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Technical Report

The present state-of-the-art of blue carbon repository in India: A meta-analysis

Anirban Akhand[1], Abhra Chanda[2]*, Yusuf Jameel[3], Rajarshi Dasgupta[4]

[1]Coastal and Estuarine Environment Research Group, Port and Airport Research Institute, Yokosuka, Kanagawa, Japan.

[2]School of Oceanographic Studies, Jadavpur University, Kolkata, West Bengal, India.

[3]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, USA.

[4] Integrated Sustainability Centre (ISC), Institute for Global Environmental Strategies, Kamiyamaguchi, Hayama, Kanagawa, Japan.

*Corresponding Author: Abhra Chanda (Email: abhrachanda1985@gmail.com)

Abstract

The present study collated data on the Indian blue carbon repository (mangroves, seagrasses, and salt marshes) from peer-reviewed literature on carbon stock assessment. This meta-analysis indicated that the blue carbon ecosystems of India could have a collective carbon stock of 67.35 Tg C (mangroves, seagrass, and salt marsh accounting for 67 Tg C, 0.0630 Tg C, and 0.0049 Tg C, respectively). Several studies have ubiquitously measured the spatial extent of mangroves (~4991 km^2) and seagrasses (~517 km^2) in India; however, the salt marshes (290 – 1398 km^2) have contradictions in estimates. The green payments against the blue carbon ecosystems of India can be as high as ~ 9.6 billion US $, whereas the social cost of carbon sequestered by these ecosystems can vary between 0.47 and 5.43 billion US $. The present study also identified the key research areas that require priority to minimize the uncertainties in blue carbon stock assessment to foster a robust ecosystem-based approach for climate change adaptation in the country. The study identified that less than half of the total mangrove habitats of India are yet to be sampled leaving a scope of substantial uncertainty in nationwide blue carbon estimates. The spatial extent of India's salt marshes is another aspect that needs to be delineated with a higher confidence level.

Keywords: Blue carbon; mangrove; seagrass; salt marsh; aboveground biomass; belowground biomass; soil carbon pool

1. Introduction

Ever since the menace of anthropogenic greenhouse gas emissions has been recognized, the global scientific community has been desperately looking for options to mitigate climate change (Alongi, 2020). In this regard, the coastal vegetated ecosystems have been identified to play a crucial role in sequestering atmospheric carbon dioxide (CO_2) that can enable us to achieve climate change mitigation at the national and global scales (Taillardat et al., 2018).

The term blue carbon refers to the carbon stored by the vegetated coastal habitats throughout the globe. By definition, blue carbon is the carbon captured by marine living organisms (Nellemann et al., 2009). Mangroves, seagrasses meadows, and tidal salt marshes are the conventional blue carbon ecosystems, which sequester carbon in their living aboveground biomass (AGB) (leaves, stems, and branches), belowground biomass (BGB) (roots), non-living biomass (like litter and deadwood), and underlying sediments (Bertram et al., 2021). Blue carbon may sequester over the short term (decennial) in biomass and over longer (millennial) time scales in sediments (Macreadie et al., 2017; 2019). The mangroves are distributed from the tropics to subtropics, whereas seagrass is abundant from the polar to tropical areas (Pendleton et al., 2012). The approximate estimates of blue carbon stock in mangroves, seagrasses, and saltmarshes per unit area are 956 Mg C ha^{-1}, 142 Mg C ha^{-1}, and 593 Mg C ha^{-1}, respectively (Twilley et al., 1992; Donato et al., 2011; Fourqurean et al., 2012; Alongi, 2014; Ouyang and Lee, 2014; Saderne et al., 2019). Carbon burial rates for the mangrove and seagrass are 34.4 ± 5.9 Tg yr^{-1}and 48–112 Tg yr^{-1}, respectively (Pendleton et al., 2012 and the references therein). Ever since the global scientific community recognized the ill effects of anthropogenic carbon emission and the menace of climate change, they have been looking for solutions to combat this evil by reducing emissions from direct deforestation and forest degradation (Andoh and Lee, 2018; Duchelle et al., 2018; Jackson and Sparks, 2020). Deforestation and forest degradation contribute to approximately 11 percent of carbon emissions, and various United Nations (UN) mechanisms, including the widely-referred Reducing emissions from deforestation and forest degradation (REDD+) program proposed offering economic incentives for developing countries to reduce emissions. The mode of operations includes reducing deforestation, halting forest degradation, conservation of forest C stocks, enhancement of forest C stocks, and sustainable management of forests (Johnson et al., 2019). In addition, under the Paris agreement, The Nationally Determined Contributions

(NDCs) provide an opportunity to report the extent of carbon captured as a measure of the country's voluntary reduction of carbon emissions. The carbon sequestration potential of the blue carbon ecosystems offers tremendous potential to offset the carbon emissions (Taillardat et al., 2018; Alongi, 2020).

Several marine ecosystems do not meet the essential criteria for inclusion within the blue carbon framework, despite participating in the global carbon cycle. For example, coral reefs and oyster reefs dominated habitats contribute to climate change adaptation through energy dissipation and contribution to sediments, but not through greenhouse gas mitigation, as the process of calcification releases CO_2 (Lovelock and Duarte, 2019). On the other hand, pelagic ecosystems, like marine fauna and phytoplankton, have been suggested to be included as blue carbon ecosystems; however, their contribution to climate change mitigation through long-term carbon preservation is still debatable (Lovelock and Duarte, 2019). In the present date, specifically, the three coastal ecosystems, namely mangroves, seagrass, and tidal marshes, are ubiquitously established as blue carbon ecosystems because of their high carbon stocks, long-term carbon storage capacity, potential to manage greenhouse gas emissions, and other adaptation characteristics (Kuwae and Hori, 2019; Macriedie et al. 2019; Chen and Xue, 2020). Owing to their potential in offsetting the atmospheric carbon imbalance, several authors have advocated that assessment of the carbon stocks in these ecosystems at a nationwide scale is beneficial for both formulating adequate conservation and adaptation strategies as well as facilitating their proper inclusion in the carbon-financing network (Taillardat et al., 2018; Gallagher, 2017).

India, in this regard, has a long coastline of > 7500 km and shelters all these three blue carbon ecosystems (Kathiresan, 2018; Jayanthi et al., 2018; Thangaradjou and Bhatt, 2018; Viswanathan et al., 2020). The mangrove ecosystem is the principal and relatively well-studied blue carbon ecosystem in India. The mangroves in India cover an area of 4991 km^2 (Indian State of Forest Report, 2021). The east coast and west coast harbor 60 % and 14 % of these mangroves, respectively. The Andaman and Nicobar Islands shelter the remaining 26%. India and Bangladesh share the Sundarban mangroves, the world's largest single tract of mangrove forest. Sundarban (2112 km^2) followed by Bhitarkanika (130 km^2) and Pichavaram (10 km^2) are some of the prominent mangrove forests of India (Dasgupta and Shaw 2013).

Seagrass meadows in India thrive in both shallow coastal water and offshore islands. India, at present, shelters approximately 517 km^2 seagrass cover (Geevarghese et al., 2016). The east coast of India shelters the majority of seagrasses in Palk Bay (330 km^2), Gulf of Mannar (69 km^2), and Chilika Lagoon (85 km^2), with smaller patches observed on the west coast in the Gulf of Kutch, Gujarat, and in the lagoons of Lakshadweep in the Arabian Sea, and the Andaman and Nicobar waters in the Bay of Bengal (Ganguly et al., 2018). Fourteen species of seagrass have been identified from the Indian coast, belonging to seven genera, of which Palk Bay has the highest seagrass species diversity (Patro et al., 2017). Thangaradjou and Bhatt (2018) reported sixteen seagrass species with an approximate cover of 500 km^2 at isolated locations along the coast, lagoons, backwaters, and estuaries. In India, salt marshes are distributed in seven coastal districts/union territories, viz. Gujarat, Daman and Diu, Maharashtra, Tamil Nadu, Puducherry, Andhra Pradesh, and Andaman & Nicobar Islands, covering an approximate area of 1600 km^2 (Banerjee et al. 2017).

In the present study, we summarized state-of-the-art data on the blue carbon repository of India (Fig. 1) and estimated the social cost of this blue carbon, i.e. the cost that the global environment has to bear for a unit carbon emission towards the atmosphere (Bertram et al., 2021). We considered three ecosystems, i.e., mangroves, seagrass, and salt marshes, as blue carbon ecosystems because only the scientific community unanimously accepts these three as blue carbon ecosystems (Lovelock and Duarte, 2019). From the available published peer-reviewed literature, we further investigated the dominant species and genera contributing to the blue carbon stock of India. We also characterized the natural and anthropogenic threats that these ecosystems face at present.

2. Methodology

2.1 Review and search strategy

We used Google search engine and literature databases 'Google Scholar', 'PubMed', 'Web of Science' and 'ScienceDirect'. We searched for the publications using key terms like 'blue carbon', 'mangrove', 'aboveground biomass', 'belowground biomass', 'mangrove soils', 'carbon stock', 'seagrass', 'saltmarsh', 'tidal marsh'. We searched these terms in combination with the name of the country 'India' and its coastal states namely 'West Bengal', 'Odisha', 'Andhra Pradesh', 'Tamil Nadu', 'Kerala', 'Maharashtra', 'Goa', and 'Gujarat', and the 'Bay of Bengal' and the 'Arabian Sea'. We also searched using the names of the coastal union territories of India, namely 'Lakshadweep', 'Daman and Diu', 'Puducherry', and the 'Andaman and Nicobar Islands'. We downloaded the published papers utilizing institutional access to 'ScienceDirect' and the 'Google Scholar' search engine. The present review and subsequent data synthesis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009).

2.2 Selection criteria of papers

Based on primary screening, 235 potentially eligible research articles were shortlisted. Followed by this, the full text of those articles was downloaded. Research articles with unavailable full-text were excluded from this review. Research articles published only in the English language were considered in this study. Selection criteria of the papers were i) articles that are original work and not review papers, ii) articles for which full-text is available on the internet, iii) articles published anytime i.e. no timeframe was set, and iv) articles that had the data of at least one of the three blue carbon ecosystems (mangrove, seagrass, and saltmarsh or tidal marsh) considered in this study.

2.3 Data extraction and compilation

Only the mean data of blue carbon stock per unit area reported from any region within India were considered in this study. Following the above-mentioned searching strategy and selection criteria, we considered 35 published papers and edited book chapters where the authors have quantified estimates of blue carbon from the different locations in India. We converted all data of the blue carbon repository to a single unit, Mg C ha^{-1}.

While collating the data, we observed that many locations were sampled more than once and have multiple results. At the same time, not all of these studies took into account all the compartments (like aboveground carbon (AGC), belowground carbon (BGC), and soil carbon) to quantify the total blue carbon stock for the entire region. Under such circumstances, we calculated the mean of blue carbon stock per unit area (from all the available studies on that site) in each of the compartments of that ecosystem and multiplied it with the total area of that site. In this way, we computed the total blue carbon in each compartment and added the resultants to derive the total blue carbon stock at each site. Many of the sites in the case of all three blue carbon ecosystems were not sampled at all. To derive an approximate estimate of the nationwide blue carbon stock for India, the existing data (on region-specific total carbon stock) for each of the ecosystems were upscaled by assuming that the already measured carbon content per unit area holds for the entire coverage of that ecosystem in the country. In other words, the average blue carbon stock per unit area of a particular blue carbon ecosystem (computed from the existing data) was multiplied to the spatial extent of the area that underwent no sampling to date. Based on the number of studies conducted and the area of each blue carbon ecosystem covered throughout India, the uncertainty in nationwide blue carbon estimation was gauged. The parameter of whether all the blue carbon compartments were considered or not also enabled us to develop an idea of the uncertain aspects of the blue carbon estimation that requires attention in the future.

3. Results and Discussion

3.1 The variability of blue carbon stock in the Indian mangrove ecosystem

Published literature suggests that the aboveground biomass contributes most to the blue carbon stock, followed by soil organic carbon and belowground biomass (Table 1). Bhitarkanika mangrove forest has the maximum range of aboveground and belowground biomass carbon (55 to 720 Mg C ha^{-1}and 23 to 220 Mg C ha^{-1}) amongst all mangrove forests of India (Rasquinha and Mishra 2020) studied so far. Though Sundarban is the largest mangrove forest in the world (and India), the carbon stock of Sundarban per unit area is lesser than Bhitarkanika, Pichavaram mangrove, and Vypin Cochin mangrove region but comparable with that observed in the Gulf of Kachchh (Table 1). Ray et al. (2011) stated that the carbon stock of Sundarban is lower than a typical terrestrial tropical forest. They also depicted that the soil pH is the principal (35.2%) contributing factor in mangrove biomass as well as carbon stock, followed by soil salinity (26.2%) and nutrients (15.2%, total inorganic nitrogen, and total extractable phosphorus). However, Banerjee et al. (2013) and Mitra et al. (2011) reported that the relatively higher salinity in the central region of Sundarban caused the subsequent lowering of biomass and hence, the carbon content in the mangrove floras of this region. Chowdhury et al. (2019) indicated that freshwater scarcity due to reduced flow from upper reaches has led to a significantly elevated degree of salinization in the mangrove soils of Sundarban. The reduced riverine flow decreased the nutrient replenishment and that, in turn, has taken a heavy toll on the proper physiological functioning of several mangrove species. However, to combat the ongoing degradation of the Sundarban mangroves (Indian part), several restoration and conservation endeavors have been undertaken in the past two to three decades that include afforestation of around 17,000 ha of mangrove habitat maintaining the intrinsic species diversity (Vyas and Sengupta 2012).

Rasquinha and Mishra (2020) emphasized the impact of harvesting mangroves on the aboveground and belowground biomass carbon stock. They observed that the local people in Bhitarkainika harvest mangroves for fuel demands. Integrated management plans to accommodate the local cultural and economic needs have become a dire need to prevent such indiscriminate harvesting. Bhomia et al. (2016) stated that harvesting pressure and changes in land use (like conversion of mangrove habitats to aquaculture) adversely affect the carbon stock of mangroves. They suggested proper management practices by enabling these communities to avail themselves of carbon offset/conservation payments under approved climate change mitigation strategies and actions.

Joshi and Ghose (2014) attributed tidal inundation level as a crucial regulatory factor for mangrove biomass while working in the Lothian Island of Sundarban. They also stated that freshwater turnover is a governing factor for mangrove growth. They further observed that low salinity regimes are principally responsible for enhanced species diversity and mixed vegetation community, which leads to higher blue carbon stocks. Sahu et al. (2016) observed that available nitrogen showed a negative correlation with total plant biomass while working on the Mahanadi mangroves.

The study of the species-specific biomass of different mangrove species showed marked variability amongst the biomass carbon stock (Table 2). In Sundarbans, *Avicennia marina* showed the highest above ground carbon (AGC) per unit area, followed by *A. alba* and *A. officinalis* (Ray et al. 2011; Banerjee et al. 2013; Raha et al. 2013). In Bhitarkanika, *A. officinalis* was the highest contributor to AGC, followed by *Heritiera littoralis* and *H. fomes*

(Anand et al. 2020; Banerjee et al. 2020). In contrast to the mangrove forests of the east coast, *Rhizophora mucronata* showed the highest AGC in the Vypin-Cochin region on the west coast of India (ShyleshChandran et al. 2020). However, in the Gulf of Kachchh, *Avicennia marina* exhibited a wide range of AGC (Thivakaran et al. 2020).

The biomass of different mangroves species showed diverse dynamics with salinity. Banerjee et al. (2013) reported a significant negative correlation of soil salinity with the biomass carbon stock of *Sonneratia apetala*, whereas a significant positive correlation with *A. alba* and *Excoecaria agallocha*. They stated that a negative correlation between *S. apetala* biomass and salinity reflects the sensitivity of this species to ambient salinity, and a significant positive correlation between salinity and other two species signifies high salinity tolerance of those species (*A. alba* and *E. agallocha*). Banerjee et al. (2012) depicted an increase in mangrove soil organic carbon and soil pH in the western part of Indian Sundarbans. Mitra et al. (2012) also reported that the mangrove forest in the eastern Indian Sundarbans exhibits comparatively lower organic carbon density, and the organic carbon and carbon density decreased with depth. Banerjee et al. (2020), while working in the Bhitarkanika mangroves, reported that with increasing carbon load in the soil, the growth of *A. marina* decreases, whereas *A. officinalis* and *X. granatum* exhibited an opposite trend. In this regard, Sandilyan et al. (2010) stated that the salinity rise has accentuated and affected almost all the mangrove habitats of India. They indicated that the change in the salinity region not only compromises the species diversity but also disrupts the biological productivity of this crucial ecosystem. In the highly saline Gulf of Kachchh region, *Rhizophora mucronata* and Ceriops tagal exhibited very low AGC; however, the AGC in *Avicennia marina* stands was significantly high in several sites (Thivakaran et al. 2020), indicating that *A. marina* acclimatizes well in the polyhaline circumstances and stores a substantial quantity of carbon.

Though the blue carbon ecosystems of India store substantial quantities of carbon; these ecosystems are under severe threats of varying types. Regional sea-level rise, coastal erosion, anthropogenic conversion to aquaculture plots, recurrent tropical cyclones are some of the potential hazards that take a heavy toll on the mangroves of India (Chaudhuri et al., 2015). Unlike the mangroves, the seagrasses and salt marshes of India have received much less attention from the perspective of assessing the threats. However, Ganguly et al. (2017) and Banerjee et al. (2018) pointed out that fishing operations with mechanically operated boats and trap nets, tourism activities, and discharge of untreated nutrient-rich discharges from industries and aquaculture ponds can significantly deteriorate the functioning of the seagrasses in India. Patro et al. (2017) mentioned a near absence of threat assessment in the Indian salt marshes; however, they pointed out that the salt marshes are also susceptible to coastal eutrophication, pollution, and overgrazing. Moreover, the perception of salt marshes as wastelands prevails in many parts of India, which leads to neglect not knowing their potential in sequestering carbon and offering various ecosystem services.

3.2 Carbon stock in the Indian seagrasses and salt marshes

The available literature suggests that amongst the seagrass distribution in India, the biomass and carbon stock data are available only from the Palk Bay and Chilka Lagoon. Unlike mangroves, the aboveground biomass carbon of the seagrass was significantly lower than the belowground biomass. Amongst the 14 species of seagrass reported from the Palk Bay, *Cymodocea serrulata* and *Syringodium isoetifolium* are the most dominant (Govindasamy and Arulpriya 2011; Ganguly et al. 2017). Ganguly et al. (2017) reported the total organic carbon stored as seagrass biomass in the Palk Bay (0.94 Mg C ha^{-1}). They also observed that the partial pressure of CO_2 in water and photosynthetically active radiation best explained the variability of net community production (NCP) of seagrass meadows in the Palk Bay. Ganguly et al. (2018) reported the aboveground biomass was between 0.20 and 0.96 Mg C ha^{-1}, whereas the belowground biomass carbon ranged between 0.31 and 2.93 Mg C ha^{-1} while working in both Palk Bay and Chilika Lagoon. Organic carbon in the top 1 m soil in the seagrass meadows ranged between 107 and 143 Mg C ha^{-1} (Ganguly et al. 2018). Ganguly et al. (2018) also reported that *Cymodocea* sp. showed the highest biomass amongst the five species studied. They recorded the highest recorded NCP from the mixed bed of *Thalassia hemprichi* and *Syringodium isoetifolium*. They also attributed biomass density, changes in species compositions, and richness to the long-term burial and storage of organic carbon.

We found only four studies on the salt marsh carbon stocks from India. Kaviarasan et al. (2019) reported the biomass and carbon stock of four salt marsh species, *Suaeda maritima*, *Sesuvium portulacastrum*, *Arthrocnemum indicum*, and *Salicornia brachiata* from Tuticorin, southeast coast of India. They reported the highest AGB in *A. indicum* in both dry and wet seasons (10.91 ± 0.15 g cm^{-2} and 14.87 ± 0.68 g cm^{-2}), whereas they reported the highest BGB in *S. maritima* in both seasons, as 2.01 ± 0.35 g cm^{-2} and 4.49 ± 0.35 g cm^{-2}, respectively. They also reported sediment organic carbon stocks, which ranged between 8.42 ± 0.64 to 54.46 ± 1.46 Mg C ha^{-1}. Chaudhary et al. (2018) observed that the salt marsh species *Salicornia brachiata* dominates the Gujarat coastlines. They observed that the AGC varied between 0.05 and 2.21 Mg C ha^{-1}, whereas the BGC ranged from 0.009 to 0.335 Mg C ha^{-1}. These observations were in parity with Rathore et al. (2016). They also worked in the coastal regions of Gujarat and reported a soil organic carbon stock varying between 4.5 and 8.2 Mg C ha^{-1}. Das et al. (2015), while working on the salt marshes in and around the Sundarban region, observed much lesser AGC and BGC compared to what was reported by Rathore et al. (2016), Chaudhary et al. (2018), and Kaviarasan et al. (2019). However, they observed a moderate range of 9.4 to 13.4 Mg C ha^{-1} in the salt marsh soils of the Sundarban.

3.3 An up-scaled estimate of total blue carbon stock in India

While several studies attempted to quantify the region-specific blue carbon stock within India; very few of these derived an area-integrated total estimate of blue carbon. According to the latest Indian State of Forest Report (2021), twelve states (including the union territories) have mangroves in their coastlines with a total area of 4991 km^2. Out of these states, five states and one union territory, namely West Bengal (2112 km^2), followed by Gujarat (1117 km^2), Andaman and Nicobar Islands (616 km^2), Andhra Pradesh (404 km^2), Maharashtra (320 km^2), and Odisha (251 km^2) comprise 97% of the country's mangrove cover. Table 1 shows that Gujarat, Andhra Pradesh, and Maharashtra, despite covering 1841 km^2 of mangroves, have only one study on carbon stock assessment and that too only from Gujarat, where the AGC was measured across several sites (Thivakaran et al. 2020). Ray et al. (2011), while working on the Sundarbans, derived that the total carbon stock in the aboveground and belowground live biomass accounts for 21.13 Tg C, whereas the soil carbon pool (up to 30 cm depth) holds as much as 5.49 Tg C, thus, comprising a total of 26.62 Tg C (in 2112 km^2). The composite mean AGC, BGC, soil carbon pool in the mangroves of Odisha (Bhiatarkanika and Mahanadi) per unit area was close to 145 Mg C ha^{-1}, 46.7 Mg C ha^{-1}, and 47 Mg C ha-1, respectively. Multiplication of these estimates with the total mangrove cover of Odisha (25100 hectares) shows that the state holds as much as 6 Tg C (in 251 km^2). Similarly, the soil and total biomass carbon observed in Pichavaram mangroves and Vypin-Cochin mangroves indicate that Tamil Nadu and Karnataka can store almost 0.003 Tg C (in 45 km^2) and 0.002 Tg C (in 9 km^2). Besides these states, the carbon content in all the mangrove compartments is not available. Thus, we upscaled the estimates observed for the 2417 km^2 area (comprising West Bengal, Odisha, Tamil Nadu, and Karnataka) for the entire country's mangrove cover of 4991 km^2 following a simple unitary method. This exercise shows that Indian mangrove forests can store almost 67 Tg C of blue carbon in the live biomass and soils (up to 30 cm depth).

Contrary to the mangroves, the seagrass ecosystem in India covers only 517 km^2 as per the latest estimates (Geevarghese et al. 2016), out of which 93% occurs in the Palk Bay, Gulf of Mannar, and Chilika Lagoon. Published records of carbon stock exist for all these three places in the recent past. Ganguly et al. (2017; 2018) observed that Palk Bay of Chilika lagoon stores almost 0.047 Tg C and 0.0098 Tg C, respectively. Recently, Kaladharan et al. (2020) measured the total blue carbon stock in the Gulf of Mannar and Palk Bay. Their observations for Palk Bay are in good agreement (0.043 Tg C) with Ganguly et al. (2017). Kaladharan et al. (2020) reported that the Gulf of Mannar stores almost 0.0018 Tg C. Thus, 93% of the seagrass stand in India together holds ~0.0586 Tg C. Extrapolating this estimate for the rest of the unsampled 7 %, the figure comes to around 0.0630 Tg C.

Unlike the seagrass ecosystems, there are contradicting observations about the total extent of salt marsh cover in the country. A recent study by Viswanathan et al. (2020) challenged the earlier estimates of salt marsh cover by Garg et al. 1998 (reported 1698 km^2 during the years 1992-93) and SAC (2011) (reported 1611 km^2 during the years 2007-08) and revised that total salt marsh cover in India sums up to only 290 km^2. They argued that the earlier studies considered all the halophytic grasslands in the coastal zones, which led to such overestimates. According to their estimate, out of the seven states where salt marshes thrive, Gujarat encompasses almost 158 km^2 followed by Tamil Nadu (58 km^2) and West Bengal (30 km^2), and these three states together comprise 85% of the country’s total salt marsh cover. The carbon stock assessment has been already carried out in these three states. Table 3 shows that based on the estimates of Rathore et al. (2016) and Chaudhary et al. (2018), Gujarat can store 0.0012 Tg C in the salt marsh ecosystems. Similarly, the estimates of Kaviarasan et al. (2019) and Das et al. (2015) indicate that the salt marshes of Tamil Nadu and West Bengal can store 0.0026 Tg C and 0.00036 Tg C, respectively. Thus, 85% of the country’s salt marsh area stores almost 0.00416 Tg C. Extrapolating this estimate for the rest of the 15%

unsampled area, Indian in totality stores around 0.0049 Tg C. However, considering the spatial extent of 1698 km^2 (as reported by Garg et al. 1998), the carbon stocks can be as high as 0.0286 Tg C (Fig. 2).

3.4 Monetary worth of India's blue carbon stock

The present meta-analysis of the existing data shows that the carbon content in Indian mangroves (67 Tg C) differs by many orders of magnitudes than that observed in the seagrasses (0.0630 Tg C) and salt marshes (0.0049 Tg C). Murray et al. (2011) mentioned that mangroves (18,000 US \$ ha^{-1}) have a much greater blue carbon value than salt marshes and seagrasses (8,000 US \$ ha^{-1}) in terms of the benefits that they provide to humankind. These estimates show that the mangroves of India are worth 8995 million US \$, and the seagrasses and salt marshes are worth 414 million US \$ and 232 million US \$, respectively. Thus, the cost of the total blue carbon stock of India in terms of areal cover amounts to 9.6 billion US \$. However, Pendleton et al. (2012) emphasized that the global environment has to bear a mean cost of 41 US \$ (as per the rate of US \$ in the year 2007) per ton of CO_2 emission due to the damage posed by an additional load of one ton of new carbon. The global scientific community refers to such cost as the social cost of carbon, and the estimates can vary from 7 US \$ to 81 US \$ per ton (Pendleton et al. 2012). According to these estimates (i.e., by multiplying the range of social cost of carbon mentioned by Pendleton et al. (2012) with the estimated carbon stock derived in this study), the social cost of carbon trapped in the Indian mangroves is worth 469 million US \$ to 5427 million US \$ (mean: 2747 million US \$). In the same line, the seagrasses and the salt marshes of India store carbon worth 0.441 million US \$ to 5.103 million US \$ (mean 2.583 million US \$) and 0.034 million US \$ to 0.397 million US \$ (mean: 0.201 million US \$), respectively. According to this approach, the cost of total blue carbon in India varies between 0.47 billion US \$ to 5.43 billion US \$ (mean 2.75 billion US \$). Pendleton et al. (2012) asserted that due to deforestation and degradation of global blue carbon, environmental damage worth 6 to 42 billion US $ occurs every year. The present estimates show that the higher margin of India's blue carbon worth is almost equivalent to the minimum amount of carbon lost every year globally.

3.6 Uncertainties in blue carbon estimation

Compared to the stretch and diversity of the blue carbon habitats and species composition, many of the states in India remain under-sampled or completely data-deficient. The present study indicated that mangroves in India could store much higher quantities of carbon than the other two ecosystems; however, as many as eight states (including the union territories) have no proper estimate of blue carbon stock in their mangrove stands. Thus, the present assessment derived on extrapolation could be both under- or over-estimates, as the present study indicated that 51.5%, 7%, and 15% of the country's mangrove, seagrass, and saltmarsh cover, respectively, remain to be sampled from the perspective of characterizing the blue carbon content. Moreover, many of the studies conducted localized sampling. A more holistic approach with an increased number of sampling points can enhance the confidence level of the data and minimize the uncertainties.

Very few of the studies considered in this paper carried out seasonal or inter-annual sampling. One-time sampling can potentially contribute to temporal bias. In underwater vegetations like seagrasses and salt marshes, the live biomass exhibits significant intra-annual variability (Chaudhary et al., 2018). Thus, future studies should focus on year-long sampling strategies and, if possible, for multiple years to better understand the standing carbon stock dynamics. More ground-based studies and quadrat analyses should resolve the controversies and contradictions in areal coverage, as observed in salt marshes. Besides only the spatial extent, characterizing the health of vegetations like mangroves plays a crucial role in assessing their biomass (Pandey et al., 2019). Lately, Bertram et al. (2021) assessed the global blue carbon stock in a country-wise manner. They mentioned that the spatial extent and the factors governing the carbon stocks in the blue carbon habitats are the two most potent aspects that add to the uncertainty of the entire estimation protocol.

Among the total carbon stock in the three blue carbon ecosystems estimated in this study, mangroves have the highest uncertainty as only 48.5 % of the country's mangrove cover remains sampled in this regard. Sampling in seagrasses and salt marshes covered almost 93% and 85% of the total area in India, respectively. Thus, the uncertainties in estimates of these two ecosystems should be much less than the mangroves. However, if future studies indicate that the salt marsh cover in India is beyond the assessment of Viswanathan et al. (2020) (290 km^2), then the degree of uncertainty would substantially increase, as there is a complete absence of carbon stock data from the salt marsh cover of many states. Mathur et al. (2020) prepared a policy brief on the Indian blue carbon habitats and their carbon sequestration potential. They considered a single mean value for the carbon stock per unit area in mangroves of India (368 Mg C ha^{-1}) and estimated a total CO_2 sequestration potential of 702.42 Tg CO_2 for the entire country. However, considering the spatial variability reported in the existing scientific literature base, we estimated that the total carbon content in the Indian mangroves (67 Tg C ≈ 245.7 Tg CO_2 equivalent) is much less than that approximated by Mathur et al. (2020).

4. Conclusion

Collating all the data acquired so far on blue carbon stock in India, this study infers that India could collectively store around 67.35 Tg C within the mangrove, seagrass, and salt marsh habitats. This measurement is almost 2.85 times lower than the other holistic estimates from India. The present study also shows that almost 99.5 % of this carbon stock is within the mangrove ecosystems. These observation advocates that mangrove restoration and conservation should receive priority. Conserving or enhancing the extent of mangroves can enable India to play a leading role in combatting global climate change due to anthropogenic carbon emissions. Effective restoration and afforestation endeavors should be taken up throughout the nation to enhance the blue carbon stock in all the conventional ecosystems. According to the latest estimates, mangroves encompass 4991 km^2 in India, and seagrass cover extends for around 517 km^2. However, there lies considerable uncertainty regarding the spatial extent of salt marshes in India. Many of the mangrove forests (or patches) in India are yet to receive any attention for measuring their carbon stock. However, adequate measurements exist for most of the prominent seagrass and salt marsh patches of this country. Biased sampling in some of the mangroves and the complete absence of data in the others could result in substantial underestimation or overestimation. Despite so many factors, the authors of this paper believe that the estimates derived in this study are close to ground reality. Future studies should orient accordingly to minimize the uncertainties and derive an estimate of blue carbon stock with more confidence, as payments and returns against the amount of carbon sequestered would play a crucial role in governing the blue economy of the near future.

References

Alongi DM (2014) Carbon cycling and storage in mangrove forests. Annu Rev Mar Sci 6:195−219. https://doi.org/10.1146/annurev-marine-010213-135020

Alongi DM (2020) Global significance of mangrove blue carbon in climate change mitigation (Version 1). Sci 2(3):57. https://doi.org/10.3390/sci2030067

Anand A, Pandey PC, Petropoulos GP, Pavlides A, Srivastava PK, Sharma JK, Malhi RKM (2020) Use of hyperion for mangrove forest carbon stock assessment in Bhitarkanika forest reserve: A contribution towards blue carbon initiative. Remote Sens 12(4):597. https://doi.org/10.3390/rs12040597

Andoh J, Lee Y (2018) National REDD+ strategy for climate change mitigation: A review and comparison of developing countries. Sustainability 10(12):4781. https://doi.org/10.3390/su10124781

Banerjee K, Paneerselvam A, Ramachandran P, Ganguly D, Singh G, Ramesh R (2018) Seagrass and macrophyte mediated CO_2 and CH_4 dynamics in shallow coastal waters. PloS One 13(10):e0203922. https://doi.org/10.1371/journal.pone.0203922

Banerjee K, Roy Chowdhury M, Sengupta K, Sett S, Mitra A (2012) Influence of anthropogenic and natural factors on the mangrove soil of Indian Sundarbans wetland. Arch Environ Sci 6:80−91.

Banerjee K, Sahoo CK, Bal G, Mallik K, Paul R, Mitra A (2020) High blue carbon stock in mangrove forests of Eastern India. Trop Ecol 61(1):150–167. https://doi.org/10.1007/s42965-020-00072-y

Banerjee K, Sappal SM, Ramachandran P, Ramesh R (2017) Saltmarsh: ecologically important, yet least studied blue carbon ecosystems in India. J Clim Chang 3(2):59−72. https://doi.org/10.3233/JCC-170014

Banerjee K, Sengupta K, Raha A, Mitra A (2013) Salinity based allometric equations for biomass estimation of Sundarban mangroves. Biomass Bioenerg 56:382−391. https://doi.org/10.1016/j.biombioe.2013.05.010

Bertram C, Quaas M, Reusch TB, Vafeidis AT, Wolff C, Rickels W (2021) The blue carbon wealth of nations. Nat Clim Chang 11(8):704-709. https://doi.org/10.1038/s41558-021-01089-4

Bhomia RK, MacKenzie RA, Murdiyarso D, Sasmito SD, Purbopuspito J (2016) Impacts of land use on Indian mangrove forest carbon stocks: Implications for conservation and management. Ecol Appl 26(5):1396−1408. https://doi.org/10.1890/15-2143

Chaudhary DR, Rathore AP, Jha B (2018) Aboveground, belowground biomass and nutrients pool in *Salicornia brachiata* at coastal area of India: interactive effects of soil characteristics. Ecol Res 33(6):1207−1218. https://doi.org/10.1007/s11284-018-1634-9

Chaudhuri P, Ghosh S, Bakshi M, Bhattacharyya S, Nath B (2015) A review of threats and vulnerabilities to mangrove habitats: with special emphasis on east coast of India. J Earth Sci Clim Chang 6(4). http://dx.doi.org/10.4172/2157-7617.1000270

Chowdhury R, Sutradhar T, Begam M, Mukherjee C, Chatterjee K, Basak SK, Ray K (2019) Effects of nutrient limitation, salinity increase, and associated stressors on mangrove forest cover, structure, and zonation across Indian Sundarbans. Hydrobiologia 842(1):191-217. https://doi.org/10.1007/s10750-019-04036-9

Chen Y, Xu C (2020) Exploring New Blue Carbon Plants for Sustainable Ecosystems. Trend Plant Sci 25(11):1067−1070. https://doi.org/10.1016/j.tplants.2020.07.016

Das S, Zaman S, Pramanick P, Pal N, Mitra A (2015) *Suaeda maritima*: a potential carbon reservoir of coastal zone. International advanced research journal in science. Eng Technol 2(5):61−65.

DasGupta R, Shaw R (2013) Changing perspectives of mangrove management in India–an analytical overview. Ocean Coast Management 80:107−118. https://doi.org/10.1016/j.ocecoaman.2013.04.010

Dinesh R, Chaudhuri SG, Ganeshamurthy AN, Pramanik SC (2004) Biochemical properties of soils of undisturbed and disturbed mangrove forests of South Andaman (India). Wetl Ecol Manag 12(5):309−320. https://doi.org/10.1007/s11273-004-0777-3

Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M, Kanninen M (2011) Mangroves among the most carbon-rich forests in the tropics. Nat Geosci 4(5):293−297. https://doi.org/10.1038/ngeo1123

Duchelle AE, Simonet G, Sunderlin WD, Wunder S (2018) What is REDD+ achieving on the ground? Curr Opin Environ Sustain 32:134−140. https://doi.org/10.1016/j.cosust.2018.07.001

Fourqurean JW, Duarte CM, Kennedy H, Marbà N, Holmer M, Mateo MA, Apostolaki ET, Kendrick GA, Krause-Jensen D, McGlathery KJ, Serrano O (2012) Seagrass ecosystems as a globally significant carbon stock. Nat Geosci 5(7):505−509. https://doi.org/10.1038/ngeo1477

Gallagher JB (2017) Taking stock of mangrove and seagrass blue carbon ecosystems: A perspective for future carbon trading. Borneo J Mar Sci Aquac 1:71−74. https://doi.org/10.51200/bjomsa.v1i0.994

Ganguly D, Singh G, Purvaja R, Bhatta R, Selvam AP, Banerjee K, Ramesh R (2018) Valuing the carbon sequestration regulation service by seagrass ecosystems of Palk Bay and Chilika, India. Ocean Coast Manag 159:26−33. https://doi.org/10.1016/j.ocecoaman.2017.11.009

Ganguly D, Singh G, Ramachandran P, Selvam AP, Banerjee K, Ramachandran R (2017) Seagrass metabolism and carbon dynamics in a tropical coastal embayment. Ambio 46(6):667−679. https://doi.org/10.1007/s13280-017-0916-8

Garg JK, Singh TS, Murthy TVR (1998) Wetlands of India. Project Report: RSAM/SAC/RESA/PR/01/98. Space Applications Centre (ISRO), Ahmedabad, pp 239

Geevarghese GA, Akhil B, Magesh G, Krishnan P, Purvaja R, Ramesh R (2018) A comprehensive geospatial assessment of seagrass distribution in India. Ocean Coast Manag 159:16−25. https://doi.org/10.1016/j.ocecoaman.2017.10.032

Gnanamoorthy P, Selvam V, Ramasubramanian R, Chakraborty S, Pramit D, Karipot A (2019) Soil organic carbon stock in natural and restored mangrove forests in Pichavaram south-east coast of India. India J Geo Mar Sci 48(5):801−808.

Govindasamy C, Arulpriya M (2011) Seasonal variation in seagrass biomass in Northern Palk Bay, India. Biodiversity 12(4):223−231. https://doi.org/10.1080/14888386.2011.653542

Harishma KM, Sandeep S, Sreekumar VB (2020) Biomass and carbon stocks in mangrove ecosystems of Kerala, southwest coast of India. Ecol Proc 9(1):1−9. https://doi.org/10.1186/s13717-020-00227-8

Indian State of Forest Report (2021) Forest Survey of India, Ministry of Environment, Forest & Climate Change, Government of India.

Jackson B, Sparks JLD (2020) Ending slavery by decarbonisation? Exploring the nexus of modern slavery, deforestation, and climate change action via REDD+. Energy Res Soc Sci 69:101610. https://doi.org/10.1016/j.erss.2020.101610

Jayanthi M, Thirumurthy S, Nagaraj G, Muralidhar M, Ravichandran P (2018) Spatial and temporal changes in mangrove cover across the protected and unprotected forests of India. Estuar Coast Shelf Sci 213:81−91. https://doi.org/10.1016/j.ecss.2018.08.016

Johnson BA, Dasgupta R, Mader AD, Scheyvens H (2019) Understanding national biodiversity targets in a REDD+ context. Environ Sci Pol 92:27−33. https://doi.org/10.1016/j.envsci.2018.11.007

Joshi HG, Ghose M (2014) Community structure, species diversity, and aboveground biomass of the Sundarbans mangrove swamps. Trop Ecol 55(3):283−303.

Kaladharan P, Zacharia PU, Thirumalaiselvan S, Anasu Koya A, Lavanya R, Batcha SM (2020) Blue carbon stock of the seagrass meadows of Gulf of Mannar and Palk Bay off Coromandel Coast, South India. India J Fish 67(4):149−153.

Kathiresan K (2018) Mangrove forests of India. Curr Sci 114(5):976−981.

Kathiresan K, Anburaj R, Gomathi V, Saravanakumar K (2013) Carbon sequestration potential of Rhizophora mucronata and Avicennia marina as influenced by age, season, growth and sediment characteristics in southeast coast of India. J Coast Conserv 17(3):397−408. https://doi.org/10.1007/s11852-013-0236-5

Kaviarasan T, Dahms HU, Gokul MS, Henciya S, Muthukumar K, Shankar S, James RA (2019) Seasonal Species Variation of Sediment Organic Carbon Stocks in Salt Marshes of Tuticorin Area, Southern India. Wetlands 39(3):483−494. https://doi.org/10.1007/s13157-018-1094-6

Krishnan KP, Bharathi PL (2009) Organic carbon and iron modulate nitrification rates in mangrove swamps of Goa, south west coast of India. Estuar Coast Shelf Sci 84(3):419−426. https://doi.org/10.1016/j.ecss.2009.07.015

Kuwae T, Hori M (2019) The future of blue carbon: addressing global environmental issues. In Kuwae T, Hori M (eds) Blue Carbon in Shallow Coastal Ecosystems, Springer, Singapore, pp 347−373. https://doi.org/10.1007/978-981-13-1295-3_13

Lovelock CE, Duarte CM (2019) Dimensions of blue carbon and emerging perspectives. Biol Lett 15(3):20180781. https://doi.org/10.1098/rsbl.2018.0781

Macreadie PI, Anton A, Raven JA, Beaumont N, Connolly RM, Friess DA, Kelleway JJ, Kennedy H, Kuwae T, Lavery PS, Lovelock CE, Smale DA, Apostolaki ET, Atwood TB, Baldock J, Bianchi TS, Chmura GL, Eyre BD, Fourqurean JW, Hall-Spencer JM, Huxham M, Hendriks IE, Krause-Jensen D, Laffoley D, Luisetti T, Marbà N, Masque P, McGlathery KJ, Megonigal JP, Murdiyarso D, Russell BD, Santos R, Serrano O, Silliman BR, Watanabe K, Duarte CM (2019) The future of Blue Carbon science. Nat Commun 10(1):1−13. https://doi.org/10.1038/s41467-019-11693-w

Macreadie PI, Nielsen DA, Kelleway JJ, Atwood TB, Seymour JR, Petrou K, Connolly RM, Thomson ACG, Trevathan-Tackett SM, Ralph PJ (2017) Can we manage coastal ecosystems to sequester more blue carbon? Front Ecol Environ 15(4):206−213. https://doi.org/10.1002/fee.1484

Mathur A, Sharma JV, Tyangi A (2020) Scope and potential of coastal ecosystem towards mitigating climate change, Policy Brief, September 2020. The Energy and Resources Institute (TERI), pp 14.

Mitra A, Banerjee K, Sett S (2012) Spatial variation in organic carbon density of mangrove soil in Indian Sundarbans. Natl Acad Sci Lett 35(3):147−154. https://doi.org/10.1007/s40009-012-0046-6

Mitra A, Sengupta K, Banerjee K (2011) Standing biomass and carbon storage of above-ground structures in dominant mangrove trees in the Sundarbans. For Ecol Manag 261(7):1325−1335. https://doi.org/10.1016/j.foreco.2011.01.012

Moher D, Liberati A, Tetzlaff J, Altman DG, Prisma Group (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med 6(7):e1000097. https://doi.org/10.1371/journal.pmed.1000097

Murray BC, Pendleton L, Jenkins WA, Sifleet S (2011) Green payments for blue carbon: economic incentives for protecting threatened coastal habitats. Green payments for blue carbon: economic incentives for protecting threatened coastal habitats. Duke Nicholas Institute for Environmental Policy Solutions Report, p 52.

Nellemann C, Corcoran E, Duarte C, Valdes L, DeYoung C, Fonseca L, Grimsditch G (2009) Blue Carbon: The Role of Healthy Oceans in Binding Carbon. UNEP, p 80

Ouyang X, Lee SY (2014) Updated estimates of carbon accumulation rates in coastal marsh sediments. Biogeosciences 11(18):5057−5071. https://doi.org/10.5194/bg-11-5057-2014

Pandey PC, Anand A, Srivastava PK (2019) Spatial distribution of mangrove forest species and biomass assessment using field inventory and earth observation hyperspectral data. Biodivers Conserv 28(8):2143−2162. https://doi.org/10.1007/s10531-019-01698-8

Patro S, Krishnan P, Samuel VD, Purvaja R, Ramesh R (2017) Seagrass and salt marsh ecosystems in South Asia: an overview of diversity, distribution, threats and conservation status. In: Prusty B, Chandra R, Azeez P (eds) Wetland Science, Springer, pp 87−104. https://doi.org/10.1007/978-81-322-3715-0_5

Pattnayak S, Kumar M, Sahu SC, Dhal NK, Behera RK (2019) Comparison of soil characteristics and carbon content of contrastingly different moist-mixed deciduous and evergreen mangrove forest in Odisha, India. Geol Ecol Landsc 3(4):239−246. https://doi.org/10.1080/24749508.2018.1545104

Pendleton L, Donato DC, Murray BC, Crooks S, Jenkins WA, Sifleet S, Craft C, Fourqurean JW, Boone Kauffman J, Marbà N, Megonigal P, Pidgeon E, Herr D, Gordon D, Baldera A (2012). Estimating global “blue carbon” emissions from conversion and degradation of vegetated coastal ecosystems. PloS One 7(9):e43542. https://doi.org/10.1371/journal.pone.0043542

Prasanna J, Anand M, Vijayasekaran D, Kumaraguru AK (2017) Allometric model for estimating above ground biomass and carbon storage in Karankadu mangrove swamp, Palk bay, Southeast coast of India. India J Geo Mar Sci 46(8):1682−1692.

Raha AK, Bhattacharyya SB, Zaman S, Banerjee K, Sengupta K, Sinha S, Sett S, Chakraborty S, Datta S, Dasgupta S, Roy Chowdhury M, Ghosh R, Mondal K, Pramanick P, Mitra, A. (2013) Carbon census in dominant mangroves of Indian Sundarbans. J Energy Environ Sci Photon 127:345−354.

Ranjan RK, Routh J, Ramanathan AL, Klump JV (2011) Elemental and stable isotope records of organic matter input and its fate in the Pichavaram mangrove–estuarine sediments (Tamil Nadu, India). Mar Chem 126(1-4):163−172. https://doi.org/10.1016/j.marchem.2011.05.005

Rasquinha DN, Mishra DR (2021) Impact of wood harvesting on mangrove forest structure, composition and biomass dynamics in India. Estuar Coast Shelf Sci 248:106974. https://doi.org/10.1016/j.ecss.2020.106974

Rathore AP, Chaudhary DR, Jha B (2016) Biomass production, nutrient cycling, and carbon fixation by *Salicornia brachiata* Roxb.: A promising halophyte for coastal saline soil rehabilitation. Int J Phytoremediat 18(8):801−811. https://doi.org/10.1080/15226514.2016.1146228

Ray R, Ganguly D, Chowdhury C, Dey M, Das S, Dutta MK, Mandal SK, Majumdar N, De TK, Mukhopadhyay SK, Jana TK (2011) Carbon sequestration and annual increase of carbon stock in a mangrove forest. Atmos Environ 45(28):5016−5024. https://doi.org/10.1016/j.atmosenv.2011.04.074

Resmi P, Manju MN, Gireeshkumar TR, Kumar CR, Chandramohanakumar N (2016) Source characterisation of Sedimentary organic matter in mangrove ecosystems of northern Kerala, India: Inferences from bulk characterisation and hydrocarbon biomarkers. Reg Stud Mar Sci 7:43−54. https://doi.org/10.1016/j.rsma.2016.05.006

SAC (2011) National Wetland Atlas. SAC/EPSA/ABHG/NWIA/ATLAS/34/2011. Space Applications Centre, ISRO, Ahmedabad, p 310.

Saderne V, Geraldi NR, Macreadie PI, Maher DT, Middelburg JJ, Serrano O, Almahasheer H, Arias-Ortiz A, Cusack M, Eyre BD, Fourqurean JW, Kennedy H, Krause-Jensen D, Kuwae T, Lavery PS, Lovelock CE, Marba N, Masqué P, Mateo MA, Mazarrasa I, McGlathery KJ, Oreska MPJ, Sanders CJ, Santos IR, Smoak JM, Tanaya T, Fourqurean JW (2019) Role of carbonate burial in Blue Carbon budgets. Nat Commun 10(1):1−9. https://doi.org/10.1038/s41467-019-08842-6

Saha A, Gobato R, Zaman S, Mitra A (2019) Biomass Study of Mangroves in Indian Sundarbans: A Case Study from Satjelia Island. Parana J Sci Educ 5(2):1−5.

Sahu SC, Kumar M, Ravindranath NH (2016) Carbon stocks in natural and planted mangrove forests of Mahanadi Mangrove Wetland, East Coast of India. Curr Sci 12(25):2253−2260. https://www.jstor.org/stable/24908469

Sandilyan S, Thiyagesan K, Nagarajan R, Vencatesan J (2010) Salinity rise in Indian mangroves–a looming danger for coastal biodiversity. Curr Sci 98(6):754-756.

Sebastian R, Chacko J (2006) Distribution of organic carbon in tropical mangrove sediments (Cochin, India). Int J Environ Stud 63(3):303−311. https://doi.org/10.1080/00207230600720498

ShyleshChandran MS, Ravi A, John SM, Sivan S, Asha MS, Mammen PC, Sajith Kumar KJ, Sruthi SN (2020) Ecosystem Carbon Stock of Selected Mangrove Forests of Vypin–Cochin Region, Southwest Coast of India. Wetlands 40:2263–2273. https://doi.org/10.1007/s13157-020-01365-7

Shynu R, Rao P, Sarma VVSS, Kessarkar PM, Murali RM (2015) Sources and fate of organic matter in suspended and bottom sediments of the Mandovi and Zuari estuaries, western India. Curr Sci 108(2):226−238. https://www.jstor.org/stable/24218162

Taillardat P, Friess DA, Lupascu M (2018) Mangrove blue carbon strategies for climate change mitigation are most effective at the national scale. Biol Lett 14(10):20180251. https://doi.org/10.1098/rsbl.2018.0251

Thangaradjou T, Bhatt JR (2018) Status of seagrass ecosystems in India. Ocean Coast Manag 159:7−15. https://doi.org/10.1016/j.ocecoaman.2017.11.025

Thivakaran GA, Sharma SB, Chowdhury A, Murugan A (2020) Status, structure and environmental variations in semi-arid mangroves of India. J For Res 31:163–173. https://doi.org/10.1007/s11676-018-0793-4

Viswanathan C, Purvaja R, Jeevamani JJJ, Samuel VD, Sankar R, Abhilash KR, Geevarghese GA, Muruganandam R, Gopi M, Raja S, Das RR, Patro S, Krishnan P, Ramesh R (2020) Salt marsh vegetation in India: Species composition, distribution, zonation pattern and conservation implications. Estuar Coast Shelf Sci 242:106792. https://doi.org/10.1016/j.ecss.2020.106792

Vyas P, Sengupta K (2012) Mangrove conservation and restoration in the Indian Sundarbans. In Macintosh DJ, Mahindapala R, Markopoulos M (eds) Sharing lessons on mangrove restoration. Mangroves for the Future and Gland, Switzerland, IUCN, pp. 93-101.

Figure captions

Fig. 1 The study area map showing the prime locations of the blue carbon ecosystems along the Indian coastline. The mangrove, seagrass, and salt marsh sites, shown in the figure are based on available pieces of literature considered in the present study.

Fig. 2 A snapshot of data on blue carbon repository in India

Table 1 The collation of data on the carbon stock in the aboveground biomass (AGB), belowground biomass (BGB), total biomass (TB), and the topsoil (up to 30 cm depth) observed in the various mangrove forests of India. As per availability, the data is reported as either mean ± standard deviation (from the mean) or range (minimum to maximum).

Place	AGB carbon (Mg C ha^{-1})	BGB carbon (Mg C ha^{-1})	TB carbon (Mg C ha^{-1})	Soil carbon (Mg C ha^{-1})	References
Sundarbans (WB)	39.9 ± 14.1	9.6 ± 3.4		17.4 ± 2.3	Ray et al. (2011)
Sundarbans (WB)	8.9 to 50.9			2.9 to 25.9	Joshi and Ghose (2014)

Sundarbans (WB)				28.5 ± 2.0	Banerjee et al. (2012)
Sundarbans (WB)				20.4 ± 5.6	Mitra et al. (2012)
Bhitarkanika (OD)				16.4 ± 2.6	Banerjee et al. (2018)
Bhitarkanika (OD)	278.9				Pandey et al. (2019)
Bhitarkanika (OD)	179.7 ± 67.0 to 196.1 ± 182.1	64.0 ± 55.0 to 68.3 ± 17.1		15.63 ± 7.22 to 16.49 ± 6.59	Rasquinha and Mishra (2020)
Bhitarkanika (OD)			7 ± 4 to 100 ± 11	92 ± 20 to 177 ± 14	Bhomia et al. (2016)
Bhitarkanika (OD)			131.06 ± 11.08		Anand et al. (2020)
Bhitarkanika (OD)	143.6 ± 38.0			5.5 ± 1.7	Banerjee et al. (2020)
Bhubaneswar and Bhitarkanika (OD)				54.3 ± 3.0	Pattnayak et al. (2019)
Mahanadi (OD)	93.2 ± 21.6			5.9 ± 1.5	Banerjee et al. (2020)
Mahanadi (OD)	62.5 ± 6.4 to 62.8 ± 11.3	26.7 ± 2.6 to 27.9 ± 4.9	89.1 ± 8.9 to 90.6 ± 16.2	54.3 ± 3.0 to 60.9 ± 5.6	Sahu et al. (2016)
Chandaka Wildlife Sanctuary (OD)				47.51 ± 2.16	Pattnayak et al. (2019)
Mandovi-Zuari (GA)				0.6 to 198.7	Krishnan and Bharathi (2009)
Mandovi-Zuari (GA)				6.9 to 38.6	Shynu et al. (2015)
Karankadu, Palk Bay (TN)	29.8 ± 12.7				Prasanna et al. (2017)
Pichavaram (TN)				34.6 ± 15.0	Ranjan et al. (2011)
Pichavaram (TN)				19.1 to 48.7	Gnanamoorthy et al. (2019)
Northern Kerala (KL)				17.3 to 259.8	Resmi et al. (2016)
Cochin Metropolis (KL)				94.8 to 253.2	Sebastian and Chacko (2006)
Vypin-Cochin Region (KL)	54.3 ± 36			18.3 ± 3.9	ShyleshChandran et al. (2020)
Kerala (KL)			58.6 ± 0.5	81.3 ± 10.2	Harishma et al. (2020)

South Andaman (AN)				34.8 ± 6.3 to 51.8 ± 8.6	Dinesh et al. (2004)
Gulf of Kachchh (GJ)	36.4				Thivakaran et al. (2020)
WB – West Bengal; OD – Odisha; GA – Goa; TN – Tamil Nadu; KL – Kerala; AN – Andaman and Nicobar Islands; GJ – Gujarat					

Table 2 The collation of data on the mangrove species-specific carbon stock in the aboveground biomass (AGB) or total biomass (TB) observed in the various mangrove forests of India. As per availability, the data is reported as either mean ± standard deviation (from the mean) or range (minimum to maximum). Standalone single values are mean without any standard deviation.

Mangrove Species	Biomass carbon (Mg C ha^{-1})	Place	Reference
Acanthus ilicifolius	0.002 to 0.02 (AGB)	Ernakulam (KL)	ShyleshChandran et al. (2020)
Aegiceras corniculatum	35.2 (AGB)	Sundarban (WB)	Joshi and Ghose (2014)
Aegiceras corniculatum	165.03 ± 10.87 (AGB)	Bhitarkanika (OD)	Anand et al. (2020)
Aegiceras corniculatum	108.77 ± 13.67 (AGB)	Bhitarkanika (OD)	Banerjee et al. (2020)
Agialitis rotundifolia	54.77 to 64.03 (TB)	Sundarban (WB)	Ray et al. (2011)
Avicennia alba	0.5 to 27.28 (TB)	Sundarban (WB)	Ray et al. (2011)

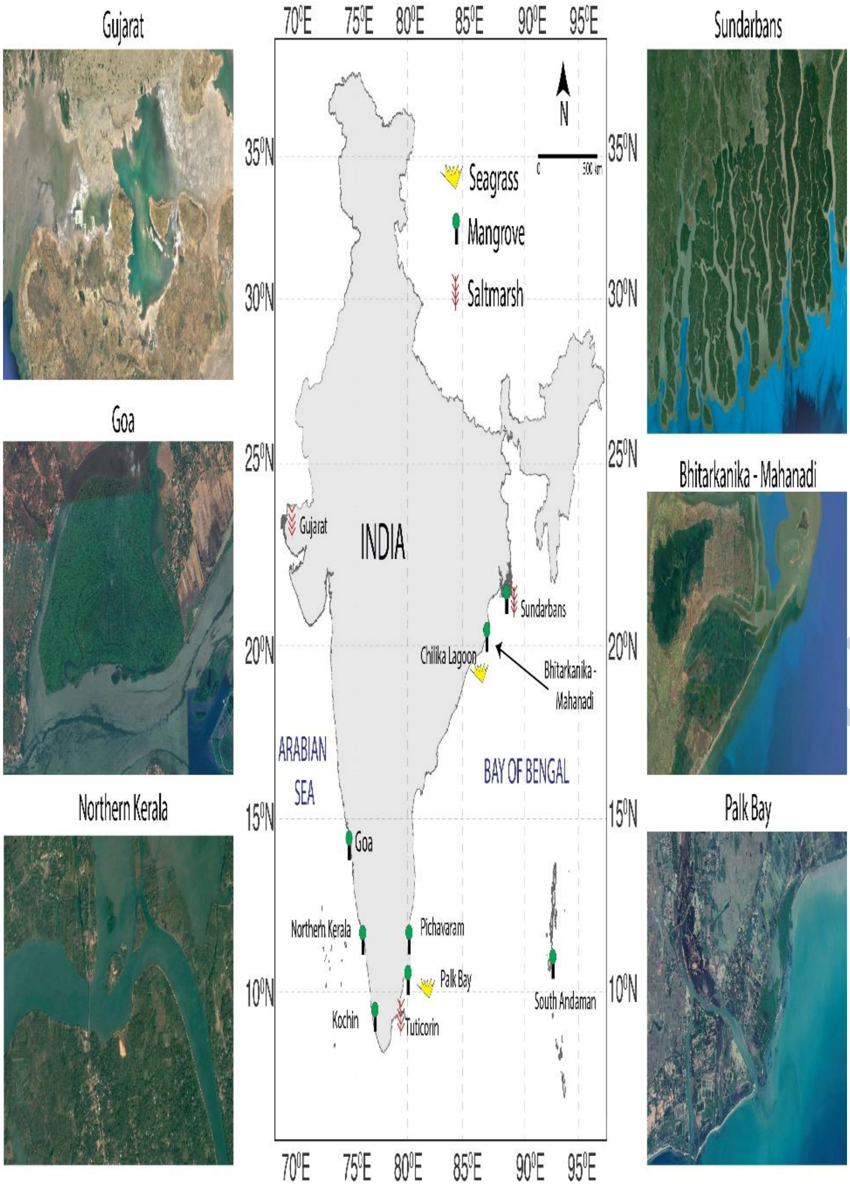
Avicennia alba	6.05 ± 1.19 to 11.02 ± 1.42 (AGB)	Sundarban (WB)	Mitra et al. (2011)
Avicennia alba	41.65 to 64.57 (TB)	Sundarban (WB)	Banerjee et al. (2013)
Avicennia alba	32.7 (AGB)	Sundarban (WB)	Joshi and Ghose (2014)
Avicennia alba	24.73 to 29.09 (AGB)	Sundarban (WB)	Raha et al. (2013)
Avicennia alba	0.5 to 27.28 (TB)	Sundarban (WB)	Ray et al. (2011)
Avicennia alba	20.22 (AGB)	Sundarban (WB)	Saha et al. (2019)
Avicennia marina	8.80 to 38.63 (TB)	Sundarban (WB)	Ray et al. (2011)
Avicennia marina	22.84 to 26.92 (AGB)	Sundarban (WB)	Raha et al. (2013)
Avicennia marina	21.14 (AGB)	Sundarban (WB)	Saha et al. (2019)
Avicennia marina	7.63 ± 1.08 to 35.65 ± 2.63 (AGB)	Bhitarkanika-Mahanadi (OD)	Banerjee et al. (2020)
Avicennia marina	67.47 ± 20.09 (TB)	Vellar-Coleroon (TN)	Kathiresan et al. (2013)
Avicennia marina	5.05 to 108.40 (AGB)	Gulf of Kachchh (GJ)	Thivakaran et al. (2020)
Avicennia officinalis	0.56 to 20.68 (TB)	Sundarban (WB)	Ray et al. (2011)
Avicennia officinalis	25.80 to 29.75 (AGB)	Sundarban (WB)	Raha et al. (2013)
Avicennia officinalis	6.70 (AGB)	Sundarban (WB)	Saha et al. (2019)
Avicennia officinalis	1.73 ± 0.01 to 280.83 ± 21.29 (AGB)	Bhitarkanika-Mahanadi (OD)	Banerjee et al. (2020)
Avicennia officinalis	1.38 to 36.16 (AGB)	Ernakulam (KL)	ShyleshChandran et al. (2020)
Bruguiera cylindrica	0.19 (AGB)	Ernakulam (KL)	ShyleshChandran et al. (2020)
Ceriops sp.	2.01 to 10.40 (TB)	Sundarban (WB)	Ray et al. (2011)
Ceriops tagal	0.18 to 2.26 (AGB)	Gulf of Kachchh (GJ)	Thivakaran et al. (2020)
Excoecaria agallocha	8.83 to 10.07 (TB)	Sundarban (WB)	Ray et al. (2011)
Excoecaria agallocha	14.93 ± 0.63 to 24.98 ± 1.02 (AGB)	Sundarban (WB)	Mitra et al. (2011)
Excoecaria agallocha	13.89 to 24.24 (TB)	Sundarban (WB)	Banerjee et al. (2013)
Excoecaria agallocha	10.20 to 11.92 (AGB)	Sundarban (WB)	Raha et al. (2013)
Excoecaria agallocha	5.83 (AGB)	Sundarban (WB)	Saha et al. (2019)
Excoecaria agallocha	6.05 ± 1.19 to 11.02 ± 1.42 (AGB)	Bhitarkanika (OR)	Anand et al. (2020)
Excoecaria agallocha	1.64 ± 0.41 to 44.95 ± 2.53 (AGB)	Bhitarkanika-Mahanadi (OD)	Banerjee et al. (2020)

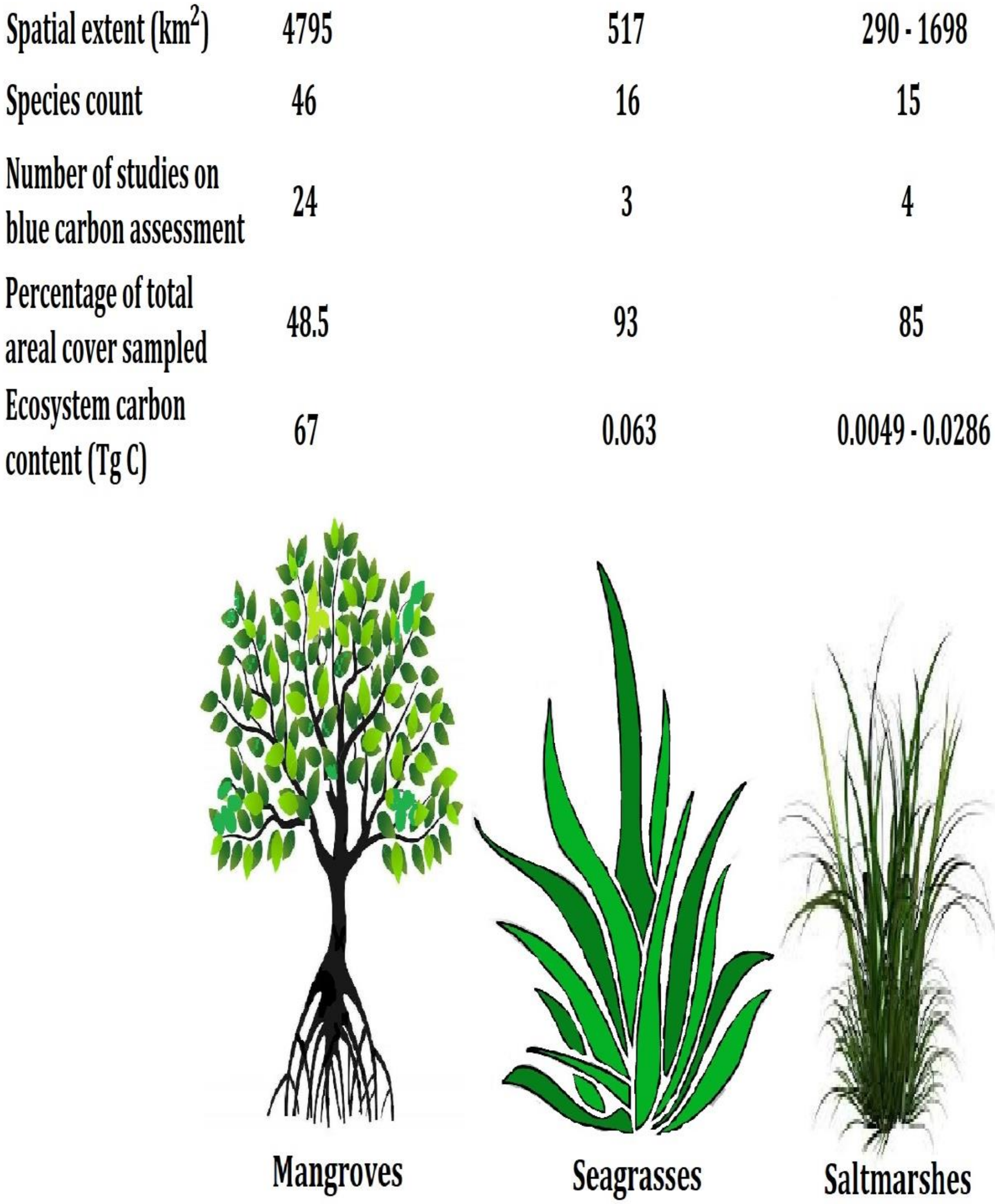
Heritiera fomes	135.20 ± 6.02 (AGB)	Bhitarkanika (OD)	Anand et al. (2020)
Heritiera littoralis	159.39 ± 11.21 (AGB)	Bhitarkanika (OD)	Anand et al. (2020)
Rhizophora mucronata	3.44 ± 1.45 to 114.05 ± 10.29 (AGB)	Bhitarkanika-Mahanadi (OD)	Banerjee et al. (2020)
Rhizophora mucronata	38.05 ± 9.53 (TB)	Vellar-Coleroon (TN)	Kathiresan et al. (2013)
Rhizophora mucronata	2.43 to 105.82 (AGB)	Ernakulam (KL)	ShyleshChandran et al. (2020)
Rhizophora mucronata	0.14 to 0.31 (AGB)	Gulf of Kachchh (GJ)	Thivakaran et al. (2020)
Sonneratia apetala	15.39 ± 1.73 to 84.79 ± 1.22 (AGB)	Sundarban (WB)	Mitra et al. (2011)
Sonneratia apetala	6.77 to 39.10 (TB)	Sundarban (WB)	Banerjee et al. (2013)
Sonneratia apetala	19.79 (AGB)	Sundarban (WB)	Saha et al. (2019)
Sonneratia apetala	21.46 to 30.26 (AGB)	Sundarban (WB)	Raha et al. (2013)
Sonneratia caseolaris	8.001 to 25.88 (AGB)	Ernakulam (KL)	ShyleshChandran et al. (2020)
Xylocarpas granatum	148.43 ± 17.90 (AGB)	Bhitarkanika (OD)	Anand et al. (2020)
Xylocarpas granatum	0.31 ± 0.10 to 3.25 ± 0.31 (AGB)	Bhitarkanika-Mahanadi (OD)	Banerjee et al. (2020)
Xylocarpas mekongensis	76.20 ± 12.36 (AGB)	Bhitarkanika (OD)	Banerjee et al. (2020)
WB – West Bengal; OD – Odisha; TN – Tamil Nadu; KL – Kerala; GJ – Gujarat			

Table 3 The collation of data on the carbon stock in the aboveground biomass (AGB), belowground biomass (BGB), total biomass (TB), and the topsoil (up to 30 cm depth) observed in the various seagrass and saltmarsh patches of India. As per availability, the data is reported as either mean ± standard deviation (from the mean) or range (minimum to maximum).

Place	AGB carbon (Mg C ha^{-1})	BGB carbon (Mg C ha^{-1})	Soil carbon (Mg C ha^{-1})	References
Palk Bay (TN) (Seagrass)	0.91 ± 0.06 to 0.97 ± 0.10	2.51 ± 0.31 to 2.91 ± 0.26	139.6 (up to 1 m)	Ganguly et al. (2017)

Palk Bay (TN) and Chilika Lagoon (OD) (Seagrass)	0.20 to 0.96	0.30 to 2.90	129 (up to 1 m)	Ganguly et al. (2018)
Tuticorin (TN) (Saltmarhses)	6.32 to 14.87 ± 0.68	1.86 ± 0.21 to 4.49 ± 0.35	8.42 ± .640 to 54.46 ± 1.46 (up to 30 cm)	Kaviarasan et al. (2019)
Gujarat coastline (GJ) (Saltmarshes)	0.05 to 2.1	0.009 to 0.335		Chaudhary et al. (2018)
Gujarat coast (GJ) (Saltmarshes)	0.77 to 1.93		4.5 to 8.2 (up to 30 cm)	Rathore et al. (2016)
Sundarban (WB) (Saltmarshes)	0.64 to 0.71	0.02 to 0.03	9.4 to 13.4 (up to 30 cm)	Das et al. (2015)
WB – West Bengal; OD – Odisha; TN – Tamil Nadu; GJ - Gujarat				


Gujarat
Goa
Northern Kerala
Sundarbans
Bhitarkanika - Mahanadi
Palk Bay
70⁰E
75⁰E
80⁰E
85⁰E
90⁰E
95⁰E
35⁰N
30⁰N
25⁰N
20⁰N
15⁰N
10⁰N
N
0
500 km
Seagrass
Mangrove
Saltmarsh
INDIA
Gujarat
Sundarbans
Chilika Lagoon
Bhitarkanika - Mahanadi
ARABIAN SEA
BAY OF BENGAL
Goa
Northern Kerala
Pichavaram
Palk Bay
South Andaman
Kochin
Tuticorin



	Mangroves	Seagrasses	Saltmarshes
Spatial extent (km^2)	4795	517	290 - 1698
Species count	46	16	15
Number of studies on blue carbon assessment	24	3	4
Percentage of total areal cover sampled	48.5	93	85
Ecosystem carbon content (Tg C)	67	0.063	0.0049 - 0.0286