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Mono-Specific Data Deficient Saltmarsh Species Has Climate Relevant Carbon Stocks from the East Coast of India

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Abstract: Despite saltmarshes being considered as nature-based solutions (NbS) towards climate change mitigation, India's saltmarsh ecosystems are least studied. This study quantifies the seasonal variation in carbon stocks mono-specific saltmarsh species (*Porteresia coarctata)* and its potential to play an important role in India's climate change mitigation plans. Seasonal (pre-and post-monsoon) sampling of *P. coarctata* surface water, biomass and 30 cm sediment core was collected across four locations on the east coast of India to quantify sediment dry bulk density (DBD), organic matter (OM%), organic carbon (Corg%), Corg stocks of sediment and biomass, total carbon (C%) and nitrogen (N%) and stable isotopes of δ13C and δ15N. In general, the sediment DBD, OM and Corg of *P. coarctata* meadows was higher in post-monsoon and was influenced by salinity and pH changes. Isotope ($\delta^{13}C$) modelling of various sediment C sources suggested, particulate organic matter (POM) contribution was highest (0.04-0.79%) followed by *P. coarctata* (0.01–052%) and other macrophytes across our study locations. The seasonal variation of $\delta^{13}C$ showed increased contribution of marine derived particulate and dissolved organic matter into *P. coarctata* meadows in post-monsoon season. Heavier $\delta^{15}N$ values were observed in post-monsoon season suggesting anthropogenic input, that was utilized by *P. coarctata* to increase its above and below-ground biomass and shoot density. The combined ecosystem (30 cm sediment + biomass) Corg stocks of *P. coarctata* was 1.7-fold higher in post-monsoon (4021.20± 917 Mg C) compared to pre-monsoon (2297.36 ±647 Mg C) season among the four locations with a sediment Corg contribution >70%. Based on the International Panel for Climate Change Tier II assessment the *P. coarctata* meadows (443 ha) can help in avoiding the pre and post-monsoon emissions of 8431.34 and 14757.84 Mg CO_2 respectively. The combined price of the total CO_2 equivalent stored in *P. coarctata* meadows in pre- and post-monsoon is US$ 14.50 and US$ 25.38 million respectively. Further studies quantifying the NbS potential of *P. coarctata* mono-specific and mixed meadows of India's coast is needed along with integration of saltmarsh ecosystems into India's National Action Plan on Climate Change.

Keywords: saltmarsh, carbon stocks, *Porterasia coarctata*, nature-based solution, stable isotopes,

1. Introduction

Marine forests (i.e., mangroves, saltmarsh and seagrass) are considered as important nature-based solutions (NbS) to capture CO_2 and store carbon (i.e., blue carbon) over a long period of time compared to the land forests (Mishra et al., 2023; Stankovic et al., 2023). Saltmarshes are one of the keystones coastal macrophytic plants, that inhabit the land and sea interface (Levin et al., 2001). These ecosystems are distributed worldwide (Mcowen et al., 2017) and provide an array of ecosystem services (Ermagassen et al., 2021). These ecosystem services include food and habitat provisioning for variety of fish and invertebrate species (Jinks et al., 2020; Whitfield, 2017), improved water quality and shoreline protection through sediment accretion and plays an important role in climate change mitigation through blue carbon sequestration (Campbell et al., 2022a; Ermgassen et al., 2021; Gilby et al., 2021; Rendón et al., 2019). However, due to various human induced habitat disturbances related to marine food provisioning (such as aquaculture and grazing), coastal developmental activities (port development, mangrove plantation, tourism activities) and climate change (such as sea level rise and temperature change effects) impacts, these ecosystems are getting lost at alarming rates (0.28% yr^{-1}) in the last decade (Campbell et al., 2022a), leading to loss of ecosystem services (such as blue carbon) and biodiversity assemblages (Campbell et al., 2022b; Mason et al., 2023a; Mishra and Farooq, 2022a; Perera et al., 2022). Despite saltmarsh ecosystems being ecologically important in climate change mitigation, there is a significant lack of studies on assessing their carbon storage potential in the Indian subcontinent (Bal and Banerjee, 2019; Mishra and Farooq, 2022a; Stankovic et al., 2023).

India's saltmarsh ecosystems cover 1% (1611.14 km^2) of the total wetland area consisting of more than 45 species (National Wetland Atlas, 2011). These saltmarsh species of India are part of the 18 species found in South Asia and inhabit the intertidal mudflat zone of India's coastal ecosystems that are frequently inundated by spring and neap tides (Gopi et al., 2019; Mcowen et al., 2017; Viswanathan et al., 2020). However, lack of studies on ecological aspects has hindered the conservation and management of saltmarsh ecosystems across various coastal states, leading to loss and die-off of India's saltmarsh ecosystems. For example, the saltmarsh plant *Porteresia coarctata* and *Sporobolus virginicus* has been extensively removed for mangrove restoration, leading to severe loss of these ecologically important ecosystems (Begam et al., 2017; Mishra and Farooq, 2022a). However, both *P. coarctata* and *S. virginicus* plants modify the surrounding sediment biogeochemistry, that not only helps in sediment accretion but also in successful restoration of mangroves, as observed in the ecosystems of Sundarbans, India (Begam et al., 2017). Despite saltmarsh ecosystems being important carbon storage systems and are distributed across east and west coast of India, studies on carbon stocks of saltmarsh ecosystems of India are minimal and mostly restricted to the east coast of India (Mishra and Farooq, 2022a, 2022b; Stankovic et al., 2023). For *P. coarctata* there are only two studies from the east coast of India showing a carbon storage range from 7 to 44.79 Mg C ha^{-1} within the top 10 cm of the sediment (Banerjee et al., 2022; Chowdhury et al., 2018). Similarly, there is a single study from the east coast of India showing carbon stocks potential of mixed saltmarsh species (i.e., *Suaeda maritima*, *Sesuvium portulacastrum*, *Arthrocnemum indicum*, *Salichornia brachiata*) present in the upper intertidal zone with sediment carbon stocks potential of 8.42 to 54.6 Mg C ha^{-1} (Kaviarasan et al., 2019). However, previous studies of *P. coarctata* carbon stocks on the east coast were limited only to protected coastal areas (such as Bhitarkanika National Park in Odisha and the Sundarbans World Heritage Site in West Bengal), where the species is found associated with mangrove ecosystems (Banerjee et al., 2022; Mishra and Farooq, 2022b). Other than these protected areas, *P. coarctata* is also found inhabiting various estuaries along the east coast of India without mangroves, which are ecologically important marine habitats for endangered fish and horseshoe crabs (Misra et al., 1988). These ecologically important *P. coarctata* meadows are traditionally overlooked and anthropogenically modified for mangrove restoration, jetty building, port development, coastal road infrastructure and coastal aquaculture (Begam et al., 2017; Mishra and Farooq, 2022a, 2022b). How these anthropogenic activities combined with seasonal changes can alter the carbon storing capacity of these mono-specific *P. coarctata* meadows along the east coast of India is less understood. Furthermore, India under its "Blue Economy" push is going to make significant stride towards its coastal infrastructure that will alter the coastal saltmarsh ecosystems and create additive pressure on conservation and management of the least studied saltmarsh ecosystems.

Therefore, this study aims to i) quantify the organic carbon stocks of a mono-specific saltmarsh species (i.e., *P. coarctata*) from the coast of Odisha and assess the socio-economic benefits of this carbon storage, ii) evalute the effects of seasonal variation in Corg stocks, and iii) the contribution of various C_{org} sources into these saltmarsh ecosystems by using stable isotopes of carbon (^{13}C). This study will help in showcasing the importance of *P. coarctata* ecosystems towards India's climate change mitigation plans and the need for conservation of these ecosystems. We hypothesize that seasonal influence of nutrient and OM positively influences sediment carbon stocks in these saltmarsh ecosystems.

2. Materials and Methods

2.1. Study Area

This study surveyed four major estuarine areas of the state of Odisha, i.e., Chandipur (200 ha), Dhamra (93 ha), Astaranga (110 ha) and Rushikulya (30 ha) that have the presence of mono-specific meadows of *P. coarctata* (Figure 1). These study locations cover the north to south latitudinal gradient of estuaries in the state of Odisha that drain into the Bay of Bengal on the east coast of India and are considered as one of the Important Coastal and Marine Biodiversity Areas (ICMBA, 2021) other than the protected Bhitarkanika National Park. The Chandipur and Dhamra estuarine areas are important breeding and feeding habitats for endangered horse-shoe crabs (Chatterji et al., 2003), whereas Rushikulya and Astaranga estuarine areas are important mass nesting sites of Olive ridley sea turtles (Mishra et al., 2022).

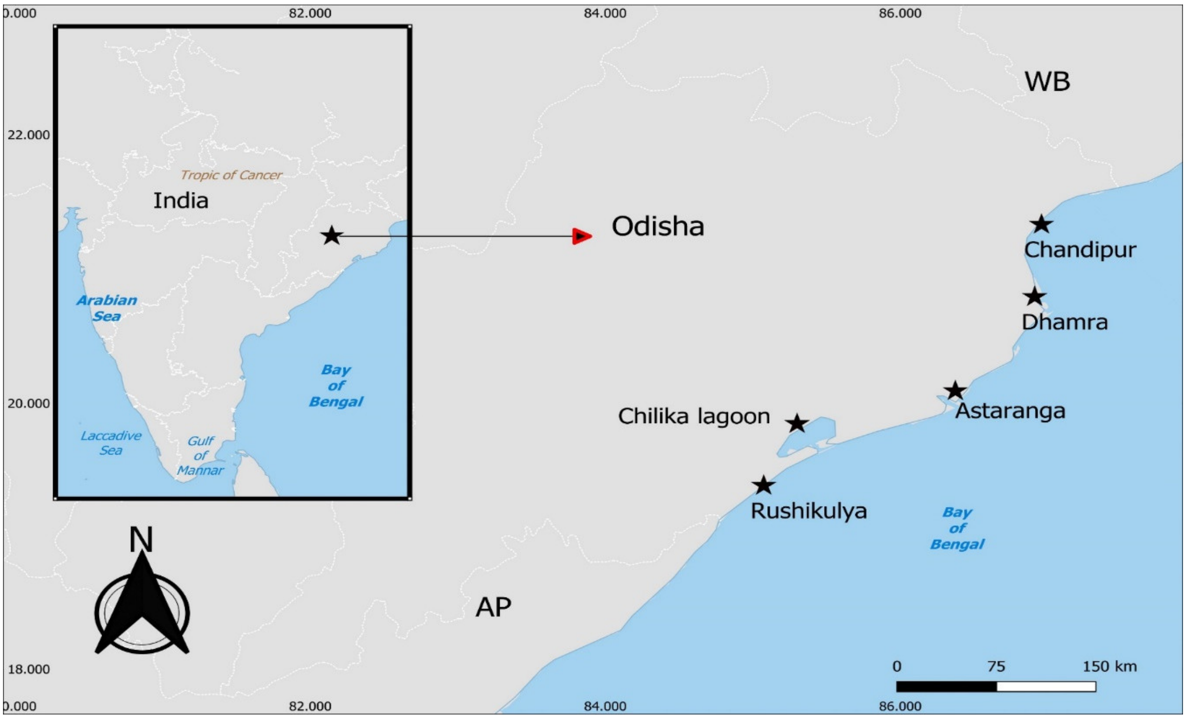

Figure 1. Map showing the study sites in the state of Odisha on the east coast of India. West Bengal (WB) and Andhra Pradesh (AP) are the neighboring coastal states of Odisha on the east coast of India.

We used a hand-held GPS to mark the total *P. coarctata* meadow area during seasonal sampling. The mono-specific *P. coarctata* meadows was found mostly present in the lower intertidal zone that received daily tidal flooding with occasional presence of another saltmarsh species such as *Myrostachia wightiana*, that was present only at Astaranga and Rushikulya locations (Figure 2). Except Astaranga, all other three estuarine area receives anthropogenic input and are subjected to habitat modification and land use changes for coastal development, such as port development and dredging (i.e., at Dhamra Port), beach modification for development of stone walls and coastal roads (i.e., at Chandipur and Rushikulya). Seasonal sampling of sediment and saltmarsh plants (for biomass) was collected once in pre-monsoon (February-May 2021) and post-monsoon (November-January 2022). Surface water (n=5) above saltmarsh ecosystems of each location was measured for pH and temperature (HI991301P, Hannah Instruments) and salinity (HI98203, Hannah Instruments) using hand held probes in each season.

Figure 2. *P. coarctata* meadows across the four locations of the study sites, a) Chandipur, b) Dhamra, c) Astaranga and d) Rushikulya across the state of Odisha, India.

2.2. Sediment Sampling and Analysis

Five replicate cores at least 1m apart, were collected from *P. coarctata* meadows using a stainless-steel sediment core (30 cm long and 5cm diameter) across the four study locations. The sediment core compaction was measured in the field and capped at both ends, stored in dark ice boxes and transported to the laboratory. In the laboratory, the total length of the sediment cores was measured and then sectioned at 5 cm intervals (5, 10, 15, 20, 25, 30 cm). Then each section was oven dried at

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60°C for 48 hr to derive the sediment dry bulk density (DBD: g DW cm^{-3}; Eq.1) following the blue carbon manual (Howard et al., 2014). The sediment C_{org} density (SCD; g cm-3; Eq.2) was calculated by multiplying the DBD with sediment C_{org} content (%). Sediment samples were then homogenized using a grind mill (Retsch, RS 200, USA). From this homogenized sediment 5 g was used in a muffle furnace at 550° C for 6 hr to determine the percentage loss on ignition (LOI%; Eq.3) of organic matter (OM) for each fraction of the sediment core.

$$DBD = (weight\ of\ dry\ sediment)/(core\ volume) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$SCD = DBD\ x\ \%Corg \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$LOI\ (\%) = \left[\frac{A-B}{A}\right] * 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where A is the initial weight of the sample and B is the amount of sample left after LOI test.

From the remaining homogenized sediment for each fraction 0.30 mg was acidified (1M HCl) to remove carbonates from the sediment. After the addition of HCl, the sediment samples were stored in a fume hood chamber, till no further bubble formation was detected. Then the sediment samples were placed in hot air oven at 60°C for 24 hours untill it completely dried. These dried sediment samples were analyzed in duplicate for composition of carbon (C), nitrogen (N) elemental concentrations and stable isotopes (^{13}C and ^{15}N) using a Flash Elemental Analyzer coupled to a Delta V IRMS {Isotope mass ratio spectrometer, Euro Vector (EA3028 EA-Nu)}. In-house standards, acetanilide (Iacet#1, $\delta^{15}N$= 1.18‰, $\delta^{13}C$=-29.53‰) were used for calibration and determination of the precision (0.2‰). Ratios of $^{13}C/^{12}C$ and $^{15}N/^{14}N$ were expressed as the relative difference (‰) between the sample and the conventional standard, Vienna Pee Dee Belemnite (VPDB) and atmospheric air for C and N respectively.

The IsoSource software (version 1.3.1) developed by the Environmental Protection Agency of the United States was used to estimate the contribution of various sources of C_{org} to the sediment OM of *P. coarctata* meadows across the four locations and both seasons (Phillips et al., 2005; Phillips and Gregg, 2001). A standard linear mixing model was used to find the source proportions that maintain the mass balance of all isotopes (Phillips and Gregg, 2001). This model calculates the ranges of all relative proportions of various sources to a mixture by evaluating all feasible combinations of each contributing source (0 to 100%), which are evaluated in small 1% increments. The $\delta^{13}C$ values of *P. coarctata* (-28.5‰), C_4 plants (-14.5‰), particulate organic matter (POM; -21.4‰) are used to estimate the relative contribution from three sources to the bulk OM in *P. coarctata* sediment beds. The $\delta^{13}C$ values for POM and C_4 plants were derived from other studies related to the coast of Odisha (Saha et al., 2022). For running the model, two parameters were set: the source increment set at 1% and the other was mass balance tolerance, which was set at 0.01‰ (Zhang et al., 2020). The mass balance tolerance at 0.01‰ indicates that the difference between the sum of the weighted isotopic values for each source and the acceptor isotopic values does not exceed 0.01‰.

The total Corg (Mg C ha^{-1}) in the sediment was calculated by adding the total Corg of each sediment core fraction of the individual saltmarsh species (Howard et al., 2014).

Sediment carbon stocks (g C m^{-2})

$$= Amount\ of\ carbon\ in\ core\ section\ A\ \left(\frac{g}{cm2}\right)$$

$$+ Amount\ of\ carbon\ in\ core\ section\ B\ \left(\frac{g}{cm2}\right)$$

$$+ Amount\ of\ carbon\ in\ core\ section\ C\ \left(\frac{g}{cm2}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Total core carbon (Mg C ha^{-1})

$$= Summed\ core\ carbon\ \{A + B + C\left(\frac{g}{m2}\right) * \left(\frac{Mg}{1000{,}000}\right) * \left(\frac{100{,}000{,}000}{ha}\right)\} \ldots\ldots\ldots (4)$$

2.3. Saltmarsh Plant Sampling and Analysis

Five random quadrats (20 cm x 20 cm) at least 1m apart from the four locations was sampled to collect saltmarsh biomass samples across each season. From each quadrat the saltmarsh plants were dug up using a hand-held spade from 10 cm depth. Then these plant samples with their roots attached were washed of any debris in the field with saltwater and stored in zip-locked plastic bags and brought to the laboratory. In the laboratory, plant samples were washed again with distilled water and any epiphytes on the leaf or shoot surface was cleaned off with a glass slide. Shoot density (individual shoots m^{-2}) was quantified by counting the total number of plant individual shoots per quadrat. Then the plant was separated in above-ground (AG: leaves) and below-ground (BG: roots+ rhizomes) biomass and oven dried at 60° C for 72 hr. These dried biomass samples were weighed first for dry biomass values (g DW m-2) and then homogenized in the grind mill(model??). Duplicate homogenized samples of 0.5 mg were used to derive the elemental and isotopic C and N composition following the methods described for the sediment samples above.

The total carbon stocks in the biomass of the *P. coarctata* meadow area were calculated by multiplying the mean C_{org} present in saltmarsh biomass and the meadows size for that location.

$$\text{Biomass carbon stocks (Mg C ha}^{-1}\text{)} = Biomass\ (g\ /m2) * C(\%) * \left(\frac{Mg}{1000000}\right) * \left(\frac{10000}{ha}\right) \ldots\ (5)$$

The total carbon stock in the biomass and in the sediment core (30 cm) was added to calculate the total carbon stock in these saltmarsh ecosystems. The carbon dioxide (CO_2) equivalent (Mg CO_2 ha^{-1}) was calculated by multiplying the CO_2 conversion factor (3.67) by the mean carbon stocks of the saltmarsh ecosystems (Howard et al., 2014) and upscaled towards the total *P. coarctata* meadow area for each location.

2.4. Valuation of Carbon Stocks

The social cost of carbon (SSC) indicates the economic cost associated with climate change related damage (or benefit) as a result of emission of one ton of CO_2 or its equivalent (Nordhaus, 2017; Ricke et al., 2018). This present study utilizes the regional approach to estimate SSC, rather than the global approach, as country level regional estimates allow better understanding of regional impacts of carbon emissions and are important for better adaptation and compensation measures (Ricke et al., 2018). We used the recent estimate of SSC for India which is US$ 86 per ton of CO_2 used (Ricke et al., 2018. Recent US$ to Indian rupees (INR conversion (USD$1= 83.11 INR) was used to estimate the price of CO_2 in INR.

2.6. Statistics

A two-way ANOVA was used to assess the statistical significance between, surface water physical parameters, sediment OM, total C and N content, stable isotopes ($\delta^{15}N$ and $\delta^{13}C$), Corg stocks, saltmarsh plant shoot densities, biomass and Corg stocks using the locations and seasons as fixed factors. All data was pre-checked for normality and homogeneity of variance using a Shapiro-Wilk and Levine's test respectively. In case of non-homogenous variances, data were ln (x+1) transformed. Pearson correlation was used to derive seasonal relationship between abiotic factors of surface water of *P. coarctata* meadows and the sediment OM and Corg content of only top 10 cm. All statistical tests were conducted at a significance level of $p<0.05$. Graph pad Prism software (Ver. 10.1.0) was used for all statistical analysis. Data is presented as mean and standard deviation (SD).

3. Results

3.1. Seasonal Variation in Physical Parameters

The physical parameters of the surface water column of *P. coarctata* varied significantly for both season and locations except for pH, which was only significantly different seasonally (two-way anova; $F_{1, 32} = 55.47$, $p<0.001$) between locations (Table 1). In general, the pH was lower in post-monsoon compared to pre-monsoon season. The lowest pH of surface water in pre-monsoon was observed at the Astaranga (7.96 ± 0.07), whereas the lowest pH in post-monsoon was observed at the surface waters of Dhamra (7.65 ± 0.24) (Table 1). The salinity was higher in pre-monsoon season compared to post-monsoon across the four study locations. The lowest and the highest salinity across the four locations in each season was observed at Astaranga (24.6 ±0.41; 9.37 ±1.91) and at Rushikulya (30.91 ± 0.77; 22 ± 1.10) respectively (Table 1). Surface water temperature of *P. coarctata* meadows followed a gradient in both seasons from low temperature in the north (Chandipur) to higher temperature in the south (Rushikulya) study locations (Table 1). The lowest (22.84 ± 1.39; 20.20 ± 0.37) and the highest (33.50 ± 1.16; 31.78 ± 0.78) temperature in pre- and post-monsoon season was observed at Chandipur and Rushikulya respectively (Table 1).

3.2. Seasonal Variation in P. coarctata Sediment Variables and Carbon Stocks

The sediment DBD varied significantly with depth across season ($F_{11,192}$=18.71, p<0.001) and locations ($F_{3,192}$=103.1, p< 0.0001) (See Supplementary S1). The DBD of the sediment was 1.2-fold higher in post-monsoon season compared to the pre-monsoon. In both seasons, the highest DBD was observed in the sediment section of Astaranga (at upper 5cm depth) and the lowest in the sediment section of Chandipur at 25-30 cm depth (Supplementary S1).

The sediment OM varied significantly with depth across seasons ($F_{11,92}$=13.81, p<0.0001) and locations (F 3, 192= 168.5, p<0.0001) (Figure 3). The sediment OM content was 1-fold higher in post-monsoon season compared to pre-monsoon across depths (Figure 3a &b). The highest sediment OM content was observed in the upper 10 cm (11.47 ± 1.92% OM) and 5cm (12.68 ± 1.30% OM) depth of the sediment core sections at Dhamra in preand post-monsoon season respectively, whereas the lowest sediment OM content (3.19–3.44% OM) was observed in the depth of 25 to 30 cm in sediment sections of Chandipur across both seasons (Figure 3 a &b).

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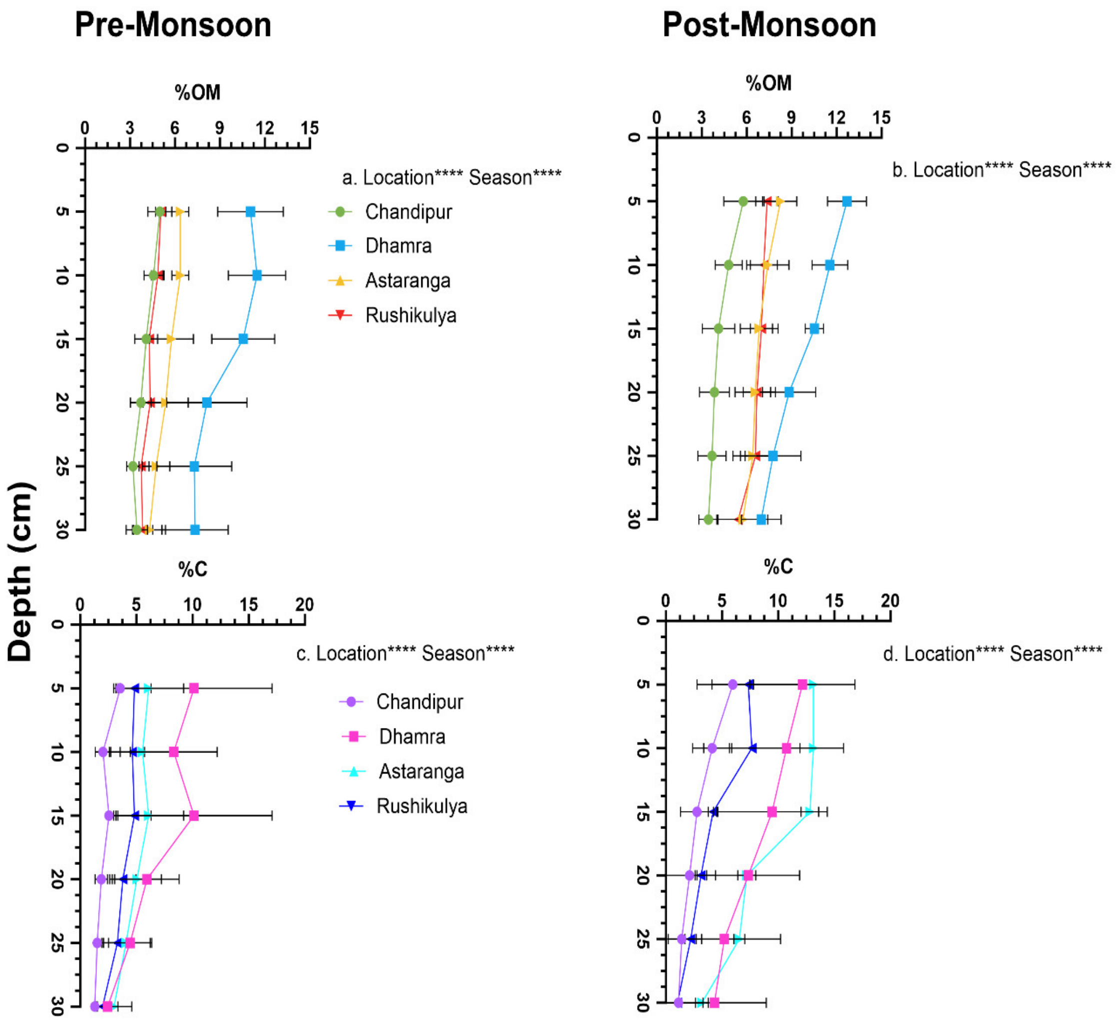

Figure 3. Seasonal variation in the sediment core sections for, a) organic matter (OM%) content and b) organic carbon (Corg%) in *P. coarctata* ecosystems across the four locations of the coast of Odisha, India. Statistical significance (p<0.05) was derived from two-way ANOVA analysis using locations and seasons as fixed factors. (p<0.0001****, p<0.001***, not significant ns).

The sediment OM content influenced the sediment C_{org}, that varied significantly with depth across seasons ($F_{33, 190}$= 1.8, p=0.006) and locations ($F_{3,190}$=72.4, p<0.0001) (Figure 3). The sediment C_{org} was 1.2-fold higher across depths in post-monsoon compared to pre-monsoon season throughout the locations. The highest sediment C_{org} content in pre-and post-monsoon was observed in the 15cm depth (12.31 ± 0.78 %C) and 5cm depth (13.14 ± 0.30% C) of the core sections respectively from Astaranga (Fig3c &d). Similarly, the lowest C_{org} content in pre- and post-monsoon was observed at Chandipur at core sections 10 (2.03 ± 0.68 %C) and 25 cm (2.41 ± 0.78 %C) depth respectively (Figure 3c&d). The sediment C_{org} stocks, varied significantly between seasons ($F_{1,32}$= 22.05, p<0.0001) and locations ($F_{3,32}$=18.6, p<0.0001) and were 1.8-fold higher in post-monsoon compared to pre-monsoon season across the four locations (Supplementary S2). Interestingly the sediment N content was very low (0.01%) across locations and seasons.

The $\delta^{13}C$ values of the sediment core sections varied significantly only across locations ($F_{3,192}$ = 49.00, p<0.001), with no significant seasonal effect (Figure 4). The heavier and lighter isotopes of $\delta^{13}C$ in post-monsoon were observed in the sediment section at15 cm (-20.04 ± 0.72 ‰) and 25 cm (-23.79 ± 0.61‰) respectively at Rushikulya. Interestingly, the heavier and lighter isotopes of $\delta^{13}C$ in pre-monsoon were observed at the sediment core section of 20 cm at Astaranga (-20.34 ± 1.73 ‰) and Dhamra (-24.48 ±0.78 ‰) respectively. The $\delta^{15}N$ values of the sediment core sections varied significantly across both locations ($F_{3,192}$ = 19.26, p<0.001) and seasons ($F_{11,192}$= 6.17, p<0.001) (Figure 4). In general, heavier $\delta^{15}N$ isotopes were observed in post-monsoon compared to pre-monsoon season. The heavier isotopes of $\delta^{15}N$ in pre-and post-monsoon season were observed at the upper 5cm of the core section at Dhamra (3.24 ± 1.08 ‰) and Rushikulya (4.41 ±1.66 ‰). Interestingly, for both seasons the lighter N isotopes were observed at 30 cm of the core section at Astaranga within a range of -0.05 to -0.04 ‰ (Figure 4). The fractional contribution of various C sources showed to the sediment C_{org} of *P. coarctata* meadows across seasons are presented in Figure 5. The contribution of POM is higher followed by *P. coarctata* (autochthonous) and contributions of C_4 plants (i.e., *M. wightiana*).

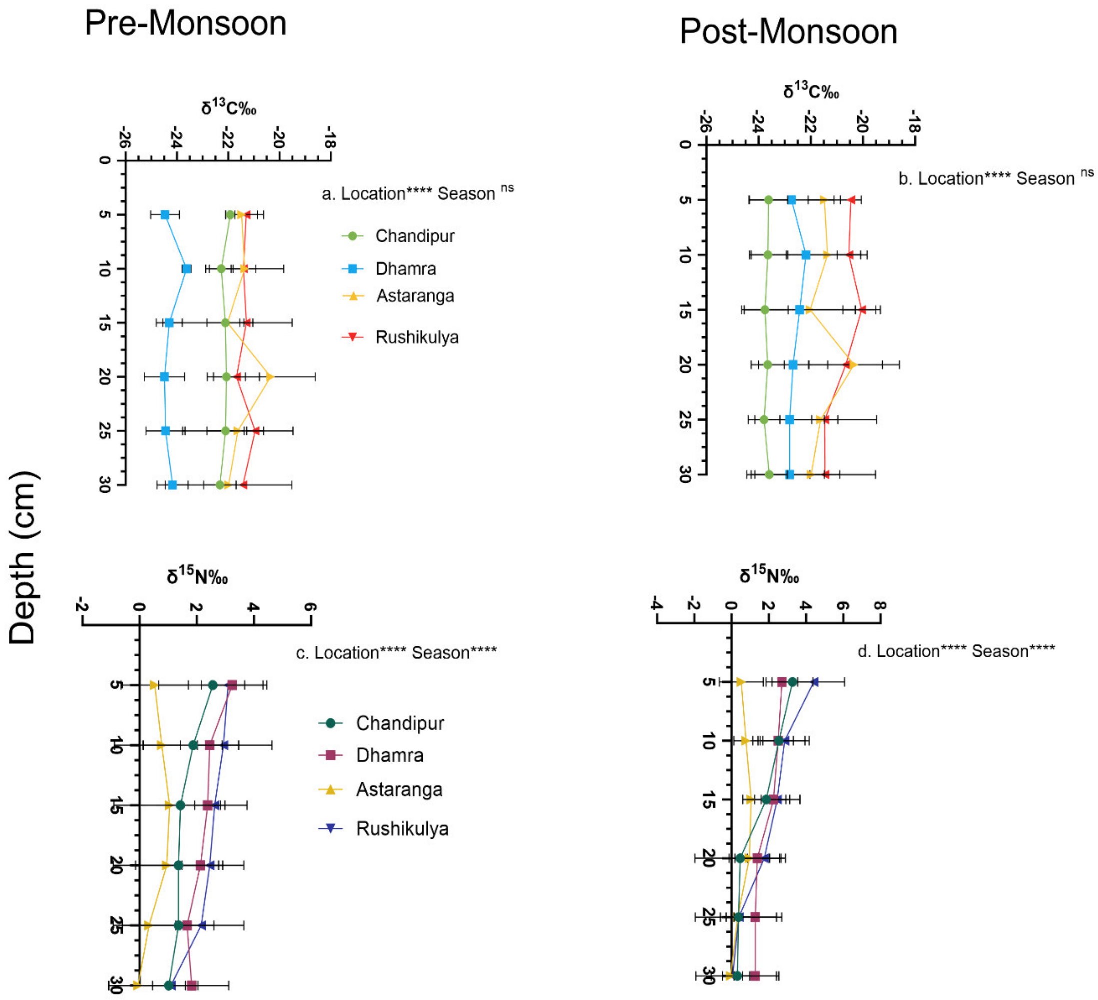

Figure 4. Seasonal variation in the sediment core sections for stable isotopes of $\delta^{13}C$ (a &b) and $\delta^{15}N$ (c & d), in *P. coarctata* ecosystems across the four locations of the coast of Odisha, India. Statistical significance (p<0.05) was derived from two-way ANOVA analysis using locations and seasons as fixed factors. (p<0.0001****, p<0.001***, not significant ^{ns}).

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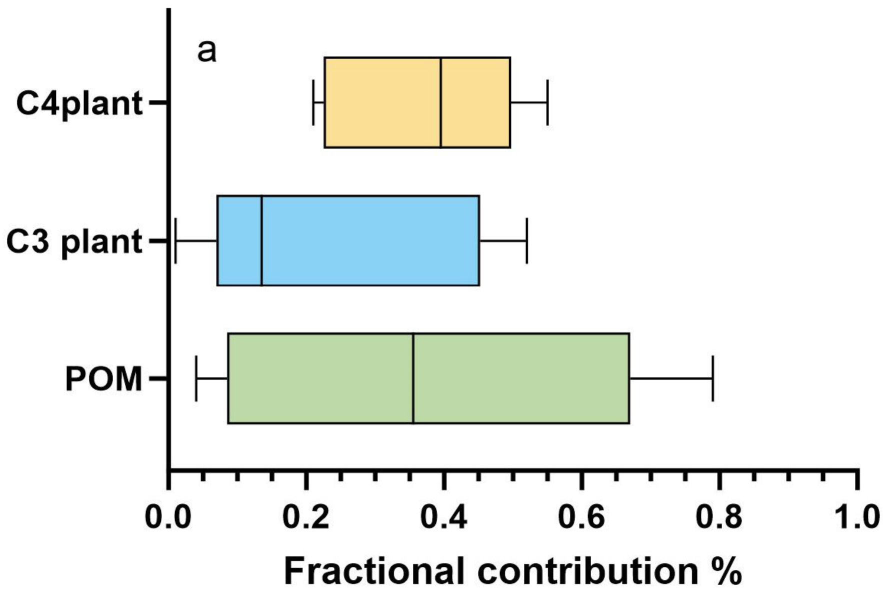

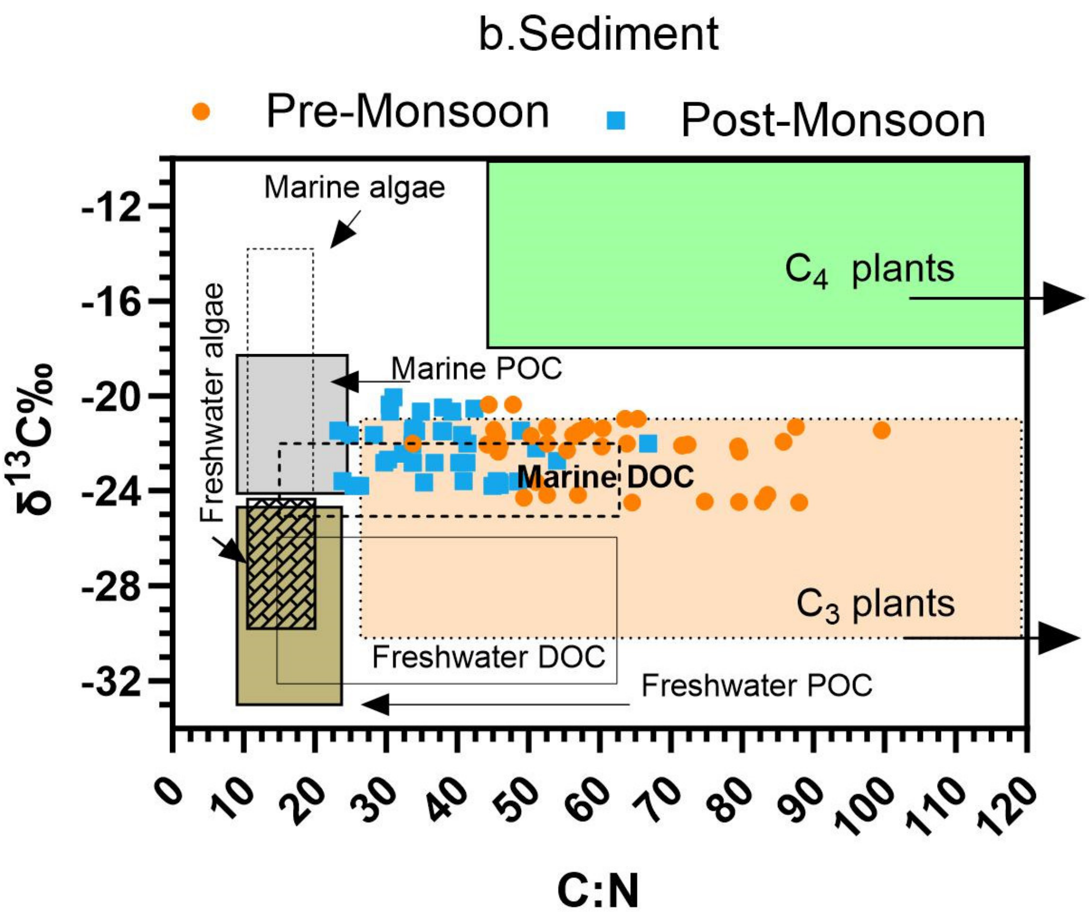

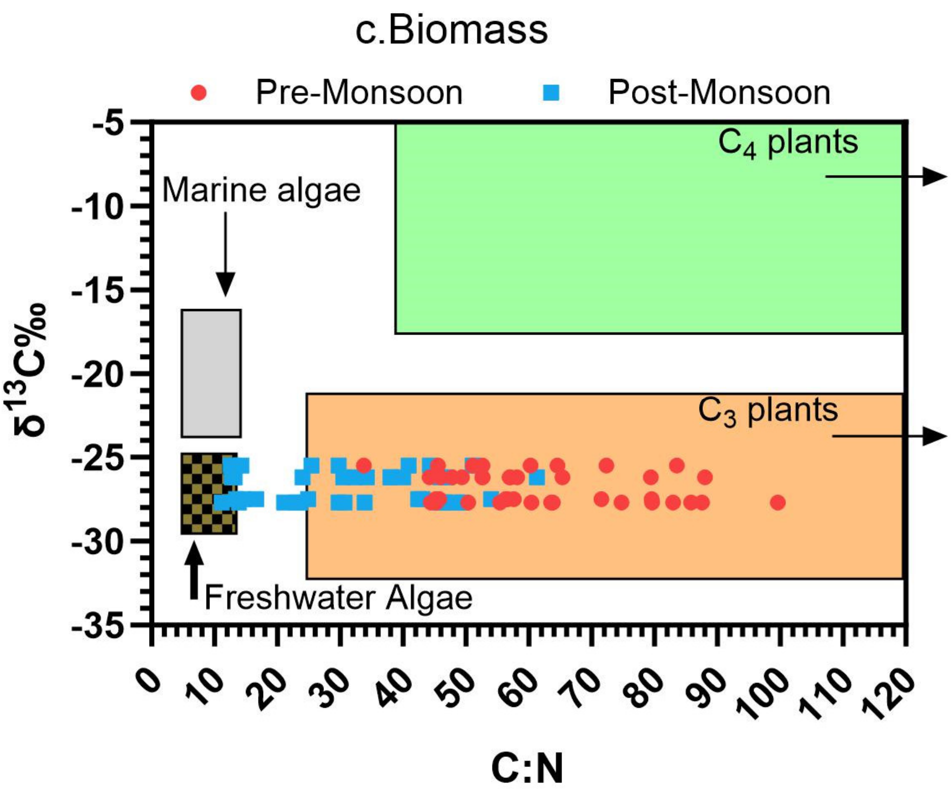

Figure 5. Contribution of a) C sources to sediment Corg in the *P. coarctata* meadows form the coast of Odisha. *M. wightiana* (C_4 plant), *P. coarctata* (C_3 plant) and particulate organic matter (POM) using IsoSource mixing, and the scatter plots of $\delta^{13}C$ versus total C: N ratio of b) sediment (Sd) and c) saltmarsh biomass in pre-and post-monsoon seasons of Odisha coast. Representative $\delta^{13}C$ and C: N ratio for organic matter inputs to coastal ecosystems from marine and freshwater macrophytes and particulate organic carbon (POC), and dissolved organic carbon (DOC) are imported from Lamb et al., (2006).

The corelationship of surface water column abiotic parameters on sediment OM and C was location-specific and significant in both seasons (Supplementary S4). In general, surface water salinity showed negative corelationship with sediment C_{org} (-0.87; p=0.04) and OM (-0.86; p=0.05) at Chandipur in both pre-monsoon and post-monsoon respectively. The surface water column pH showed positive corelationship with sediment C_{org} at Chandipur (0.95; p=0.005) and Astaranga (0.86; p=0.01) only in post-monsoon season. The surface water temperature showed positive corelationship with sediment C_{org} only in post-monsoon season at Dhamra (0.86, p=0.05) (Supplementary S4).

3.3. Seasonal Variation in P. coarctata Density, Biomass and Carbon Stocks

The shoot density of *P. coarctata* varied significantly across both seasons ($F_{1,72}$ =127.5, p<0.001) and the four locations ($F_{3,72}$= 17.97, p<0.001) (Figure 6a). In general, the shoot density of *P. coarctata* in post-monsoon season was 1.6-fold higher compared to pre-monsoon season (Figure 5). The highest density of *P. coarctata* in pre-monsoon and post-monsoon season was observed at Dhamra (1319.28 ± 109.86 ind. m^{-2}) and Astaranga (2354.76 ± 570.29 ind.m^{-2}) locations respectively. In contrast, the lowest density of *P. coarctata* in both seasons was observed at Chandipur (Figure 6).

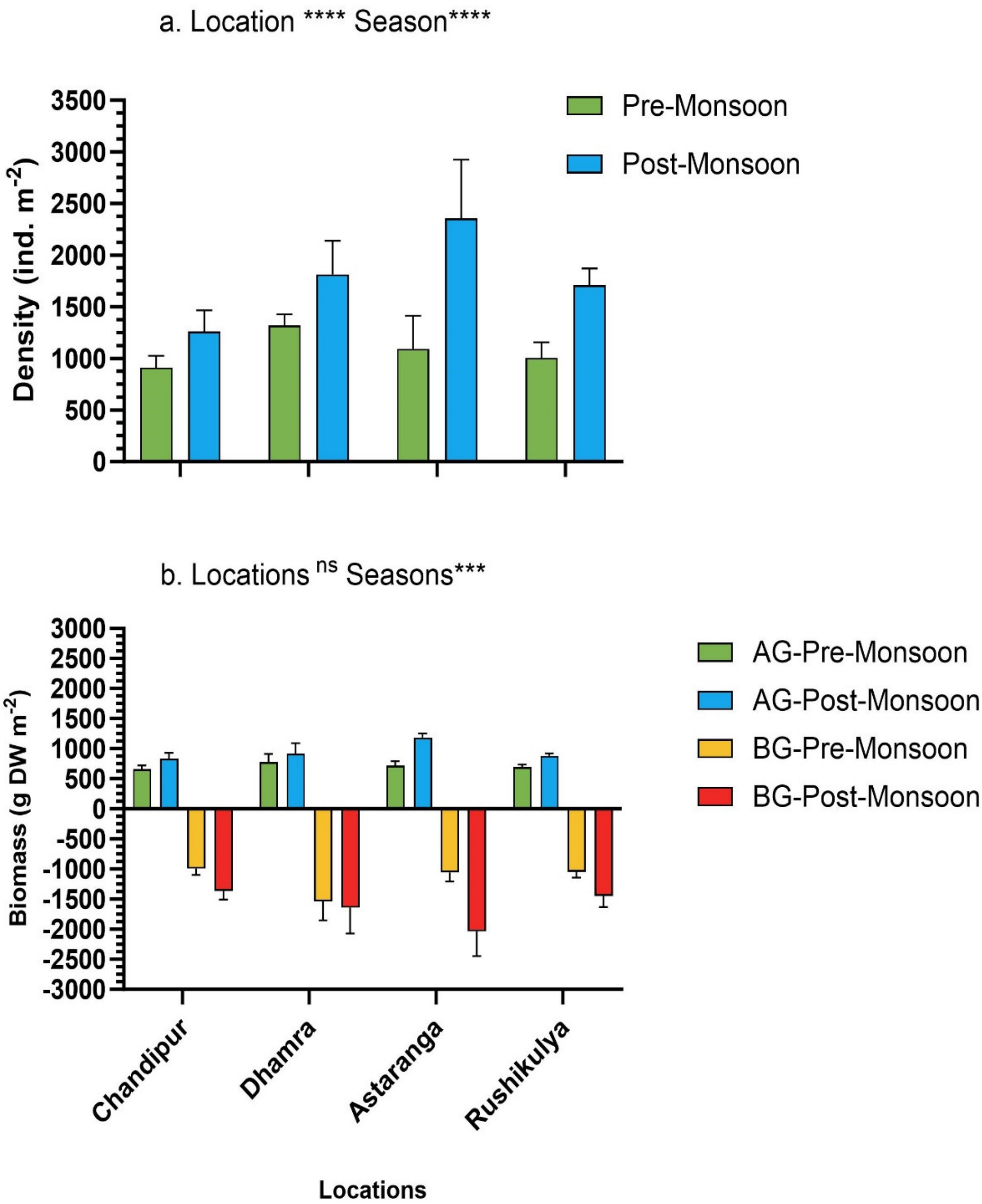

Figure 6. Seasonal variation in *P. coarctata* a) shoot density (individuals m^{-2}) and b) biomass (g DW m-2) across the four study locations of the coast of Odisha, India. Statistical significance ($p<0.05$) was derived from two-way ANOVA analysis using locations and seasons as fixed factors. ($p<0.0001$****, $p<0.001$***).

The AG- and BG-biomass of *P. coarctata* varied significantly only between seasons ($F_{3,64} = 864.4$, $p<0.0001$) and not between locations (Figure 6b). In general, the AG and BG-biomass of *P. coarctata* was 1.3-fold and 1.4-fold higher in post-monsoon compared to pre-monsoon season (Figure 6b). The highest and lowest AG and BG-biomass was observed at Astaranga (1180.55 ± 71.59 g DW m^{-2}; 2038.03 ± 407.44 g DW m^{-2}) and Chandipur (836.66 ± 92.54 g DW m^{-2}; 1361.75 ± 147.53 g DW m^{-2}) respectively in each season (Figure 5b). The total biomass Corg stocks were 1.4-fold higher in the post-monsoon season compared to pre-monsoon. (Supplementary S2).

The $\delta^{13}C$ showed no variation between seasons, whereas $\delta^{15}N$ in the biomass of *P. coarctata* were significant and different between locations (F 3,64=8.48, $p<0.0001$) and seasons (F 3,64 = 8.34, $p<0.0001$)

(Supplementary S3). The heavier $\delta^{15}N$ were observed in post-monsoon compared to pre-monsoon season in both AG and BG-biomass of *P. coarctata*. In AG-biomass the heavier isotopes of N were observed at Astaranga (7.19 ± 0.05 ‰) and in BG-biomass it was observed at Chandipur (6.02 ± 0.65 ‰) (Supplementary S3).

3.4. Ecosystem Carbon Stocks and Different Source Contribution to Sediment Organic Carbon Pool

The *P. coarctata* ecosystem (sediment up to 30 cm + biomass) C_{org} stocks varied significantly between seasons ($F_{1,32}$= 32.22, p<0.001) and location ($F_{3,32}$ = 37.47, p<0.001) (Figure 7). In general, the mean ecosystem C_{org} stocks of *P. coarctata* was 1.7-fold higher in post-monsoon compared to pre-monsoon season across the four locations. Among the four locations, the highest and lowest C_{org} stocks in pre-monsoon were observed at Dhamra (33.53 ± 13.37 Mg C ha^{-1}) and Rushikulya (12.01 ± 1.25 Mg C ha^{-1}) (Figure 6a). Consequently, in post-monsoon, the highest and lowest ecosystem C_{org} stocks were observed at the *P. coarctata* meadows of Astaranga (68.04 ± 6.16 Mg C ha^{-1}) and Chandipur (14.55 ± 3.29 Mg C ha^{-1}) respectively.

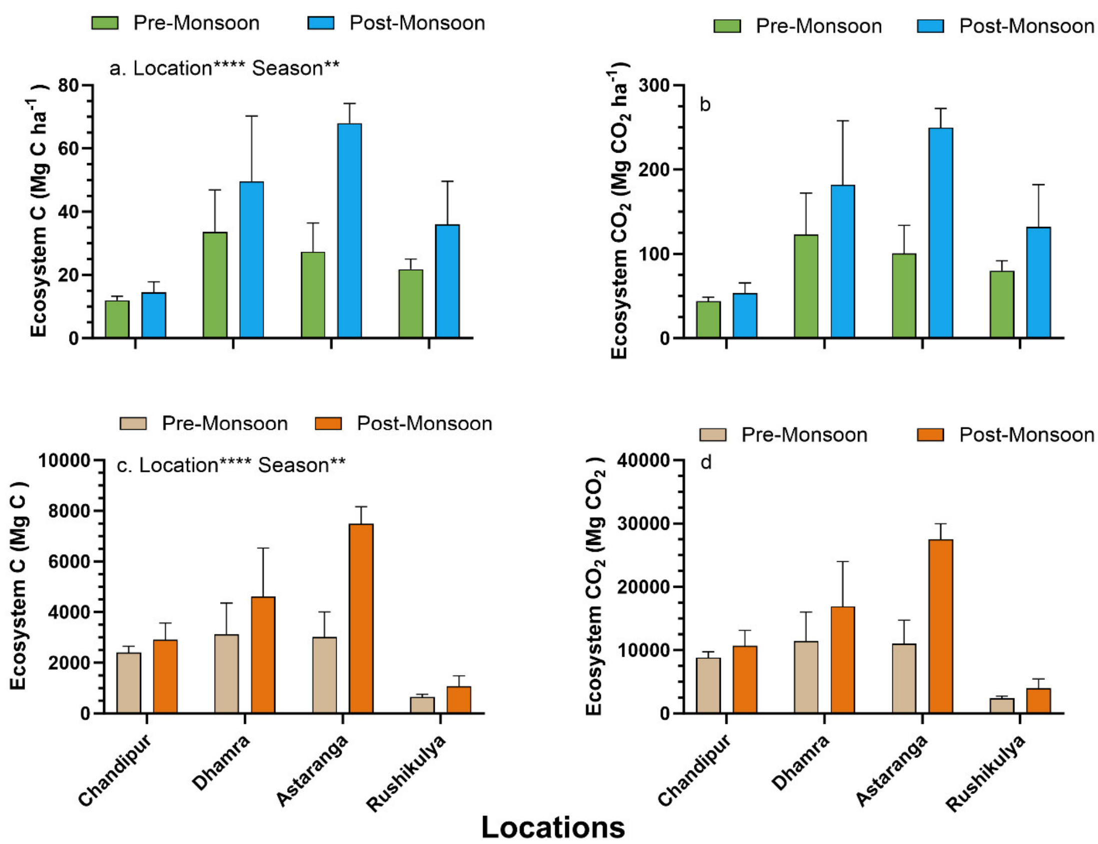

Figure 7. Seasonal variation in *P. coarctata* total carbon stocks (a & c) and CO_2 equivalent (b & d) across the four study locations of the coast of Odisha, India. Statistical significance (p<0.05) was derived from two-way ANOVA analysis using locations and seasons as fixed factors. (p<0.0001****, p<0.001***). No statistical significance was carried out for CO_2 equivalent data.

The mean CO_2 equivalent in *P. coarctata* ecosystem ranged from 44.08 to 123 Mg C ha^{-1} in pre-monsoon to 53.42 to 249 Mg CO_2 ha^{-1} in post-monsoon across the four locations (Figure 7b). The total CO_2 equivalent stocks across 433 ha of *P. coarctata* meadows across the four locations were highest in post-monsoon (14757.84 ± 9606.39 Mg CO_2) compared to pre-monsoon season (8431.34 ± 4606 Mg CO_2). The combined total price of CO_2 stocks in 433 ha of *P. coarctata* meadows in pre-monsoon is

US$ 14.50 million and post-monsoon is US$ 25.38 million. The price in INR for pre-monsoon is 1205.25 million and that of post-monsoon is 2109.61 million (Supplementary S4).

4. Discussion

Carbon stocks in saltmarsh ecosystems is considered as Nature-based Solution (NbS) towards climate change mitigation (Chowdhury et al., 2023; Mason et al., 2023b; Stankovic et al., 2023), but lack of regional scale information on saltmarsh carbon stocks data hinders their integration into intended nationally determined contributions (NDCs) under Paris Climate Agreement, 2015 (Dencer-Brown et al., 2022). Further research gaps also include, few well -studied locations globally (e.g., Western Atlantic saltmarshes of the United States, North-western European saltmarshes), that are often contextualized as being comparable to other saltmarsh areas in the tropical settings. Consequently, this generalization also hampers generating data on saltmarsh species-specific carbon stocks and the local seasonal effects and habitat settings on carbon storage in these coastal ecosystems (McMahon et al., 2023; Quevedo et al., 2023; Yando et al., 2023). This study addressed these knowledge gaps for *P. coarctata*, that has 84% of its distribution as mono-specific patches across the east coast of India as compared to its distribution in areas with other saltmarsh species and mangrove ecosystems (Begam et al., 2017; Mishra and Farooq, 2022b; Viswanathan et al., 2020; Yando et al., 2023). Our results indicate, there is an increase in seasonal nutrient input during monsoon season along the coast of Odisha that is reflected in the post-monsoon (Saha et al., 2022; Samantaray and Sanyal, 2022; Srinivasan et al., 2013), resulting in increase in biomass and carbon storage capacity (Figure 6). Consequently, seasonal change in nutrients and OM also positively influenced the sediment carbon stocks in the *P. coarctata* meadows along the coast of Odisha, India (Figure 7).

4.1. Influence of Physical Parameters on the Sediment Variables (DBD, OM, Corg%) and Carbon Stocks of P. coarctata Meadows

The surface water quality of saltmarsh ecosystems of our study locations is influenced by the seasonal (effect of monsoon) changes in water quality of the north-western Bay of Bengal and the local riverine input. The general trend of increase in pH, temperature and salinity in pre-monsoon and decrease in post-monsoon of the surface water in *P. coarctata* meadows across our study locations, concur with similar observations for Chandipur, Dhamra, Astaranga and Rushikulya estuarine areas from the coast of Odisha (Ambade et al., 2022; Mohanty et al., 2019; Shaik et al., 2015; Shrinivas et al., 2023; Sundaray et al., 2006; Swain et al., 2021). These changes in salinity and pH are a result of high influx of riverine freshwater into the estuarine areas resulting in decrease of salinity and pH during monsoon and the subsequent increase of salinity and pH in post-monsoon as the effect of monsoon driver dilution weakens (Bhadury and Sen, 2020; Shrinivas et al., 2023).

In our study, surface water salinity was negatively correlated with sediment OM and Corg at Chandipur and Rushikulya locations (Table 1). This correlation was previously observed for the *P. coarctata* meadows of Chandipur and for the estuarine areas of Rushikulya (Naik et al., 2020; Saha et al., 2022), where the daily tidal influx resulted in deposition of increased coarse grain fraction into the *P. coarctata* meadows. Subsequently, the high tidal flow and low residence time of water in the *P. coarctata* meadows also resulted in washing out of sedimentary OM resulting in low sediment C_{org}. This effect is clearly observed in our studies, as *P. coarctata* meadows in this study inhabited the low tidal zones that received daily tidal forcing and the subsequent loss of sediment OM resulting in low sediment C_{org}. However, riverine input in monsoon deposits a large influx of land derived OM into these saltmarshes, but during post-monsoon season when the riverine water flow reduces, the tidal influx and loss of OM mechanism takes over these open saltmarshes resulting in low sediment C_{org}. Secondly, salinity induces salt ion toxicity that have detrimental effects on plant productivity and subsequent contribution of autochthonous OM into the *P. coarctata* meadows (Saha et al., 2022). This was evident in our study where the salinity showed negative corelationship with sediment OM in the top 10 cm (Supplementary S3).

Consequently, grazing by cattle is an important factor in the *P. coarctata* meadows of Chandipur and Rushikulya (Figure 2a), which reduces significantly the canopy height (<5 cm) of the plants (authors personal observation). Despite *P. coarctata* being considered as highly efficient in sediment trapping, the reduction in canopy height by cattle grazing also significantly reduces this eco-engineering trait of the species as observed for other marine macrophytes and saltmarsh ecosystems globally (Islam et al., 2022; Mishra and Apte, 2020; Mishra et al., 2021; Tessier et al., 2003), thus reducing their capacity to filter particulate OM during daily tidal influx. This reduction due to grazing also affects the *P. coarctata* density which is lowest at Chandipur and Rushikulya compared to the other two locations. However, grazing at these two locations is halted during the monsoon (due to flooding risks to cattle's), which helps the *P. coarctata* meadows to avoid the grazing pressure and increase their density and biomass, as observed in the post-monsoon season (Figure 6).

The sediment OM range observed from surface to 30 cm depth in pre-monsoon (3.12–11.47%) and post-monsoon (3.44–12.68%) seasons in this study are within and higher than the sediment OM range observed for other saltmarsh species (4.13–7.13%) from the east coast of India (Kaviarasan et al., 2019), but lower than sediment OM (4.9-16.9 %) observed from Gulf of Kutch, Gujarat on India's west coast (Jagtap et al., 2002). Similarly, the variation observed in this study for high sediment C_{org} in post-monsoon (2.42–13.44%) compared to pre-monsoon season (2.03–12.31%) has also been observed in the *P. coarctata* meadows from the Bhitarkanika National Park (0.64-2.71%), from Sundarbans (2.0–4.0%) (Banerjee et al., 2022; Chowdhury et al., 2023), and other mixed saltmarsh species (2.18-3.81%) ecosystems of India (Kaviarasan et al., 2019). The higher sediment C_{org} in our study sites could be due to higher autochthonous contribution from *P. coarctata* associated plant materials (roots, rhizomes and leaves) and sediment trapping capacity of these plants due to their high densities at locations like Dhamra and Astaranga. It is also important to note here that these high sediment C_{org} in both seasons were mostly observed at Dhamra and Astaranga locations, which have local anthropogenic impacts. In Dhamra, there is a continuous bottom dredging (due to the presence of port) and associated OM deposition to *P. coarctata* meadows, whereas in Astaranga there is agricultural and aquaculture run-off into *P. coarctata* meadows and associated increase of primary productivity that contributed towards high sediment OM and C_{org} (Akhtar et al., 2021; Pradhan et al., 2009; Pramanik, 2019). These dense *P. coarctata* meadows at Astaranga also trap inflowing mangrove leaves and decaying matter (observed during field sampling) that can enrich the sediment C_{org}. Conversely, these dense *P. coarctata* meadows also trap high amount of autochthonous OM derived from *P. coarctata* biomass, that may have contributed towards the high C_{org} in the sediment. This relationship between high OM input resulting in high C_{org} was observed in our study (Supplementary S5). Consequently, various saltmarsh species inhabiting the low intertidal areas and have demonstrated high sediment C_{org} globally (Chen et al., 2016; Miller et al., 2023; Qu et al., 2019; Yuan et al., 2022).

In our results, there is a positive influence of sediment OM on *P. coarctata* sediment C content in post-monsoon season, when nutrient inflow from different sources is higher from riverine and land run-off resulting in high primary productivity and generation of marine POM (Figure 5b). These different sources of OM input in the sediment are clearly inferenced from the sediment $\delta^{13}C$ isotopic signatures, showing presence of marine particulate organic carbon (POC) and dissolved organic carbon (DOC) (Figure 5b). Seasonal influence showcasing input of marine POC and DOC has been observed for the *P. coarctata* meadows of Chandipur from the east coast of India, but for Dhamra, Astaranga and Rushikulya these are first time inferences (Saha et al., 2022).

In general, the contribution of sediment C_{org} to the total ecosystem carbon stocks is higher compared to plant biomass contributions in blue carbon ecosystems (Human et al., 2022; Miller et al., 2022; Nazneen et al., 2022; Perera et al., 2022; Stankovic et al., 2023). This study, followed a similar pattern for blue carbon ecosystems, with sediment C_{org} contributing >70% of the ecosystem Corg stocks, and *P. coarctata* total biomass (AG +BG) contributing 30% in pre-monsoon and 29% in post-monsoon season (Figure 7). This variation in sediment and biomass contribution towards total ecosystem carbon stocks has also been observed for *P. coarctata* meadows along the east coast that are adjacent to mangrove ecosystems (Banerjee et al., 2022; Begam et al., 2017; Chowdhury et al., 2023) and with other mixed saltmarsh species from the coast of India (Kaviarasan et al., 2019). In this study, the highest mean sediment C_{org} stocks were observed in the mono-specific patches of *P. coarctata* meadows of Astaranga (57.04 ±5.99 Mg C), which is 1.3-fold higher than previously observed sediment C_{org} stocks for *P. coarctata* meadows of the Mahanadi delta (44.79 ± 0.23) and the Bhitarkanika National Park (42.08 ± 1.15) that are adjacent or mixed with various mangrove species (Table 2). One of the reasons for these differences in sediment C_{org} stocks is the sediment core depth sampled. In this study we have used sediment core depth till 30 cm (thus including the long-term C_{org} stocks) and the other authors have used sediment C_{org} from the top 10 cm only, which is very dynamic and subjected to significant loss of OM and associated C_{org} due to tidal fluctuations and decompositions (Campbell et al., 2022b; Mason et al., 2023a; McMahon et al., 2023; Perera et al., 2022). Consequently, the other difference between mono-specific and adjacent/mixed with mangrove *P. coarctata* meadows may be the vegetation structure of *P. coarctata*, which is low when present with mangroves (due to shading, grazing or competition with other saltmarsh species) compared to mono-specific meadows, where the plant canopy height can reach 60 cm in post-monsoon with dense shoots and roots (Mishra and Farooq, 2022a). The role of dense AG and BG vegetation cover is directly proportional to the higher accumulation and burial of sediment C_{org} compared to low dense vegetation areas (Alongi, 2020; Mcleod et al., 2011).

Similarly, the *P. coarctata* sediment C_{org} stocks observed in this study are also similar to sediment C_{org} stocks (at 30 cm) of mixed mangrove ecosystems of the Mahanadi delta (54.3 ± 7.4 Mg C) and Bhitarkanika Mangrove (54.3 ±3.0 Mg C) ecosystems and 3-fold higher than Bhitarkanika Mangrove ecosystems of the east coast of India, that are subjected to continuous wood harvesting and anthropogenic habitat disturbances (Bhomia et al., 2016; Pattnayak et al., 2019; Rasquinha and Mishra, 2021; Sahu et al., 2016). This suggests mono-specific dense *P. coarctata* meadows can have similar sediment C_{org} stocks that of mixed mangrove ecosystems, which informs about the ecological importance of *P. coarctata* meadows towards climate change mitigation.

The total meadow area of the *P. coarctata* at each location also influenced the total C_{org} stocks on ecosystem scale with Astaranga (110 ha) having the highest (10497 Mg C) and Rushikulya (30 ha) the lowest (1734.91 Mg C) C_{org} stocks across both seasons, even though Chandipur (200 ha) had the lowest mean sediment and biomass C_{org} stocks among the four locations (Figure 6a).

4.2. Influence of Seasonality on P. coarctata Traits and Carbon Stocks

Even though the majority of the C stocks are stored in the sediment, the vegetative component is still an important part of the overall C_{org} stocks assessment of estuarine systems (Nazneen et al., 2022; Radabaugh et al., 2017; Stankovic et al., 2023). This was observed in our study, where *P. coarctata* biomass contributed 30% towards the total ecosystem Corg stocks in both seasons. The BG-biomass of *P. coarctata*, contributed 1.6-fold higher biomass than AG-biomass towards the ecosystem Corg stocks and this contribution was higher in post-monsoon season (Figure 6). This is a direct influence of sediment deposition (during monsoon) or erosion (during pre-monsoon) at these study locations, which leads to *P. coarctata* investing increased amount of energy towards BG-structures to survive in the changing environment. This behaviour of *P. coarctata* has not been previously reported from India, but *P. coarctata* meadows from the coast of Bangladesh and other saltmarsh species from the coast of the USA have shown this unique feature of increase BG-biomass growth in response to sediment deposition or erosion (Hughes et al., 2018; Mariotti and Carr, 2014; Rahaman et al., 2013; Tang et al., 2020; Wu et al., 2021). This BG-biomass growth is also supported by increase in nutrient input in the monsoon and its subsequent utilization in post-monsoon season as evidenced by total N content in biomass of *P. coarctata* (Supplementary S7). This external N input is also further supported by the $\delta^{15}N$ values which were heavier in post-monsoon season and values >5‰ in biomass (5.2–7.8‰) indicated anthropogenic input (Supplementary S3). This external N input was higher in Chandipur, Dhamra and Rushikulya locations of our study, through riverine input, whereas at Astaranga, this external N input was dominated by aquaculture outflows (Akhtar et al., 2021; Pradhan et al., 2009). Similar influence of external N input and variation in stable isotope signatures have been observed from the coast of India for *P. coarctata* (Saha et al., 2022) and from the coast of China for invasive saltmarsh species like *Spartina alterniflora* and other seagrass species (Du et al., 2019; Jiang et al., 2019; Lin et al., 2021). This external N input also supported the growth of salt-tolerant estuarine micro and macroalgae that were attached to the *P. coarctata* leaf and rhizome structures as epiphytes, as inferenced from $\delta^{13}C$ isotopes of biomass (Figure 5c). This showcases, the influence of seasonality on the *P. coarctata* biomass generation and its contribution towards the total ecosystem C_{org} stocks, which has been observed for saltmarsh ecosystems around South Asia (Billah et al., 2016; Hena et al., 2007; Hossain et al., 2016; Perera et al., 2022; Prasad et al., 2014) and in other areas (Chen et al., 2016; Human et al., 2022; Miller et al., 2023; Qu et al., 2019; Yuan et al., 2022).

4.3. Total Carbon Stocks of P. coarctata Ecosystems

The *P. coarctata* ecosystem (sediment 30 cm + biomass) C_{org} stocks showed high standard deviation between the four locations in post-monsoon compared to pre-monsoon season (Figure 7) because of the C_{org} differences in saltmarsh sediment and biomass. Secondly, the total meadow size of *P. coarctata* for each of the four locations [i.e., Chandipur (200 ha), Dhamra (93 ha), Astaranga (110 ha) and Rushikulya (30 ha)] were different. For example, the total ecosystem C_{org} stocks in Chandipur was lowest (12-14 Mg C ha^{-1}) among the four locations in both seasons, but when extrapolated to the total meadow size, the *P. coarctata* meadows of Rushikulya was observed with lower Corg stocks (Figure 7). This suggests that the total area of the saltmarsh meadow plays an important role while quantifying the ecosystem wide C_{org} stocks (Campbell et al., 2022b; Human et al., 2022; McMahon et al., 2023; Perera et al., 2022; Saha et al., 2022). A similar impact of saltmarsh meadow size affecting the ecosystem C_{org} stocks has been observed for *P. coarctata* meadows from the east coast of India that were associated with mangroves(Banerjee et al., 2022; Begam et al., 2017; Chowdhury et al., 2023).

The total C_{org} stock in our studies is limited to the top 30 cm of sediment depth across mono-specific P. coarctata meadows and the recommended standard extrapolation to sediment depth of 1m was avoided. Similarly, in terms of saltmarsh meadow perspective, the estimated C_{org} stocks is only for 443 ha, as the total area of *P. coarctata* meadows for the coast of Odisha is not available. Avoiding this extrapolation was necessary, because in India there is significant lack of species-specific studies on saltmarsh C_{org} stocks and this extrapolation would have provided biased information about *P. coarctata* C_{org} storage potential, as saltmarsh carbon storage is a species-specific trait as observed from the current available literature (Table 2). Other than species-specific traits the C_{org} stocks in saltmarsh ecosystems is also dependent on local abiotic factors, hydrodynamics, land runoff, anthropogenic habitat disturbances, and grazing (Cruz de Carvalho et al., 2020; Di Bella et al., 2015; Gorham et al., 2020a; Islam et al., 2022; Radabaugh et al., 2017; Yang et al., 2020). Based on the International Panel for Climate Change (IPCC, 2014) Tier II assessment the *P. coarctata* meadows (443 ha) of the four locations in pre-monsoon and post-monsoon can help in avoiding the emissions of 8431.34 and 14757.84 Mg CO_2 respectively (Howard et al., 2014). Based on the amount of C_{org} stored in the *P. coarctata* meadows from the coast of Odisha, the price of CO_2 stored is around US$39.88 million and INR 3314.87 million. Our values are for the first time estimate the CO_2 equivalent storage potential for saltmarsh ecosystems of India.

4.4. P. coarctata Ecosystem Carbon Stocks and Their Role in India's NDC

India, has pledged to reduce 33-35% of its CO_2 emissions by 2030 under its Intended Nationally Determined Contributions (INDC) commitment under Paris Climate Agreement (UNFCC, 2015). The National Action Plan on Climate Change (NAPCC) has emphasized on the importance of conservation and management of India's blue carbon ecosystems towards achieving the NDC's, where mangrove ecosystems are in focus. This study showcases that, saltmarsh ecosystems of India have similar potential for carbon storage as that of mangroves, when least disturbed. According to this study, the total CO_2 equivalent reduction potential across pre and post-monsoon season for *P. coarctata* meadows from the coast of Odisha (Chandipur + Dhamra + Astaranga + Rushikulya= 443 ha) is 8431.34 and 14757.84 Mg CO_2. However, it is important to note here that *P. coarctata* meadows of this study represent only 443 ha area of India's coastal area and have the potential to accumulate 0.0009% (23189.18 tons) of India's current 2.5 billion tons of CO_2 emissions per year (Karstensen et al., 2020). This fraction is very small considering India's total CO_2 emissions. However, it is important to note here the *P. coarctata* meadows of this study only represent 443 ha of India's 290 km^2 of saltmarsh ecosystems which will showcase a different carbon storage and emission avoidance capacity. It is further important to map out the mono-specific meadows of *P. coarctata* and the *P. coarctata* meadows that are associated with other saltmarsh or mangrove ecosystems along the coast of India to quantify their carbon storage potential as seascape connectivity between coastal ecosystems plays an important role in increasing carbon stocks (Banerjee et al., 2017; Begam et al., 2017; Mishra and Apte, 2020; Mishra et al., 2023).

Furthermore, the blue carbon storage potential of species-specific saltmarsh ecosystems needs more detailed studies where the influence of anthropogenic pollution, habitat disturbances and the effects of climate change on carbon storage potential can be explored. Saltmarsh ecosystems of India are also missing in any of the climate change mitigation plans (Koshy et al., 2018; Ramesh et al., 2018; Stankovic et al., 2023), whereas mangroves are considered as the sole NbS towards climate change mitigation. Recent studies have showcased that both saltmarsh and seagrass ecosystem of India have significant capacity to store carbon in their ecosystems (Bal and Banerjee, 2019; Banerjee et al., 2022; Mishra et al., 2023; Stankovic et al., 2023)and combined with mangroves they can help in achieving India's NDCs. However, this study showcases the importance of mono-specific saltmarsh meadows that inhabits the lower intertidal zone, whereas there are other saltmarsh species that inhabits the high tide zone (Gopi et al., 2019; Mishra and Farooq, 2022b, 2022a; Viswanathan et al., 2020) and have significant carbon storage capacity and also are associated with mangroves along the coast of India. Loss of these saltmarsh ecosystems can turn these carbon sink ecosystems as carbon sources to fuel up the climate change (Campbell et al., 2022b; Gorham et al., 2020b; Perera et al., 2022; Serrano et al., 2019). Therefore, these blue carbon ecosystems need better protection and management and can be added into the Mangroves for the Future programs of the NAPCC. Therefore, together will mangroves and seagrass, these saltmarsh ecosystems can play an important role as NbS towards climate change mitigation and adaptation plans of India (Mishra and Farooq, 2022a; Perera et al., 2022; Stankovic et al., 2023)

5. Conclusion

This study for the first time estimated the C_{org} stocks in mono-specific meadows of *P. coarctata* meadows without adjacent mangrove ecosystems across pre-monsoon and post-monsoon seasons from the coast of Odisha, India. This study addressed one of the important knowledge gaps (having an IPCC Tier-II assessment) in saltmarsh blue carbon research in India, showcasing the carbon storage potential of an ecologically important yet data deficient saltmarsh species (Mishra and Farooq, 2022a; Phillips, J., & Yang, 2017). There is a significant loss of these ecosystems towards coastal development and mangrove restoration (Begam et al., 2017; Mishra and Farooq, 2022a), despite these mono-specific patches of *P. coarctata* meadows have similar or higher range of climate relevant C_{org} stocks compared to mangroves. Notably for the first time this study provides information about the CO_2 equivalent in P. coarctata meadows and the social cost of carbon for saltmarsh ecosystems of India. Further studies are required to analyse the effects of various anthropogenic disturbances and habitat connectivity between saltmarsh and mangrove ecosystems, particularly as NbS for climate change mitigation plans for the state of Odisha and India. Integration of saltmarsh ecosystem services with NAPCC is essential and important for better management of non-mangrove ecosystems from India's coast.

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