expressed as $\mu\text{g N g}^{-1}$ soil. The $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ measurements were used to characterize inorganic nitrogen availability across mangrove and saltmarsh sediments and to evaluate their relationships with the observed N_2O fluxes.

2.8 Collection and measurement of greenhouse gases

Greenhouse-gas fluxes (CH_4 , N_2O , and CO_2) were measured using the closed-chamber technique, following the standardized procedures described by Bhattacharyya et al. (2013, 2019). A Perspex chamber measuring 53 cm in length $\times$ 37 cm in width $\times$ 71 cm in height was used for gas collection. The chamber was fitted onto an aluminium base plate inserted into the sediment to provide an airtight enclosure during gas sampling. Gas sampling was conducted during the morning period between 08:00

and 12:00 h using a 50-mL gas-tight tri-valve syringe. Gas samples were collected at 0 and 30 min following chamber closure. The collected samples were transferred appropriately and analyzed for CH₄, N₂O, and CO₂ concentrations using a TRACE 1110 gas chromatograph (Thermo Fisher Scientific, USA). GHGs fluxes were calculated from the change in gas concentration between the initial and final sampling periods, chamber volume, chamber footprint area and sampling duration. The calculations followed the standard equations described by Bhattacharyya et al. (2012, 2013, 2016, 2019).

The flux was calculated using:

$$CH_4 \text{ flux } \left(mg \, m^{-2} hr^{-1} \right) = \frac{\Delta X_{CH_4} \times EBV_{STP} \times 16 \times 60 \times 10^{-3}}{22.4 \times A \times T}$$

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$$N_2O \text{ flux } \left(\mu g \, m^{-2} hr^{-1} \right) = \frac{\Delta X_{N_2O} \times EBV_{STP} \times 44 \times 60 \times 10^{-3}}{22.4 \times A \times T}$$

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$$CO_2 \text{ flux } \left(mg \, m^{-2} hr^{-1} \right) = \frac{\Delta X_{CO_2} \times EBV_{STP} \times 44 \times 60 \times 10^{-3}}{22.4 \times A \times T}$$

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Where, ΔX represents the difference between gas concentrations at the initial and final sampling times (ppmV), EBV_{STP} represents the effective chamber volume at standard temperature and pressure (cm³), T represents the sampling interval (min), and A represents the chamber base area (m²). CH₄ and CO₂ fluxes were expressed as mg m⁻² h⁻¹, whereas N₂O flux was expressed as $\mu g \, m^{-2} \, h^{-1}$.

2.9 Statistical analysis

Statistical analyses were conducted using R software (version 2026.08.1 + 195; Released: 2026-08-18). A two-way analysis of variance (ANOVA) was conducted using the base aov function to evaluate the effects of location (L), ecosystem type (E; mangroves vs. saltmarsh), and their interaction (L × E) on soil physicochemical properties (pH, EC, and salinity), soil nitrogen fractions (NO₃⁻-N: nitrate nitrogen; NH₄⁺-N: ammoniacal nitrogen) and greenhouse gases (GHGs) fluxes (CH₄, N₂O and CO₂). Differences among treatments were considered statistically significant at $p \leq 0.05$. A three-way analysis of variance (ANOVA) was conducted to evaluate the effects of location (L), ecosystem type (E), depth (D), and their interactions (L × E, L × D, E × D and L × E × D) on bulk density, SOC concentration and SOC stock across the five sediment depth intervals (0–15, 15–30, 30–45, 45–60 and 60–100 cm). Statistical significance

was evaluated at $p \leq 0.05$. Post-hoc comparisons were performed using Duncan's Multiple Range Test (DMRT) to identify significant differences among treatment means across all $L \times E$ combinations. The DMRT analysis was implemented using the *duncan.test* function from the *agricolae* package in R. Pearson correlation analysis was performed to examine relationships among soil physicochemical properties, SOC stock, inorganic nitrogen concentrations and CH_4 , N_2O , and CO_2 fluxes. Correlation coefficients were used to identify the strength and direction of associations between sediment carbon storage, environmental conditions and GHGs exchange.

3. Results

3.1 Soil physicochemical properties

Soil physicochemical properties differed between mangrove and saltmarsh ecosystems across the three sites (Table 2). Mangrove and saltmarsh sediments exhibited significant differences in pH, electrical conductivity and salinity across the three study sites (Table 2). In mangroves, pH ranged from 7.84 ± 0.08 to 8.05 ± 0.08 , EC from 11.90 ± 0.68 to $17.80 \pm 0.65 \text{ mS cm}^{-1}$, and salinity from 1.72 ± 0.06 to 2.18 ± 0.05 ppt. Saltmarsh sediments exhibited higher pH values of 8.08 ± 0.06 to 8.24 ± 0.07 , EC values of 18.40 ± 0.74 to $24.60 \pm 0.82 \text{ mS cm}^{-1}$, and salinity values of 2.34 ± 0.07 to 3.02 ± 0.08 ppt. Among the mangrove sites, Site I exhibited the highest EC and salinity, followed by Site III and Site II. Saltmarsh sediments showed the same site-level pattern, with the highest EC and salinity at Site I and the lowest values at Site II. Overall, saltmarsh sediments consistently exhibited higher pH, EC and salinity than the corresponding mangrove sediments across all three sites, indicating a comparatively stronger saline influence within the low-lying intertidal saltmarsh environment.

Table 2
Soil physico-chemical properties and salinity of degraded mangroves and saltmarsh ecology in Sagar Island, Sundarban, India.

Location	Vegetation	pH	Electrical conductivity (mS cm ⁻¹)	Salinity (ppt)
Site I	Mangroves	8.05 ± 0.08	17.80 ± 0.65	2.18 ± 0.05
	Saltmarsh	8.24 ± 0.07	24.60 ± 0.82	3.02 ± 0.08
Site II	Mangroves	7.92 ± 0.07	11.90 ± 0.68	1.72 ± 0.06
	Saltmarsh	8.08 ± 0.06	18.40 ± 0.74	2.34 ± 0.07
Site III	Mangroves	7.84 ± 0.08	14.50 ± 0.57	1.96 ± 0.05
	Saltmarsh	8.17 ± 0.07	21.20 ± 0.79	2.72 ± 0.07
ANOVA Statistics ($p \leq 0.05$; LSD)				
Factors	L		E	L×E
pH	0.010		0.008	0.015
Electrical Conductance	0.122		0.099	NS
Salinity	NS		NS	0.530
[Note: L: locations; E: ecosystem (Mangroves/Rice); NS: non-significant; ± values indicate the standard deviations of the replicated data].				

3.2 Vertical variation in bulk density and SOC concentration

Bulk density exhibited a progressive increase with sediment depth across both ecosystems (Table 3). In mangrove sediments, bulk density increased from 0.94 g cm⁻³ at 0–15 cm to 1.47 g cm⁻³ at 60–100 cm at Site I, from 1.00 to 1.58 g cm⁻³ at Site II, and from 0.98 to 1.63 g cm⁻³ at Site III. Saltmarsh sediments showed a comparable depth-dependent increase, reaching 1.53, 1.49 and 1.67 g cm⁻³ at 60–100 cm at Sites I, II and III, respectively. SOC concentration exhibited contrasting vertical distributions between mangrove and saltmarsh sediments (Table 3). SOC concentration showed an opposite ecosystem-level pattern, with mangrove sediments generally exhibiting greater carbon accumulation with depth, while saltmarsh sediments contained greater SOC concentration in surface sediments. Mangroves SOC increased progressively with depth at all three sites. At Site I, SOC increased from 0.68% at 0–15 cm to 0.97% at 60–100 cm. A similar increase occurred at Site II, from 0.61% to 0.86%, and at Site III, from 0.65% to 0.91%. Saltmarsh sediments exhibited the opposite depth-wise pattern. SOC concentration declined progressively with depth from 0.82% to 0.54% at Site I, 0.75% to 0.51% at Site II, and 0.79% to 0.53% at Site III between the surface and deepest sediment horizons. The three-way ANOVA framework evaluated the effects of location, ecosystem type and depth, together with their interactions, on bulk

density, SOC concentration and SOC stock (Table 3). The observed depth-dependent patterns demonstrate a strong contrast in the vertical organization of sediment carbon between mangrove and saltmarsh ecosystems.

Table 3

Soil bulk density, soil organic carbon (SOC) concentration, and SOC stock across different soil depths in mangroves and saltmarsh ecology in Sagar Island, Sundarban, India.

Location	Soil depth	Mangroves			Saltmarsh		
		Bulk density (g cm ⁻³)	SOC (%)	SOC stock (Mg ha ⁻¹)	Bulk density (g cm ⁻³)	SOC (%)	SOC stock (Mg ha ⁻¹)
Site I	0–15 cm	0.94 ± 0.13	0.68 ± 0.034	9.59 ± 0.07	0.96 ± 0.11	0.96 ± 0.11	11.81 ± 0.04
	15–30 cm	1.01 ± 0.12	0.75 ± 0.030	11.36 ± 0.06	1.04 ± 0.13	1.04 ± 0.13	11.70 ± 0.07
	30–45 cm	1.09 ± 0.14	0.82 ± 0.042	13.41 ± 0.09	1.12 ± 0.16	1.12 ± 0.16	11.42 ± 0.06
	45–60 cm	1.18 ± 0.13	0.89 ± 0.036	15.75 ± 0.07	1.25 ± 0.09	1.25 ± 0.09	11.44 ± 0.04
	60–100 cm	1.47 ± 0.13	0.97 ± 0.047	57.04 ± 0.25	1.53 ± 0.10	1.53 ± 0.10	33.05 ± 0.09
Site II	0–15 cm	1.00 ± 0.16	0.61 ± 0.035	9.15 ± 0.08	0.93 ± 0.10	0.93 ± 0.10	10.46 ± 0.04
	15–30 cm	1.07 ± 0.10	0.67 ± 0.025	10.75 ± 0.04	1.02 ± 0.07	1.02 ± 0.07	10.56 ± 0.04
	30–45 cm	1.16 ± 0.10	0.73 ± 0.040	12.70 ± 0.06	1.11 ± 0.13	1.11 ± 0.13	10.49 ± 0.05
	45–60 cm	1.29 ± 0.14	0.79 ± 0.031	15.29 ± 0.06	1.22 ± 0.11	1.22 ± 0.11	10.43 ± 0.05
	60–100 cm	1.58 ± 0.14	0.86 ± 0.046	54.35 ± 0.26	1.49 ± 0.12	1.49 ± 0.12	30.40 ± 0.10
Site III	0–15 cm	0.98 ± 0.13	0.56 ± 0.038	8.28 ± 0.08	0.75 ± 0.10	0.95 ± 0.12	10.02 ± 0.05

[Note: SOC: soil organic carbon; L: locations; E: ecosystem (Mangroves/ Saltmarsh); NS: non-significant; ± values indicate the standard deviations of the replicated data].

Location	Soil depth	Mangroves			Saltmarsh		
		Bulk density (g cm ⁻³)	SOC (%)	SOC stock (Mg ha ⁻¹)	Bulk density (g cm ⁻³)	SOC (%)	SOC stock (Mg ha ⁻¹)
	15–30 cm	1.10 ± 0.09	0.63 ± 0.029	10.44 ± 0.04	0.81 ± 0.32	1.05 ± 0.05	10.13 ± 0.03
	30–45 cm	1.19 ± 0.08	0.69 ± 0.042	12.37 ± 0.05	0.87 ± 0.20	1.14 ± 0.10	9.97 ± 0.03
	45–60 cm	1.34 ± 0.08	0.75 ± 0.035	15.14 ± 0.04	0.93 ± 0.38	1.27 ± 0.10	9.77 ± 0.04
	60–100 cm	1.63 ± 0.12	0.82 ± 0.048	53.66 ± 0.24	1.67 ± 0.15	1.55 ± 0.09	27.47 ± 0.08
ANOVA Statistics ($p \leq 0.05$; LSD)							
Factors	L	E	L×E	D	L×D	E×D	L×E×D
Bulk density	NS	NS	NS	0.093	NS	NS	NS
SOC	0.006	0.005	0.009	NS	NS	0.011	0.019
SOC stock	0.822	0.671	NA	1.061	1.838	1.501	NS
[Note: SOC: soil organic carbon; L: locations; E: ecosystem (Mangroves/ Saltmarsh); NS: non-significant; ± values indicate the standard deviations of the replicated data].							

3.3 Depth-wise SOC stock and cumulative sediment carbon storage

Depth-specific SOC stocks reflected the combined effects of SOC concentration, bulk density and sediment thickness (Table 3 and Fig. 3). In mangrove sediments, SOC stock increased progressively through the profile. Site I increased from 9.59 Mg C ha⁻¹ at 0–15 cm to 57.04 Mg C ha⁻¹ at 60–100 cm, while Site II increased from 9.15 to 54.35 Mg C ha⁻¹ and Site III from 8.28 to 53.66 Mg C ha⁻¹. Saltmarsh sediments showed relatively stable or gradually declining SOC stocks across the 15-cm intervals, followed by a larger integrated contribution from the 60–100 cm layer because of its greater thickness. At Site I, SOC stock ranged from 11.81 Mg C ha⁻¹ in the 0–15 cm layer to 11.44 Mg C ha⁻¹ in the 45–60 cm layer, with 33.05 Mg C ha⁻¹ accumulated within the 60–100 cm interval. Corresponding values were 10.46–10.43 Mg C ha⁻¹ and 30.40 Mg C ha⁻¹ at Site II and 10.02–9.77 Mg C ha⁻¹ and 27.47 Mg C ha⁻¹ at Site III. The cumulative 0-100 cm SOC stock was consistently greater in mangroves than in

saltmarshes (Fig. 3). Mangrove SOC stocks were 107.15, 102.24 and 99.89 Mg C ha⁻¹ at Sites I, II and III, respectively, compared with 79.42, 72.34 and 67.35 Mg C ha⁻¹ in the corresponding saltmarsh ecosystems. Site I therefore represented the highest sediment carbon storage for both ecosystem types. The higher cumulative SOC stock of mangroves was associated particularly with the increasing contribution of deeper sediment horizons, whereas saltmarsh carbon storage was dominated by surface sediment SOC concentration.

3.4 Soil inorganic nitrogen fractions

Soil inorganic nitrogen exhibited distinct site-level variation across the mangrove and saltmarsh ecosystems (Table 4). In mangroves, NO₃⁻-N concentrations increased from 17.0 ± 1.1 µg N g⁻¹ soil at Site I to 19.0 ± 0.8 and 20.0 ± 1.0 µg N g⁻¹ soil at Sites II and III, respectively. NH₄⁺-N concentrations showed a stronger increase across the sites, from 32 ± 2.5 µg N g⁻¹ soil at Site I to 43 ± 2.5 and 46 ± 3.0 µg N g⁻¹ soil at Sites II and III, respectively. Saltmarsh sediments exhibited NO₃⁻-N concentrations of 18.0 ± 0.9, 18.0 ± 1.0 and 21.0 ± 1.1 µg N g⁻¹ soil at Sites I, II and III, respectively. Corresponding NH₄⁺-N concentrations were 38 ± 2.7, 40 ± 2.8 and 49 ± 3.2 µg N g⁻¹ soil, respectively. Thus, both NH₄⁺-N and NO₃⁻-N generally increased toward Site III, with NH₄⁺-N representing the larger inorganic nitrogen fraction in both ecosystems. The two-way ANOVA showed that the effects of location, ecosystem type and their interaction were statistically non-significant for both NO₃⁻-N (p = 0.152, 0.124 and 0.215, respectively) and NH₄⁺-N (p = 0.363, 0.296 and 0.513, respectively). These results indicate that the observed statistical differences in inorganic nitrogen pools among sites and ecosystems occurred within the measured variability of the replicated observations.

Table 4

Soil nitrogen fractions and GHGs fluxes in mangroves and saltmarsh ecology in Sagar Island, Sundarban, India.

Location	Ecology	Nitrogen fractions		CH ₄	N ₂ O	CO ₂
		(μg N g ⁻¹ soil)		(mg m ⁻² h ⁻¹)	(μg m ⁻² h ⁻¹)	(mg m ⁻² h ⁻¹)
		NO ₃ ⁻ -N	NH ₄ ⁺ -N			
Site I	Mangroves	17.0 ± 1.1	32 ± 2.5	0.422 ± 0.02	75.4 ± 2.7	104.0 ± 3.7
	Saltmarsh	18.0 ± 0.9	38 ± 2.7	0.317 ± 0.01	89.8 ± 2.9	156.7 ± 2.1
Site II	Mangroves	19.0 ± 0.8	43 ± 2.5	0.348 ± 0.01	82.3 ± 5.4	134.3 ± 7.2
	Saltmarsh	18.0 ± 1.0	40 ± 2.8	0.284 ± 0.04	94.7 ± 2.6	194.4 ± 6.1
Site III	Mangroves	20.0 ± 1.0	46 ± 3.0	0.371 ± 0.03	84.5 ± 4.5	123.8 ± 5.9
	Saltmarsh	21.0 ± 1.1	49 ± 3.2	0.311 ± 0.06	95.3 ± 3.8	178.2 ± 6.7
ANOVA Statistics (<i>p</i> ≤ 0.05; LSD)						
Factors	L		E		L×E	
NO ₃ ⁻ -N	0.152		0.124		0.215	
NH ₄ ⁺ -N	0.363		0.296		0.513	
CH ₄	0.003		0.003		0.005	
N ₂ O	1.442		1.177		NS	
CO ₂	2.565		2.095		3.628	
[Note: NO ₃ ⁻ -N: nitrate nitrogen; NH ₄ ⁺ -N: ammoniacal nitrogen; CH ₄ : methane; N ₂ O: nitrous oxide; CO ₂ : carbon dioxide; L: locations; E: ecosystem (Mangroves/ Saltmarsh); NS = non-significant; ± value indicates the standard deviations of the replicated data].						

3.5 Greenhouse-gas fluxes

Greenhouse-gas fluxes showed distinct patterns between mangrove and saltmarsh ecosystems (Table 4). CH₄ fluxes in mangroves were 0.422 ± 0.02, 0.348 ± 0.01 and 0.371 ± 0.03 mg m⁻² h⁻¹ at Sites I, II and III, respectively. Saltmarsh CH₄ fluxes were comparatively lower, with values of 0.317 ± 0.01, 0.284 ± 0.04 and 0.311 ± 0.06 mg m⁻² h⁻¹ at Sites I, II and III, respectively. The highest CH₄ flux was

recorded in Site I mangroves, whereas the lowest occurred in Site II saltmarshes. N_2O fluxes ranged from 75.4 ± 2.7 to $84.5 \pm 4.5 \mu\text{g m}^{-2} \text{h}^{-1}$ across mangrove sites and from 89.8 ± 2.9 to $95.3 \pm 3.8 \mu\text{g m}^{-2} \text{h}^{-1}$ across saltmarsh sites. Saltmarshes consistently exhibited higher N_2O fluxes than the corresponding mangrove ecosystems. Site III showed the highest N_2O flux in both ecosystems, reaching $84.5 \pm 4.5 \mu\text{g m}^{-2} \text{h}^{-1}$ in mangroves and $95.3 \pm 3.8 \mu\text{g m}^{-2} \text{h}^{-1}$ in saltmarshes. CO_2 fluxes exhibited the strongest ecosystem contrast among the three GHGs. Mangrove CO_2 fluxes were 104.0 ± 3.7 , 134.3 ± 7.2 and $123.8 \pm 5.9 \text{ mg m}^{-2} \text{h}^{-1}$ at Sites I, II and III, respectively, whereas saltmarshes recorded significantly higher values of 156.7 ± 2.1 , 194.4 ± 6.1 and $178.2 \pm 6.7 \text{ mg m}^{-2} \text{h}^{-1}$, respectively. Site II saltmarshes exhibited the highest CO_2 flux across all ecosystem-site combinations. The ANOVA results revealed a significant effect of location, ecosystem type and their interaction on CH_4 fluxes ($p = 0.003$, 0.003 and 0.005 , respectively). CO_2 fluxes showed numerical variation among locations, ecosystems and their interaction, with the reported ANOVA statistics of 2.565, 2.095 and 3.628, respectively. N_2O showed the reported ANOVA statistics of 1.442 for location and 1.177 for ecosystem, while the location $\times$ ecosystem interaction was reported as non-significant (NS). Overall, the GHG results demonstrated a clear ecosystem contrast: mangroves exhibited higher CH_4 fluxes, whereas saltmarshes exhibited higher CO_2 and N_2O fluxes across all three sites. This pattern occurred alongside the contrasting SOC-storage profiles observed between the two ecosystems.

3.6 Correlation study

Pearson correlation analysis revealed strong positive associations among pH, EC and salinity, whereas SOC stock showed strong positive correlation with CH_4 and strong negative correlations with N_2O and CO_2 fluxes. CH_4 was positively correlated with SOC stock, while N_2O and CO_2 exhibited strong positive intercorrelation. Inorganic N fractions showed a strong positive relationship with each other, with comparatively weaker associations with the GHGs fluxes (Fig. 4).

4. Discussion

4.1. Contrasting vertical SOC distribution and carbon storage

The most prominent finding of the present study was the contrasting vertical organization of SOC between mangrove and saltmarsh sediments (Gao et al., 2019; Sun et al., 2019; Yan et al., 2024). Mangrove sediments exhibited a progressive increase in SOC concentration from the surface toward 100 cm, whereas saltmarsh sediments showed a consistent decline with depth (Gong et al., 2025; Singh et al., 2026). This resulted in substantially higher cumulative 0-100 cm SOC stocks in mangroves (99.89 – $107.15 \text{ Mg C ha}^{-1}$) than in saltmarshes (67.35 – $79.42 \text{ Mg C ha}^{-1}$). Such habitat-level differences are consistent with the broader recognition that mangroves generally retain higher sediment carbon stocks

than saltmarshes, although carbon storage varies considerably with geomorphic position, vegetation structure, sediment characteristics and hydrological setting (Hossain et al., 2026).

The progressive increase in mangrove SOC with depth indicates substantial carbon accumulation within deeper sediment horizons, highlighting the importance of subsurface processes in maintaining the sediment carbon reservoir (Huang et al., 2025). Whereas, substantial belowground carbon inputs associated with root production, rhizodeposition and root turnover may progressively transfer organic carbon into deeper sediment horizons, where burial under waterlogged and reducing conditions can favor its preservation (Bolan et al., 2026). The increasing bulk density with depth further indicates progressive sediment compaction and burial, providing a physical framework for incorporation of carbon into deeper horizons (Luk et al., 2023).

The saltmarsh profile exhibited a fundamentally different pattern. Surface SOC concentrations were comparatively high but declined progressively toward 100 cm, indicating a predominantly surface-oriented carbon distribution (Assavapanuvat et al., 2025). This pattern may reflect higher dependence on recent surface litter deposition, shallow-root inputs and tidal organic-matter delivery, followed by progressive transformation of organic substrates during burial (Zheng et al., 2026). The observed pattern reflects a significant difference in the vertical allocation of stored carbon between the two ecosystems, with mangroves retaining a higher proportion of SOC in deeper sediment horizons, whereas saltmarshes showed greater carbon concentration in surface sediments.

The present mangroves contained a larger accumulated carbon reservoir but showed lower CO₂ fluxes, whereas saltmarshes contained a smaller 0-100 cm SOC pool but exhibited significantly higher CO₂ fluxes (Kaviarasan et al., 2025). This distinction is particularly important for blue-carbon assessment because a large sediment carbon pool reflects historical accumulation and preservation, whereas CO₂ flux represents the rate of contemporary carbon turnover (Reithmaier et al., 2023).

4.2. Higher saltmarsh CO₂ flux and lower SOC storage

Saltmarshes exhibited consistently higher CO₂ fluxes (156.7-194.4 mg m⁻² h⁻¹) than mangroves (104.0-134.3 mg m⁻² h⁻¹). The highest value occurred at Site II saltmarsh, which also represented a highly anthropogenically influenced location. This pattern is particularly informative because saltmarshes simultaneously possessed lower cumulative SOC stocks. Carbon concentrated near the sediment surface remains more directly exposed to fluctuating oxygen availability, tidal wetting and drying, and microbial respiratory processes (Spivak et al., 2019; Wang et al., 2026). Such conditions can promote more active decomposition of relatively accessible organic substrates and enhance CO₂ production (Gulley et al., 2020; Bai et al., 2026). In contrast, the increasing SOC concentration with depth in mangroves indicates greater allocation of carbon into deeper horizons, where restricted oxygen availability and physical burial can reduce the fraction of stored carbon undergoing rapid mineralization (Zheng et al., 2025). The earlier Sundarban study similarly identified strong site-to-site differences in soil CO₂ flux and reported higher CO₂ fluxes at sites closer to human habitation, highlighting the sensitivity of

carbon turnover to local environmental conditions (Nayak et al., 2025). Recent comparative work across tropical mangrove and saltmarsh environments also demonstrates strong habitat differences in sediment CO₂ efflux and emphasizes the roles of organic-matter inputs, sediment moisture and tidal connectivity in controlling GHG exchange. Thus, the present results highlight the importance of integrating sediment SOC storage, carbon turnover and associated GHGs exchange when evaluating the climate-regulation function of coastal ecosystems.

4.3. Mangrove CH₄ flux and saline carbon dynamics

Mangrove sediments exhibited higher CH₄ fluxes (0.348–0.422 mg m⁻² h⁻¹) than saltmarshes (0.284–0.317 mg m⁻² h⁻¹). The highest CH₄ flux occurred at Site I mangroves, which also possessed the greatest mangrove SOC stock (104.04 Mg C ha⁻¹). This spatial correspondence suggests that higher sediment carbon availability can provide a larger substrate reservoir for anaerobic carbon transformation (Gebert et al., 2024). Methane production and oxidation in coastal sediments are strongly regulated by salinity, sulfate availability, redox conditions and microbial competition (Nayak et al., 2025). Methanogens compete with sulfate-reducing microorganisms for common carbon substrates, while methanotrophic communities can oxidize CH₄ before it reaches the atmosphere (Padhy et al., 2021). The present results therefore indicate a balance between two opposing processes: higher carbon availability in mangrove sediments may support CH₄ production, while saline and periodically reducing conditions simultaneously impose strong controls on methane production, oxidation and transport (Wang et al., 2023; Qin et al., 2025). This explains that the ecosystem with the larger SOC reservoir also exhibited higher CH₄ flux without implying a simple positive relationship between total SOC and methane emission (Hu et al., 2024).

4.4. Salinity-driven carbon and GHGs dynamics in saltmarshes

Saltmarsh sediments in the present study consistently exhibited higher EC and salinity than the corresponding mangrove sediments at all three sites. This environmental contrast is important when interpreting the GHGs results because salinity modifies microbial carbon metabolism and the balance among competing anaerobic pathways (Yin et al., 2022).

The higher salinity of saltmarshes coincided with their lower CH₄ fluxes, consistent with the established influence of saline conditions on methanogenesis and sulfate reduction (Padhy et al., 2021). Saltmarshes exhibited significantly higher CO₂ fluxes than mangroves, indicating greater carbon mineralization under their saline sediment conditions (Sasmito et al., 2025). The contrasting CH₄ and CO₂ responses suggest that salinity may shift carbon processing toward CO₂ production while constraining methane formation (Capooci et al., 2024).

4.5. N₂O dynamics and nitrogen cycling

N₂O exhibited a pattern distinct from both SOC and CH₄. Saltmarshes showed consistently higher N₂O fluxes (89.8–95.3 µg m⁻² h⁻¹) than mangroves (75.4–84.5 µg m⁻² h⁻¹). The highest N₂O flux occurred at Site III saltmarsh, where NH₄⁺-N and NO₃⁻-N also reached their highest measured values (49 ± 3.2 and 21.0 ± 1.1 µg N g⁻¹ soil, respectively). This correspondence indicates that nitrogen availability provides a more direct framework for interpreting the N₂O response than total SOC storage (Neal et al., 2023).

Across both ecosystems, NH₄⁺-N was the dominant inorganic nitrogen fraction. The higher N₂O fluxes in saltmarshes therefore occurred alongside generally greater inorganic-N availability (Bartolucci et al., 2026). Tidal inundation and drainage can repeatedly generate microsites with contrasting oxygen availability, creating conditions for coupled nitrification and denitrification (Kaushal et al., 2025). Under such conditions, NH₄⁺ can be oxidized to nitrate under relatively oxic microsites, while nitrate can subsequently undergo denitrification in adjacent oxygen-limited microsites, with N₂O released as an intermediate or terminal product depending on environmental conditions (Gillini et al., 2026). The present results therefore support an important conceptual separation: SOC storage, CH₄ production and N₂O production are interconnected through the sediment environment but are controlled by different proximate processes (Maqbool et al., 2025).

4.6. Implications for blue-carbon conservation and environmental management

The principal management implication of this study is that blue-carbon value and GHG regulation should be evaluated together rather than independently. Mangroves at the study sites retained more carbon within the 0-100 cm sediment profile, particularly through higher deep-sediment carbon storage, demonstrating their importance as subsurface carbon reservoirs. Saltmarshes, despite their smaller cumulative SOC stocks, exhibited higher CO₂ and N₂O fluxes and therefore contributed disproportionately to contemporary carbon and nitrogen turnover.

At the same time, mangroves exhibited higher CH₄ fluxes, indicating that higher sediment carbon storage can coexist with enhanced methane emission under specific coastal sediment conditions (Jiang et al., 2025). Coastal wetland climate benefits therefore depend on the balance between carbon accumulation, carbon preservation, CO₂ mineralization, CH₄ production/oxidation and N₂O production (Gubamwoyo et al., 2026). This integrated perspective is increasingly recognized as necessary for credible blue-carbon accounting and restoration assessment. Recent research specifically emphasizes that GHGs emissions can offset part of the climate benefits attributed to coastal-wetland carbon storage and that both sediment and aquatic GHG pathways require consideration in blue-carbon assessments (Kristensen et al., 2025).

The present study consequently advances the conventional blue-carbon assessment by connecting depth-resolved sediment carbon storage with ecosystem-level multi-GHG exchange across contrasting mangrove and saltmarsh habitats. Rather than treating SOC as a single carbon-storage metric, the

results demonstrate that the vertical location of carbon within the sediment profile provides additional information about its likely turnover environment. The combination of deep SOC enrichment in mangroves, surface SOC dominance in saltmarshes, higher saltmarsh CO₂ and N₂O fluxes, and higher mangrove CH₄ fluxes reveals two contrasting biogeochemical configurations within the same tropical coastal landscape.

This distinction has direct relevance for the environmental management of the Sundarban. Conservation of degraded mangroves can protect a substantial subsurface carbon reservoir, while saltmarsh management requires attention to both surface carbon turnover and nitrogen-mediated N₂O emissions (Mason et al., 2023). Site-specific restoration planning should therefore integrate sediment depth, carbon storage, salinity, hydrological connectivity and GHGs fluxes, rather than relying on carbon stock alone. The findings provide a quantitative basis for linking blue-carbon conservation with broader greenhouse-gas management in tropical coastal ecosystems.

Conclusion

This study demonstrated that degraded mangrove and saltmarsh ecosystems of the Sundarban possess distinct carbon-storage and greenhouse-gas regulation characteristics. The contrasting vertical distribution of SOC indicates that mangroves retain a higher proportion of carbon within deeper sediment horizons, whereas saltmarshes maintain comparatively greater carbon concentration near the sediment surface. The stronger subsurface carbon retention in mangroves highlights their importance as long-term sediment carbon reservoirs, while the surface-oriented carbon distribution of saltmarshes reflects a different carbon-storage configuration. The contrasting GHG responses further highlight the importance of ecosystem-specific carbon dynamics. Mangroves showed higher CH₄ exchange, whereas saltmarshes exhibited higher CO₂ and N₂O exchange, demonstrating that carbon storage and individual GHGs fluxes can respond differently to the environmental conditions of coastal wetlands. Differences in salinity, sediment characteristics, carbon distribution and inorganic nitrogen availability provide an integrated framework for understanding these ecosystem-level responses. Overall, the findings highlight the site-specific nature of carbon storage and GHGs regulation in degraded coastal wetlands of the Sundarban. Maintaining mangrove vegetation and protecting deeper sediment carbon reservoirs, together with appropriate management of saltmarsh environments and their active carbon and nitrogen cycling, can strengthen the climate-regulation function of these ecosystems. Integrating blue-carbon conservation with ecosystem-specific GHGs management and restoration planning can therefore support the long-term environmental management of tropical coastal landscapes.

Declarations

Author Contribution

S.K.N. conceived and designed the study, conducted the field and laboratory investigations, performed the data analysis and interpretation, and wrote the original manuscript. R.B. contributed to the study design, interpretation of results, and critical revision of the manuscript. S.R.P. contributed to field investigations, data collection, and critical review of the manuscript. S.K.N., R.B. and S.R.P. reviewed and approved the final manuscript.

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Figures

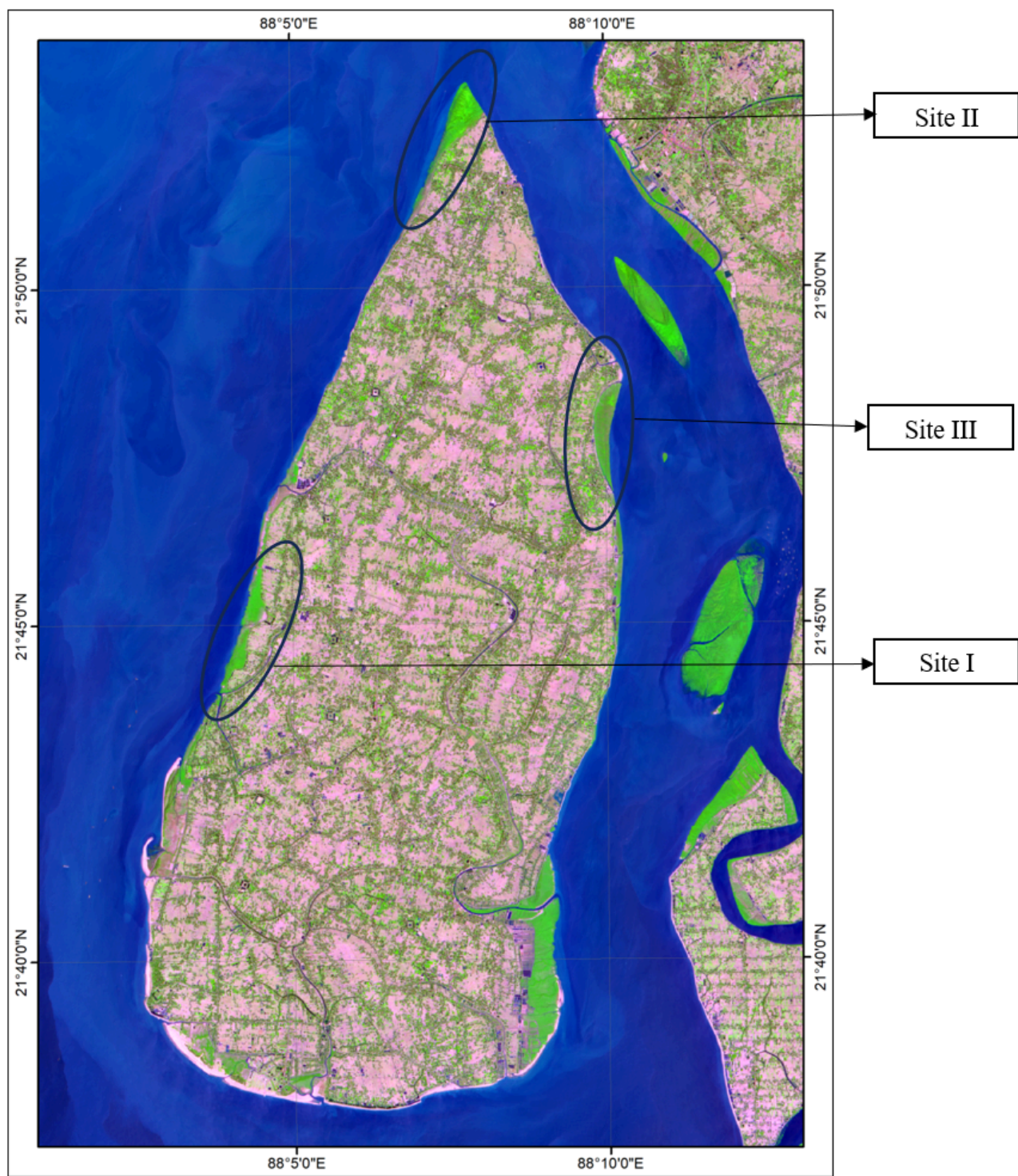


Figure 1

Study sites of the degraded mangroves and saltmarsh ecology in Sagar Island of Sundarban, India.



Figure 2

Field sampling activities and ecosystem characteristics in the study area: (a) GHGs sampling in the mangrove ecosystem, (b) salt-marsh vegetation, (c) soil sampling in the salt-marsh ecosystem, and (d) soil sampling in the degraded mangroves in Sagar Island of the Sundarban, India.

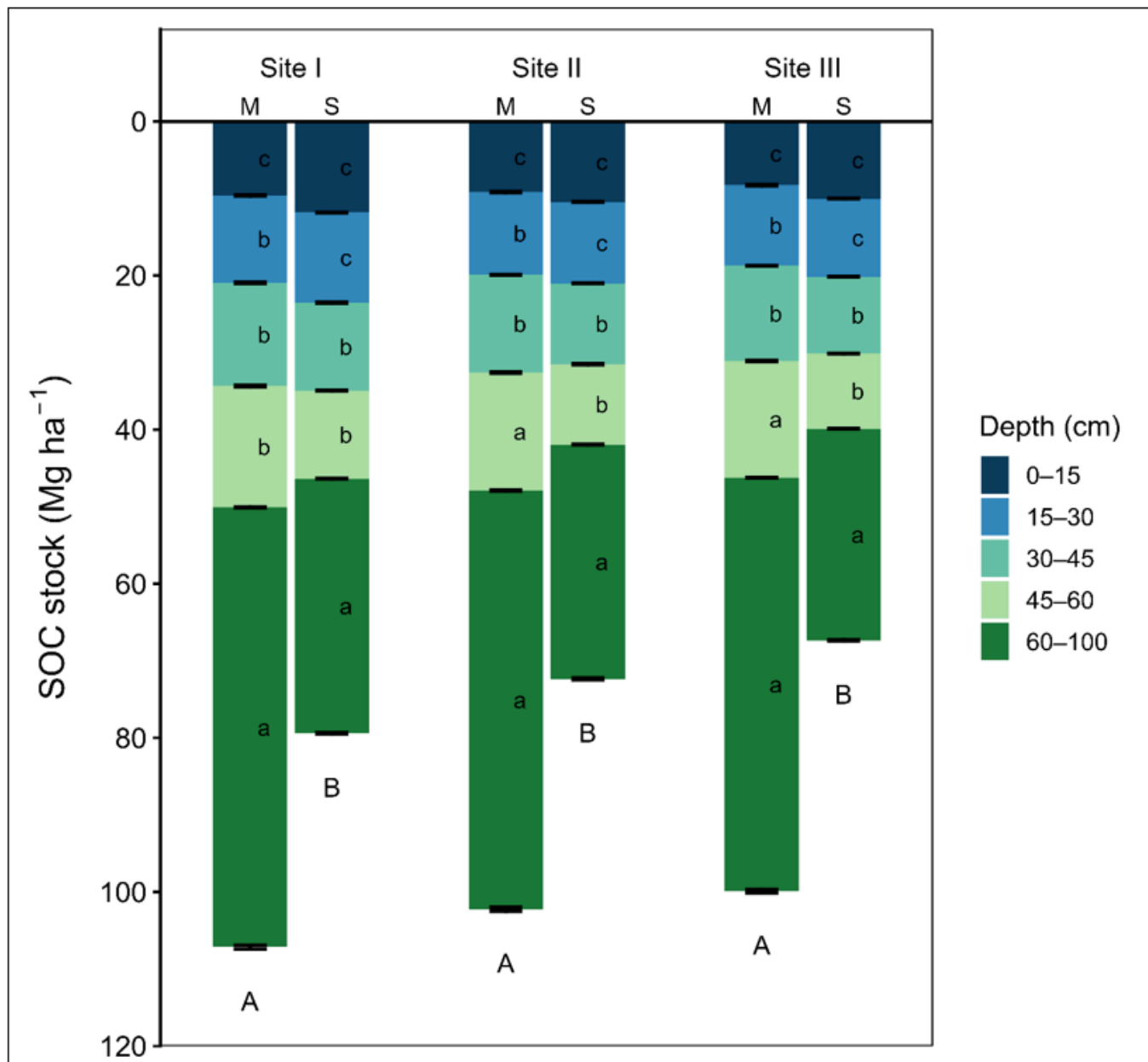


Figure 3

Soil organic carbon (SOC) stock across the 0-100 cm sediment profile at each sampling site and ecosystem type. Capital letters indicate significant differences among sites, while lowercase letters indicate significant differences among depth layers within the same site at $P \leq 0.05$. M denotes mangrove, and S denotes salt-marsh ecosystem. Error bars represent standard errors.

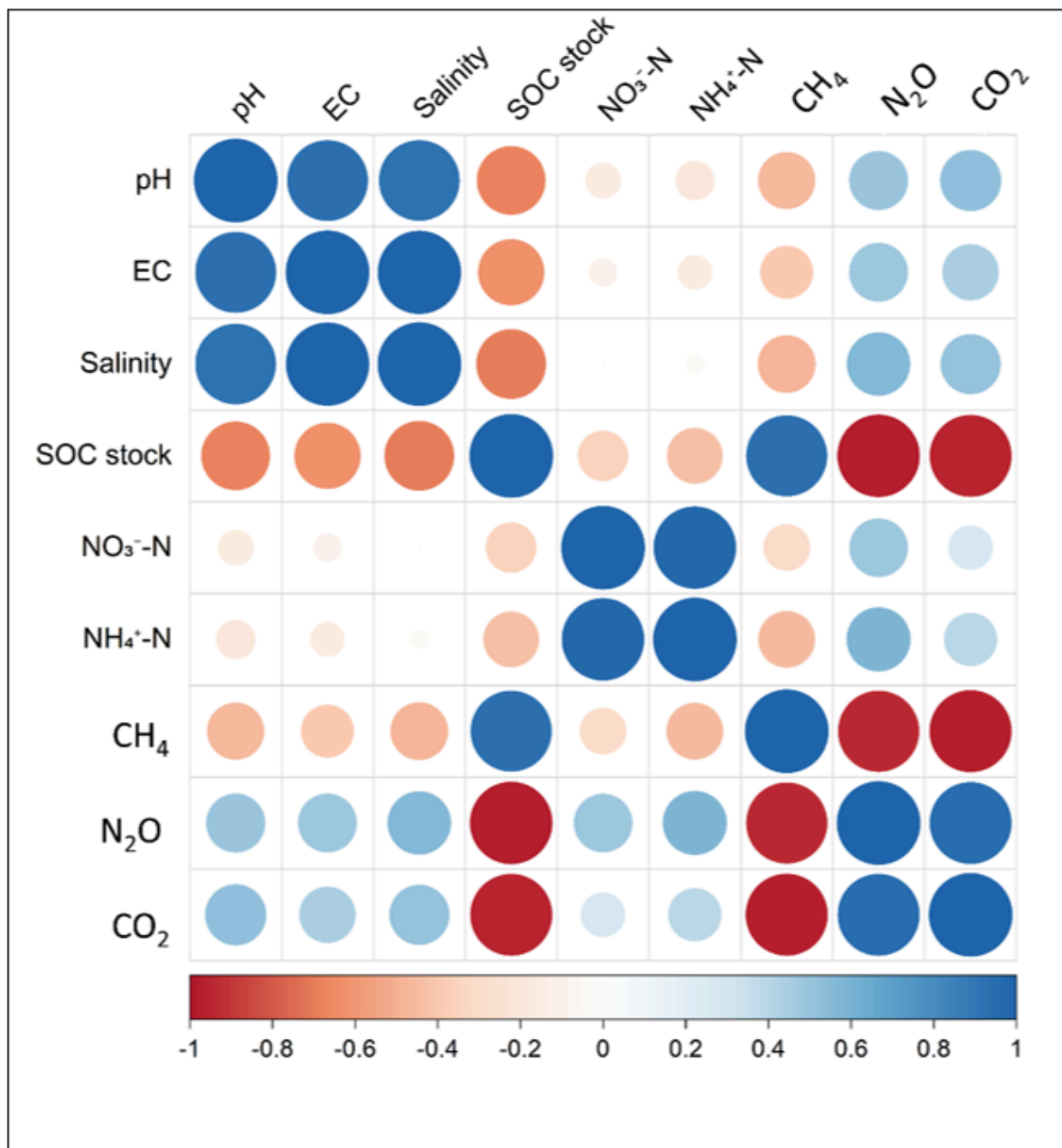


Figure 4

Correlation matrix showing Pearson correlations between CH₄ and N₂O fluxes and various soil parameters [EC: electrical conductance; SOC: soil organic carbon; NO₃⁻-N: nitrate nitrogen; NH₄⁺-N: ammoniacal nitrogen; CH₄: methane; N₂O: nitrous oxide].