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Quantification of blue carbon in seagrass ecosystems of Southeast Asia and their potential for climate change mitigation

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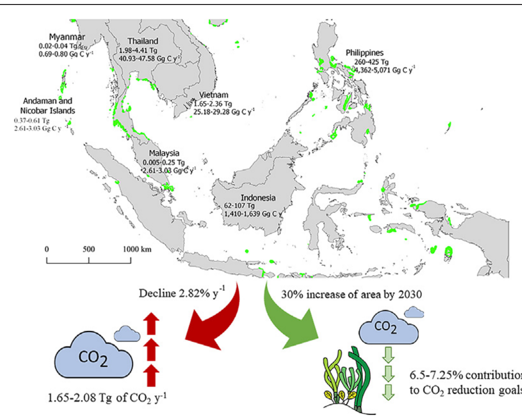
HIGHLIGHTS

- Seagrass ecosystems in Southeast Asia can store large amounts of organic carbon.
- Blue carbon in seagrass can contribute towards offsetting countries' CO_2 emission.
- Under current loss rate all meadows will disappear by 2060 and emit plenty of CO_2.
- Current meadows have high potential to contribute CO_2 reduction goal by 2030.

GRAPHICAL ABSTRACT



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A B S T R A C T

Seagrasses have the ability to contribute towards climate change mitigation, through large organic carbon (C_{org}) sinks within their ecosystems. Although the importance of blue carbon within these ecosystems has been addressed in some countries of Southeast Asia, the regional and national inventories with the application of nature-based solutions are lacking. In this study, we aim to estimate national coastal blue carbon stocks in the seagrass ecosystems in the countries of Southeast Asia including the Andaman and Nicobar Islands of India. This study further assesses the potential of conservation and restoration practices and highlights the seagrass meadows as nature-based solution for climate change mitigation. The average value of the total carbon storage within seagrass meadows of this region is 121.95 ± 76.11 Mg ha^{-1} (average ± SD) and the total C_{org} stock of the seagrass meadows of this region was 429.11 ± 111.88 Tg, with the highest C_{org} stock in the Philippines (78%). The seagrass meadows of this region have the capacity to accumulate 5.85–6.80 Tg C $year^{-1}$, which accounts for $214.6–249.4 million USD. Under the current rate of decline of 2.82%, the seagrass meadows are emitting 1.65–2.08 Tg of CO_2 $year^{-1}$ and the economic value of these losses accounts for $21.42–24.96 million USD. The potential of the seagrass meadows to the offset current CO_2 emissions varies across the region, with the highest contribution to offset is in the seagrass meadows of the Philippines (11.71%). Current national policies and commitments of nationally determined contributions do not include blue carbon ecosystems as climate mitigation measures, even though these ecosystems can contribute up to 7.03% of the countries' reduction goal of CO_2 emissions by 2030. The results of this study highlight and promote the potential of the southeast Asian seagrass meadows to national and international agencies as a practical scheme for nature-based solutions for climate change mitigation.

1. Introduction

Seagrass ecosystems are globally distributed covering the five important bioregions of the world oceans except for Antarctica (Hemminga and Duarte, 2000; Short et al., 2007; McKenzie et al., 2020). Seagrasses form complex interlinkage with other coastal ecosystems that are important in maintaining a wide range of ecological functions (Medina-Gomez et al., 2016; Mishra and Apte, 2020; United Nations Environment Programme, 2020) in the marine environment. Seagrasses provide 24 different types of ecosystem services (Nordlund et al., 2016), which include habitat and nurseries for commercially important fish population, various marine megafauna (Sueversm et al., 2019), and feeding and breeding habitats for endangered dugongs of the Indo-Pacific (D'Souza et al., 2015; Unsworth et al., 2018; Infantes et al., 2020). Other important ecosystem services include shoreline protection from storm surges and prevention of coastal erosion (Ondiviela et al., 2014; Potouroglou et al., 2017) which contribute towards climate change adaptation through the accretion of the sediments and seabed elevation. Furthermore, seagrass meadows contribute towards climate change mitigation through carbon sequestration and storage (Kennedy et al., 2010; Mcleod et al., 2011; Fourqurean et al., 2012; Lavery et al., 2013). Globally, seagrass meadows store up to 19.9 Pg of C_{org} (Fourqurean et al., 2012) and unlike terrestrial ecosystems, the C_{org} stored in sediments can stay trapped for centuries and/or millennia (Duarte et al., 2005; Macreadie et al., 2014). Through this ecosystem service, seagrass meadows contribute 10–18% of the total ocean oceanic carbon burial despite covering less than 0.1% of the total ocean floor (Duarte et al., 2005; Mcleod et al., 2011). Regardless of being among the most valuable ecosystems, they are drastically declining globally (Short et al., 2011) at the rate of 0.4–2.6% per year (Pendleton et al., 2012).

Although seagrass ecosystems have roles supporting global diversity, human wellbeing, climate change adaptation and mitigation, this ecosystem remains poorly documented in the Southeast Asian region (Waycott et al., 2009), with only 62 ISI publications between the 1980s and 2010 (Ooi et al., 2011) and only 23% focusing on science from 1222 publications from 1973 to 2016 (Fortes et al., 2018). In the last few years, the studies have been slowly increasing, with the high focus on blue carbon, in most of the countries of the region, and few regional publications have emerged (Vanderklift et al., 2019; Thorhaug et al., 2020) demonstrating the importance of this ecosystem in today's fast-changing world. Moreover, regional blue carbon projects and working groups have started to form. In 2015, the results from the international project on Indonesia's blue carbon sink were published (Alongi et al., 2016), and to this day it remains the only publication on blue carbon ecosystems on the national scale within this region. In 2010, IOC Sub-Commission for the Western Pacific (WESTPAC) started the regional seagrass mapping working group, with the members from Japan, Malaysia, Thailand, Vietnam, and Indonesia. The goal of this working group is to standardize methods of seagrass mapping and through it map the services of this ecosystem. In 2017, the first regional project, Comprehensive Assessment and Conservation of Coastal Blue Carbon Ecosystems and its Services (BlueCARES) was launched between Japan, the Philippines, and Indonesia. The project aimed at investigating the blue carbon potential of mangroves and seagrasses in addressing climate change issues. In 2019, the Coral Triangle Initiative on Coral Reefs, Fisheries and Food Security (CTI-CFF) established the CTI-CFF's Climate Change Adaptation Working Group (CCAWG) which pushed to raise awareness on climate action for coastal and marine ecosystem conservation and adaptation. In 2019, the Commonwealth Scientific and Industrial Research Organization (CSIRO) together with Indian Ocean Rim Association (IORA), established IORA Blue Carbon Hub, with the headquarters at Indian Ocean Marine Research Center at University of Western Australia, Perth, with the goal to establish sustainable blue economies through capacity building within IORA member states, development of the robust policy and finance mechanisms and to develop partnerships with the organizations of the region. Since the countries of this region started to address blue carbon within seagrass meadows and form working groups and projects, the regional overview of these ecosystems emerged as a next step to raise awareness and the possibility of inclusion of this ecosystem in climate change mitigation policies.

The Indo-Pacific bioregion, which includes Southeast Asia, represent one of the seagrass hotspots, supporting up to 21 different seagrass species that cover 22.3% of the total coastal area (Fortes et al., 2018). However, more than 637 million people currently live in this region, and it is predicted that more than 70% of the population will be living in the coastal zones by 2030 (Neumann et al., 2015). This rapid population growth and expansion of the urban areas are exerting substantial pressure on critical coastal ecosystems, which include seagrasses, coral reefs, and mangroves.

This study provides information about blue carbon in seagrass ecosystems on a regional scale. The goal of the study is to estimate C_{org} storage (sediment and living biomass) and stocks of seagrass meadows in each country in the Southeast Asian region including the Andaman and Nicobar Islands of India (ANI). Moreover, this study estimates the potential of conservation and restoration practices of the region to mitigate CO_2 emissions, and to highlight the potential efficacy of seagrass meadows as a natural solution in climate change mitigation through blue carbon strategies and policies on the regional level.

2. Methodology

Key seagrass researchers in South and Southeast Asia were identified, through IOC Sub-Commission for the Western Pacific (WESTPAC) and whom are currently active in the blue carbon seagrass research and asked for their participation in the project. Countries that accepted the participation included India (ANI), Indonesia, Malaysia, Myanmar, Philippines, Thailand, and Vietnam. Each participant was provided with the data sheet with the guideline to contribute raw data (published and unpublished) from their country. Original data were collected from 2014 to 2019 and the outputs synthesized in this study from April 2019 until February 2020.

2.1. Data acquisition

The data sheet consisted of 5 major types of information: location, time of collection, seagrass information, other notes, and personal information of the contributor. The location section included information such as longitude, latitude country and site name. The time of collection was comprised of the year and date of collection. The seagrass information section included information about plot code, species present within the plot (Table S1), substrate type, coverage within the plot (%), and above and belowground biomass (g DW m^{-2}) if this information was available. Other notes referred to the information of the availability of the map of the area, size of the seagrass meadow (ha) and the reference in case this data was already published. Personal information was used to contact the participant in case of any questions about the data and included full name and their e-mail addresses.

All the data received were arranged by location and year of collection. In total, there were 95 sites across Southeast Asia (Fig. 1). The greatest number of sites were in Indonesia (40), followed by Myanmar (23), Vietnam (17), Thailand (6), Philippines (4), ANI - India (3) and Malaysia (2). The full list of the sites and their location can be found in Table S2. Although many sites are covered in this study, there were some unrepresented areas in the region such as, coasts of Malaysia, Borneo and Java in Indonesia. In Indonesia there is a general lack of studies in these areas (Wahyudi et al., 2020), while the data was not available for the coasts of Malaysia. Before analysis, data were further divided based on the recorded distribution of species in the plots: monospecific, if only a single species was present, and mixed, where two or more species were present.

2.2. Data analysis

Each data set, monospecific and mixed (total number of samples per seagrass type and country is presented in Table S3) was analyzed separately following the same workflow (Fig. 2). The coverage (%) of each sample was provided and was a starting input for the series of equations, in which the results of the previous unit, representing the predictor for the subsequent unit carbon stock up to 1-m depth, was estimated (Fig. 2A). All presented values for carbon storage and stock are in the top meter of the sediment. In case when above or belowground biomass was provided, this was used as a starting input. Separate equations were used for monospecific and for mixed data set, and the full description can be read in Stankovic et al. (2018a). Average values ± standard deviation (SD) for each country were considered as representatives and used for further calculations. The values of total C_{org} for monospecific, mixed and all samples were analyzed for significant difference between the countries using one-way ANOVA and post hoc analysis was done using the Tukey test. Underlying assumptions of ANOVA were checked for violations using residual plots.

Upscaling the carbon estimates to the national level was done using the average values of carbon stock and total seagrass area in the country (Fig. 2B). The estimates of the seagrass area in each country were obtained from the most recent publications of the remote sensing data, National reports, and agencies. The full summary of the seagrass area estimates in each country used here can be found in Table S4. The data on total C_{org} stock in Southeast Asia is represented as the average value ± standard deviation (SD) and the range of the values is given of 95% of confidence interval (CI).

To estimate the value of C_{org} within these ecosystems on the national level, C_{org} global accumulation rates were used as the regional rates are not available. To account for carbon from allochthonous sources, the total C_{org} sink of the seagrass meadows was calculated by the sum of their net community production and the non-seagrass derived carbon, which is being trapped by the canopy (Duarte et al., 2013a). Thus, the C_{org} accumulation rates used in this study were in the range of 160 to 186 g C m^{-2} $year^{-1}$ (Duarte et al., 2013a).

Estimates of the habitat loss and the potential loss of C_{org} through remineralization were calculated per country. The annual loss of the seagrass ecosystems in this region has not been estimated yet, so the review of temporal scale changes of seagrass meadows in the region was done. Using the known seagrass cover changes from the literature (Luong et al., 2012; Blanco et al., 2014; Chen et al., 2016; Bramante et al., 2018; Daud et al., 2018; Hossain et al., 2019; Vo et al., 2020; Stankovic et al., 2021), the average value of those losses (2.82% $year^{-1}$) was assumed to be a regional annual loss of the seagrass meadows. Following the disturbance of these ecosystems, a portion of the sediment C_{org} becomes exposed to aerobic conditions and decomposes at the rate of 0.042 $year^{-1}$, resulting in the remineralization of 25% of the sediment C_{org} within the first 3 years (Lovelock et al., 2017). The potential value of the C_{org} storage in the seagrass ecosystem was calculated assuming the monospecific trading price of US$10 for ton of CO_2 for ASEAN countries (Nurdianto and Resosudarmo, 2016).

The potential of seagrass ecosystems as a nature-based solution for climate change mitigation is provided through the current total carbon stock and the possibility of CO_2 offsets per country and the potential greenhouse (GHG) offset in the case of restoration by 2030. The current carbon burial is used in terms of the amount of CO_2 being accumulated within the meadow at present and total CO_2 emissions for the whole country (Mt $year^{-1}$). The information of CO_2 emissions was from 2018 and followed the most recent publication of Crippa et al. (2019) while the population number of 2018 was recorded from World population review (https://www.worldometers.info/world-population/). Total CO_2 emissions per country include sources form fossil fuel use (combustion and flaring), industrial production (cement, steel, chemicals, and urea), and product use. The total CO_2 emissions of ANI, India follow the values from Ramachandra and Shwetmala (2012). Since the restoration of the seagrass meadows is not currently in any global, regional or national declarations and/or resolutions, this study assumes 30% of the increase of seagrass area by 2030, which is a lower estimate of the seagrass loss range for Southeast Asian countries by the 1990s (Fortes, 1995) and similar to the global resolution of mangrove area proposed by Global Mangrove Alliance (http://www.mangrovealliance.org/). The potential offset of GHG through the restoration actions are added to the current potential offset and recalculated to estimate the value and total CO_2 offset per country for 2030.

Other tropical ecosystems (terrestrial and coastal) were included in the study as the means of comparison of C_{org} storage between the ecosystems. In terrestrial ecosystems, primary tropical forests and peatlands, bogs and marshes, were included, while mangrove forests were included as coastal ecosystems. These ecosystems were selected as they have the ability to store large amounts of C_{org} and/or they are frontier ecosystems for climate change mitigation and nature-based solutions. The data of these ecosystems were obtained from various sources and the full information can be found in Supplementary information 2.

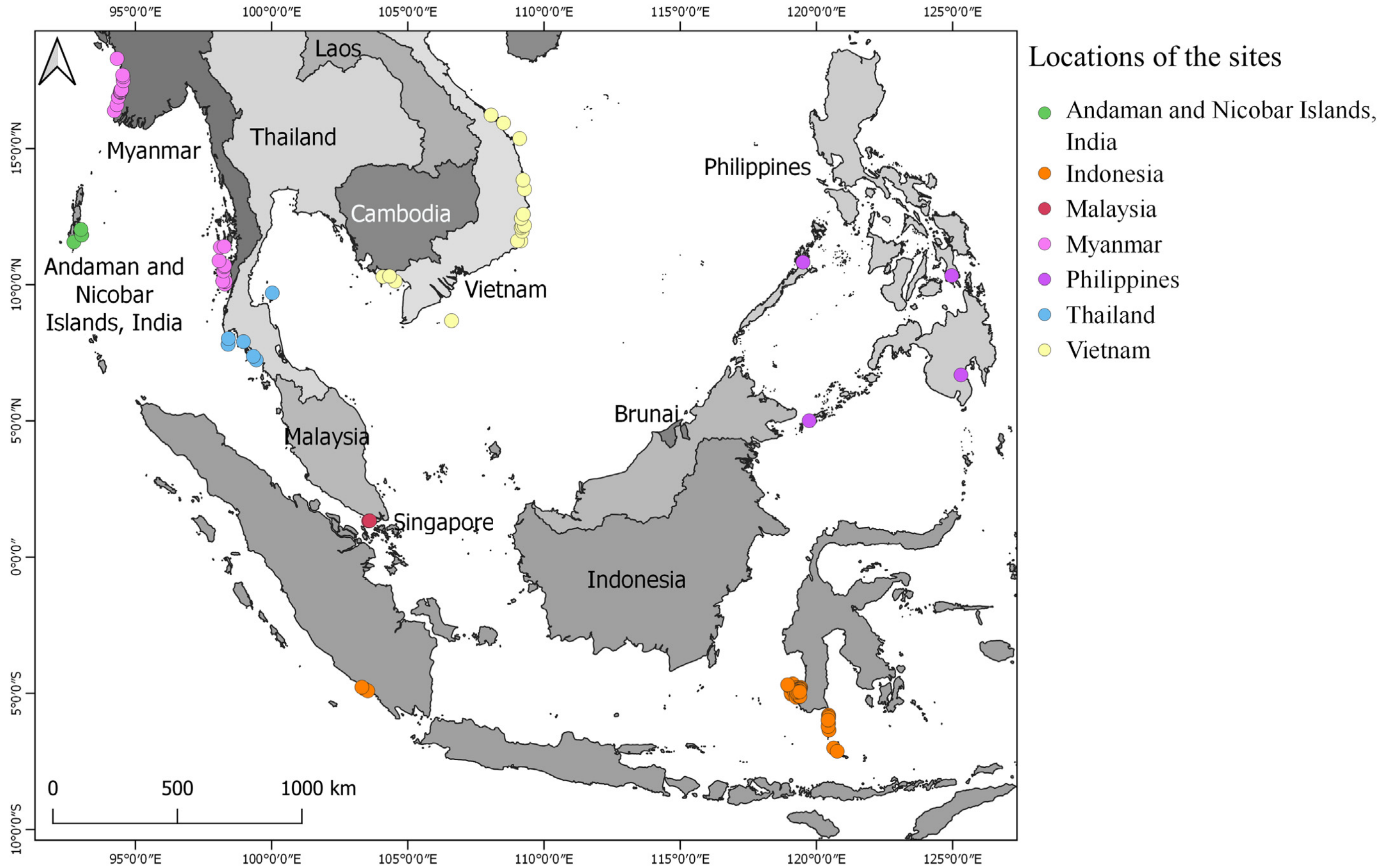

Fig. 1. Location of sites in each country across Southeast Asia including Andaman and Nicobar Islands of India

2.3. Assumptions and limitations

Organic carbon estimation within the ecosystems is calculated using a model for monospecific and mixed-species developed in Thailand (Stankovic et al., 2018a). Although same species are recorded across the region, the composition of the specific locations was slightly different. Moreover, the model relies on the biomass of the species to estimate C_{org} in the sediment, addressing only autochthonous carbon sources. It is important to note that in the seagrass ecosystems, carbon from non-living detritus (Tanaya et al., 2018) and allochthonous sources (Kennedy et al., 2010; Fourqurean et al., 2012; Serrano et al., 2016) plays important role in contributing to the bulk of C_{org} pool. Indeed, mangrove and macroalgae-derived C_{org} has increasingly been shown to supplement the blue carbon contributions by seagrasses in tropical systems (e.g. Quak et al., 2016; Chen et al., 2017; Hidayah et al., 2019; Rahayu et al., 2019; Tuntiprapas et al., 2019; Arina et al., 2020). Moreover, the studies have also shown that carbon of anthropogenic origin (black carbon) also gets trapped within seagrass ecosystems, especially in rural adjacent meadows (Chew and Gallagher, 2018; Gallagher et al., 2019).

Upscaling the C_{org} to the national level requires seagrass area per country. The quality of the values used in the study varies from country to country. Some countries or parts of the country, such as Vietnam (Luong et al., 2012) and ANI of India (Paulose et al., 2013; Geevarghese et al., 2018; Bayyana et al., 2020) have mapped seagrass ecosystems on the national scale using remote sensing and have produced more accurate extents of the ecosystem. On the other hand, the areal estimates of other countries rely on the older data sets (from more than 20 years ago) obtained through visual assessments and perceptual surveys, with limited validation. Thus, it is crucial to express the need for the updated areal estimates of the seagrass ecosystems on the national scale. Furthermore, as the rate of habitat loss was not available for this region, this study uses calculated value using already published temporal series of seagrass area change in each of the country (Luong et al., 2020; Blanco et al., 2014; Chen et al., 2016; Bramante et al., 2018; Daud et al., 2018; Hossain et al., 2019; Stankovic et al., 2021; Vo et al., 2020). Although this rate is slightly higher than the global estimate, the studies used to calculate the rate for the region is based on several local sites in each of the countries. Therefore, it is most probably underestimating the real rate of seagrass decline and it is essential to add the necessity for the regional and/or national rate of seagrass ecosystem loss.

3. Results and discussion

3.1. Blue carbon in seagrass ecosystems in Southeast Asia

Estimated average C_{org} storage within seagrass ecosystems in the Southeast Asian region had value of 121.95 ± 76.11 Mg ha^{-1}, with more than 97% of the carbon stored in sediment ($\tilde{x} = 118.72$ Mg ha^{-1}) and less than 3% in living biomass ($\tilde{x} = 3.23$ Mg ha^{-1}). Total C_{org} storage, as well as within biomass and sediment, is 5 times higher than previously recorded for Indo-Pacific (24.21, 23.60 and 0.61 Mg C ha^{-1} for C_{org} storage in entire ecosystem, in sediment and in living biomass, respectively; Fourqurean et al., 2012). The values of total C_{org} storage per country were significantly different [F(6, 526) = 11.62, $p <$ 0.005; Table S5], with the highest values recorded in ANI, India (184.24 ± 23.84 Mg ha^{-1}), followed by Myanmar (136.67 ± 64.77 Mg ha^{-1}), Thailand and Vietnam (134.20 ± 73.89 and 133.16 ± 36.97 Mg ha^{-1}, respectively), Philippines (123.49 ± 63.38 Mg ha^{-1}), Malaysia (108.63 ± 89.43 Mg ha^{-1}) and Indonesia (97.60 ± 41.49 Mg ha^{-1}). In most of the countries, monospecific seagrass beds stored more C_{org} within the ecosystem than in mixed beds (Fig. 3), except in

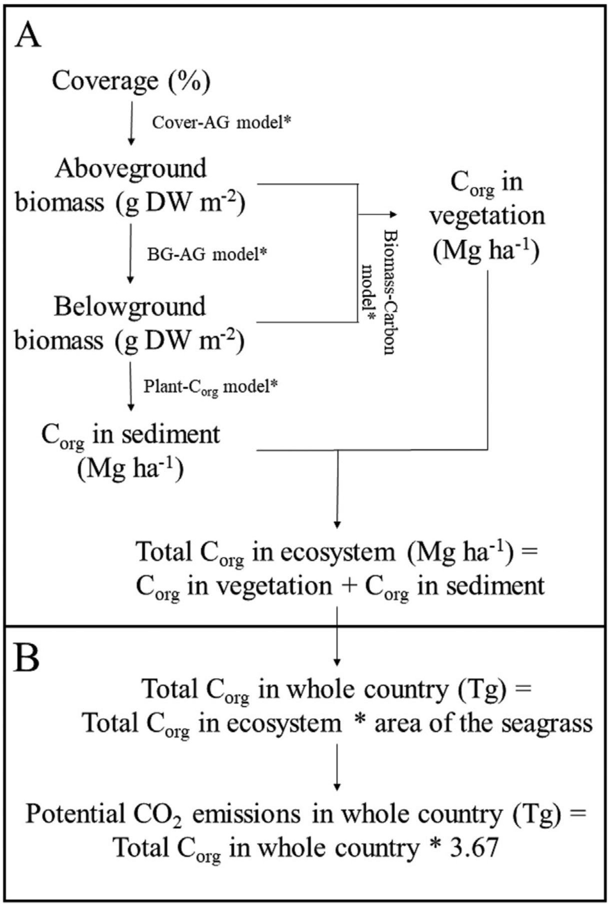

Fig. 2. The workflow for estimation potential C_{org} stock and CO_2 emissions on the ecosystem scale (A) and whole country (B). Note: *model equations were taken from Stankovic et al. (2018b).

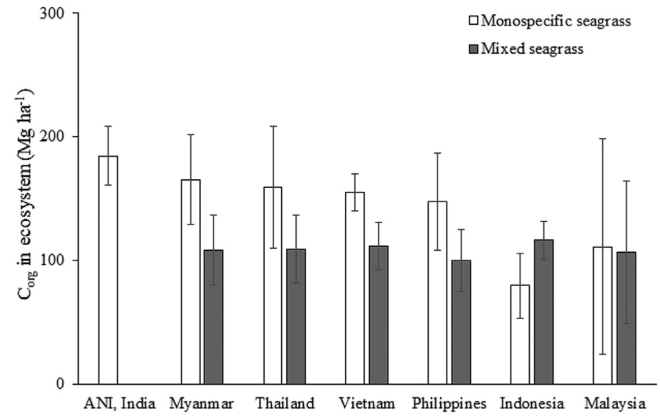

Fig. 3. Average estimated values of C_{org} (Mg ha-1) within monospecific and mixed seagrass meadows in each country

Indonesia and Malaysia. In Indonesia, C_{org} storage had an opposite trend, and it was higher in mixed than in monospecific meadows, as most of the reported seagrass meadows within this country were mixed. On the other hand, in Malaysia, the estimates were similar in both meadow types, as most of the mixed meadows had *Enhalus acoroides* within a bed and this larger size species have the ability to store higher amounts of C_{org} than other species (Stankovic et al., 2017). There was a significant difference of the monospecific and mixed meadows between the countries [F(6, 200) = 10.48, $p < 0.005$; F(5, 320) = 3.324, $p < 0.005$, respectively; Table S5], with the highest C_{org} of the ecosystem in monospecific meadows recorded in ANI of India (184.25 ± 23.84 Mg ha^{-1}), while in mixed was in Indonesia (116.19 ± 15.52 Mg ha^{-1}). On the other hand, the lowest estimated values of C_{org} in monospecific were in Indonesia (79.61 ± 26.45 Mg ha^{-1}) and in the Philippines for mixed meadows (99.62 ± 25.22 Mg ha^{-1}). On the country scale, other studies indicated values of the C_{org} storage within the range as reported in this study for Thailand (110–133 Mg C ha^{-1}; Stankovic et al., 2018b), Indonesia (40–83 Mg C ha^{-1} and 119 Mg C ha^{-1}; Rahayu et al., 2019 and Alongi et al., 2016, respectively), Malaysia (43–101 Mg C ha^{-1}; Rozaimi et al., 2017) and Vietnam (136 Mg C ha^{-1}; Luong and Nga, 2017). However, in the Philippines reported values of the C_{org} stock have been much less than in this study (59 Mg C ha^{-1}; Gevaña et al., 2015). Organic carbon stock in the seagrass ecosystems of Myanmar and ANI of India has not been reported yet suggesting a large knowledge gap in the Andaman Sea. The recent studies (Mishra and Apte, 2020; Mishra et al., 2020) suggested that the seagrass population trends of some species in ANI is declining due to increased anthropogenic pressure, thus it is of the highest importance to assess the current status of C_{org} while the seagrass meadows are pristine and use the information to initiate proper conservational measures.

The total area of seagrass cover in these countries is 3.66 Mha, which represents ~6–12% of the global seagrass coverage (30–60 Mha; Duarte et al., 2013b). Although they cover a small portion of the global coastal area, seagrasses in this region are responsible for 1.64–5.52% of the total global seagrass C_{org} stock (Table 1). Total average blue carbon stock in the seagrass ecosystem in these Southeast Asian countries was 429.11 ± 111.88 Tg of C_{org} (419.53–438.69 Tg at 95% of CI), with 419.74 ± 104.54 Tg in sediment (410.79–428.69 Tg at 95% of CI) and 9.37 ± 7.33 Tg (8.74–9.99 at 95% of CI) in biomass. The highest amount of stored C_{org} stock (78%) was recorded in the Philippines followed by Indonesia and Thailand (Table 1). The rest (1%) of C_{org} stock was distributed in Vietnam, ANI of India, Malaysia, and Myanmar (Table 1). Similar regional studies on blue carbon stock in seagrass ecosystems have been conducted in various global regions. The seagrass ecosystems along the eastern coast of the Pacific Ocean (Baja California) and the Gulf of Mexico reported more than 2 times lower C_{org} stock (Thorhaug et al., 2019; Herrera-Silveira et al., 2020) than the seagrass meadows in Southeast Asia (Table 2). Higher C_{org} stock was recorded in the tropical region of the Gulf of Mexico and Yucatan Peninsula, 2.8 and 46.9 Tg C_{org} respectively (Thorhaug et al., 2019; Herrera-Silveira et al., 2020) than in the subtropical region of the eastern coast of Pacific Ocean (Baja California) and the Gulf of Mexico, 1.2 and 182.1 Tg C_{org}, respectively (Thorhaug et al., 2019; Herrera-Silveira et al., 2020; Table 2). In contrast, seagrass meadows in Australia can support two times more C_{org} within their habitats, with stocks of up to 1051 Tg C_{org} (Serrano et al., 2019). Although the seagrass area was similar in the tropical and subtropical regions of Australia, the C_{org} stock was higher in the subtropical region, with 439 Tg of C_{org}, while the tropical region recorded mediocre C_{org}

Table 1
Estimates of organic carbon stock (total, in sediment and in living biomass) in each country of Southeast Asia.
Source: Fourqurean et al. (2012).

Country	C_{org} stock (Tg)					
	Total		Sediment		Living biomass	
	Min	Max	Min	Max	Min	Max
Philippines	259.17	425.21	225.45	411.54	3.17	13.68
Indonesia	62.08	107.50	61.38	104.80	0.70	2.70
Thailand	1.98	4.41	1.95	4.24	0.02	0.17
Vietnam	2.06	2.95	2.03	2.86	0.03	0.08
ANI, India	0.37	0.61	0.37	0.58	0.006	0.03
Malaysia	0.005	0.25	0.004	0.22	0.0004	0.03
Myanmar	0.02	0.04	0.03	0.04	0.0007	0.003
Total SEA	325.69	540.98	321.21	524.28	4.47	16.70
Global[1]	9800	19,800	4200	8400	75.5	151

Table 2
Worldwide comparison of C_{org} storage and stocks in seagrass ecosystems.

Region	Seagrass area (ha)	C_{org} storage (Mg ha^{-1})	C_{org} stock (Tg)	Reference
North Pacific coast	47,400	26.1 ± 13	1.2	Herrera-Silveira et al., 2020
Gulf of Mexico (Mexico)	341.9	66.1 ± 10	0.02	Herrera-Silveira et al., 2020
Yucatan Peninsular	413,317	113.7 ± 7	46.9	Herrera-Silveira et al., 2020
Gulf of Mexico (USA)	947,327	170	182.1	Thorhaug et al., 2018
Gulf of Mexico (Mexico)	25,000	11.2	2.8	Thorhaug et al., 2018
Australia	9,256,900–12,772,000	112 ± 88	906.5	Serrano et al., 2019.
West Africa	4,832,247	139.2	673	Bryan et al., 2020
Southeast Asia	3,655,829.14	121.95 ± 76.11	429	This study

stock (Serrano et al., 2019). Moreover, slightly higher C_{org} values were recorded in the seagrass meadows in West Africa, 673 Tg of C_{org} (Bryan et al., 2020), with the seagrass area only 0.7 times larger than in Southeast Asia (Table 2). The effects of climatic regions in C_{org} storage in seagrass meadows have been poorly documented with few available studies (Miyajima et al., 2015) which suggested that temperate meadows compared to tropical and subtropical have higher soil C_{org} stocks (Mazarrasa et al., 2018). However, the intensive flowthrough of Pacific and Indian Ocean currents that feed the local coastal upwellings across the South China Sea, and the upwellings from Arabian Sea which affect Western Indian Ocean (Southon et al., 2002) creates an environment that has the potential to support large productivity of the coastal environment.

The carbon accumulation capacity of the seagrass meadows in Southeast Asia is estimated to be 5.84–6.79 Tg C year^{-1}, which assimilates 21.42–24.90 Mt of CO_2 per year (Table 3). The yearly value of services of these seagrass meadows in terms of CO_2 sequestrations accounts for $21.42–24.91 million USD. On the national level, seagrass meadows in the Philippines support the highest estimates of carbon accumulation, following Indonesia, while meadows in Malaysia and Myanmar had the lowest accumulation rates (Table 3). These country scale differences could be essential in the implementation of the carbon credits schemes and climate change mitigation strategies such as carbon policies, payment for ecosystem services schemes, and reduction of CO_2 emissions targets.

3.2. Threats and decline

Although seagrass meadows cover only 22.3% of the coastline in Southeast Asia (Fortes et al., 2018), the value of ecosystem services they provide to the local and global diversity and human well-being has increased in the last 15 years (Costanza et al., 2014; Nordlund et al., 2016). However, they are experiencing a sharp worldwide decline (Orth et al., 2006; Short et al., 2011; United Nations Environment Programme, 2020), with a higher loss rate than tropical forests (Achard et al., 2014). At the current rate of seagrass decline (2.82% year^{-1}), around 102,888 ha of seagrass meadows is lost every year in Southeast Asia (Table 4). If this rate of loss continues, without any significant improvement in the implementation of conservation measures, seagrass meadows in these countries will be completely gone by 2060.

Table 3
Estimated accumulation and assimilation in each country of Southeast Asia.

Country	C_{org} accumulation (Gg C year^{-1})		CO_2 assimilation (Mt CO_2 year^{-1})		Economic value (US$ year^{-1}) (10^4)	
	Min	Max	Min	Max	Min	Max
Philippines	4361.95	5070.77	16.01	18.61	16,008.36	18,609.72
Indonesia	1410.55	1639.30	5.14	5.98	5143.68	5979.53
Thailand	40.93	47.58	0.15	0.17	150.21	174.62
Vietnam	25.18	29.28	0.09	0.10	92.43	107.44
ANI, India	4.71	5.47	0.01	0.02	17.28	20.09
Malaysia	2.61	3.03	0.09	0.01	9.57	11.13
Myanmar	0.69	0.80	0.0025	0.0029	2.52	2.94

Note: Gg represents gigagram of C_{org} and Mt CO_2 represents metric tons of carbon dioxide.

The loss of the seagrass vegetation will exert significant negative effects on various ecosystem functions, among the least known but very important, is the loss of the sequestration ability and erosion of the already stored carbon (Marbà et al., 2015). This loss in the sediment triggers remineralization and the emissions of trapped C_{org}. In total 0.15–0.72 Tg of C_{org} every year is at risk of remineralization, which accounts for potential CO_2 emissions of 0.56–2.66 Tg each year (Table 4). Moreover, the loss of the C_{org} sequestration results in the reduction of 164.62–191.37 Gg of C_{org} every year, which accounts for the lack of 605.16–702.33 Gg of the sequestered CO_2 each year (Table 4). The economic value of these losses' accounts for approximately $22.53–27.86 million USD (Table 4). On the country-scale, the Philippines and Indonesia had the largest changes and losses, following Thailand and Vietnam, with the least amount of losses in ANI of India, Malaysia, and Myanmar (Table 4).

It has been reported that human activities, coastal development with land reclamation, trawling, agricultural runoff, and sedimentation (Fortes, 1995; Kirkman and Kirkman, 2002; Halpern et al., 2007; Grech et al., 2012; Unsworth et al., 2018; Mishra and Apte, 2021; Mishra et al., 2020) are major threats and have remained as such over the last 20 years (Fortes et al., 2018). As the result of these activities, Vietnam lost up to 50% of the seagrass meadows within the last three decades (Luong et al., 2012; Chen et al., 2016; Tinh et al., 2020). The meadows in the proximity of the intensive human activities in Malaysia and Indonesia experienced a sharp decrease in the last 20 years of 35–67% and more than 90%, respectively (Daud et al., 2018; Hossain et al., 2019). Even with these losses, seagrass ecosystems yearly emit much less CO_2 than mangrove ecosystems (Table S6). Among other tropical ecosystems (terrestrial and coastal), tropical forests have the highest potential CO_2 emissions, even with the lowest rate of loss compared with the other ecosystems (peatland, mangrove, and seagrass; Table S6). The lower rates of CO_2 emissions of blue carbon ecosystems, mangroves, and seagrasses (less than 1% of the potential CO_2 emissions; Table S6), suggest their high potential as a nature-based solution for climate change mitigation.

3.3. Potential of Southeast Asian seagrasses for climate change mitigation

Seagrass meadows provide a high potential for mitigation of greenhouse gasses (GHG), especially CO_2. The economic value of C_{org} of the meadows of Southeast Asia is $15,744.92 ± 4109.19 (10^6 USD), as around 1574.20 ± 41.59 Tg of CO_2 is trapped within these seagrasses. The full economic value of the seagrass meadows per country is represented in Table 5. The potential of these meadows per country to mitigate current CO_2 emissions is represented in the ability to offset the countries' total CO_2 emissions. The contribution of the seagrass meadows to offset the total country's CO_2 emissions, however, depends on the country. In some countries, such as the Philippines, ANI of India, and Indonesia, seagrass ecosystems have the potential to partially offset 11.71, 3.02, and 1.00%, respectively, of the total country's emission. However, for the other Southeast Asian countries (Myanmar, Thailand, Vietnam, and Malaysia) seagrass contribution towards the CO_2 offset is less than 1% of the total country's CO_2 emission (Table 5).

Although the contribution towards offsetting total countries' CO_2 emissions is not very high, through proper restoration practices and

Table 4
Potential annual loss of CO_2 emissions from the loss of the sediment of seagrass habitat and its economic value from Southeast Asian countries.

Country	Habitat loss[a] (ha year^{-1})	C_{org} in sediment in risk of remineralization[b] (Gg C year^{-1})	Potential CO_2 emissions (Gg CO_2 year^{-1})	Economic value of potential CO_2 emissions per year[c] (10^6 US$)	Lack of C_{org} sequestration[d] (Gg C year^{-1})	Potential lack of CO_2 sequestration (Gg CO_2 year^{-1})	Economic value of lack of CO_2 sequestration per year[c] (10^6 US$)
Philippines	76,879.40	381.57–603.40	1400.38–2214.48	14.00–22.14	123.01–143.00	451.44–524.79	4.51–5.25
Indonesia	24,702.27	71.62–110.03	262.86–403.81	2.63–4.03	39.52–45.95	145.05–168.62	1.45–1.69
Thailand	721.39	2.65–6.10	9.40–22.40	0.10–0.22	1.15–1.34	4.24–4.92	0.042–0.049
Vietnam	443.87	2.30–3.17	8.45–11.64	0.08–0.11	0.71–0.83	2.61–3.03	0.026–0.030
ANI, India	82.99	0.45–0.73	1.63–2.66	0.01–0.02	0.13–0.15	0.49–0.57	0.0049–0.0057
Malaysia	45.97	0.01–0.58	0.03–2.11	0.0004–0.02	0.074–0.085	0.27–0.31	0.0027–0.0031
Myanmar	12.13	0.07–0.10	0.25–0.37	0.003–0.004	0.019–0.023	0.07–0.08	0.0007–0.0008

[a] Habitat loss per year was assumed to be 2.82% (calculated from the published literature).
[b] Emission estimates assume that 25% of the sediment C_{org} in the top meter of sediment was remineralized within the first 3 years, at the rate of 0.042 year^{-1} (Lovelock et al., 2017).
[c] The economic value of a ton of CO_2 was assumed to be $10 USD (Nurdianto and Resosudarmo, 2016).
[d] C_{org} sequestration rates are the sum of their net community production and the non-seagrass derived carbon, which is being trapped by the canopy, and it assumed to be 160 to 186 g C m^{-2} year^{-1} (Duarte et al., 2013a).

conservation measures the contribution can be increased (Lafratta et al., 2020). As the result of the restoration seagrass contribution towards the offset of total countries' CO_2 emissions can increase by 2030. Comparing to the other tropical ecosystems, mangroves and seagrasses can contribute 68.33–99.77% of the total C_{org} burial of the restoration by 2030 (Fig. S1). Through the restoration practices and proper conservation measures, only seagrass meadows can contribute up to 1.43% towards CO_2 offset of total countries' CO_2 by 2030 (business-as-usual, BAU scenario). However, this ecosystem's potential is one of the most poorly represented as a nature-based solution (Chausson et al., 2020). The mechanisms developed to mitigate climate change and limit the global temperature rise to less than 2 °C include a number of agreements implemented by the United Nations Intergovernmental Panel on Climate Change (IPCC). All the countries in the Southeast Asian region pledged to decrease yearly CO_2 emissions through nationally determined contributions (NDC; https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx). Current commitments of each country are probably insufficient, suggesting that mitigation and adaptation efforts also need to include enhanced carbon sequestration through restoration, conservation, and avoidance of emissions from the destruction of natural ecosystems, especially blue carbon habitats (Vanderklift et al., 2019). Based on the current NDCs, nature-based solutions are mostly included in adaptation and mitigation components in Indonesia, Vietnam, Myanmar, while only mitigation or adaptation components are included in Malaysia and Thailand, and the Philippines, respectively (Seddon et al., 2020). In Asia-Pacific, only 14 countries included coastal and marine habitats in their NDCs (Seddon et al., 2020), but only a few had specific actions, such as Bangladesh, Madagascar, and Sri Lanka (Vanderklift et al., 2019). However, in the NDCs of other countries benefits of blue carbon ecosystems (mostly in terms of coastal protection) are mentioned without clear goals or they were not included. If these ecosystems, especially seagrass meadows, are included in the mitigation measures (through conservation, restoration, and CO_2 emission avoidance), they could contribute 6.45 and 7.03% of the countries' reduction goal for conditional and unconditional CO_2 emission by 2030, respectively.

Table 5
Potential economic value of seagrass meadows and CO_2 emissions per country in Southeast Asia.

Country	Economic value of CO_2[a] ($10 t CO_2^{-1}) (10^6 $)	Total country CO_2 emissions for 2018[b,c] (Mt CO_2)	Seagrass contribution for the total country's CO_2 emissions (%)
Philippines	12,364.42 ± 3240.96	147.86	10.83–12.59
Indonesia	3165.23 ± 797.99	557.53	0.92–1.07
Thailand	125.99 ± 35.95	281.04	0.05–0.06
Vietnam	95.83 ± 12.30	271.47	0.03–0.04
ANI, India	19.20 ± 2.58	0.618	2.80–3.25
Malaysia	3.47 ± 0.82	257.84	0.003–0.004
Myanmar	1.34 ± 0.32	32.65	0.007–0.009

[a] Nurdianto and Resosudarmo (2016).
[b] Crippa et al. (2019).
[c] Ramachandra and Shwetmala (2012).

Despite the high potential of blue carbon to contribute to climate change mitigation, the financial mechanisms and policies are still poorly developed (Vanderklift et al., 2019). Currently, the blue carbon monetary schemes rely on the voluntary carbon market approaches, which depend on the implementation of Article 6 of the Paris Agreement, which supports CO_2 emission reduction through markets involving public and private bodies (UNFCCC, 2015). In Thailand, voluntary national carbon market approach T-VER (http://www.tgo.or.th/2015/english/index.php), initiated in 2013, includes carbon credit schemes verified through mangrove forests. However, the mechanism only relies on the carbon within the living biomass, which represents only a small portion of the blue carbon ecosystem potential (Murray et al., 2011). However, the inclusion of sediment carbon storage can significantly increase natural ways to climate change mitigation (Bossio et al., 2020). Similarly, in Malaysia, national-level policy has been institutionalized with room to incorporate policies for conserving and enriching carbon pools in natural ecosystems to mitigate climate change (Ministry of Natural Resources and Environment, 2010). However, this is yet to be fully realized for Malaysian seagrass resources. Vietnam is currently developing a carbon payment for forest environmental services (C-PFES) policy, under which forest owners will receive payments for the absorption and carbon storage services of their forest. Under this policy, mangrove forests are identified as the key element in the investment options through restoration (Michaelowa et al., 2018), but seagrasses have not been included yet. Although the voluntary carbon market remains underdeveloped in Vietnam, the options of incorporating carbon tax and/or fees into Environmental Protection Tax have been explored (Michaelowa et al., 2018). In the Philippines, an enabling policy for the country's adherence to the carbon market mechanism was put in place by 2004, however, the first project's program started in 2012. The Memorandum of Cooperation between Japan and the Philippines on Low Carbon Growth Partnership was signed on January 12, 2017, under which the Memorandum of Agreement (MOA) implements the Joint Crediting Mechanism (JCM), a bilateral system where the Philippines deals directly with only one country. Although the need of creating and protecting carbon sinks has been recognized in many other countries, such as Indonesia and India, carbon trading regulations and/or markets have not yet been established. In Indonesia, it has been mentioned that the new set of regulations with guidelines and plans on carbon trading are currently under preparation.

4. Conclusion

This study provides national and regional estimates of the C_{org} stock within seagrass ecosystems of Southeast Asia. Total C_{org} stock was 429.11 ± 111.88 Tg within seagrass meadows of this region, and these ecosystems can accumulate 5.85–6.80 Tg C_{org} yearly. However, under the current rate of decline (2.82% $year^{-1}$), these meadows are emitting 0.65–2.08 Tg of CO_2 $year^{-1}$, and by 2060 most of the meadows will completely disappear. Although current national policies and agendas within the countries of the region do not include seagrass meadows, their potential for climate mitigation measures is manifested in the ability to contribute up to 7.03% of the countries' reduction goal of CO_2 emissions by 2030.

It is important to emphasize that the carbon estimates presented in this work should be considered as the most recent, but the studies in this region on seagrass keep on increasing which will contribute towards more accurate assessments in the future. The importance of this study is in highlighting the potential of seagrass meadows in this region as a carbon sink and to promote it to the national and international agencies and government offices as a scheme for nature-based solutions for climate change mitigation. The use of these ecosystems as a nature-based solution is appealing, as they provide various ecosystem services towards climate change mitigation and adaptation, suggesting their potential to address multiple sustainable goals (Chausson et al., 2020). The ability of national intentions to include these ecosystems into NDCs varies on the countries' economic development, while measurable targets and actions have yet to be fully developed (Chausson et al., 2020).

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CRediT authorship contribution statement

Conceptualization: AP
Methodology: MS, JP, EK, AP
Formal analysis: MS, JP, EK
Investigation and data providing: All
Writing review and editing: All
Supervision: AP
Project administration and Fund acquisition: AP.

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.

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