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Jagadish Mandal
Department of Oceanography, Techno India University, West Bengal, EM4/1, Salt Lake Sector V, Kolkata, India.

Nagaraj Narayan Sannabhadti
Department of Oceanography, Techno India University, West Bengal, EM4/1, Salt Lake Sector V, Kolkata, India.

Prosenjit Pramanick
Department of Oceanography, Techno India University, West Bengal, EM4/1, Salt Lake Sector V, Kolkata, India.

Subhra Bikash Bhattacharyya
Department of Oceanography, Techno India University, West Bengal, EM4/1, Salt Lake Sector V, Kolkata, India.

Sufia Zaman
Department of Oceanography, Techno India University, West Bengal, EM4/1, Salt Lake Sector V, Kolkata, India.

Abhijit Mitra
Department of Oceanography, Techno India University, West Bengal, EM4/1, Salt Lake Sector V, Kolkata, India.

Correspondence:
Nagaraj Narayan Sannabhadti
Department of Oceanography, Techno India University, West Bengal, EM4/1, Salt Lake Sector V, Kolkata, India.

Spatio-temporal Variations of Carbon Stock in Peat Soil of Shrimp Ponds: A Case Study from Indian Sundarbans

Jagadish Mandal, Nagaraj Narayan Sannabhadti, Prosenjit Pramanick, Subhra Bikash Bhattacharyya, Sufia Zaman, Abhijit Mitra

Abstract
This study investigates Peat Soil Organic Carbon (PSOC) dynamics across ten stations in the Indian Sundarbans that experienced shrimp farming and subsequent mangrove restoration. Using the Walkley-Black method, we observed significant increases in PSOC levels from 1994 to 2024. The results exhibited significant spatio-temporal variations of PSOC between the stations and years, which may be attributed to magnitude/complete absence of shrimp farming in the region. The gradual hike in PSOC values underscores the importance of mangrove restoration programs in mitigating climate change and restoring degraded ecosystems.

Keywords: Indian Sundarbans, Peat Soil Organic Carbon (PSOC), shrimp farming, eco-restoration.

1. Introduction

Mangrove ecosystems are crucial for coastal resilience, acting as one of the most efficient carbon sinks due to their exceptional capacity for carbon sequestration, particularly through Soil Organic Carbon (SOC) storage [6-7, 13, 15-17, 19-20]. However, extensive aquaculture practices, preferably shrimp farming, have led to the widespread conversion of mangrove forests, resulting in notable environmental degradation and a significant loss of soil carbon [11, 14]. The global trend of mangrove deforestation for shrimp aquaculture has greatly diminished soil carbon storage, effectively reversing these ecosystems' function as carbon sinks [1, 4, 9, 10]. In the Indian Sundarbans, a designated UNESCO World Heritage site, the practice of shrimp farming expanded rapidly during the late 1980s and early 1990s, leading to substantial mangrove loss. By 1994, vast areas of mangroves were cleared to establish shrimp ponds, causing reduced SOC levels in these regions [18]. In response, an afforestation initiative was launched in 2000 to rehabilitate these abandoned shrimp ponds and restore the mangrove ecosystem. SOC levels in these areas have shown significant recovery since the afforestation program began, highlighting the restoration potential of such degraded ecosystems.

Peat soil in shrimp ponds experiences substantial changes in SOC due to inadequate management practices. SOC levels often decline over time as organic matter oxidizes under aerobic conditions during pond water aeration and pond drying phases. Peat soils within shrimp ponds undergo extensive SOC depletion due to inefficient pond management practices. As the ponds dry, aerobic conditions lead to oxidation of organic matter in the soil, further decreasing SOC levels over time. Moreover, intensive shrimp farming can exacerbate SOC depletion through increased microbial activity and nutrient leaching. The accumulation of shrimp feed and waste fosters heightened microbial activity, accelerating SOC losses within the soil. Since the implementation of this afforestation program, which we firmly believe as nature-based solution, SOC levels in the area have shown substantial recovery, highlighting the potential for ecosystem restoration in these degraded landscapes. This study expands on prior work by analysing SOC recovery across ten stations in the Indian Sundarbans, each with a history of shrimp farming followed by afforestation efforts initiated in 2000. Few islands within the jurisdiction of Reserve Forest area acted as '*exceptions to the rule*' as shrimp culture was never permitted in these areas by the West Bengal Forest Department. SOC levels were assessed at three key intervals, namely during November 1994, 2014, and 2024 with the aim to evaluate the restoration program's impact on peat soil carbon sequestration. This research aims to provide insights into the interplay between afforestation, mangrove regeneration, and SOC recovery over time, contributing to broader ecosystem restoration efforts and climate change mitigation strategies.

2. Materials and Methods

2.1 Study Area

The study was conducted at ten stations in the Indian Sundarbans namely Harinbari (Stn. 1), Chemaguri (Stn. 2), Sagar South (Stn. 3), Lothian Island (Stn. 4), Prentice Island (Stn. 5), Canning (Stn. 6), Sajnekhali (Stn. 7), Chotomollakhali (Stn. 8), Satjelia (Stn. 9), and Pakhiralaya (Stn. 10) as highlighted in Fig. 1. These areas were initially used for shrimp farming in the 1990s, except Lothian Island (Stn. 4), Prentice Island (Stn. 5), and Sajnekhali (Stn. 7) leading to a loss of mangroves and degradation of soil carbon. In 2000, afforestation programs were introduced to restore these ecosystems.

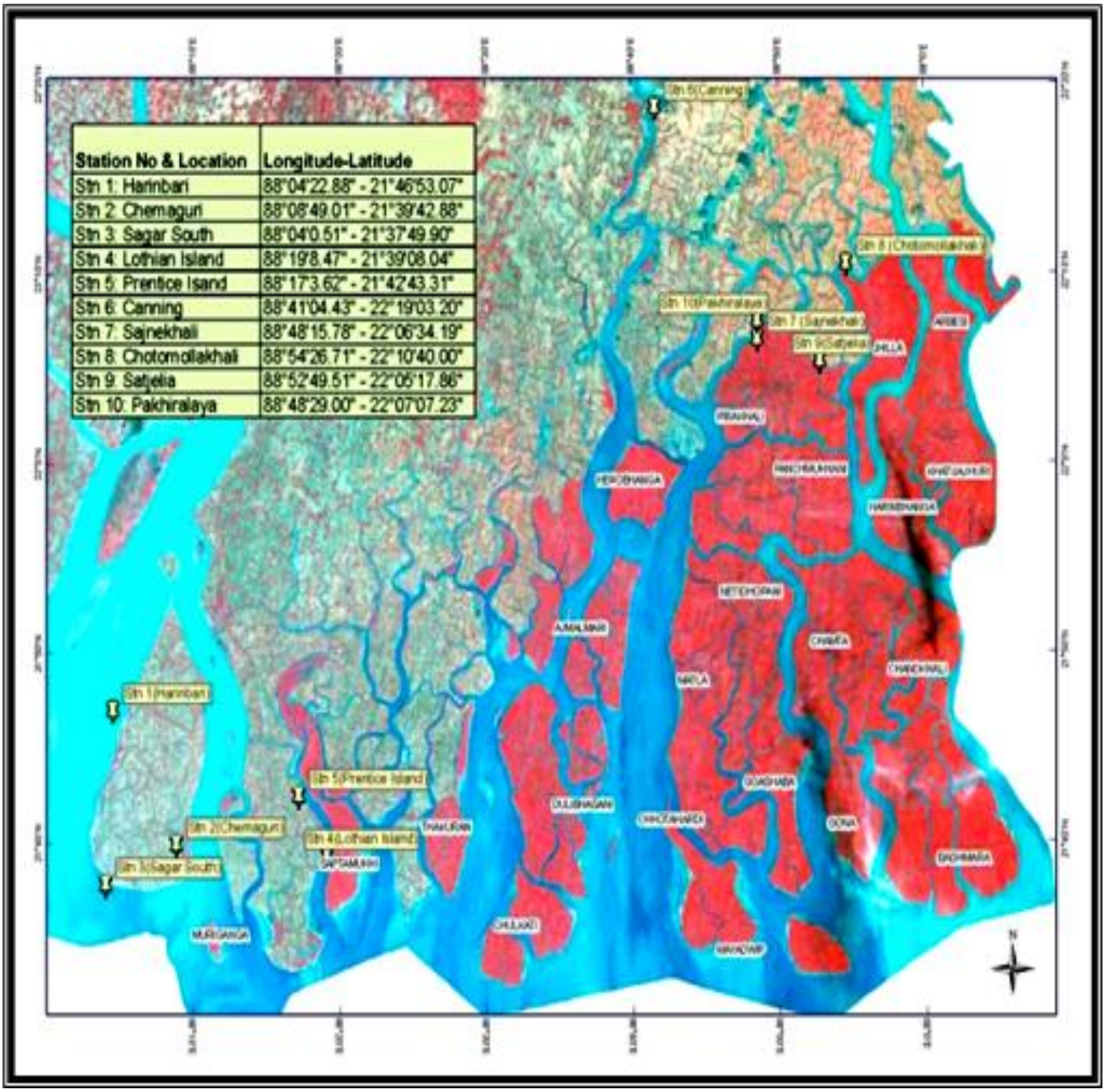

Fig. 1. Sampling stations in Indian Sundarbans for assessing peat soil organic carbon during the study period

2.2 Soil Sampling and Analysis

Soil samples were collected at three-time intervals (1994, 2014, and 2024) from the 50-75 cm depth layer using a corer. The Walkley-Black method [22] was employed to analyse PSOC (Fig. 2). The samples were taken from each station in triplicate to ensure accuracy.

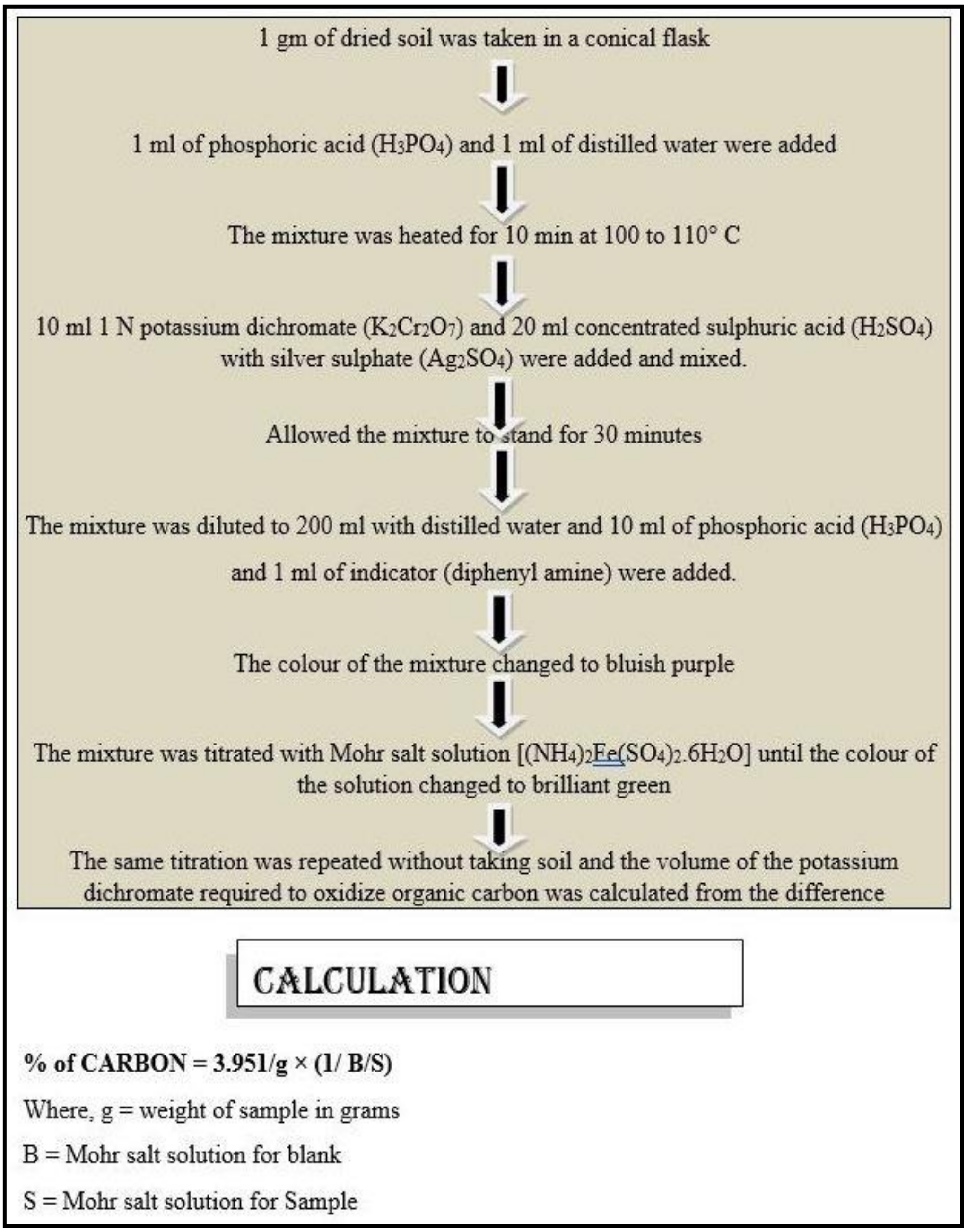

Fig. 2. Flowchart of Peat Soil Organic Carbon (PSOC) analysis by Walkley-Black Method

2.3 Statistical Analysis

A two-way ANOVA was performed to compare PSOC levels across stations and over time, allowing us to assess the effectiveness of the restoration programs.

In a two-way ANOVA, two factors are analysed simultaneously to examine their individual and interactive effects on the dependent variable (here, PSOC levels). In this case (i) Stations represent one factor, with multiple levels (10 different stations), and (ii) Time represents the second factor, with multiple levels (3 different time points).

By comparing PSOC levels across ten stations and over time, the analysis can evaluate the main effects of each factor and any interaction effect between them, which provides insights into the restoration program's effectiveness at different locations and times.

3. Results

The PSOC levels at the 10 stations showed a significant recovery over time. In 1994, during the peak shrimp farming period, the PSOC values ranged from 0.48% at Canning (Stn. 6) to 2.63% at Lothian Island (Stn. 4). By 2014, the PSOC levels had increased across all stations, and by 2024, significant gains were observed, with the highest increase (93.75%) at Canning (Stn. 6), where PSOC rose from 0.48% to 0.93%. The results in Table 1 indicate significant spatial variations in PSOC levels across stations, likely due to the varying presence or complete absence of shrimp farming in the region. A few islands within the Reserve Forest area are exceptions in terms of PSOC hike over time, as the West Bengal Forest Department never permitted shrimp culture in these areas, and hence, the PSOC values in 1994 were not very low in islands like Lothian Island (Stn. 4), Prentice Island (Stn. 5), and Sajnekhali (Stn. 7), leading to relatively low percentage increases in PSOC on these islands over time (Figs. 3 and 4).

Table 1: Spatio-temporal variation of PSOC in Indian Sundarbans.

Stations	PSOC (%) in November 1994	PSOC (%) in November 2014	PSOC (%) in November 2024	Increase (%)
Harinbari (Stn. 1)	0.97	1.31	1.55	59.79
Chemaguri (Stn. 2)	0.71	0.95	1.22	71.83
Sagar South (Stn. 3)	0.91	1.20	1.48	62.64
Lothian Island (Stn. 4)	2.63	2.94	3.21	22.05
Prentice Island (Stn. 5)	2.59	2.90	3.16	22.01
Canning (Stn. 6)	0.48	0.71	0.93	93.75
Sajnekhali (Stn. 7)	2.51	2.79	3.09	23.11
Chotomollakhali (Stn. 8)	0.57	0.78	1.03	80.70
Satjelia (Stn. 9)	0.63	0.87	1.10	74.60
Pakhiralaya (Stn. 10)	0.85	1.09	1.41	65.88

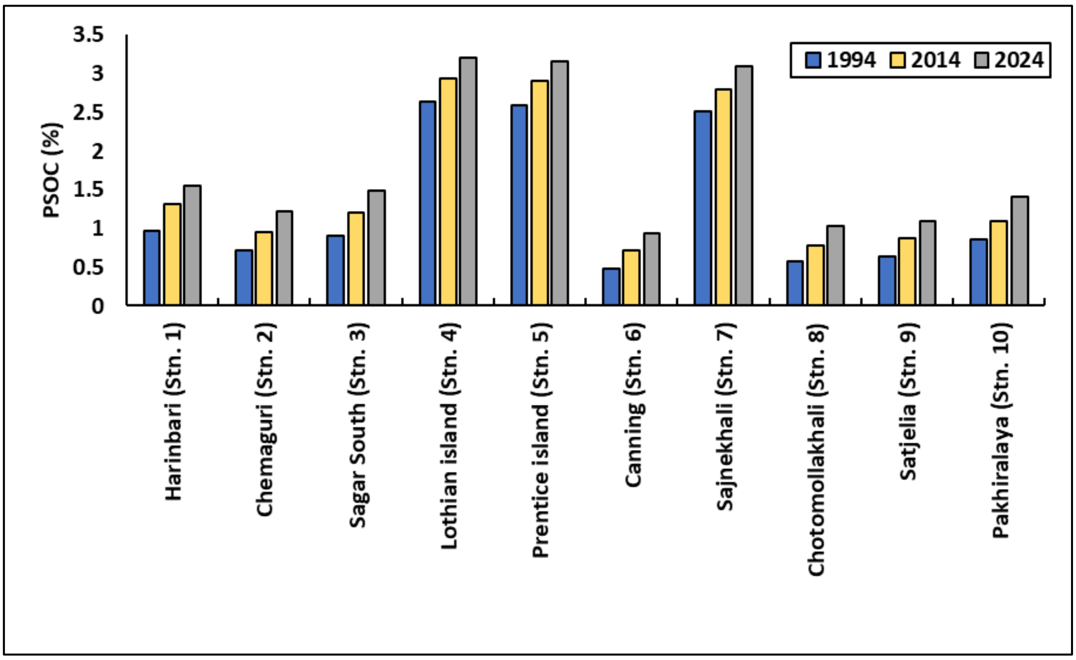

Fig. 3. Percentage value of PSOC in ten selected stations during 1994, 2014 and 2024

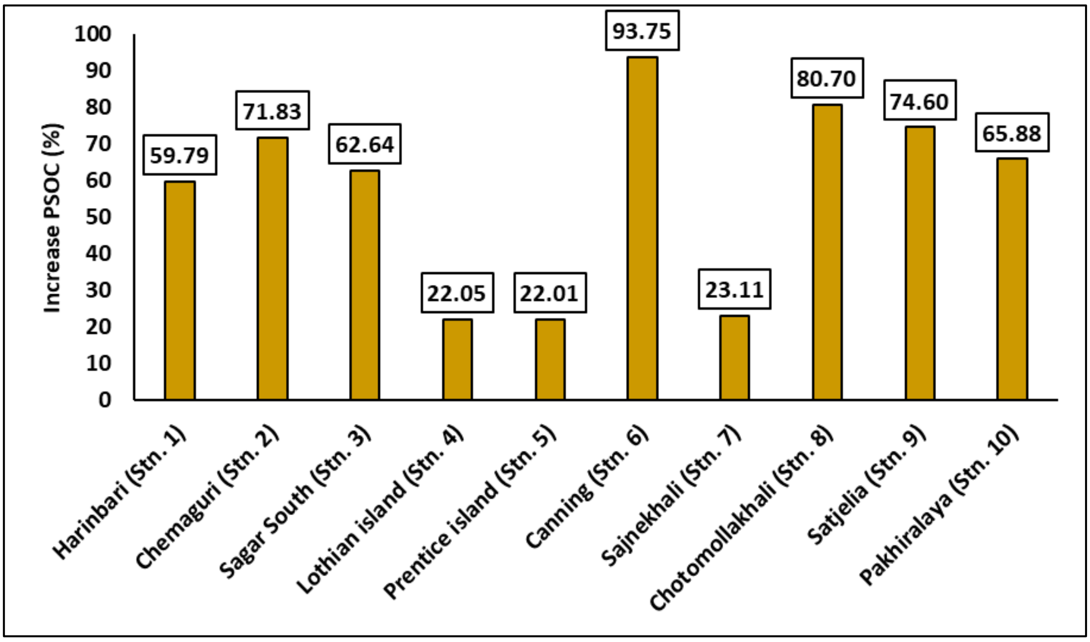

Fig. 4. Increase % of PSOC value in the selected stations from 1994 to 2024

The results presented in Table 2, analysed through ANOVA, confirm significant variations across the stations and years at 1% level of significance ($p < 0.01$).

Table 2: ANOVA showing spatio-temporal variation of PSOC.

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between stations	23.13974	9	2.571082	2673.0539	2.95E-26	2.4563
Between years	1.420487	2	0.710243	738.4124	5.32E-18	3.5546
Error	0.017313	18	0.000962			
Total	24.57754	29				

4. Discussion

Shrimp farming, conducted at the expense of mangrove ecosystems, has been shown to cause a notable decline in soil organic carbon (SOC) levels. Mangroves are recognized as efficient carbon sinks, and their removal disrupts their natural carbon storage functions [2-3]. Converting mangrove areas into shrimp ponds leads to heightened carbon release due to soil disturbance and oxidation, which collectively result in significant SOC loss. This transition reduces the ecosystem’s carbon sequestration capacity and leads to increased carbon emissions.

Despite being located at greater depths, peat soils in shrimp farms are affected during the active culture period as pond aeration and water exchange processes heighten oxidation and nutrient leaching. These practices introduce oxygen deeper into the soil, accelerating the breakdown of organic matter. Additionally, the accumulation of shrimp waste and uneaten feed intensifies microbial activity, depleting the soil's organic carbon and nutrients over time, which accelerates soil degradation.

The study results underscore the positive impact of afforestation efforts on SOC levels in previously abandoned shrimp ponds. Regenerating mangrove stands have played an essential role in gradually restoring soil carbon reserves, with SOC levels increasing steadily over the 30-year period from 1994 to 2024. This indicates the strong carbon sequestration potential of mangrove ecosystems when managed and restored effectively, even following extensive degradation. The main species planted in these sites were *Avicennia marina*, *Avicennia alba*, *Avicennia officinalis* and *Sonneratia apetala*. Past researches have shown that mangrove biomass is directly correlated with SOC levels [5, 8, 12, 21].

We observed that the station-wise increased PSOC value is as per the order Canning (Stn. 6) (93.75%) > Chotomollakhali (Stn. 8) (80.70%) > Satjelia (Stn. 9) (74.60%) > Chemaguri (Stn. 2) (71.83%) > Pakhiralaya (Stn. 10) (65.88%) > Sagar South (Stn. 3) (62.64%) > Harinbari (Stn. 1) (59.79%) > Sajnekhali (Stn. 7) (23.11%) > Lothian Island (Stn. 4) (22.05%) > Prentice Island (Stn. 5) (22.01%). We propose restoring mangrove ecosystems in degraded areas, such as abandoned shrimp ponds, holds significant potential for climate change mitigation by boosting carbon sequestration in peat soils. SOC recovery in these areas also underscores the critical role of coastal ecosystems in national carbon accounting. This study further highlights the importance of long-term monitoring and sustainable management practices to maintain soil carbon stocks in mangrove ecosystems.

5. Conclusion

The restoration of mangrove ecosystems in the Indian Sundarbans has yielded notable increases in PSOC levels across various stations, showcasing mangrove afforestation as a cost-effective, nature-based solution for soil health recovery and climate change mitigation. The observed variations in carbon sequestration rates across stations are linked to the extent or absence of shrimp farming in the region. In areas like Lothian Island (Stn. 4), Prentice Island (Stn. 5), and Sajnekhali (Stn. 7) where shrimp culture was never permitted by the West Bengal Forest Department, the initial PSOC levels in 1994 were comparatively high, resulting in lower percentage increases over time. Conversely, stations with lower initial SOC levels due to extensive shrimp farming, such as Canning (Stn. 6) and Chotomollakhali (Stn. 8), experienced the most significant gains. These findings underscore the role of mangrove afforestation programs in enhancing carbon stocks in degraded ecosystems, highlighting the capacity of mangrove species to deliver substantial environmental benefits while restoring soil health across such vulnerable landscapes.

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