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Blue carbon assessments of seagrass and mangrove ecosystems in South and Southeast Asia: Current progress and knowledge gaps

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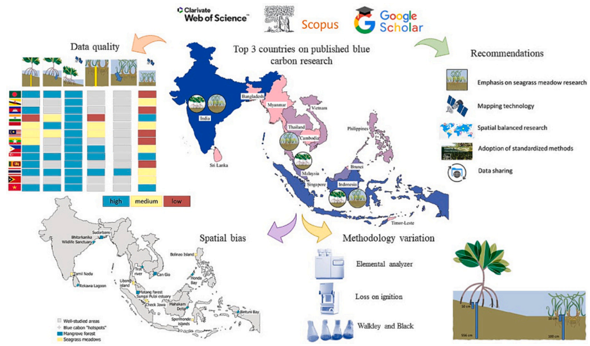
HIGHLIGHTS

- Blue carbon estimates are limited for several countries in SE and SEA region.
- The lack of blue carbon estimates is more prominent in seagrass ecosystems.
- Highest mangrove and seagrass carbon stocks are in Indonesia and the Philippines.
- High difference in data quality and quantity between mangroves and seagrasses.
- Blue carbon studies are spatially biased towards more familiar sites.

GRAPHICAL ABSTRACT



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ABSTRACT

Coastal blue carbon ecosystems can be an important nature-based solution for mitigating climate change, when emphasis is given to their protection, management, and restoration. Globally, there has been a rapid increase in blue carbon research in the last few decades, with substantial investments on national scales by the European Union, the USA, Australia, Seychelles, and Belize. Blue carbon ecosystems in South and Southeast Asia are globally diverse, highly productive and could represent a global hotspot for carbon sequestration and storage. To guide future efforts, we conducted a systematic review of the available literature on two primary blue carbon ecosystems—seagrasses and mangroves—across 13 countries in South and Southeast Asia to assess existing national inventories, review current research trends and methodologies, and identify existing knowledge gaps. Information related to various aspects of seagrass and mangrove ecosystems was extracted from 432 research articles from 1967 to 2022. We find that: (1) blue carbon estimates in several countries have limited data, especially for seagrass meadows compared to mangrove ecosystems, although the highest reported carbon stocks were in Indonesia and the Philippines with 4,515 and 707 Tg within mangrove forest and 60.9 and 63.3 Tg within seagrass meadows, respectively; (2) there is a high difference in the quantity and quality of data between mangrove and seagrass ecosystems, and the methodologies used for blue carbon estimates are highly variable across countries; and (3) most studies on blue carbon stocks are spatially biased towards more familiar study areas of individual countries, than several lesser-known suspected blue carbon hotspots. In sum, our review demonstrates the paucity and variability in current research in the region, and highlights research frontiers that should be addressed by future research before the robust implementation of these ecosystems into national climate strategies.

1. Introduction

The climate change is causing various impacts, from sea-level rise, increase climate variabilities, intense and more frequent fires, wildfires, and droughts globally, which have damaging effects on the marine, terrestrial and freshwater ecosystems, as well as the human-well-being (IPCC, 2022). The changes have severe socio-economic impacts, especially in low to middle developed countries, which tend to be the most vulnerable to the impacts of climate change (IPCC, 2022). As atmospheric carbon dioxide (CO_2) continues to rise [421 ppm as of May 2022 (NOAA, 2023)] with considerable implications for warming of the atmosphere and consequent effects for nature and people, scientists and policymakers are turning to strategies to limit and/or offset carbon emissions. Currently there are many alternative approaches to address climate change impacts on human-well-being, development and economy, but there is a growing recognition that these challenges have to be interlined with natural systems, as more coherent approaches to tackle global climate change are needed (Seddon et al., 2020). These approaches rely on the protection and restoration of natural carbon sinks that can continue to capture and store carbon over long-term periods of time.

The Indo-Pacific region hosts Earth's largest and most diverse mangrove forests and seagrass meadows. It harbors 37 % of the world's mangrove area and approximately 23 % of the world seagrass area, comprising 42 and 21 species, respectively (Bunting et al., 2022; McKenzie et al., 2020; Short et al., 2007). These ecosystems support diverse ecological communities that enhance food security, promote livelihoods, and sustain the well-being of coastal population (Friess et al., 2020; Nordlund et al., 2016). These coastal ecosystems are also able to sequester and store large amounts of organic carbon (C_{org}) in ecosystems, known as 'blue carbon' (Nellemann et al., 2009). This ecosystem service is an outcome of the interplay between i) the primary productivity of these plants, i.e. absorption of atmospheric CO_2 through photosynthesis and storage as plant biomass and sequestration into sediment through root exudates; ii) the retention of allochthonous particles through the action of aboveground structures that reduce water flow; and iii) the combined effect of the relatively low oxygen and high salinity that reduces decomposition and remineralization in the sediment (Lovelock and Duarte, 2019; Mazarrasa et al., 2015; Mishra et al., 2023). Mangrove forests cover approximately 13.7 million ha globally (Macreadie et al., 2021), accumulating C_{org} at the rate of 24.17 Tg C yr^{-1} (Breithaupt and Steinmuller, 2022), whereas seagrass meadows potentially cover 16–165 million ha worldwide (Macreadie et al., 2021) with C_{org} accumulation rates varying 25.6 and 306.9 Tg C yr^{-1} (assuming the C_{org} accumulation rates is between 160 and 186 g C m^{-2} $year^{-1}$, Duarte et al. (2013). This leads to estimated combined C_{org} stocks in biomass and sediment between ~3,130 and 12,300 Tg C in mangrove forests and ~1,732 and 21,000 Tg C in seagrass meadows (Macreadie et al., 2021).

As a result, the mitigation potential of these ecosystems is 762–1,530 Tg CO_2 per year (Macreadie et al., 2021) and the conservation, management and restoration of these ecosystems have been increasingly integrated into climate change mitigation strategies seeking to reverse the impacts of past and present CO_2 emissions. The potential of these ecosystems has been highlighted in the national (Meng et al., 2019; Murdiyarso et al., 2023; Serrano et al., 2019), regional (Bryan et al., 2020; Herrera-Silveira et al., 2020; Sharma et al., 2023; Stankovic et al., 2021; Thorhaug et al., 2020), and global reviews (Gao et al., 2022; Howard et al., 2017; Macreadie et al., 2021) in terms of science and policy (Herr et al., 2017; Howard et al., 2023; Sidik et al., 2023), emphasizing the current gaps, issues and recommendations across various scales.

South and Southeast Asia are the world's most densely populated regions, representing 29 % of the global population (United Nations Department of Economic and Social Affairs, 2022). About half of these people are concentrated in low elevation coastal zones (LECZ) (Neumann et al., 2015), for which model projections predict a substantial increase in human population, reaching up to 70 % concentrated in the LECZ by 2060 (Neumann et al., 2015). Human population growth has intensified anthropogenic pressures, i.e. from fishery, conversion and modification of ecosystems for aquaculture and other uses, alongside coastal development and pollution, leading to substantial reductions in the total extent and quality of blue carbon ecosystems in these regions (Dunic et al., 2021; Richards and Friess, 2016). The present day estimated area of the seagrass meadows in South and Southeast Asia is 888.43 km^2 and 24,411.96 km^2, respectively (Supplementary 3 Table S2). However, it is estimated that the seagrass meadows have been declining at the rate of 4.7 % per year (Sudo et al., 2021). The mangrove forest currently occupy the area of 8720.45 and 48,222.25 km^2 in South and Southeast Asia, respectively (Bunting et al., 2022). The rate of mangrove ecosystem loss has decreased during the last two decades 2000–2020 (Bhowmik et al., 2022), with the global average of 0.16 (Bunting et al., 2022). The anthropogenic disturbance in mangrove and seagrass ecosystems have resulted in lower C_{org} stock potential comparing to the undisturbed ecosystems (Rozaimi et al., 2017; Stankovic et al., 2018a; Zakaria et al., 2021). The declines in the C_{org} stock potential are the result of increased greenhouse gas emissions from decomposition of organic matter and resuspension of sediment carbon, that also inhibit future carbon sequestration capacity of these ecosystems (Adame et al., 2021; Macreadie et al., 2019; Marbà et al., 2015).

There is increasing interest in using natural climate solutions (NCS) such as blue carbon to reduce greenhouse gas emissions and remove CO_2 from the atmosphere. However, only few countries in the South and Southeast Asian region have included blue carbon ecosystems into their nationally determined contributions (NDCs), the primary mechanism for outlining a countries' targets and mitigation actions. In the South and Southeast Asian region, most countries have included coastal and/or marine habitats in their NDC, except for Thailand, Philippines, Timor-Leste and Bangladesh (Francis and Wilkman, 2022). However, only Myanmar, Sri Lanka, Cambodia and Vietnam have specifically cited various conservation and restoration activities in these ecosystems as a part of their mitigation strategies (Francis and Wilkman, 2022). Given the increased attention on the climate change mitigation potential of coastal ecosystems, it is likely that more countries throughout the region will incorporate mangrove- and seagrass-specific conservation actions into their NDCs, as the distribution of other blue carbon ecosystems, such as tidal marshes is very limited in the region (McOwen et al., 2017; Mishra and Farooq, 2022). In that context, this review aims to synthesize published literature on C_{org} stocks, sequestration rates, and greenhouse gas fluxes, in mangrove and seagrass ecosystems of the countries of South (Sri Lanka, India, and Bangladesh) and Southeast Asia (Brunei, Cambodia, Indonesia, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, and Vietnam) to:

1. provide up-to-date national assessments of blue carbon (stocks, sequestration, and emissions rates) and its variability across different ecosystems;
2. highlight existing knowledge on blue carbon through identification of potential dense blue carbon spots (well-studied areas)
3. assess the methods currently used in C_{org} stock assessment.

2. Methods

2.1. Literature search and criteria for selection

A search of existing peer-reviewed literature on blue carbon was conducted to identify the range of the studies in South and Southeast Asian countries. We searched online databases and search engines including Web of Science (WoS), SCOPUS and Google Scholar (GS) for articles published from 1967 to July 2022. The main keywords used in the search were ("organic AND carbon" OR "carbon AND storage" OR "blue AND carbon" OR "carbon AND flux" OR "carbon AND accumulation" OR "carbon AND sequestration"), combination of the type of habitat: (seagrass OR mangrove), as well as individual country names in South and Southeast Asia (Bangladesh, Brunei, Cambodia, India, Indonesia, Malaysia, Myanmar, Philippines, Singapore, Sri Lanka, Thailand, Timor-Leste, and Vietnam). The search has been focused primarily on mangrove forests and seagrass meadows, as these ecosystems are present in all of the countries within the region, while the salt marshes are present in only few countries (India, Sri Lanka, Bangladesh, Cambodia and Vietnam) with a limited distribution. These keywords were selected to maximize the search potential of the articles within these databases. The search was limited to the title, abstract and keywords of the publication, with at least one of the main keywords, while document type included academic articles, review articles and conference proceedings.

A total of 1,144 research articles were recovered in the first search (WoS = 450, SCOPUS = 603, and GS = 91), which were further filtered to exclude the duplicates and those in which there was no quantification of blue carbon (stock, sequestration, and flux) in seagrass and/or mangrove ecosystems. Furthermore, articles in which the study locations were not part of any of the South and Southeast Asian countries were also excluded. Global or regional scale research and review articles were included, if these articles included relevant countries of interest to this study, however, they were not included in the data summary, but were used as most up-to date references for each country for data comparison. Articles that provided data on C_{org} obtained from the sediment, above and belowground parts of the living plants as well as the dead parts such as litter, wood debris and dead wood, were included. After the initial screening, 433 articles were selected for the final review, and they were recorded in a database (see Supplementary 1).

2.2. Data analysis

The data was organized following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta Analysis) protocol (Page et al., 2021). Each of the papers was coded according to article information (author(s), title, journal, and year of publication), location (country and location of the study site), description of the study site (type of habitat, health of the ecosystem, protection status, species and tidal zone), methods and response variable of the study (organic carbon: C_{org} content, stock, sequestration, CO_2 and CH_4 flux). The full description of each group and variables is available in Supplementary 2. If a research article included more than one country, location, habitat type or health in their article, then each variable (e.g., country, habitat, etc.) was listed as a separate study. For example, in Stankovic et al. (2018a), authors provided C_{org} value for various types of seagrass meadows along Andaman coast of Thailand, and data was extracted per ecosystem species groups, protection status and health, resulting in total of 6 studies from this article.

Quantitative data on carbon stocks or fluxes from the articles were transformed into standard units (Supplementary 3, Table S1) according to Howard et al. (2014) and reported as a range. If the data was not available in the article text, table or supplementary data, it was extracted from the figures using Web-Plot-Digitizer (Rohatgi, 2022). For studies that did not report accessible quantitative values, the information was still collated on their methods and locations for use in a descriptive qualitative synthesis. To assess the trajectory of blue carbon science in this region we identified trends between the number of publications and year. The national C_{org} stocks were calculated using minima and maxima values of the extracted C_{org} stocks and total extent of the ecosystem (Supplementary 3 Table S2) to obtain the maximum potential of these ecosystems. To delineate areas of high C_{org} stock, the two standard deviation ranges of C_{org} stocks were created and the locations with C_{org} stock higher than the upper SD were identified as C_{org} blue carbon "hotspot" areas for each ecosystem. Additionally, the blue carbon estimates obtained for each country were evaluated using qualitative confidence which was based on the methodological variabilities (in estimating C_{org} stock) employed by each study and current mapping attempts of the ecosystem (Supplementary 3 Table S3). This "confidence" assessment was done by grouping the methods used by authors to obtain the data into three categories: high, medium, and low, where the methods that produce most precise results were classified as high, medium as the methods that slightly over/underestimate the data and low as the methods that provide high over/under estimation of the data (Supplementary 3 Table S3). The confidence categories for C_{org} stock, sequestration rate and areal extent for each country were distinguished by the proportion of the methods used for each methodology and number of studies. All data processing and analysis was performed using R statistical software (R Studio: Integrated Development for R, 2020) using tidyverse (Wickham et al., 2019), dplyr (Wickham et al., 2023), ggplot2 (Wickham, 2016) and xlsx (Dragulescu and Arendt, 2020) packages.

3. Results and discussion

From the 432 papers, 654 studies were identified: 551 for mangrove ecosystems, and 103 for seagrass meadows. The first recorded article on C_{org} was from 1987 on mangrove ecosystems in India, while in 1989 the earliest C_{org} data was published on seagrass ecosystems of Indonesia, which is only few years after the first scientific publication that highlighted the importance of coastal ecosystems as carbon sinks in 1981 (Smith, 1981). Since then, the number of published blue carbon studies has experienced an exponential increase ($R^2 = 0.85$), especially after 2010, when the term 'blue carbon' was first published (Nellemann et al., 2009, blue-colored box on Fig. 1). Since then, several blue carbon methodologies have been proposed (orange-colored boxes on Fig. 1) which was followed by a steep increase in the number of studies in the South and Southeast Asian region with the annual percentage growth rate of 20.89 % yr^{-1}. A similar trend has been observed on the global scale, with approximately the same annual increase in the number of studies (de Paula Costa and Macreadie, 2022; Jiang et al., 2022; Zhong et al., 2023). India ($n = 162$) had the highest number of studies for mangroves followed by Indonesia ($n = 109$), with the least in Timor-Leste ($n = 3$, Fig. 2). The highest number of seagrass studies were recorded from Indonesia ($n = 31$) followed by Thailand ($n = 29$), while countries like Bangladesh, Sri Lanka and Timor-Leste currently report no seagrass studies in the peer-reviewed literature and conference proceedings (Fig. 2).

3.1. Blue carbon quantitative review

3.1.1. Blue carbon assessments by country

Country-specific C_{org} stock estimates for mangrove ecosystems were

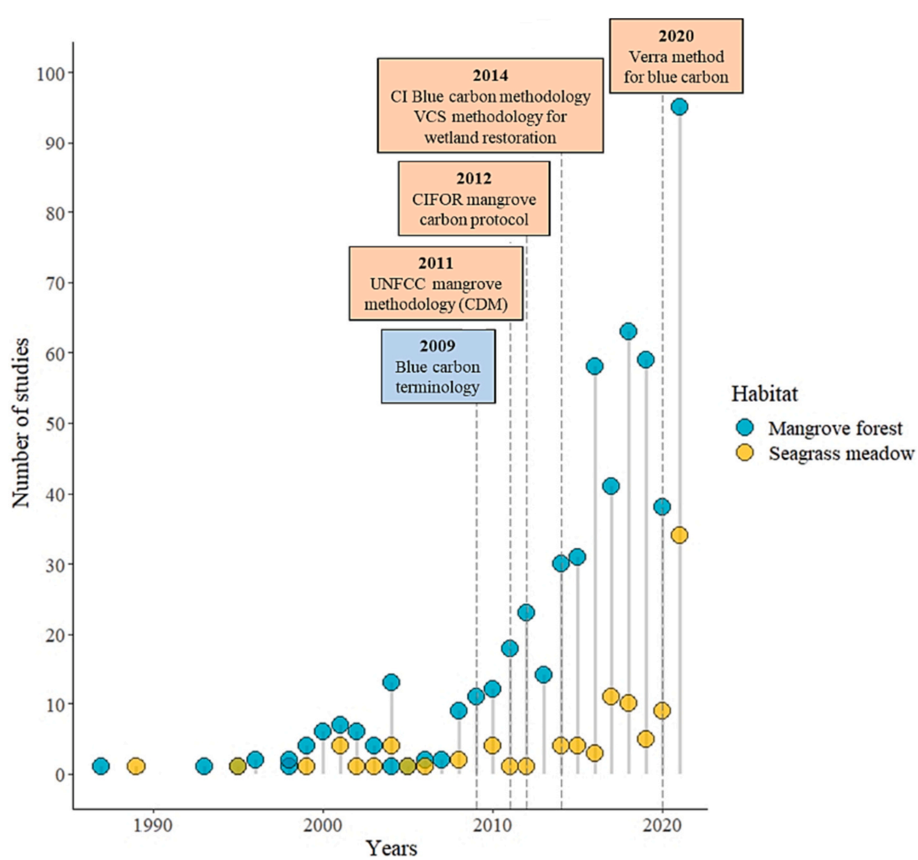

Fig. 1. The number of studies of blue carbon in South and Southeast Asia by habitat type across years.

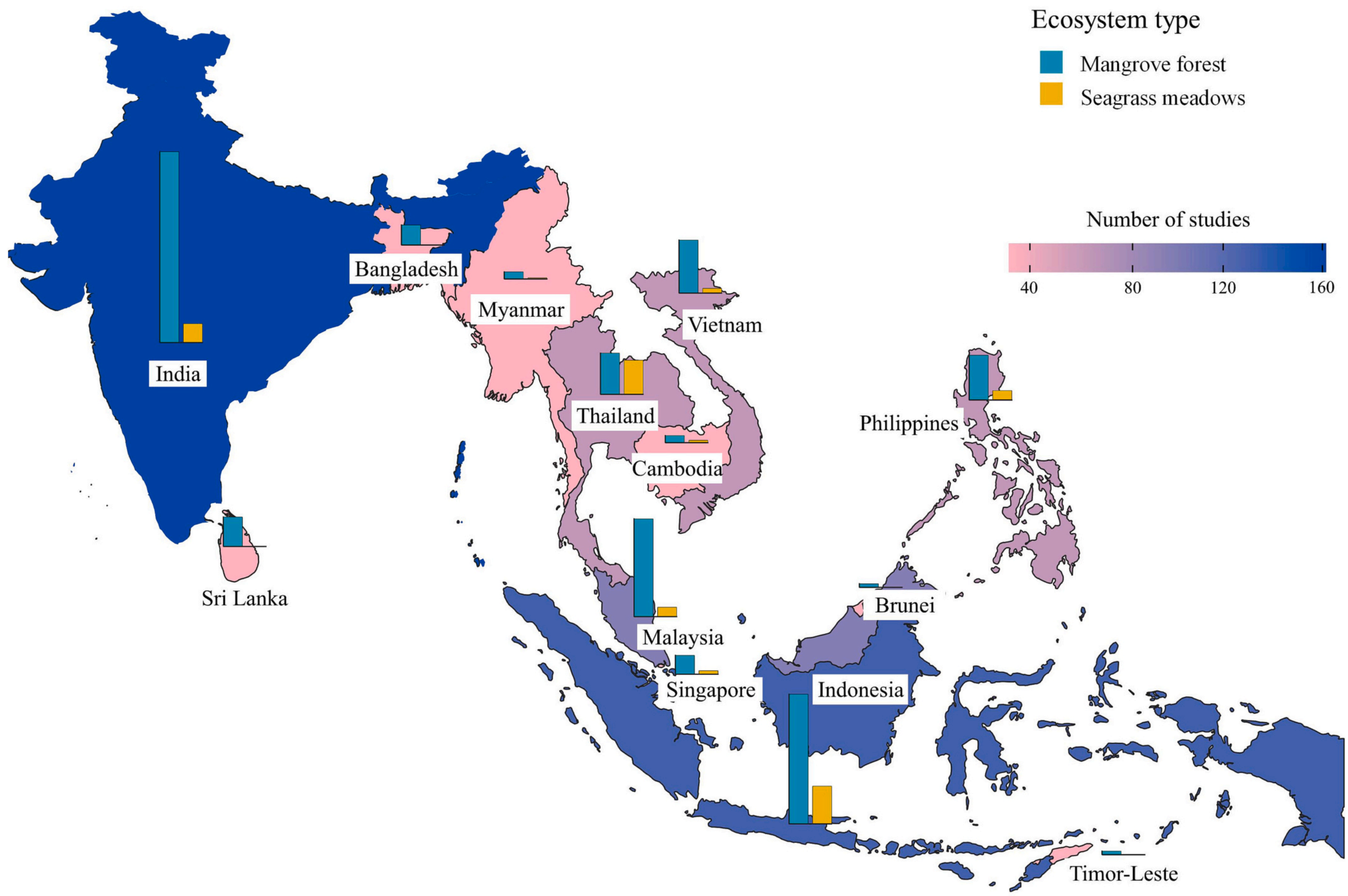

Fig. 2. The geographical distribution of published blue carbon research within South and Southeast Asia, shaded by the number of studies reported per country and the relative proportion of studies within each habitat type shown as inset bar graphs.

available for most countries in South and Southeast Asia (Tables 1 and 3). The C_{org} estimates of the non-living biomass such as litter, woody debris and downed wood were only available in few countries (Table 1). The highest total C_{org} stock (above, belowground living biomass and top 100 cm of sediment) was recorded in Indonesia with up to 1,528.8 Mg C ha^{-1}, followed by the Philippines (up to 1,301.48 Mg C ha^{-1}) and the India (up to 1,168.29 Mg C ha^{-1}). On contrary, the lowest total C_{org} stocks were recorded in Bangladesh (up to 391.59 Mg C ha^{-1}), Myanmar (up to 555 Mg C ha^{-1}), and Sri Lanka (up to 581.92 Mg C ha^{-1}). The total C_{org} stock of several other countries like Cambodia, Malaysia and Thailand had total C_{org} stocks of approximately 900 Mg ha^{-1}, whereas in Vietnam and Singapore the total C_{org} stock was lower (up to 549.58 and 741.5 Mg C ha^{-1}). Our study showcases that the mangrove C_{org} stock in most countries for this region was underestimated, when compared with previously reported C_{org} stock values by other studies for this region (Atwood et al., 2017; Hamilton and Friess, 2018; Macreadie et al., 2021; Sanderman et al., 2018). The exceptions were the total C_{org} stock values for mangrove forests of Myanmar in our studies, which was largely congruent with those (Atwood et al., 2017; Hamilton and Friess, 2018; Macreadie et al., 2021; Sanderman et al., 2018) and total C_{org} stock of Indonesia which was slightly higher than previously reported (Donato et al., 2011). Despite the availability of C_{org} stock estimates for mangrove ecosystems in Brunei and Timor Leste from regional and global studies (Atwood et al., 2017; Hamilton and Friess, 2018; Hutchison et al., 2014; Macreadie et al., 2021; Sanderman et al., 2018), these values were excluded from Tables 1 and 3, as these values have not been confirmed with field data and should be used with careful consideration.

Compared to the mangrove forests, the estimates of C_{org} stocks in seagrass ecosystems are limited to a few countries (Tables 2 and 3). It is important to note that no country in this region has estimated the C_{org} stocks of seagrass litter, which is an important source of carbon in the coastal sediments, although the methodology for the estimation is available from Howard et al. (2014), but it is not included in the IPCC wetlands supplement (IPCC, 2014). The highest total C_{org} stocks (above, belowground living biomass and top 100 cm of sediment or depth to refusal) was recorded in India, followed by Thailand and Singapore with up to 275.88, 208.95 and 156.03 Mg C ha^{-1} respectively. The lowest total C_{org} stock values were recorded in the Philippines (up to 42.44 Mg C ha^{-1}) and Indonesia (up to 69.49 Mg C ha^{-1}). However, the data of the sedimentary C_{org} stock within these two countries is limited to the depth of 67 and 50 cm, respectively, suggesting that the total C_{org} stock of these countries will most likely be higher when the sedimentary C_{org} estimations are collected up to a standard 100 cm depth. This viewpoint is validated by a recent review of C_{org} stocks of Philippines seagrasses (Corcino et al., 2023), where total C_{org} stock was 104.14 Mg C ha^{-1} in naturally disturbed seagrass meadows. In Indonesia, the recent study estimated total sedimentary C_{org} stocks up to 117.4 Mg C ha^{-1} within MPA (Rahayu et al., 2023). Similar to mangrove ecosystems, the data on the C_{org} stocks of seagrass ecosystems is available from the regional/global studies (Macreadie et al., 2021; Stankovic et al., 2021; Thorhaug et al., 2020) for Cambodia, Myanmar, and Vietnam, but this data is not included in the Tables 2 and 3 as these country-specific values are yet to be validated in the field. The globally reported and/or modelled values for C_{org} stock of seagrass meadows (Macreadie et al., 2021; Stankovic et al., 2021; Thorhaug et al., 2020) overestimate C_{org} for the seagrass meadows in India, Indonesia and the Philippines and slightly underestimate the C_{org} stock in Malaysia. However, the C_{org} stocks for seagrass meadows for Singapore and Thailand fall within the range from Tables 2

Table 1
A summary of biomass C_{org} stock values (Mg C ha^{-1}) in mangrove ecosystems for each country. The stocks are expressed as a range (min-max), as well as average ± standard deviation (SD). Absence of SD in the table means no SD value was available in the literature.

Countries	AGC[1] min – max average ± SD	BGC[2] min – max average ± SD	Total biomass carbon min – max average ± SD	DWC[3] min – max average ± SD	WDC[4] min – max average ± SD	Litter min – max average ± SD
Bangladesh	0.06–300.04 (107.15 ± 20.73)	1.43–16.78 (149.30 ± 7.05)	28.03–160.19 –	–	–	–
Brunei	–	–	–	–	–	–
Cambodia	10–70 –	1.00–50 –	–	–	0.1–10 –	–
India	0.27–574.98 (170.33 ± 44.69)	0.15–459.14 (56.63 ± 14.40)	13.52–494.5 (251.15)	2.5–6.3 –	–	1.09–3.55 –
Indonesia	0.03–742.6 (168.29 ± 61.21)	0.16–211.2 (26.39 ± 17.72)	0.10–467.4 (24.28)	0.1–34 (8.26 ± 6.30)	–	0.98–1.18 –
Malaysia	12.18–231.2 (367.30)	12.20–18.3 (8.72)	7.04–1009.7 (79.91)	8.1–73.4 –	–	0.56–1.96 –
Myanmar	7.30–165 –	6.20–56.00 –	15.90–85.8 –	–	–	–
Philippines	11.00–559.58 (90.06 ± 34.58)	6.75–182.36 (31.79 ± 13.02)	12.60–125.8 –	–	3.77–5.81 –	–
Singapore	22.06–280.8 (108 0.12 ± 20.31)	3.14–120.7 (27.51 ± 3.70)	160.00–220 (133.15)	–	–	–
Sri Lanka	75.46–189.11 (107.84 ± 12.10)	7.87–199.18 (39.15 ± 3.75)	0.09–0.17 –	0.48–0.56 –	–	–
Thailand	27.68–310.30 (162.31 ± 21.81)	23.30–40.40 (33.6 ± 9.10)	–	–	0.8–3 –	–
Timor-Leste	–	–	–	–	–	–
Vietnam	4.2–311.7 (90.13 ± 15.83)	0.40–159.59 (17.21 ± 3.72)	90–115 –	0.08–8.4 (3.56 ± 0.19)	–	–

[1] AGC – aboveground carbon.
[2] BGC – belowground carbon.
[3] DWC – downed wood carbon.
[4] WDC – wood debris carbon.

Table 2
A summary of biomass C_{org} stock values (Mg ha^{-1}) in seagrass ecosystems in individual countries of South and Southeast Asia. The stocks are expressed as a range (min-max), as well as average ± SD. Absence of SD from the table means no SD values were present in the literature.

Countries	AGC[1] min – max average ± SD	BGC[2] min – max average ± SD
Bangladesh	–	–
Brunei	–	–
Cambodia	–	–
India	3–57.15	5.0–68.18
Indonesia	0.01–1.85 (0.65)	0.05–1.84 (1.31)
Malaysia	–	–
Myanmar	–	–
Philippines	(0.77 ± 0.23)	0.59–6.78
Singapore	0.1–1.4	0.10–0.43
Sri Lanka	–	–
Thailand	0.10–9 (0.68 ± 0.31)	– (3.05 ± 0.12)
Timor-Leste	–	–
Vietnam	–	–

[1] AGC – aboveground carbon.
[2] BGC – belowground carbon if it was reported as a separate carbon pool.

and 3.

Beyond carbon stock, measuring the flux of greenhouse gases (CO_2, CH_4 and N_2O) is important for estimating the climate change abatement potential of blue carbon ecosystems (Banerjee et al., 2019; Ganguly et al., 2018). In blue carbon ecosystems CH_4 is produced in the sediments during anaerobic microbial degradation of organic carbon, and it rapidly oxidizes into CO_2 in the atmosphere, which offsets the sink capacity of the blue carbon ecosystems represented by the C_{org} burial (Oreska et al., 2020; Rosentreter et al., 2021; Saderne et al., 2023; Yau et al., 2023). However, information on greenhouse gas emissions from

Table 3
A summary of the non-extrapolated organic carbon stock in the sediment (Mg ha^{-1}) across different core depths of mangrove and seagrass ecosystems in South and Southeast Asia.

Countries	Sediment (≤ 100 cm depth) min - max	Sediment (> 100 cm depth) min - max
Mangrove forest		
Bangladesh	13.30–74.77	–
Brunei	–	–
Cambodia	50–850	–
India	0.08–134.17	–
Indonesia	2–575	520–2429.7
Malaysia	45.67–658.4	–
Myanmar	109–334	145–211
Philippines	10.61–559.54	46.77–2014.56
Singapore	8.40–340	–
Sri Lanka	10.09–1334.81	–
Thailand	5.58–553	462.67–1172.8
Timor-Leste	–	–
Vietnam	4.84–884.4	341.9–926.91
Seagrass meadows		
Bangladesh	–	–
Brunei	–	–
Cambodia	–	–
India	2.23–150.55	–
Indonesia	0.32–65.80[1]	–
Malaysia	0.10–201.10	–
Myanmar	–	–
Philippines	13.95–41.08[2]	–
Singapore	4.19–146.60	–
Sri Lanka	–	–
Thailand	14.20–205	–
Timor-Leste	–	–
Vietnam	–	–

[1] Core reached only up to 67 cm depth.
[2] Core reached only up to 50 cm depth.

seagrass and mangrove ecosystems within South and Southeast Asia is very limited and has been mostly focused on mangrove ecosystems (Table 4). The highest CO_2 flux of mangrove forest were in Myanmar (up to 2,712.25 mmol CO_2 m^{-2} day^{-1}), followed by the Philippines (up to 799.20 mmol CO_2 m^{-2} day^{-1}) (Table 4), which demonstrates that these regions are C_{org} sources. Within South and Southeast Asia, these two countries have been identified as hotspots of mangrove ecosystem loss (Gandhi and Jones, 2019), resulting in a release of trapped carbon. On the other hand, measurements of CO_2 emissions in seagrass ecosystems are lacking in many countries, except India, Indonesia, and Thailand (Table 4). The CO_2 flux within the seagrass ecosystems was the highest in Indonesia with over 500 mmol CO_2 m^{-2} day^{-1}, while the lowest was in India, with up to 72.6 mmol m^{-2} day^{-1}. The values of CO_2 flux within the seagrass ecosystems falls within the range reported for this region 32–700 mmol m^{-2} day^{-1} (Kennedy et al., 2004). However, the recent review highlighted the large uncertainties of carbon flux estimates and the need on the standardized methods to calculate flux components (Sharma et al., 2023).

Methane emissions from blue carbon ecosystems are scarcer comparing to CO_2 emissions for both ecosystems, and they have been measured for only a few countries, with the highest CH_4 flux were in India (Table 4). Among the five countries, the highest CH_4 flux from sediment is reported in India for mangrove ecosystems and India is the only country with CH_4 flux data for seagrass ecosystems (Table 4). The difference in the volume of CH_4 fluxes of the mangrove sediment between the countries is result of variation in abiotic factors (such as seasonality, salinity, temperature, pH) and the tidal dependent exposure of sediment to oxygen and methanotrophic (CH_4-oxidizing) bacteria (Arai et al., 2021; Chauhan et al., 2015; Nazareth and Gonsalves, 2022). Secondly, anthropogenic pollution and habitat disturbances play an important role in creating an imbalance between the methanogenesis and methanotrophy resulting in release of CH_4 from sediment (Alperin et al., 1992; Chauhan et al., 2015).

Table 4
A summary of the carbon dioxide (CO_2) and methane (CH_4) flux (mmol m^{-2} day^{-1}) in mangrove and seagrass sediments of South and Southeast Asian region. Positive values indicate the source and negative sink for each given gas.

Countries	CO_2 flux (mmol m^{-2} day^{-1}) min – max	CH_4 flux (mmol m^{-2} day^{-1}) min - max
Mangrove forest		
Bangladesh	–	–
Brunei	–	–
Cambodia	–	–
India	0.01–582.24	0.08–8,097
Indonesia	−0.03–103.98	−0.14–217.26
Malaysia	2.56–214	–
Myanmar	104.61–2,712.25	1.7–5.14
Philippines	20.74–799.20	388.8–660.98
Singapore	43.86 ± 20.11[a]	–
Sri Lanka	–	–
Thailand	31–77	–
Timor-Leste	–	–
Vietnam	66.5 ± 25.6	0.001–51.61
Seagrass meadows		
Bangladesh	–	–
Brunei	–	–
Cambodia	–	–
India	2.59–72.6	0.01–0.39
Indonesia	501.85 ± 208.53[a]	–
Malaysia	–	–
Myanmar	–	–
Philippines	–	–
Singapore	–	–
Sri Lanka	–	–
Thailand	49.01–95.3	–
Timor-Leste	–	–
Vietnam	–	–

[a] Only average values were obtained.

The estimation of carbon sequestration rates was more common for mangrove forests in the region, with the highest values recorded in Indonesia and Thailand and the lowest in Bangladesh and Singapore (Table 5). However, the estimated values are the result of several different methods used in the studies and the quality of these estimates should be carefully considered (Section 3.1.2). In contrast, carbon sequestration rates in seagrass ecosystems were only estimated from a single study in Thailand (Table 5). The paucity of estimates of flux and sequestration rates, especially in seagrass meadows, comprises one of the major knowledge gaps across the region.

3.1.2. National Blue Carbon Inventories

The total C_{org} stock per country was estimated by utilizing the total area of mangrove and seagrass ecosystems from various sources (Supplementary 3 Table S2). However, due to limitations of the quality of the obtained total extent for seagrass ecosystems across the region (Supplementary 3 Table S3), the total C_{org} stocks per country reported in this study should not be considered as final.

We expect country-specific updates of these estimates in the near future, when maps of these ecosystems with higher accuracy become available. The highest total C_{org} stock was in Indonesia with over 4,500 Tg C across both ecosystems (Fig. 3), with approximately 95 % of the total carbon pool in mangrove ecosystems and about 5 % in seagrass meadows, which is considerably lower than reported in Murdiyarso et al. (2015) mostly due the difference of the mangrove extent. The lowest total C_{org} stock for any country was in Singapore, with less than 1 Tg including both ecosystems (Fig. 3). This is higher than reported in Friess et al. (2023), who used a variety of field-based and remote sensing approaches to estimate blue carbon stocks to be 482,257–490,023 Mg C. In addition, the C_{org} stocks from India are much higher than reported in Akhand et al. (2022), who did a recent meta-analysis of all three blue carbon ecosystems, which are most likely due to deeper sediments reported in this study as well as higher above and below ground carbon within the trees. In most of the countries in the region, the mangrove carbon pool represented more than 90 % of the total carbon pool, while the seagrass carbon pool represented less than 3 %.

However, the total C_{org} stock estimates in each country (Fig. 3) should be perceived with some assumptions, such as variability in the method used for data collection (Section 3.2 for C_{org} sediment stock), as well as the uncertainty of the total area of the ecosystem, which is especially noteworthy for the seagrass meadows. Based on these variations, assessments of confidence for each country and ecosystem type are provided (Table 6). Among all countries within the region, only mangrove data from Singapore delivers high confidence values in all four categories, while countries like Vietnam, Thailand, Malaysia, Indonesia, and India, should adopt more robust methodologies for acquiring certain data from mangrove forests (Table 6). Although Bunting et al. (2022) provides high quality, globally consistent and

Table 5
Carbon sequestration rates (g m^{-2} y^{-1}) in mangrove and seagrass ecosystems across the South and Southeast Asian region.

Countries	Mangrove forest min – max	Seagrass meadows min - max
Bangladesh	200–275	–
Brunei	–	–
Cambodia	–	–
India	7.7–875	–
Indonesia	5–1722	–
Malaysia	20–760	–
Myanmar	–	–
Philippines	–	–
Singapore	70–170	–
Sri Lanka	–	–
Thailand	100–1263.3	2.97–3.09-
Timor-Leste	–	–
Vietnam	120–602.7	–

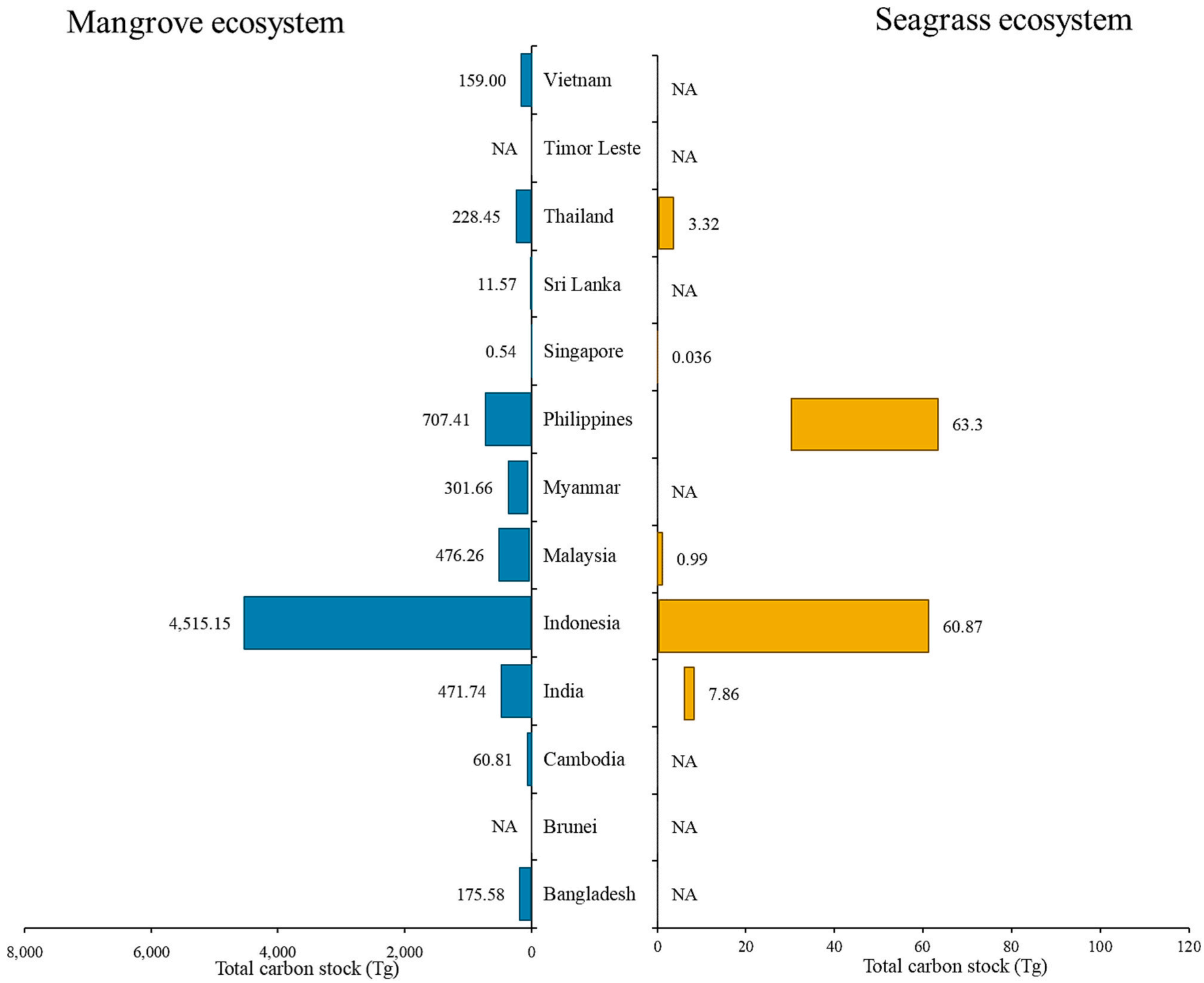

Fig. 3. The range of total C_{org} stock in mangrove and seagrass ecosystems in the countries of South and Southeast Asia. *Note:* different scales of the total carbon stock (Tg) between ecosystems.

comparable results on the mangrove area in these countries, government reports of the several countries, such as India (Forest Survey of India, Ministry of Environment Forest and Climate Change 2021), Indonesia (Ministry of Environment and Forestry of The Republic of Indonesia 2021), Thailand (DMCR, 2021, https://marinegiscenter.dmcr.go.th/gis/) and Vietnam (MARD, Announcement of National Forest Status in 2019, Hanoi, Vietnam, 2020. In Vietnamese) are using country-derived values, which suggest much higher areal extents of the mangrove ecosystems than reported in Bunting et al. (2022). On the other hand, the areal extents of the seagrass meadows for all the countries in the region are incomplete and with medium to low confidence data assessments, suggesting that a key priority is generating valid extent maps for this ecosystem. The difficulty of the seagrass mapping is closely related to the quality and variability of coastal waters in the region. The excess sediment particles affect the water quality and reduce the transparency, and as a result the ability for satellite to "see" the bottom is very limited. However, in recent years, techniques have been developed to map seagrass meadows in optically complex waters (Kovacs et al., 2022), so such practices should be attempted along the coastline to provide a national scale seagrass map. The data quality of carbon sequestration rates is mostly high for mangrove forest in majority of the countries, there are still some differences within the used methods. Countries like Indonesia, Singapore, Vietnam, Thailand have used ^{210}Pb to estimate carbon accumulation rates (CAR) within the sediment, as these estimates provide the values in the last ca 100 years and their changes over time. Due to long integration period, ^{210}Pb-derived CAR estimates are not affected by interannual variability and provide the assessments of CAR changes from the "baseline" condition (Arias-Ortiz et al., 2018). In addition, surface elevation table (SET) have been used to determine elevation changes of the sediment and carbon in Bangladesh and Indonesia. The surface changes of the sediment are usually measured seasonally every year to establish the trends and changes of C_{org} (Howard et al., 2014). Both methods are standardized practice in measuring CAR in coastal sediments, however the direct comparison of these two methods has not been done. These confidence assessments can serve as a reference point on what countries should improve for each ecosystem, so more precise estimates of carbon inventories can be reached.

3.2. Blue carbon priority areas

Our literature review revealed, blue carbon studies were conducted across 140 locations in the South and Southeast Asia region (Fig. 4). Studies focused on mangroves are most prevalent and capture various estimates of C_{org} stock across the entire geography of countries such as India, Thailand, Sri Lanka and peninsular Malaysia (Fig. 4A). In two of these countries the highest number of studies are located, i.e., Matang Mangrove Forest Reserve in Malaysia (n = 28), and Sundarbans

Table 6
Color coded qualitative confidence assessments on the blue carbon data for mangrove and seagrass ecosystems.

Countries	C_{org} soil stock	Sequestration rate	Areal extent
Mangrove forest			
Bangladesh	high	high	high
Brunei	-	-	high
Cambodia	high	-	high
India	low	medium	high
Indonesia	medium	high	high
Malaysia	medium	medium	high
Myanmar	medium	-	high
Philippines	high	-	high
Singapore	high	high	high
Sri Lanka	high	-	high
Thailand	high	high	high
Timor-Leste	-	-	high
Vietnam	high	high	high
Seagrass meadow			
Bangladesh	-	-	low
Brunei	-	-	medium
Cambodia	-	-	low
India	low	-	high
Indonesia	medium		medium
Malaysia	medium	-	low
Myanmar	-	-	low
Philippines	high	-	medium
Singapore	high	-	high
Sri Lanka	-	-	low
Thailand	high	high -	medium
Timor-Leste	-	-	medium
Vietnam	-	-	high

Note: the description of confidence assessments for each category can be found in Supplementary 3 Table S3.

bordering India and Bangladesh (n = 19 in each location; Fig. 4A). On the other hand, the research on blue carbon in mangrove forests is lacking in countries like Indonesia, Philippines, Vietnam, and Bangladesh, with many studies concentrated in few selected locations, such as Central Java province in Indonesia, Palawan and Iloilo province in Philippines and Can Gio Mangrove Forest in Vietnam (Fig. 4A). Additionally, published mangrove research in countries like Myanmar and Timor-Leste is limited to a single location (Fig. 4A). Despite the high spatial variability in blue carbon efforts, they can still provide usable data for national inventories, with the caveat that specific locations may deviate from the national average as a result of local environmental factors.

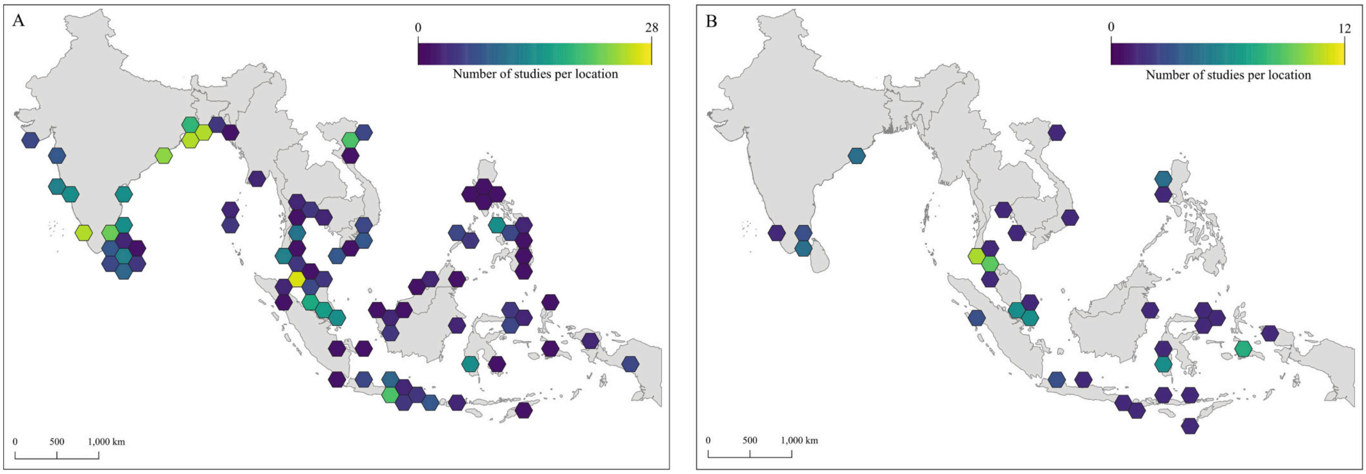

Fig. 4. Locations and the number of the study sites for mangrove ecosystems (A) and seagrass meadows (B).

Unsurprisingly, given the overall few numbers of studies, the geographic scope of research of seagrass blue carbon is much more limited in most of the countries in the region (Fig. 4B). The majority of the research is focused to couple of the study sites, such as Libong island in Thailand, the coast of Tamil Nadu including the Gulf of Mannar region in India, Merambong shoal in Malaysia, Spermonde islands in Indonesia, Bolinao Island in Philippines, Check Jawa in Singapore (Fig. 4B). However, the seagrass meadows along the coastlines of various countries in the region remain understudied, especially in Myanmar, Sri Lanka and east Malaysia, where not a single study on blue carbon in seagrass meadows has been conducted.

The importance of capturing the spatial variability of blue carbon lies within high variability of the C_{org} stocks across: 1) geomorphological settings and geophysical processes (Rovai et al., 2018) for mangrove sedimentary C_{org} stock, 2) bioclimatic drivers and tidal amplitudes and age of mangrove biomass and consequently C_{org} stock (Rovai et al., 2021) and 3) species composition/identity and traits, followed by geomorphological setting of the area for the seagrass C_{org} stock (Kennedy et al., 2022). These issues are further compounded by varying resolutions across remote sensing techniques, ranging from sub-meter (e.g., Planet) to 10 or even 30 m resolution, depending on the period of observation, and thus our ability to census the exact conditions under which the species live, or even assess them at all (e.g., for seagrass species below the depth of 20 m). Knowledge on these variations within the spatial settings can eliminate bias estimates for the predictions of potential carbon stocks or avoided emissions following conservation and/or enhanced carbon sequestration after restoration efforts of the ecosystem.

Besides well-studied sites, blue carbon "hotspots" were identified as the locations with high C_{org} stock (Table 7). Sustainable management of the ecosystems exist at a few sites, such as Bintuni Bay in Indonesia, Bhitarkanika Wildlife Sanctuary in the state of Odisha, India and Trat River in Thailand. In addition, this type of management has demonstrated that high C_{org} stocks can be sustained within the ecosystem (Murdiyarso et al., 2021), proving an opportunity for nature climate solutions. At Bintuni Bay in Indonesia, large portion of the mangrove area (north and east parts) is under the protection of the Government of Indonesia, while the southern part is under the management of PT. Bintuni Utama Murni Wood Industries (Yudha et al., 2021). This area is systematically managed for timber, thinning is carried out during 20 or 30-year rotation (Ministry of Environment and Forestry 2016) by Forest Management Enterprise (FME) since 1988 and it has been extended until 2052 (Yudha et al., 2021). However, it has been suggested that this rotation period should be extended to 30–40 years for secondary forests within this area to maintain ecological processes and biodiversity (Sillanpää et al., 2017).

Table 7
Mangrove and seagrass blue carbon "hotspot" areas across South and Southeast Asia.

Location	Country	Total Corg stock ($Mg\ ha^{-1}$) min-max	Potential threats
Mangrove forest			
Bintuni Bay, West Papua	Indonesia	1306.5–1735.3	Spread of oil palm plantations in the future
Bhitarkanika Wildlife Sanctuary	India	376.6–2084.0	Natural erosion in the eastern parts, conversion to agricultural land
Honda Bay, Palawan	Philippines	328.88–1151.5	Aquaculture, cultivated crops and salt ponds
Mahakam Delta, Kalimantan	Indonesia	704–1663	Deforestation due to aquaculture development since 1990s
Rekawa Lagoon	Sri Lanka	1172.3–1334.8	Deforestation due to aquaculture, crop fields, salt ponds and other build up areas
Trat River	Thailand	812.8–1337.3	–
Seagrass meadows			
Libong island	Thailand	69.1–205.9	Sedimentation and increase of the human pressure
Sungai Pulai estuary (Tanjung Adang-Merambong Shoal)	Malaysia	201.1 ± 27.7	Building of the Tanjung Pelepas Port in 2000 caused severe changes in the area (high sedimentation) which caused the complete disappearance of Tanjun Adang Darat Shoal and decline of Tanjun Adang Laut and Merambong Shoal. Since then, these shoals have been recovering slowly, especially in the last decade.

Mangrove forests in Bhitarkanika Wildlife Sanctuary, India, are part of the Bhitarkanika Conservation Area, however the intact forests are part of the National Park, while the mangrove forests within Bhitarkanika Wildlife Sanctuary are degraded (Hussain and Badola, 2010). Within the Bhitarkanika Conservation Area there are over 300 villages, and the majority of the people heavily rely on the mangrove ecosystems for their income (Hussain and Badola, 2010). In the last few decades, the mangrove areas were affected by degradation for commercial use, agriculture or aquaculture, animal grazing and collection of non-wood forest products leading to massive fragmentation and biodiversity changes (Acharya et al., 2021). In addition, the natural erosion of the sediments along the majority of the coastline increased significantly between 2005 and 2014, especially from Gahiramatha beach to Kanika Island (Barik et al., 2016).

Mangrove forests along the Trat River, Thailand have been under the management of the Mangrove Forest Learning and Development Center No.1 of the Department of Marine and Coastal Resources (DMCR) since 1980s when the development of timber and charcoal ceased in this area (Kida et al., 2021). On the other hand, in other locations, mangrove areas have been affected by various threats (Table 7). The mangrove forests in the Mahkam Delta in Indonesia have been heavily affected by a large-scale deforestation since late 1980s due to construction of aquaculture ponds (Bosma et al., 2016; Dutrieux et al., 2014). Although the deforestation of the mangrove forest peaked in 1990s, with 58,790 ha of mangrove deforested by early 2000s, when the deforestation slowed down, the conversion to aquaculture increased covering 46.2 % of the delta by 2006 (Aslan et al., 2021). Since then, the massive abandonment of the ponds has been detected, with the rate of 834 ha yr^{-1} since 2010 (Aslan et al., 2021). The mangrove area at Honda Bay, Philippines stretches along narrow coastline area and are interrupted by non-forest areas, such as aquaculture ponds, crops, salt ponds and other build up areas. The southern part is in the close proximity to Puerto Princesa City, and most of the mangrove clearing is localized in this region. On the other hand, the northern areas of mangrove forests remained intact, and community based sustainable tourism is more frequent (Dangan-Galon et al., 2016).

The most well-studied areas in seagrass meadows are those exposed to the heavy anthropogenic pressure, such as land reclamation for coastal activities, transportation routes, deteriorating water quality, water pollution, and high nutrient inputs (Table 7). Consequently, these well-studied areas have experienced a decline of seagrass meadows to various extents or complete disappearance. The well-studied blue carbon meadows at Libong island in Thailand belong to Koh Libong Non-Hunting Wildlife Sanctuary. However, the seagrass meadows at this location are still under threat of human pressure and sedimentation. The seagrass meadows at this location have declined by the rate of 3.2 % yr^{-1} from 2009 due to increase of the anthropogenic developmental activities on the island and in its surrounding areas (Stankovic et al., 2020). Additionally, since 2014 the seagrass meadows are experiencing a severe decline in diversity, coverage, and extent mostly due to an increase in sedimentation. On the other hand, seagrass meadow in Sungai Pulai estuary in Malaysia has shown recovery in the last decade, but coastal reclamation and development in the surrounding area are still ongoing (Hossain et al., 2018). The seagrass meadows at the shoal are in proximity to the Sungai Pulai Forest Reserve Ramsar Site, but their protection relies on national and state legislations. The integrated approach to the management and conservation has been identified for unprotected seagrass meadows, including Tanjung Adang-Merambong Shoal (Bujang et al., 2006), but no policies or guidelines have been specifically issued to include seagrass meadows. Currently, under the Malaysian National Policy on Biological Diversity 2016–2025, seagrass beds are included into Goal 3 of "safeguarding the key ecosystems, species and genetic diversity", within that it is planned that seagrass meadows will be protected and restored through inclusion into MPAs. However, due to political and administrative reasons, the focus on the biodiversity-related policies could limit impactful changes in Malaysia (Tong, 2020).

3.3. Methods used to assess blue carbon

3.3.1. Assessing sediment organic carbon

While carbon stocks have been quantified in mangroves and seagrasses using various methods for decades, standardized protocols have been globally published and available since 2012 (orange-colored boxes on Fig. 1), which provide a wide array of options for C_{org} data collection depending on available facilities and budget. From this review, the two most common variations for estimating sediment C_{org} involved: 1) the methods used for estimating C_{org} content (%), and 2) the depth of sediment cores. The variability of these methods subsequently influences the estimation of C_{org} stocks and should be addressed in the future, as in most cases this variability may lead to less accurate estimates of blue carbon stocks in these ecosystems.

To quantify sediment C_{org}, the most common method employed was an elemental analyzer (EA; $n = 205$), which was mostly used for mangrove forests ($n = 156$), followed by seagrass ($n = 42$). The second most common method (classified as other) used to assess sediment C_{org} content was the Walkley and Black (1934; hereafter WB) method, especially in mangrove forests ($n = 151$). The third most used method was a conversion factor ($n = 66$), which was used to convert biomass and/or sediment organic matter content to carbon. The conversion of sedimentary organic matter to carbon content was particularly used in mangrove studies, with a few studies in seagrass meadows. Conversion factors were most commonly used in the studies that reported ecosystem diversity, current status and health of the ecosystem to add on the component of the blue carbon stock. The least common method used was loss on ignition (LOI; $n = 62$), which was almost equally applied in sediment C_{org} estimation of mangroves and seagrass sediments ($n = 32$ and $n = 30$, respectively). However, the use of EA and WB doubled from 2014 onwards, while the use of LOI and conversion factors increased 8 and 12-fold, respectively. The increase of EA and LOI methods was expected as they are considered as the standard methods for improved accuracy in sedimentary C_{org} estimation and are reasonably easy to employ (Howard et al., 2014). The wet combustion method (WB) has lower accuracy because "the use of H_2O_2 does not always result in complete digestion of sediment organic carbon equally" (Howard et al., 2014). In a recent study, the average concentration of sedimentary OM of coastal plains were significantly different under different treatments when WB was used, while the values were not significantly different when EA and LOI methods were applied (Roper et al., 2019). Furthermore, the results of this study suggest non-significant correlation between EA/LOI and WB method in coastal plain soils (Roper et al., 2019). We recommend that similar comparisons are made in a variety of coastal and marine sediments.

3.3.2. Geographic variation in sedimentary organic carbon methods

Among the countries, Vietnam, Thailand, and Singapore used EA in ~60 % of studies that assessed sedimentary C_{org} stock, while Bangladesh, the Philippines and Malaysia used EA for ~40 % of the studies. The rest of the studies used a combination of other three methodologies (i.e., WB, LOI and conversion factors). Among all countries, India and Indonesia have used the most combination of the four C_{org} estimation methods than other countries. In India, the majority of the studies (~60 %) have used "other" methods to estimate sedimentary C_{org}, while in Indonesia the most common method to estimate sedimentary C_{org} was conversion factor (in ~40 % of the studies), while only 30 % of the studies used EA in both of the countries. Although the availability of more precise methods, such as EA might be more common in the high and upper-middle income economies, there were countries from lower-middle income economies, such as Vietnam and Timor-Leste which used it with similar frequency as higher income economies.

When compared, the minima and maxima of C_{org} (%) derived from EA and LOI were similar for mangrove and seagrass ecosystems. However, greater differences were observed between these methods for seagrasses than mangrove ecosystems within countries (Table 8). In mangrove ecosystems, the low variation between sediment C_{org} content is most likely a result of similarities between geomorphic settings of the sites within the country coupled with a fairly consistent methodology. In contrast, sediment C_{org} content (%) in seagrass ecosystems was highly variable in most countries (Table 8). These variations are probably a

Table 8
Comparison of the C_{org} content (%) obtained by two different methods elemental analyzer (EA) and Loss on Ignition method (LOI) in mangrove and seagrass ecosystems of South and Southeast Asian region.

Countries	C_{org} content (%) EA		C_{org} content (%) LOI	
	min	max	min	max
Mangrove				
Bangladesh	0.12	4.4	–	–
Brunei	–	–	–	–
Cambodia	–	–	–	–
India	0.15	18.32	5.42	15.52
Indonesia	0.8	26.24	3.06	25
Malaysia	0.56	10.28	3.76	8.76
Myanmar	–	–	–	–
Philippines	0.3	21.2	0.45	4.06
Singapore	2	10	2	10
Sri Lanka	0.32	31.61	0.32	3.4
Thailand	0.37	7.35	0.9	9.8
Timor-Leste	0.71	9.96	–	–
Vietnam	0.21	9.98	0.61	3.85
Seagrass				
Bangladesh	–	–	–	–
Brunei	–	–	–	–
Cambodia	–	–	–	–
India	0.69	1.98	–	–
Indonesia	0.35	2.43	1.3	5.8
Malaysia	0.09	2.42	0.09	2.02
Myanmar	–	–	–	–
Philippines	1.3	2.1	0.43	1.81
Singapore	1	1.2	0.91	1.32
Sri Lanka	–	–	–	–
Thailand	0.02	8.34	0.09	1.48
Timor-Leste	–	–	–	–
Vietnam	0.18	0.58	–	–

result of the low number of studies in seagrass meadows within this region, with five or less studies per method in several countries. Furthermore, some studies used their own linear regression equations to convert OM from LOI to organic carbon (Phang et al., 2015; Rattanachot et al., 2018), while some studies have used the equation from Fourqurean et al. (2012). This equation was derived using fewer data points from the South and Southeast Asian seagrass meadows compared to the other ocean regions, and its robustness in predicting sedimentary C_{org} in the region remains untested, but arguably may be more accurate than the globally derived values. Although this general equation has demonstrated that the model can explain high proportion of variance in sediment C_{org} globally ($R^2 > 0.8$), the regionally produced models (Alemu et al., 2022; Phang et al., 2015; Stankovic et al., 2018b) could explain between 13 and 48 % of the variations when applied in the estuarine seagrass meadows and between 70 and 72 % of the variations when used for sandy and reef-associated seagrass habitats (Alemu et al., 2022; Rattanachot et al., 2018). However, the parametrization of these models is done using the locally derived data, producing more accurate but less precise models comparing to the globally derived equations. These results suggest that the inherent variability of seagrass ecosystems (geomorphology) and their substrates (mud, muddy-sand, sand-coral reef) requires conversion values that are specific to the location of interest, rather than regional or even global approximations that are easy to apply but may provide less reliable estimates of C_{org} stocks. A recent global review on the sampling methodologies on blue carbon ecosystems suggested EA and LOI, as preferred method for the C_{org} stock assessments and locally derived and validated conversions of OM to C_{org}, which can lead to spatially representative data using limited budgets (Fest et al., 2022).

3.3.3. Depth at which sedimentary organic carbon is estimated

Sediment core depth was the second most variable part in methodology for data collection of sediment C_{org}. A common depth of 100 cm was used for sediment core sampling in both mangroves ($n = 75$) and seagrass ($n = 12$) ecosystems, followed by 30 cm depth ($n = 34$ and n = 7, respectively). Additionally, some studies collected surface sediment (< 5 cm) in mangrove ($n = 26$) and seagrass (n = 7) ecosystems, and some studies collected sediment cores from 300 cm depth in mangrove ($n = 9$) ecosystems; and one study collected from a core depth of 556 cm. The differences in the depth of the core clearly lead to variability in carbon estimates (Fig. 5), which is particularly important when the C_{org} stocks are being extrapolated to 100 cm. The current method of extrapolating the C_{org} stocks from shallower depths to 100 cm, where the data from the specific depth is multiplied by the ratio of the 100 and obtained depth, underestimates the C_{org} stocks up to 3 times in mangrove forests (Fig. 5A) and between 1.5 and 10 times in seagrass meadows (Fig. 5B), providing large uncertainties of C_{org} stocks.

Nevertheless, many countries sampled <100 cm core depth, with the highest proportion of such studies in India (84 %) and Bangladesh (80 %). Similarly, all the studies in the seagrass ecosystems in Indonesia, Philippines and Vietnam collected sediment from <100 cm depth. However, ~50 % of studies from Singapore and Thailand collected their sediment cores from a depth <100 cm in seagrass ecosystems, while ~70 % studies in Malaysia collected the core to 100 cm depth. It is highly possible that selection of the depth is based on the length of the available corer, the depth of refusal for these different geologies, and/or simply decision based, but the published methodologies suggest that 100 cm cores are standard, with recommendations of the collection of deeper sediments for more specified assessments. In addition, in shallow sediments when the depth of the sediment is lower than the core, the depth to refusal is measured, and the core depth selection should be accompanied with the information on the depth to refusal. Recent reviews on the sediment sampling of mangrove forests recommend to include at least 100 cm core depth, as well as the information on the sediment depth below 100 cm (Fest et al., 2022). However, the total depth sampled will depend on the objectives of the study, and if carbon accounting is being considered, where only top 100 cm is relevant (IPCC, 2014).

4. Conclusions

4.1. Current trends and existing knowledge gaps in blue carbon research in South and Southeast Asia

Overall, our review showcases that blue carbon research is expanding in South and Southeast Asia, like in many parts of the world, and generating more robust data that can be used for generating policy frameworks for better conservation of blue carbon ecosystems. However, these efforts are sporadically distributed throughout the region, use a variety of methods, and exhibit an unequal emphasis on mangrove ecosystems rather than on seagrass meadows. There are substantial gaps in the types of data assessed by many countries across the region on seagrass meadows, with only Thailand and Singapore reporting stocks, sequestration, and emission rates. In addition, the lack of high-quality maps of the extent of seagrass meadows for many countries greatly hinders the ability to accurately estimate national-scale potential of C_{org} stocks for this ecosystem.

The methodology used to assess C_{org} stocks varies across the countries and the selection of the methods is mostly based on the researchers' decisions and analysis costs of elemental analysis (EA). This disconnect is especially prominent in seagrass meadows in the region compared to mangrove forests. In addition, the use of the lower accuracy methods to obtain the C_{org} content (%) is very common across the region, and the comparison/adjustment among methods for sediment of coastal ecosystems are necessary in the near future to promote greater interoperability.

The identification of the well-studied blue carbon areas has suggested that many studies are spatially biased towards specific sites,

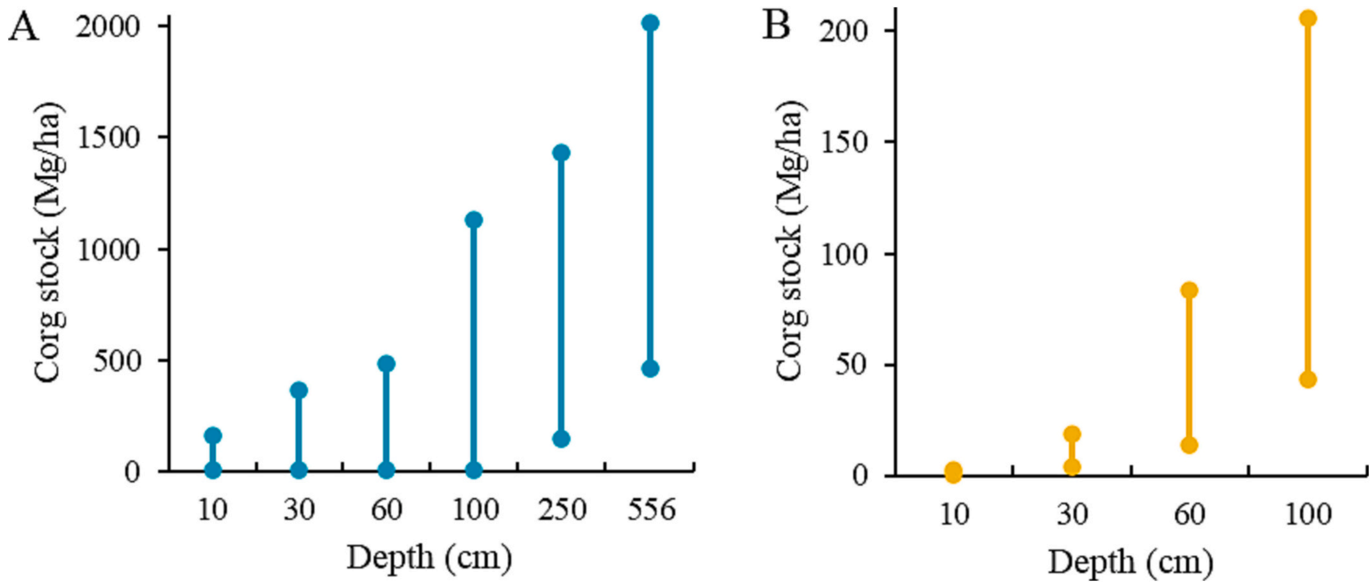

Fig. 5. The range of the non-extrapolated sedimentary C_{org} stock (Mg ha^{-1}) across different core depths in mangrove ecosystems (A) and seagrass meadows (B) used in the studies across South and Southeast Asia.

largely those that are already protected or those experiencing heavy impacts and therefore losses, and the range of conditions that influence blue carbon storage is most probably not captured, especially in the seagrass meadows. Several mangrove well-studied areas are sustainably managed which reflects in high ecosystem services like carbon storage, which provides a strong blueprint for seagrass studies which are relatively unmanaged and subject to multiple anthropogenic stressors.

4.2. Future perspectives and directions

As international efforts seek to establish greater protections for blue carbon ecosystems under policies like NDCs, we must ensure that the science behind the generation of data is robust enough to reduce uncertainties and ensure the most accurate estimation of carbon. Based on the results of this extensive review several perspectives and recommendations should be considered in the future studies:

- higher research emphasis on the seagrass meadows, as there are substantial gaps in assessing blue carbon in this ecosystem;
- improved mapping techniques, especially in seagrass meadows, as the variability of the conditions (intertidal, subtidal, different water qualities) and species combinations creates challenges for the current mapping approaches;
- spatially balanced research, with the focus on the underrepresented sites;
- adoption of standardized methods and use consistent core depths to ensure consistency and comparability of data across the region. In particular, we would advise to adopt standardized methods and ensure all cores are taken to at least 100 cm depth if the data are to be used for carbon accounting purposes (or to depth to refusal in shallower sediments),
- interoperability and data sharing of the OM and C_{org} content across various geomorphological settings into global databases (such as https://serc.si.edu/coastalcarbon/data or other region-specific databases) all of which will contribute towards generation of more robust estimates of country and habitat specific Corg stocks.

With the increasing interest of the blue carbon science and further anticipated increases in the near future, the gaps and issues highlighted throughout this review can provide both inspiration and guidance towards integrating the blue carbon ecosystems of South and Southeast Asia into the global strategy of nature-based solutions to combat climate change.

CRediT authorship contribution statement

MS and AP developed the original concept. MS, AKM, YPR designed the manuscript, with critical concept re-design of MV, DF, JL and JDGE. MS, AKM, YPR acquired and analyzed the data with the support of MC, TV and SHF. MS, AKM, YPR, JL, DM, DF, MV, SHF, JDGE and AP contributed to the manuscript writing and revisions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No new data were created.

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Appendix A. Supplementary data

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