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Assessing Estuarine pH Regulation by Saltmarsh Biomass Using Python-Based IDW Spatial Modelling in the Indian Sundarbans

Sulekha Kundu, Arpita Dutta, Jayanta Poray and Abhijit Mitra

Abstract

Saltmarsh habitats play an important yet unexplored role in regulating coastal water chemistry in tropical deltaic environments. Based on field observations from 24 sampling stations in the Indian Sundarbans, this study documents spatial variability in total biomass of the saltmarsh grass *Porteresia coarctata* and corresponding pH of the ambient aquatic phase during 2nd to 17th December 2024. Biomass values ranged from 213.44 to 401.67 g dry wt. m⁻², with the lowest biomass recorded at exposed estuarine stations such as Sagar Island and Jambu Island, and the highest biomass observed at eastern Indian Sundarbans like Arbesi, Herobhanga, Panchmukhani, and Mayadwip. Ambient water pH varied between 7.97 and 8.32, showing consistently higher values at stations supporting dense *P. coarctata* stands. The table-derived dataset reveals a clear positive correlation between saltmarsh biomass and pH, suggesting enhanced alkalinity buffering in high-biomass marshes. Spatial interpolation using a Python-based Inverse Distance Weighting (IDW) algorithm was applied to generate continuous biomass and pH surfaces, enabling visualization of buffering gradients across the deltaic landscape. The computational approach strengthens the spatial interpretation of marsh-driven carbonate regulation patterns. These results highlight the role of *P. coarctata* marshes as effective nature-based regulators of estuarine water chemistry, contributing to resilience under increasing climate variability and acidification stress.

Keywords: *Porteresia coarctata*; saltmarsh biomass; estuarine pH buffering; Indian Sundarban

Introduction

The mangrove dominated Indian Sundarbans supports wide spectrum of flora and fauna that plays a vital role in modulating biogeochemical processes at the land–sea interface (Agarwal et al. 2019; Roy et al. 2021, Saha et al. 2021; Ahmed et al. 2022, Ghosh et al. 2023). Among these, the salt-tolerant grass *Porteresia coarctata* forms extensive saltmarshes along tidal creeks, mudflats, and estuarine margins, particularly in zones exposed to fluctuating salinity and tidal energy. While mangroves have been widely recognised for their role in blue carbon storage and coastal buffering, comparatively very less attention has been given to the ecological functions of saltmarsh grasses in tropical deltaic environments. Thus, this component of blue carbon is practically unexplored till date in terms of their ecosystem services. Primary production by *P. coarctata* contributes substantial organic matter to estuarine sediments, influencing microbial respiration, nutrient cycling, and carbonate system dynamics. These processes trigger alteration of ambient water pH and alkalinity, thereby enhancing the buffering capacity of coastal waters against acidification (Ghosh et al. 2024).

In this study, we integrate ecological field observations with computational geospatial analysis to quantify and visualize these biogeochemical linkages. Specifically, we apply a Python-based Inverse Distance Weighting (IDW) interpolation framework to generate continuous spatial surfaces of saltmarsh biomass and ambient pH from discrete station data. We also compute correlation coefficient values to statistically evaluate the strength and direction of the biomass–pH relationship, thereby testing the hypothesis that increasing *P. coarctata* biomass enhances estuarine alkalinity buffering. By combining deterministic spatial modelling with quantitative correlation analysis, this approach aims to provide a

comprehensive scenario of saltmarsh-mediated carbonate regulation within the Indian Sundarban delta complex. Carbon dioxide removal has been identified as an essential complement to rapid emission reductions for meeting global climate targets, with major emphasis on governance gaps and long-term feasibility (Mace et al. 2021; Meadowcroft 2013). Nature-based climate solutions are increasingly favoured due to their capacity to restore ecosystems and support vulnerable communities, although uncertainties related to permanence, monitoring, and complex ecosystem dynamics remain significant challenges (Freeman and Zerriffi 2015; Griscom et al. 2017; Anderson et al. 2019). In contrast, engineering-based approaches such as direct air capture provide traceable removals but deliver limited ecological or social co-benefits (McQueen et al. 2021). Farming of coastal flora has recently emerged as a multifunctional nature-based solution, contributing to climate mitigation, nutrient removal, food security, and coastal livelihoods (Duarte et al. 2017; Gentry et al. 2017). Several researches demonstrate that underlying sediments of coastal and estuarine vegetation exhibit considerable carbon burial (Duarte et al. 2025), while enhanced alkalinity generation through carbonate dissolution and sulfate reduction supports long-term carbon sequestration

(Reithmaier et al. 2023; Saderne et al. 2021).

2. Methodology

Saltmarsh grass biomass was quantified using a quadrat-based harvesting approach. At each sampling station, *Porteresia coarctata* biomass was collected from a clearly demarcated area of 1 m² during the low-tide phase. Fresh plant material was transported to the laboratory, oven-dried to constant weight, and expressed as dry biomass (g dry wt m⁻²). To ensure representativeness and analytical robustness, ten replicate quadrats were sampled at each station, and the mean biomass value was used for subsequent analysis as part of quality assurance of the dataset. Field sampling was carried out at 24 stations across the Indian Sundarban during 2nd to 17th December 2024 (Fig. 1), coinciding with low tide conditions to minimize tidal dilution effects. The selected stations exhibit marked variations in salinity and density of mangrove vegetation. The pH of the ambient aquatic phase was measured in situ using a calibrated digital pH meter with an accuracy of ±0.02 pH units. All measurements were conducted following standard field protocols to maintain consistency and data reliability across stations.

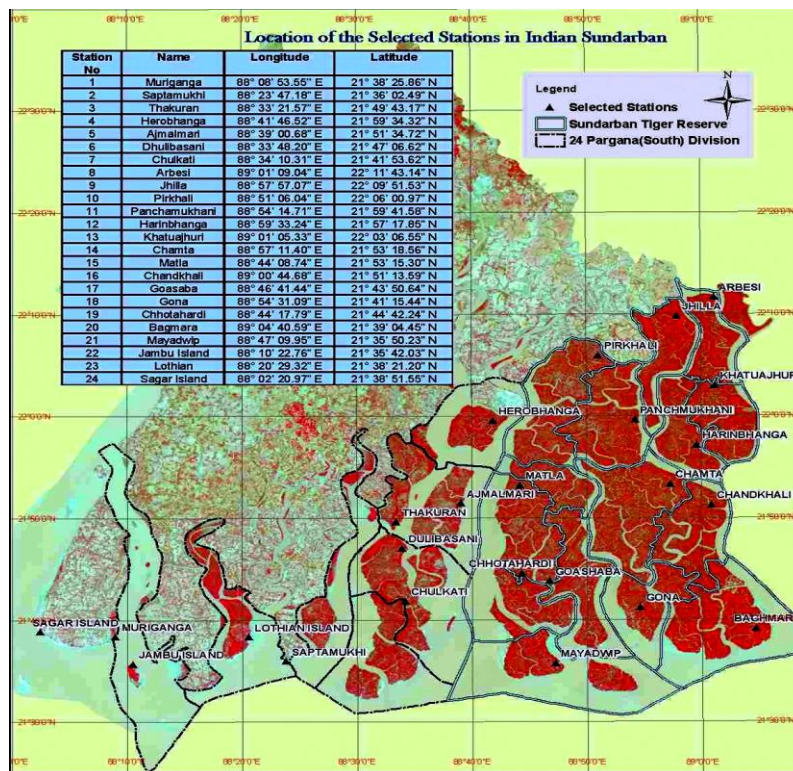


Fig. 1: 24 sampling stations across Indian Sundarbans.

Subsequent spatial analysis was performed using a Python-based Inverse Distance Weighting (IDW) interpolation algorithm to generate continuous spatial surfaces of biomass and pH from the discrete station measurements (Fig. 2). The

IDW implementation uses SciPy, specifically from `scipy.spatial import distance_matrix`. This means the interpolation relies on SciPy's spatial module to compute distances.

```

# Inverse Distance Weighting (IDW) Interpolation in Python

import numpy as np
import matplotlib.pyplot as plt
from scipy.spatial import distance_matrix

def idw_interpolation(x, y, z, xi, yi, power=2):
    dist = distance_matrix(np.column_stack([xi, yi]),
                           np.column_stack([x, y]))
    weights = 1 / (dist ** power + 1e-12)
    weights /= weights.sum(axis=1)[:, None]
    zi = np.dot(weights, z)
    return zi

# Example usage:
# x, y = known coordinates
# z = known values (e.g., biomass or pH)
# xi, yi = grid coordinates for prediction

```

Fig. 2: Python Implementation of the Inverse Distance Weighting (IDW) Algorithm for Spatial Interpolation.

The IDW method assigns weights inversely proportional to the distance between known sampling points and prediction locations, thereby emphasizing local influence while constructing interpolated surfaces across the study area. In addition, the strength of the relationship between saltmarsh biomass and ambient pH was

quantified using the Pearson correlation coefficient (r), computed through statistical analysis in Python (Fig. 3). This combined computational framework enabled both spatial visualization and quantitative assessment of the biomass–pH linkage across the Indian Sundarbans.

```

# Pearson Correlation Analysis in Python

import numpy as np
from scipy.stats import pearsonr

# Example data arrays
biomass = np.array([289.54, 301.48, 335.45, 393.44])
ph = np.array([8.04, 8.09, 8.21, 8.27])

# Compute Pearson correlation
r_value, p_value = pearsonr(biomass, ph)

print('Pearson r =', r_value)
print('p-value =', p_value)

```

Fig. 3: Python Script for Computing the Pearson Correlation Coefficient (r)

3. Results

Substantial spatial variability was observed in the biomass of *Porteresia coarctata* and the pH of the ambient aquatic phase across the 24 sampling stations in the Indian Sundarbans. Total biomass ranged from 213.44 g dry wt. m^{-2} at Sagar Island to 401.67 g dry wt. m^{-2} at Arbesi, indicating pronounced heterogeneity between exposed coastal sites and comparatively sheltered inner estuarine locations. Stations such as Arbesi, Herobhanga, Panchmukhani, Mayadwip, and Jhilla consistently exhibited higher biomass values (>380 g dry wt. m^{-2}), whereas lower biomass was recorded at Sagar Island, Jambu Island, Muriganga, and Matla. Ambient water pH varied from 7.97 to 8.32, with the lowest values associated with

low-biomass, high-energy coastal stations and higher pH recorded at biomass-rich marshes.

Python-based Inverse Distance Weighting (IDW) interpolation of both biomass (Fig. 4) and pH (Fig. 5) datasets generated continuous spatial surfaces that clearly depicted a west–east gradient across the delta. The biomass IDW surface highlighted high-productivity zones in sheltered eastern sectors, while the pH IDW surface correspondingly showed elevated alkalinity in these same regions, reinforcing the spatial coherence between vegetation density and carbonate regulation. Conversely, interpolated pH surfaces indicated relatively lower buffering capacity in exposed western estuarine areas.

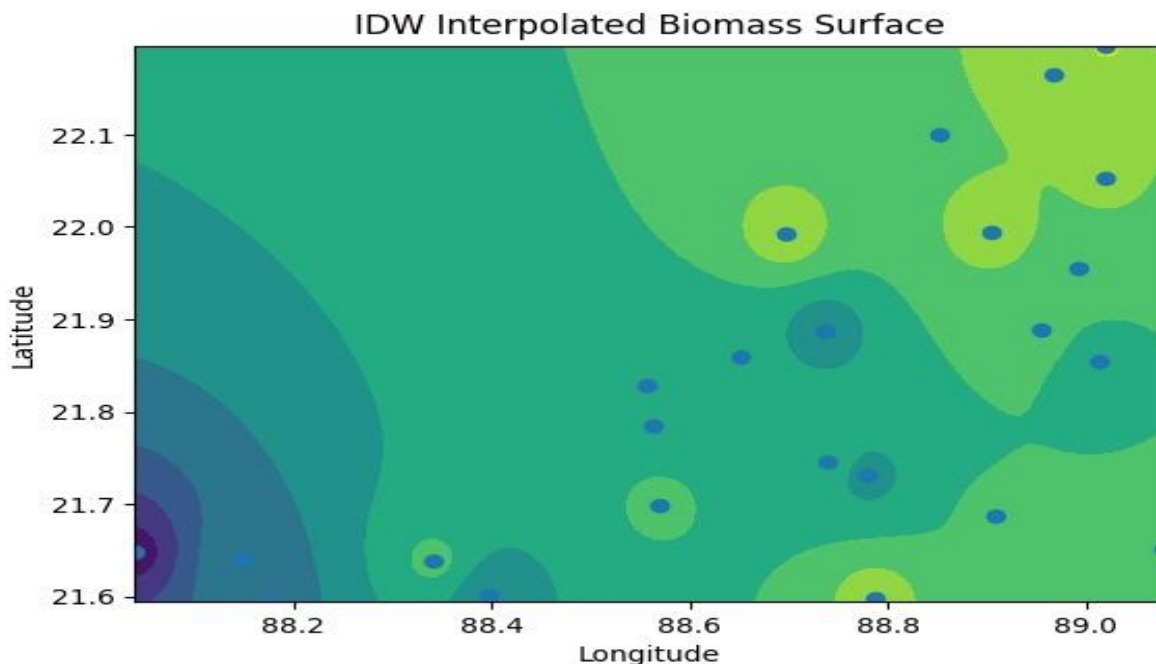


Fig. 4: IDW-Interpolated Spatial Surface of *Porteresia coarctata* Biomass (g dry wt. m⁻²) Across the Indian Sundarbans.

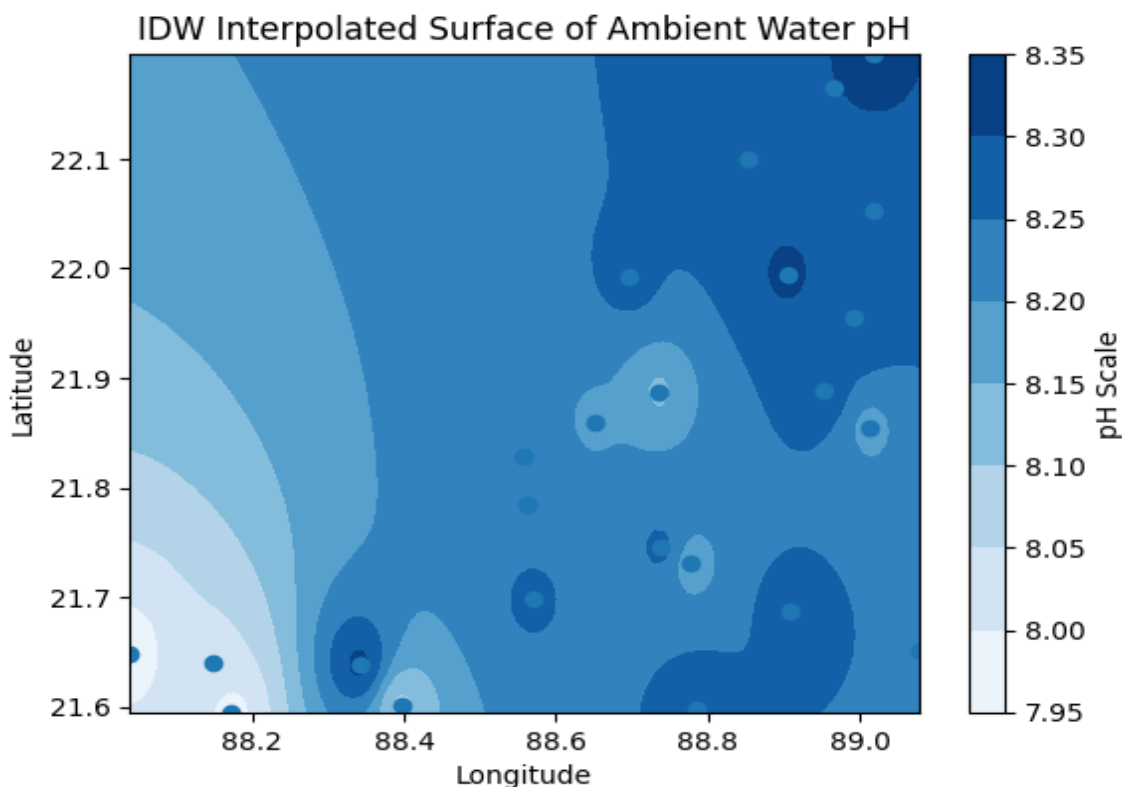


Fig. 5: IDW-Interpolated Spatial Surface of Ambient Water pH Across the Indian Sundarbans.

Statistical analysis further demonstrated a strong positive relationship between biomass and pH (Pearson $r = 0.925$), quantitatively confirming that dense *P. coarctata* stands are associated with enhanced estuarine alkalinity buffering in the Indian Sundarbans (Fig. 6).

4. Discussion

The present investigation demonstrates a pronounced spatial coupling between the biomass of *Porteresia coarctata* and ambient estuarine pH across the Indian Sundarbans, providing strong empirical evidence that tropical saltmarsh

systems function as biologically mediated regulators of coastal carbonate chemistry. The high Pearson correlation coefficient ($r = 0.925$) indicates a robust and statistically meaningful relationship, suggesting that variations in marsh productivity exert a measurable influence on local alkalinity dynamics. Such a strong correlation is notable within estuarine systems, where hydrodynamic mixing, tidal flushing, and freshwater inputs often obscure clear biogeochemical linkages.

The observed west–east gradient, characterised by lower biomass and reduced pH at exposed stations (e.g., Sagar

Island, Jambu Island) and elevated biomass and higher pH at sheltered inner estuarine locations (e.g., Arbesi, Panchmukhani, Mayadwip, Herobhanga), reflects the interaction between geomorphology, hydrodynamic energy, and vegetation structure. High-biomass marshes likely enhance carbonate buffering through multiple interconnected pathways. Increased primary production results in greater organic matter deposition within sediments, stimulating anaerobic microbial processes such as sulfate reduction. This process generates alkalinity in the form of bicarbonate ions, which may subsequently diffuse or advect into the overlying water column. In addition, organic matter mineralization can promote carbonate dissolution within sediment porewaters, further increasing total alkalinity. The export of alkalinity-enriched porewater (inorganic carbon outwelling) from vegetated sediments has been documented in other coastal blue carbon systems and may plausibly contribute to the elevated pH observed in biomass-rich sectors of the delta.

Such sediment-water interactions are widely recognised as key regulators of carbonate chemistry in estuarine ecosystems. Vegetated coastal sediments often export alkalinity and dissolved inorganic carbon to the overlying water column through porewater exchange processes, thereby enhancing buffering capacity against acidification. Similar mechanisms have been reported in several estuarine and coastal systems where benthic metabolism and sediment diagenesis regulate carbonate dynamics and pH variability (Cai et al., 2004).

The magnitude of the recorded pH variability (7.97–8.32; $\Delta\text{pH} \approx 0.35$ units) is ecologically significant in estuarine environments, where even small shifts in pH can alter carbonate saturation states and influence the physiology of calcifying and non-calcifying organisms. The spatial coherence between the IDW-interpolated biomass and pH surfaces reinforces the hypothesis that vegetation density modulates buffering gradients across the deltaic landscape. While mangroves have been widely recognised for their role in carbon sequestration and alkalinity generation, the present findings highlight that mangrove associate species can exert comparable localized influence on carbonate chemistry, thereby broadening the conceptual framework of tropical nature-based climate solutions.

Importantly, the buffering effect identified in this study appears to operate at a local to meso-scale within the estuarine matrix. Whether such regulation can offset projected long-term acidification under rising atmospheric CO_2 scenarios requires further investigation. Nonetheless, dense *P. coarctata* stands evidently enhance short-term resilience of estuarine waters by moderating pH variability and strengthening biogeochemical feedbacks. In this context, saltmarshes should be recognised not only as carbon-storing ecosystems but also as active regulators of inorganic carbon cycling as suggested by several researchers (Mitra, 2013; Mitra and Zaman, 2015; Mitra, 2020).

Overall, the findings advance the understanding of tropical saltmarsh ecosystems as multifunctional nature-based solutions that contribute to estuarine acidification mitigation. Protecting and restoring *P. coarctata* marshes may therefore enhance carbonate regulation, strengthen climate adaptation strategies, and support the long-term ecological stability of the Sundarban delta complex.

5. Conclusion

This study depicts a clear empirical evidence that the tropical saltmarsh grass *Porteresia coarctata* plays a measurable and ecologically significant role in regulating estuarine carbonate chemistry in the mangrove dominated Indian Sundarbans. The strong positive relationship between biomass and ambient pH ($r = 0.925$), together with spatial interpolation results, demonstrates that dense saltmarsh stands enhance alkalinity buffering across the deltaic landscape. Stations supporting higher biomass of the saltmarsh grass exhibited higher aquatic pH values.

The observed pH gradient ($\Delta\text{pH} \approx 0.35$ units) suggests that saltmarsh-mediated buffering can meaningfully influence estuarine water quality and potentially enhance resilience against acidification stress. These findings broaden the conceptual understanding of blue carbon ecosystems by highlighting that non-woody tropical saltmarshes, in addition to mangroves, function as active regulators of inorganic carbon cycling rather than merely passive carbon sinks.

From a climate adaptation and coastal management perspective, conservation and restoration of *P. coarctata* can be considered as a low-cost, nature-based strategy for strengthening estuarine buffering capacity and ecological stability. Future research integrating seasonal monitoring, direct alkalinity measurements, sediment flux quantification, and coupled hydrodynamic–biogeochemical modelling will be essential to quantify long-term mitigation potential and re-design policy integration within coastal planning frameworks.

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