2023

Blue Carbon Opportunities: seagrass carbon storage and accumulation rates at Trang, Thailand

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10.25958/p8vr-zv31
Lavery PS, Lafratta A, Palahan R, Sanlee M, Stankovic M, Panyawai J, Serrano O, Masqué P. (2023) Blue Carbon Opportunities: seagrass carbon storage and accumulation rates at Trang, Thailand. TECHNICAL REPORT for the IKI Seagrass Ecosystem Services Project. Edith Cowan University and Save Andaman Network.
https://doi.org/10.25958/p8vr-zv31

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TECHNICAL REPORT

For the IKI Seagrass Ecosystem Services Project

Paul Lavery, Anna Lafratta, Rujinun Palahan, Maneewan Sanlee, Milica Stankovic, Janmanee Panyawai, Oscar Serrano, Pere Masque

Report prepared as a contribution to the IKI Project "Conservation of biodiversity, seagrass ecosystems and their services – safeguarding food security and resilience in vulnerable coastal communities in a changing climate" funded through the International Klimate Initiative (IKI)

The IKI Project is a partnership between the CMS, Edith Cowan University, Project Seagrass, Seagrass Watch, Murdoch University, MRS, Blue Ventures, SAN, C3, ZSL, MareCet and Yapeka. The collaboration enhances the understanding of seagrass ecosystem services and the capacity to develop and deliver science-based policy solutions in seagrass conservation. It brings together scientists, policy experts, business development experts and conservation NGOs across the globe to provide expert and independent advice on seagrass ecosystems services and how these might be relevant to policy and financial solutions to marine conservation issues. This report deals specifically with the assessment of seagrass blue carbon ecosystem services.

This project was co-funded by IKI and Edith Cowan University

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Citation

Lavery PS, Lafratta A, Palahan R, Sanlee M, Stankovic M, Panyawai J, Serrano O, Masqué P. (2023) *Blue Carbon Opportunities: seagrass carbon storage and accumulation rates at Trang, Thailand.* TECHNICAL REPORT for the IKI Seagrass Ecosystem Services Project. Edith Cowan University and Save Andaman Network.

Data: The complete data set for the IKI SES Project, Blue Carbon component is available through a Creative Commons License at: https://doi.org/10.25958/md28-dq98

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GLOSSARY

Above ground storage/stock	Carbon stored in above-ground biomass (e.g. trunks, stems, leaves) or other above-ground carbon sinks.
Accumulation rate	The rate at which atmospheric CO_2 is sequestered. Usually reported as a mass per unit area per year.
Activity	An action undertaken to reduce anthropogenic GHG emissions; or an action undertaken to increase anthropogenic GHG removals by sinks.
Additional/Additionality	The effect of a project activity to reduce anthropogenic GHG emissions below the level that would have occurred in the absence of the project activity; or The effect of a project activity to increase net GHG removals by sinks above that would have occurred in the absence of the activity.
Allochthonous carbon	Carbon (organic or inorganic) formed at a site distant to that where it is found.
Autochthonous carbon	Carbon (organic and inorganic) formed at the site where it is found.
Below ground storage	Carbon stored below ground level as biomass (e.g. roots and rhizomes) or sedimentary/soil carbon.
Biomass	The total quantity (usually weight) of organisms in a given area or volume.
Blue Carbon	The carbon stored and sequestered in coastal ecosystems such as mangrove forests, seagrass meadows or tidal marshes.
CAR (Carbon Accumulation Rate)	The mass of organic carbon that accumulates in a soil, over a specified period of time, usually one year.
Carbon pools	Above-ground biomass, below-ground biomass, litter, dead wood and soil/sediment organic carbon.
C_{org}	Organic carbon (i.e. the carbon contained within living and dead organic matter)
CO_2	Carbon dioxide, a gas composed of one carbon and two oxygen atoms. It is a major component of the global carbon cycle and a key greenhouse gas
$CO_{2\text{-}eq}$	a measure of the environmental impact of one tonne of any greenhouse gases in comparison to that of one tonne of CO_2.
Dating methods	The various methods used to age sediments/soils or carbon within sediments/soils, thereby allowing the accumulation rate to be determined. The most common methods involve the use of the radioisotopes Carbon-14 or Lead-210.
Emissions	An amount of a substance (usually a gas) that is released into the environment (usually the atmosphere). The commonly considered emissions are CO_2, CH_4, N_20.

GHG (greenhouse gas)	A greenhouse gas listed in Annex A to the Kyoto Protocol. With respect to blue carbon ecosystems, the commonly considered GHGs are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)
LoI (Loss on Ignition)	The amount of material lost from a sample when combusted at about 500°C. It is taken as an approximation of the amount of organic matter.
Organic carbon	Carbon, both particulate and dissolved, found in an organic compound, including living organisms, detritus, litter, and dissolved compounds
Project	An action by a private or public entity which coordinates and implements any policy/measure or stated goal that leads to GHG emission reductions or net anthropogenic GHG removals by sinks that are additional to any that would occur in the absence of the action.
Remineralization	The process in which organic carbon is transformed into inorganic forms, such as carbon dioxide (CO_2)
SAR (Sediment accumulation rate)	the net rate of vertical accumulation of sediment at a site.
Sediment	Naturally occurring material broken down by weathering and erosion, and transported to a place where it accumulates. Sediments are relatively unstructured and not formed by interaction of biological, physical and chemical processes.
Sedimentary carbon	Organic and inorganic carbon stored within sediments
Sequestration	The capture and long-term storage of atmospheric carbon dioxide.
Sink	a reservoir that accumulates and stores carbon-containing compounds. The term sink implies that the storage is long-term (or semi-permanent).
Soil	A complex, structured mixture of organic matter, minerals, gases, liquids and living organisms formed by the interaction of the parent material, organisms, climate and relief.
Soil carbon	Organic and inorganic carbon stored within soils
Stocks (of carbon)	The total amount of, in this case, carbon stored in an area or volume. Used interchangeably with 'store'.
Verification	The periodic, independent evaluation and retrospective determination of monitored GHG emission reductions that have occurred because of a project activity.

Units used this this report

kg	Kilogram	1,000 grams
t	Metric tonne	1,000 kg
Mt	Megatonne	10^6 (or 1 million) tonnes
Mg	Megagrams	10^6 (or 1 million) grams = 1 tonne
ha	Hectare	10,000 m^2 = 0.01 km^2
km^2	Square kilometre	10^6 (1 million) m^2 = 100 ha
Mg ha^{-1}	Megagrams per hectare	10^6 (1 million) g per ha = 0.1 kg m^{-2}

1 EXECUTIVE SUMMARY

1.1 Background and Objectives

Seagrasses provide many ecosystem services, including carbon sequestration, yet they are frequently neglected in decision-making. Seagrass meadows of the Indo-Pacific support up to one billion people through their provision of inshore fisheries. They also provide critical habitat for many marine species, including the Dugong (*Dugong dugong*), which is listed a vulnerable on the IUCN Red List. At the same time, seagrasses in the region are declining because of coastal development, deforestation, unsustainable resource extraction, and environmental degradation. Limited data exists on seagrass status, their ecosystem services and value in the region, information that can incentivise effective seagrass conservation.

The Seagrass Ecosystem Services Project (SES project) was established to provide critical data on the state and condition of seagrass ecosystems and to promote the integration of Seagrass Ecosystem Services (SES) into evidence-based decision-making and business models to ensure the sustainability of seagrasses across the Indo-Pacific. The project focused on five priority sites in SE Asia, including the Trang region in Thailand, and addressed a range of seagrass ecosystem services, including carbon sequestration (or Blue Carbon). The Thai NGO, Save Andaman Network (SAN), implemented the blue carbon assessment, supported with training and expert advice from Edith Cowan University (ECU).

This technical report presents the outcomes of the assessment of Blue Carbon function in seagrass meadows at the priority site of Trang, on the Andaman coast of Thailand. The assessment was implemented with the following goals:

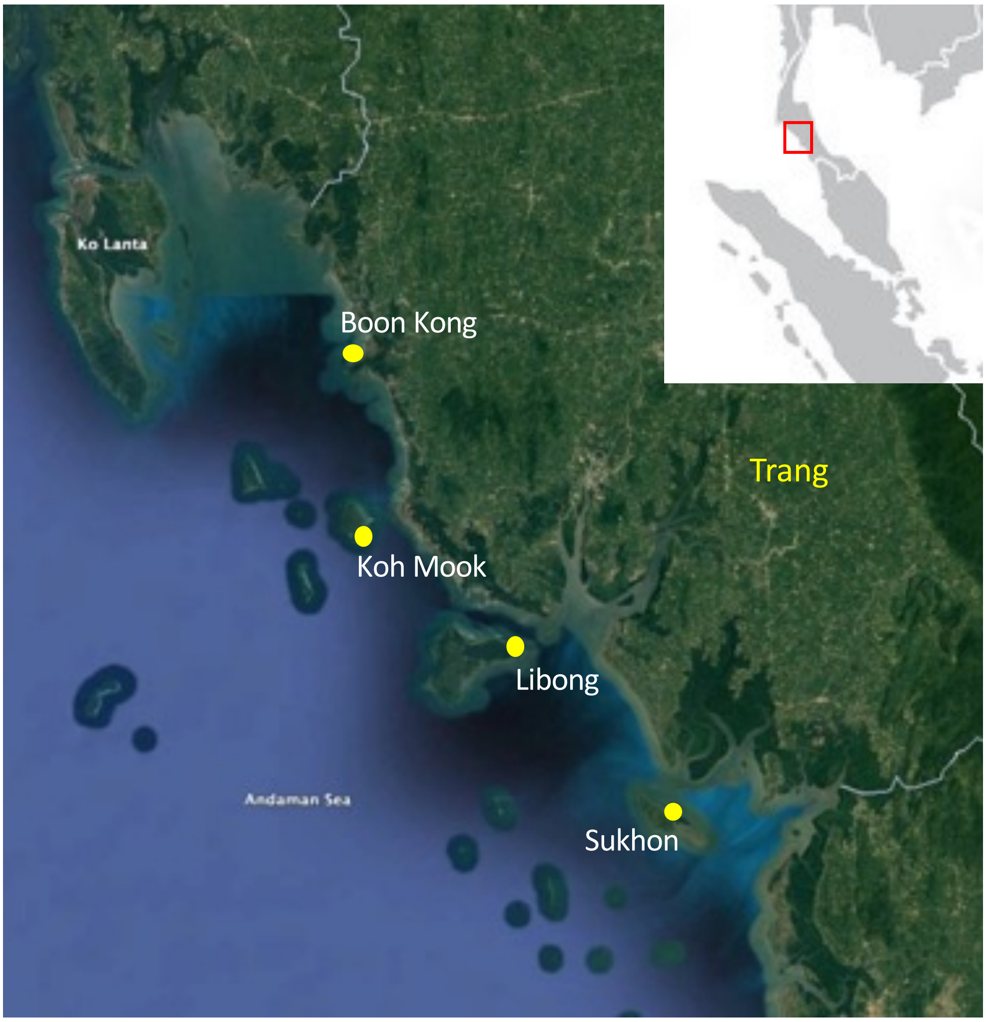
- Obtain information that can be used to inform decision makers of the value of seagrasses for CO_2 capture and storage, and to inform the design of BC projects;
- Build the capacity of local NGO and communities to undertake Blue Carbon SES assessments;
- Collect data to undertake a Seagrass Blue Carbon assessment at the priority sites; and
- Build capacity within the NGO to integrate the Blue Carbon Assessment into policy guideline development, decision-making and management.

1.2 Assessment design

The Blue Carbon Assessment was undertaken at four *Enhalus acoroides* seagrass meadow sites in Trang (**Error! Reference source not found.**):

- a Reference site (Mook Island);
- two sites impacted by the predominant disturbances in the area, sediment deposition (Libong Island) and trawl fishing (Sukhon Island); and
- a seagrass restoration site (Boon Kong Island). Globally, there is very little knowledge on the effectiveness of seagrass restoration to restore carbon sequestration function, largely due to the lack of accessible restoration sites to sample.

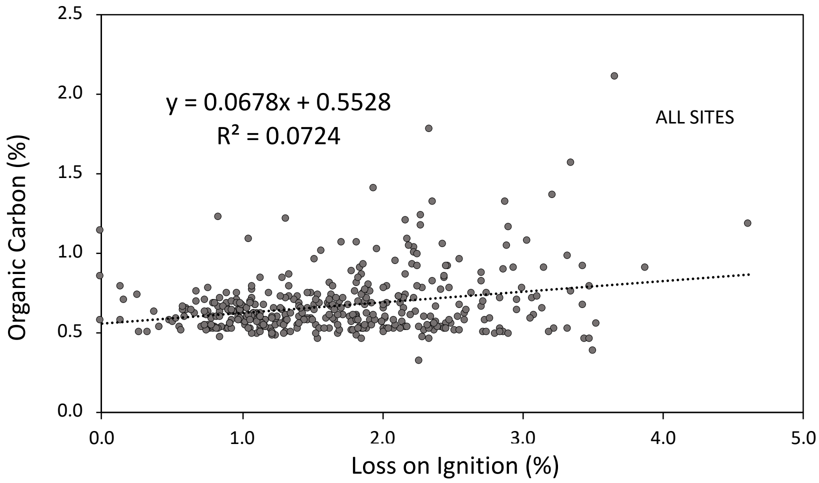
At each site, four seagrass cores were collected to determine the carbon characteristics for comparison of undisturbed and disturbed sites. The methods used followed published protocols, modified to suit the local circumstances of the national partner while providing scientifically robust estimates of the stocks and accumulation rates.



ES Figure 1. The location of the four sampling sites used by SAN in the Blue Carbon assessment for the Trang region in Thailand. See Table X for details of site characteristics and location coordinates.

1.3 Soil C_{org} stocks and accumulation rates in Trang seagrass ecosystem

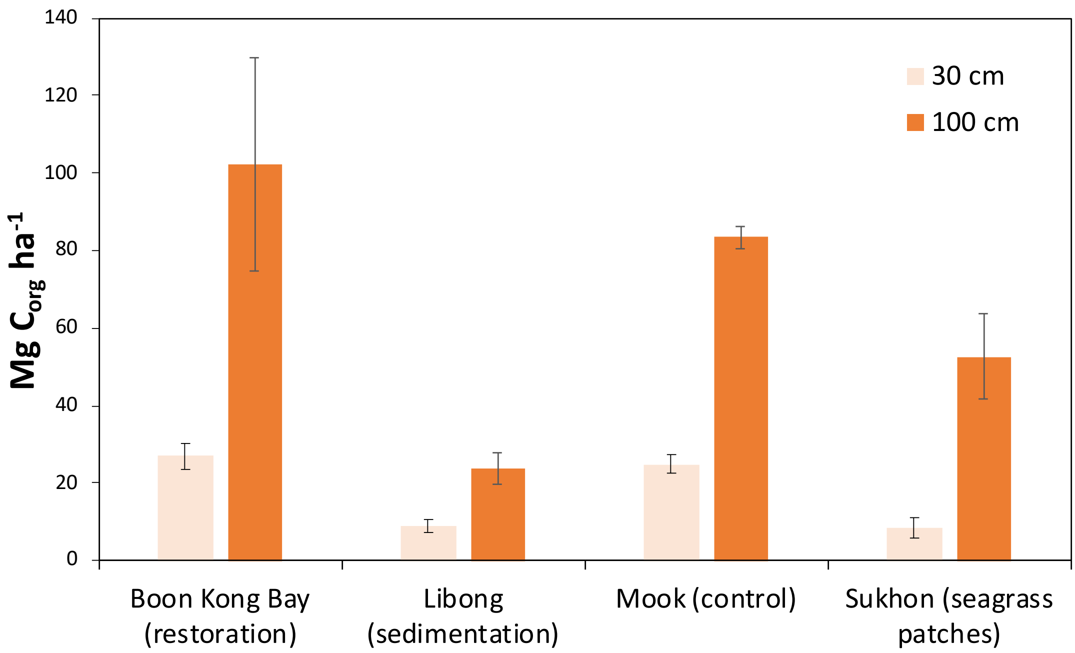
A key objective of the Blue Carbon assessment was to apply a cost-effective means for NGOs and communities to estimate carbon stocks in their seagrass soils, which involved establishing a relationship between the expensive and more difficult to measure Organic Carbon (OC) content, and the cheaper and easier to measure Organic Matter (OM; through Loss on Ignition, or LoI). The relationship between OC and OM was weak (ES Figure 2), for reasons which remain unclear, and so the published, global relationship was applied instead. It is recommended that further effort be put into developing a relationships between OC and OM for different regions within the country, taking into account differing geomorphologies.



ES Figure 2. Relationship between soil organic matter (LoI) and organic carbon using pooled data from all sites.

Soil C_{org} Stocks

The mean soil C_{org} stocks at the undisturbed and restored seagrass sites (Mook and Boon Kong) were higher than at the disturbed sites, Libong and Sukhon). In the top 1 m, the Mook meadow had 84 ± 6 Mg C_{org} ha^{-1} and the Boon Kong site had 102 ± 55 Mg C_{org} ha^{-1}, while the disturbed Libong and Sukhon sites had 24 ± 8 and 53 ± 22 Mg C_{org} ha^{-1}, respectively. Assuming the Mook and the Boon Kong site are representative, healthy *Enhalus acaroides* meadows in the region can be assumed to have stocks in the order of 80-100 Mg C_{org} ha^{-1}, similar to those reported for elsewhere on the Andaman coast, though at the lower end of the range.



ES Figure 3 Mean (± SE) organic carbon (C_{org}) stocks in 30 cm and 100 cm-thick seagrass soil deposits collected in Thailand. C_{org} was estimated from Loss on Ignition data using the regression from Fourqurean et al. (2014)

C_{org} accumulation rates

Only long-term carbon accumulation rates could be estimated for the sites, using the radiocarbon dating, with a mean of 0.08 ± 0.02 Mg ha^{-1} y^{-1} (ES Table 1), which is low in comparison to most reported rates for seagrasses. Site conditions prevented application of radio-isotope methods to determine short-term rates (i.e. last 100 years) which, typically are higher than long-term accumulation rates, and reflect the contemporary conditions at a site. Therefore, the rates reported here for Trang should be viewed as conservative estimates until short-term rates can be determined.

ES Table 1. Estimated mean ± SD long-term C_{org} accumulation rates at the four seagrass sites in Trang. The std errors refer to the uncertainties in the age-depth model, with a single core analysed at each of the four sites.

Ecosystem	Sediment Accumulation Rate ($cm\ y^{-1}$)		C_{org} Accumulation Rate ($g\ C_{org}\ m^{-2}\ y^{-1}$)	
	Mean	s.d.	Mean	s.d.
Koh Mook	0.063	0.001	9.8	2.6
Libong	0.119	0.003	8.9	0.4
Sukhon	0.128	0.001	5.8	0.1
Boon Kong	0.136	0.002	8.2	0.7

1.4 Potential for carbon abatement

The differences in soil C_{org} stocks among the sites was used to estimate the potential for avoided greenhouse gas (GHG) emissions and enhanced CO_2 sequestration in the seagrass ecosystems. Using the difference in stocks between healthy and disturbed meadows, and making assumptions which are detailed in the main report, the potential avoided emissions associated with management of healthy meadows to prevent their disturbance is estimated to be 48 – 134 t $CO_{2\text{-}eq}$ per hectare of meadow (ES Table 2). The potential for enhanced sequestration through seagrass meadow restoration was estimated to be 0 - 33 kg $CO_{2\text{-}eq}$ ha^{-1} y^{-1}.

ES Table 2. Estimated potential abatement for Trang seagrass meadows. Estimates are based on the difference between healthy and disturbed meadows and assume 50% remineralisation of disturbed stock.

STOCK ($kg\ C_{org}\ m^{-2}$)				AVOIDED EMISSIONS			
Healthy		Disturbed		($t\ C_{org}\ ha^{-1}$)		($t\ CO_{2\text{-}eq}\ ha^{-1}$)	
Koh Mook	Boon Kong	Libong	Sukhon	Min	Max	Min	Max
7.85	10.22	2.89	5.26	13	37	48	134

For illustrative purposes only, a first-order estimate was made of the potential stocks in Thailand's seagrass meadows and, for the period 2014-2017, the potential annual emissions associated with seagrass loss. On the basis of a number of assumptions which, again, are detailed in the main report, Thailand's seagrass meadows are estimated to contain between 0.96 and 1.88 Mt of organic carbon in the top 1 m of their soils, equivalent to 3.5 to 6.9 Mt of $CO_{2\text{-eq}}$ (Table 7). Conservation of these meadows will ensure this carbon is not emitted to the atmosphere and will continue to assimilate an additional 0.02 – 0.06 Mt of $CO_{2\text{-eq}}$ each year. Losses of seagrass meadows between 2014 and 2017 could potentially have resulted in an emission of 0.95 to 1.97 Mt per year of CO_2. The estimates indicate the significantly higher abatement to be gained by avoiding losses of seagrasses meadows rather than attempting to restore them.

1.5 Lessons learnt

The four SES case studies, including that undertaken at Trang, have provided valuable insights into methodological and logistical issues that could affect the capacity to implement blue carbon projects by NGOs working in the region. These included:

Determining Carbon Accumulation Rates

Most carbon crediting schemes and inventories require estimates of Carbon Accumulation Rates (CAR), however, there is a paucity of CAR measurements for SE Asia, especially short-term CAR which are critical to blue carbon projects. Determining CARs typically involves either dating the soil using radioisotope techniques or directly measuring accumulation using surface elevation tables (SET). Generally, there was little success in using radioisotope techniques to establish short-term CARs. In Thailand this was due to the local environmental conditions at the study sites, a problem not uncommon in seagrass sites. Efforts to establish SETs were also unsuccessful due to the theft of the measuring rods but offers the most promising way forward.

Methodological issues with determining %C_{org} using %LOI

It is common in BC studies to use the relationship between organic matter (LOI) and organic carbon (C_{org}) to estimate the C_{org} content of a soil when financial constraints limit the number of C_{org} analyses that can be performed. We attempted that approach here, but it was generally unsuccessful due to:

1. the relationship being weak and with significant uncertainties for the C_{org} data; or
2. being unable to analyse the samples for C_{org} content due to legal constraints on exporting the samples for analysis.

Overcoming these two barriers will be an important step for allowing NGO and community groups in the region to undertake carbon sequestration assessments.

Permits

Some of the SES project sites, including Thailand, experienced difficulty obtaining permits needed to undertake the blue carbon assessments. These issues related either to:

1. Permits to undertake field sampling (as was the case for SAN in Thailand); or
2. Permits to export soil samples for chemical analysis.

In some cases, the lack of permit severely compromised to outcomes of the project. The lesson here is that it is critical to understand the permitting requirements in countries before commencing a blue carbon assessment and that sufficient time needs to be allowed for obtaining those permits.

Training delivery

The SES Project was initially structured around in-country, face-to-face training sessions, for the technical partners to build capacity among the NGO partners. COVID-19 travel restrictions prevented face-to-face training and necessitated a shift to on-line training resources, which were useful in allowing the NGO partners to implement the assessments. However, the impact of no face-to-face training became apparent as the project developed: what could effectively be explained face-to-face in a two- or three-hours discussion proved almost impossible to convey using other approaches. The lack of opportunity to hold the planned in-person workshops had a detrimental effect on the efficiency and the quality of the outcomes of the blue carbon assessments. While the outcomes are still valuable, there is no doubt that any future capacity building should prioritise in-person training.

1.6 Conclusions and Recommendations

- Healthy and restored seagrass meadows in the Trang region have soil C_{org} stocks of 84-102 Mg C_{org} ha^{-1}, comparable to stocks measured in other areas of Thailand and previously in Trang.
- Disturbance appears to reduce the soil C_{org} stocks. The meadows disturbed by sedimentation and fishing activity had stocks of 24 ± 8 and 53 ± 22 Mg C_{org} ha^{-1}, respectively.
- Trang seagrass meadows have long-term carbon accumulation rates of about 5.8 – 9.8 (mean: 8 ± 2) g C_{org} m^{-2} y^{-1}.
- The potential abatement associated with conservation of seagrass meadows in the region was estimated to be 48 – 134 t $CO_{2\text{-}eq}$ per hectare, while restoration was estimated to have potential enhanced sequestration of up to 33 kg $CO_{2\text{-}eq}$ ha^{-1} y^{-1}.
- Reported losses of 8.5 km^2 of seagrass per year in Thailand were estimated to represent a potential emission of 175 – 300 t $CO_{2\text{-}eq}$ y^{-1}.
- The values generated in this assessment of seagrass carbon stocks, carbon accumulation rates and potential carbon abatement, can be used to inform decision makers and the broader community about the value of seagrasses, and to make first order estimates of the potential abatement opportunity for seagrass blue carbon projects.
- The SES Project has successfully achieved the key objectives of:
    - Building capacity to undertake blue carbon assessments,
    - Generating data for application in policy and future blue carbon projects,
    - Identification of partner organisations to assist in future blue carbon projects.

- The blue carbon assessment saw the following activities completed as parts of Work Packages I, II, III and IV of the SES Project:
    - **Activity I.1:** Modify or develop new methodological tools for monitoring seagrass ecosystem services (carbon sequestration);
    - **Activity I.2:** Four trainings (one per site) provided to local stakeholders on assessment of seagrass status (blue carbon status) – through on-line instructional videos and a face-to-face workshop which all five National partners participated in;
    - **Activity I.4**: Data collection at four sites, with community participation, to build on and integrate with any existing data concerning the location, extent, conservation, and SES of seagrass meadows and megafauna;
    - **Activity II.1**: SES (blue carbon) data collection, analysis, and assessment at four sites to determine the different ways in which seagrass is providing value and what the loss of these services would cost;
    - **Activity II.2**: Five workshops (one per site) provided to local stakeholders on understanding assessment and valuation of key SES. Total of ≥50 community members. Due to COVID travel restrictions, the five workshops (one per site) were replaced with a single workshop to which all six of the project's NGOs participated;
    - **Activity IV.1**: Training to build capacity of stakeholders (decision-makers, Protected Area managers and NGOs) to utilise SES assessment and valuation. Training for the blue carbon component was provided through a face-to-face workshop (Bogor, 2023) for all six project National Partners.

Recommendations

- **It is recommended that** the findings of this assessment be used to inform policy and seagrass restoration efforts in Thailand.
    - The information generated in this assessment should be used to inform decision makers and the broader community about the value of seagrasses in carbon abatement, to argue for the inclusion of seagrass ecosystems in the NDC and for the inclusion of seagrass projects in government strategies for the conservation of vegetated habitats. The data generated in this assessment can also provide an initial indication of the carbon credit potential of seagrass blue carbon projects in voluntary carbon trading market operating in Thailand.

- **It is recommended that future efforts to undertake seagrass blue carbon assessment use the approaches, based on the experience gained during the SES Project:**
    - Further effort be applied to generate more robust Organic Carbon: Organic Matter relationships for seagrass meadows in Thailand;

- The National Partner work collaboratively with local university/research partners to implement assessments, in particular the LoI and organic carbon analyses;
- Direct measurement of soil accumulation rates be made using surface elevation rods, horizon markers or rSETs, rather than relying solely on radio-isotopic approaches; and
- Future efforts to build capacity in seagrass ecosystem service (blue carbon) assessment prioritise the inclusion of face-to-face field and laboratory techniques training.

Acknowledgments

This project (The Seagrass Ecosystem Services -or SES- Project) was funded by the International Climate Initiative (IKI) of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety of the Federal Government of Germany (Project 18_IV_094_Asia_M_Seagrass Ecosystems), the Secretariat of Convention on the Conservation of Migratory Species of Wild Animals (CMS) and by Edith Cowan University. The project team is grateful for the support provided by: Donna Kwan, Nicola Piludu for initial project coordination; Fiona Walsh for stepping it very short notice to edit instructional videos; and Thunyatorn Wattanamaytawee, Pathiwat Mueangklang and Jaenwit Maenkaew for research and field assistance. We thank Ankje Frouws, Leah Beltran and Maddy Hoffman for their laboratory assistance. We also thank Prof. Anchana Prathep for her support of the collaboration between PSU and SAN, and Assistant Professor Pontep Wirachwong from RMUTSV for assistance with initial site surveys.

2 Introduction and Aims

This report summarises the activities and findings of a Blue Carbon (BC) assessment undertaken by Save Andaman Network (SAN) with technical assistance from Edith Cowan University (ECU). The assessment was undertaken as part of a broader assessment of seagrasses at selected seagrass sites in the Trang region, on the west coast of Thailand, as part of the IKI- funded project "Conservation of biodiversity, seagrass ecosystems and their services – safeguarding food security and resilience in vulnerable coastal communities in a changing climate", hereafter referred to as the SES (Seagrass Ecosystem Services) project'. The full SES project was a collaboration among six National Partners (NGOs based in five SE Asian Countries) supported by four Technical Partners and two Implementing Partners. The project was designed to enhance the understanding of seagrass ecosystem services and the capacity of the National Partners to develop and deliver science-based policy solutions in seagrass conservation. It brings together scientists, policy experts, business development experts and conservation NGOs across the globe to provide expert and independent advice on seagrass ecosystems services and how these might be relevant to policy and financial solutions to marine conservation issues.

Seagrasses provide many ecosystem services, including the provision of human food, biogeochemical cycling (including carbon sequestration), biodiversity protection and coastal protection. Yet they are frequently neglected in decision-making, leading to alarming rates of loss – 29% of global seagrass meadows have been lost and, at the end of the last century, the remaining beds were declining at a rate of 110 km^2 per year. Seagrass meadows of the Indo-Pacific support up to one billion people through their provision of inshore fisheries. They also provide critical habitat for many marine species, supporting biodiversity including the Dugong (*Dugong dugong*), which is listed a vulnerable on the IUCN Red List. At the same time, seagrasses in the region are declining because of coastal development, deforestation, unsustainable resource extraction, and environmental degradation. Limited data exists on seagrass status, their ecosystem service (including carbon storage capacity) and economic value in the region. This information is essential to inform and incentivise effective seagrass conservation. Beyond a better understanding of the role and value of seagrass to tropical marine ecosystems, a coordinated research and decision-making response is needed if effective seagrass management is to occur in the Indo-Pacific.

The SES project was established to provide critical data on the state and condition of seagrass ecosystems. It also aimed to promote the integration of Seagrass Ecosystem Services (SES) into evidence-based decision-making and business models to ensure the productivity and sustainability of seagrasses across the Indo-Pacific. The project focused on five priority sites in SE Asia, one in each of five target countries, and applied a 'bottom-up' approach designed to empower local communities to collect and provide the data needed to inform decision-makers and to develop sustainable financing for the conservation of seagrasses and associated biodiversity that are tailored to the specific environmental and economic contexts of the country and community. Consistent with that approach, it was intended that the National Partners would implement the program, supported with training and expert advice from the Technical Partners.

In each of the five priority sites, the project was implemented via five work packages:

WP1. Assessment: primary data collection using biological SES assessments and participatory approaches with local communities.

WP2. Integration: build capacity for integration, develop policy guidelines and integrate SES into decision-making and management.

WP3. Business models: conceptualise 3 models for 5 pilot sites and build community capacity to implement them.

WP4. Communications: develop a strategy and tools for the promotion of SES services and biodiversity.

WP5. Project Management and Coordination.

This technical report presents the outcomes of components of the SES assessment (WP1) and Integration (WP2), specifically, the assessment of Blue Carbon function in seagrass meadows at the priority site in Thailand. The assessment was implemented by Save the Andaman Network (SAN), supported by technical experts at Edith Cowan University (ECU). The goals were to:

- Build the capacity of local NGO and communities to undertake Blue Carbon SES assessments;
- Collect data necessary to undertake a Seagrass Blue Carbon assessment at priority sites identified by the NGO (WP1);
- Build capacity within the NGO to integrate the Blue Carbon Assessment into policy guideline development, decision-making and management (WP2).

Before describing the activities undertaken (Section 3) and the outcomes of the BC Assessment (Section 4), the following material in this section introduces some relevant background on blue carbon, seagrasses and the concept of 'blue carbon projects'.

2.1 What is Blue Carbon?

Blue carbon, also known as coastal carbon, refers to the atmospheric CO_2 which is captured and stored in coastal vegetated ecosystems, either as plant biomass or in the soils, referred to as sedimentary organic carbon. Seagrass, mangrove and tidal marsh ecosystems are recognised as making a significant contribution to the global carbon cycle (Nellemann et al. 2009), due to their ability to bury organic carbon (C_{org}) in their soils at rates, and for storage periods, that are orders of magnitude higher than in many terrestrial ecosystems (McLeod et al. 2011). Interest in BC intensified following the release of two reports in 2009 (Laffoley & Grimsditch 2009, Nellemann et al. 2009), which highlighted the exceptional capacity of these ecosystems to sequester atmospheric carbon, and the subsequent efforts of governments to embed blue carbon into their climate change mitigation and/or adaptation policies (Martin et al. 2016). This, together with the high rates of loss of BC ecosystems globally, make them of significant interest for national and regional climate change mitigation strategies. The conservation, restoration and creation of BC ecosystems have the potential to increase carbon capture and storage, mitigate climate change, support carbon crediting systems and provide numerous co-benefits, including the provision of habitat for endangered species such as the dugong (*Dugong dugon*). Globally, seagrasses occupy about 600,000 km^2 and account for 12% of total carbon stored in ocean sediments. However, significant ongoing losses of seagrasses result in a reduced capacity to mitigate climate change as well as losses to economic sectors dependent on the extensive ecosystem services that seagrass meadows provide.

Seagrass Blue Carbon

Blue carbon ecosystems store C_{org} in two main pools: the above-ground pool, mainly comprising living biomass and litter; and the below-ground pool, comprising roots and rhizomes, dead below-ground plant organs, buried litter and soil (or sedimentary) C_{org}. The majority of the C_{org} stocks in blue carbon ecosystems are found in this below-ground pool (Duarte et al. 2013a), typically more than 90% of total C_{org} stocks in tidal marshes and seagrasses and in the order of 65-75% in mangroves (Nellemann et al. 2009, Alongi 2014; Serrano et al. 2019). This predominant storage of C_{org} within the below-ground pool (hereafter referred to as soil C_{org}) makes this the pool of primary interest in many blue carbon initiatives (Sutton-Grier et al. 2014), especially in seagrass ecosystems.

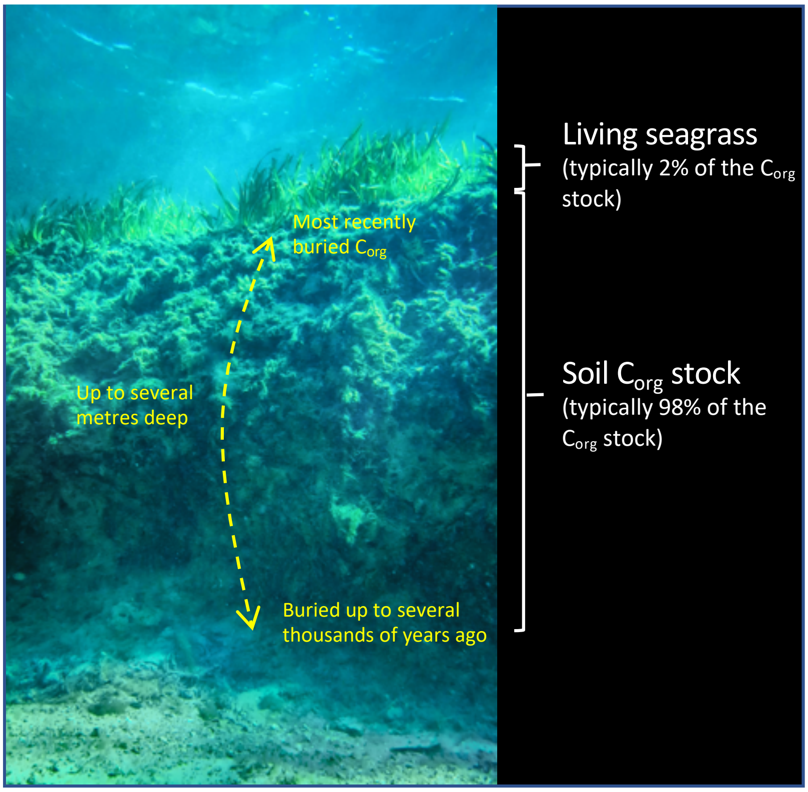


Figure 1 A profile through a seagrass meadow made possible by the erosion of an escarpment wall and revealing the large amount of organic carbon-rich soil below the relatively thin living layer. Numbers in the figure are based on Serrano et al. (2019) for Australian seagrass ecosystems.

The capacity of different seagrass ecosystems to trap and store carbon in their soils varies. Up to 45-fold differences in soil organic carbon stocks have been reported among seagrass habitats, while their annual carbon accumulation rates can vary by up to 70-fold (Lavery et al. 2013; Serrano et al. 2019; Mazarrasa et al. 2021). This variation is driven by many factors, including species composition, geomorphological settings, soil characteristics, and biological features which interact to control the capture and storage of C_{org} in seagrass ecosystems (Adame et al. 2013, Ouyang & Lee 2014a, Serrano, et al. 2016). Understanding this variability and the factors that control the stocks and accumulation rates is key to identifying opportunities to enhance C_{org} stocks or avoid emissions of GHG, thereby contributing to the mitigation of GHG emissions and forming the basis for potential inclusion of BC activities within carbon crediting programs.

How do SG capture and store carbon?

Seagrass meadows trap and accumulate two types of carbon – autochthonous and allochthonous carbon. Autochthonous carbon is carbon which the seagrass plants, and other primary producers in the meadow, have produced through photosynthesis and turned into plant biomass. This biomass can then experience several fates. It may be consumed by herbivores, such as dugongs or be exported, in the form of dead leaves shed by the plant. Through the process of remineralisation, this carbon is likely to be turned back in inorganic forms, such as carbon dioxide and, potentially, re-enter the atmosphere as gaseous emissions (Fig X). However, some of the biomass be buried in the sediments, where it can accumulate and be isolated from the atmosphere for millennia. Most of this buried carbon comes from the below-ground biomass of the seagrass (rhizomes and roots) which are incorporated into the sediments when the tissues die. Allochthonous carbon refers to organic carbon which originated in a different place but has accumulated in the seagrass meadow, largely dead plants and animals which drifts into a meadow. The seagrass canopy slows the water movement and facilitates the trapping of the material, where it falls into the sediment and is buried.

Most of the organic carbon accumulated in seagrass meadows is found in the sediments – typically more than 95%. This is because the sediments have characteristics which assist the accumulation and preservation of the carbon, while in the seagrass canopy conditions favour remineralisation. The vertical growth of the seagrass plants and the trapping of particles by the canopy results in vertical accumulation of the sediment and burial of material in it. Once buried, the carbon is isolated from oxygen, which slows down its remineralisation. Furthermore, because the sediments are permanently wet (even inter-tidal sediments) they are not subjected to fires. The constant burial, lack of oxygen and absence of fire all promote the accumulation and preservation of carbon in seagrass sediments. In contrast, the seagrass canopy (and terrestrial soils) is exposed to high levels of oxygen and physical disturbance which work against the accumulation and preservation of carbon, and terrestrial soils also experience fire which rapidly remineralises the stored organic carbon to carbon dioxide. For these reasons, seagrasses and other blue carbon ecosystems tend to have much higher rates of carbon accumulation in their soils than terrestrial ecosystems.

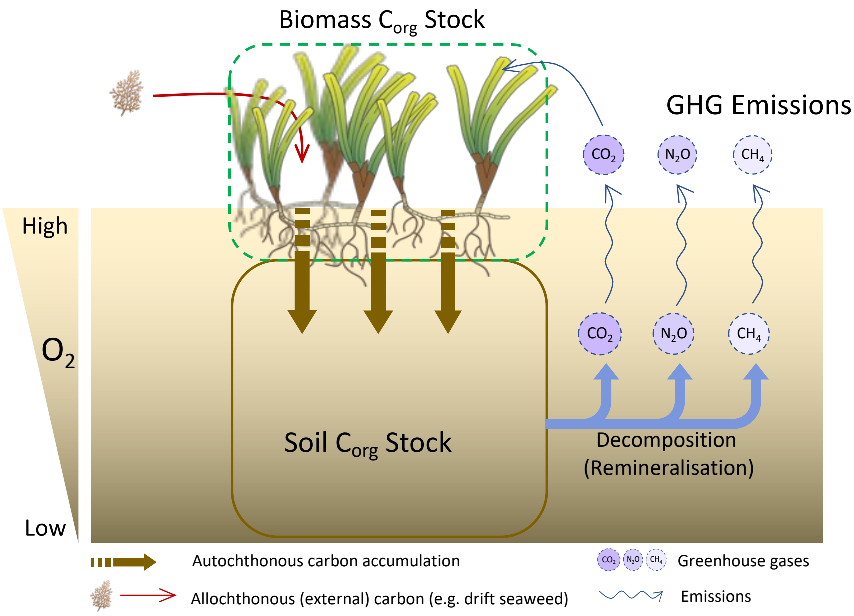


Figure 2 Carbon stocks, accumulation and greenhouse gas emissions in seagrass meadows

What is a Seagrass Blue Carbon Project?

A seagrass Blue Carbon Project refers to any action which is designed to maintain or enhance the capture and storage of carbon by seagrass ecosystems. These actions (or projects) can take many forms, ranging from the conservation of existing, healthy seagrass meadows through to the restoration of degraded seagrass meadows or even the creation of seagrass meadows in places that did not previously support them. The motivation for these actions are also quite varied. In some instances, the goal is to conserve habitat for the range of ecosystem services it provides, carbon capture being just one of these. In other cases, actions may contribute to regional or national goals to mitigate climate change, contributing to Nationally Determined Contributions. In yet other instances the goal may be to generate income through carbon credits which can be used for a variety of purposes, including funding of conservation initiatives. Of course, these motivations are not mutually exclusive.

In most instances, any seagrass blue carbon project will need to demonstrate the potential or actual effectiveness in carbon capture. Where the actions are feeding into Greenhouse Gas (GHG) inventories, NDCs or Crediting projects, then a formal estimation or verification of the carbon capture will likely be required. Such assessments require information on how much carbon the seagrass site captures each year (i.e. the **sequestration** rate or **Carbon Accumulation Rate**, CAR), the total amount they have buried in their soils (the soil **C_{org} stock**) and the **emissions** of GHGs from the meadow (Fig X). For seagrasses, and many other ecosystems, this information will likely be incomplete, requiring estimates to be made with some degree of uncertainty. The IPCC has classified their methods for estimating GHG emissions into three tiers based on their complexity and data requirements (IPCC 2006, 2019). Tier 1 is the most basic method, Tier 2 intermediate and Tier 3 most demanding, with Tiers 2 and 3 generally considered to be more accurate. In the absence of locally-derived information on seagrass C_{org} stocks, CAR and GHG emissions, global default values could be used to estimate the amount and rate of C_{org} capture at a specific site, providing a tier 1 estimate. Determining region-specific values for C_{org} stocks and sequestration rates will allow tier 2 or tier 3 estimates (i.e. estimates based on regional data or modelling) to be applied. The benefit of deriving tier 2 or 3 estimates is that they provide a more accurate estimate of carbon capture, or possible carbon emissions following disturbance, for use in nationally determine contributions, and the greater certainty may be rewarded in the size of carbon credits that might be derived in a blue carbon project.

There is a paucity of case studies to inform the potential enhancement of carbon capture and storage following specific management actions such as seagrass restoration projects. The potential opportunities for seagrass ecosystems in carbon mitigation strategies is based on the presumption that restoration can return the C_{org} sequestration rates to those of undisturbed ecosystems, yet this remains to be tested. The 'SES Project' was designed to generate data to fill critical knowledge gaps around BC in the study region, thus supporting the ability to demonstrate one of the values of seagrasses to local communities and decision-makers and to assist in any future efforts to develop seagrass blue carbon projects by providing data to underpin tier 2 or tier 3 estimates of GHG inventories.

Blue Carbon Projects & data requirements

The specific information requirements for any BC assessment will depend on the purpose of the assessment. Broadly, assessment can be undertaken to:

a) provide an understanding of the function and value of a seagrass ecosystem, which might educate stakeholders (such as local communities through to regional or national governments) and, thereby, influence policy or decision-making;
b) to provide data that can underpin carbon accounting activities, such as those needed for GHG accounting or measuring performance against NDCs; or
c) to provide the information required as part of the verification process for a blue carbon crediting project. Sometimes, the assessment may need to meet more than one of these objectives.

The data requirements and methods for a baseline survey (a, above) will be for the assessment team to decide, and there is comprehensive guidance available on this (e.g. Howard et al. 2014; Rahmawati et al 2019). For assessments which feed into formal GHG accounting or crediting schemes, it is likely that the data requirements and methods will be specified by national or international governance bodies (e.g. the IPCC) or by a verification agency (e.g. VERRA: www.verra.org/programs/verified-carbon-standard; or Gold Standard: https://www.goldstandard.org/). In all these cases, there is usually a requirement to assess the carbon characteristics of an undisturbed meadow and a disturbed meadow. The undisturbed meadow defines the baseline condition and provides insights into the ecosystem service being provided by existing seagrass meadows, in terms of carbon capture. The disturbed meadow provides insights into the impact humans can have on carbon emissions if a meadow is disturbed or if a disturbed meadow is rehabilitated.

For GHG inventories and general information for influencing policy, the undisturbed condition demonstrates how much carbon a healthy seagrass meadow can sequester each year – i.e., the ecosystem service being provided. It also provides insight into how much carbon could be released to the atmosphere (i.e. an emission) if the meadow was disturbed. The difference between the healthy and disturbed meadow provides further insight into the potential emission from a seagrass meadow if it were disturbed. Conversely, it can be used to demonstrate how much additional carbon would be captured if the disturbed meadow were restored to a healthy condition.

For blue carbon crediting project, measurements of healthy and disturbed meadows can be critical in estimating its carbon abatement potential. Most project verification schemes require the project to demonstrate two features of any carbon capture: additionality and permanence. Additionality implies that the carbon which a project captures is additional to that which would have been captured in the absence of the project. For example, if the project was restoration of a seagrass meadow, the only carbon eligible to receive credits is that which can be shown to have accumulated because of the restoration; any carbon that would have accumulated in the absence of the restoration would not be eligible. In this situation it is necessary to define the baseline condition (or the condition before any project is implemented – often referred to as the Business as Usual (or BAU) condition – as this indicates the amount of carbon that would accumulate without the project. The BAU case is often estimated by measuring the disturbed area. It is then necessary to estimate how much carbon will be sequestered by the project. This can be done in many ways, but one way is to measure the sequestration in a healthy meadow and assume that the project will result in similar characteristics. The difference between the Project estimate and the BAU estimate represents the additionality and is the amount of carbon potentially eligible for credits.

Additionality can be achieved through:

1) **Enhanced sequestration** – in this case, the project occurs on a disturbed site and results in an improvement in the seagrass such that more carbon is being accumulated (sequestered) each year. An example of this is a seagrass restoration project on a disturbed site; and
2) **Avoided Emissions** – in this case, the project acts to conserve an area that would otherwise have been disturbed. By avoiding the disturbance, the project is also ensuring that the emissions associated with the disturbance are also avoided. An example of this might be declaring a marine Protected Area on a site that would otherwise have been dredged for development.

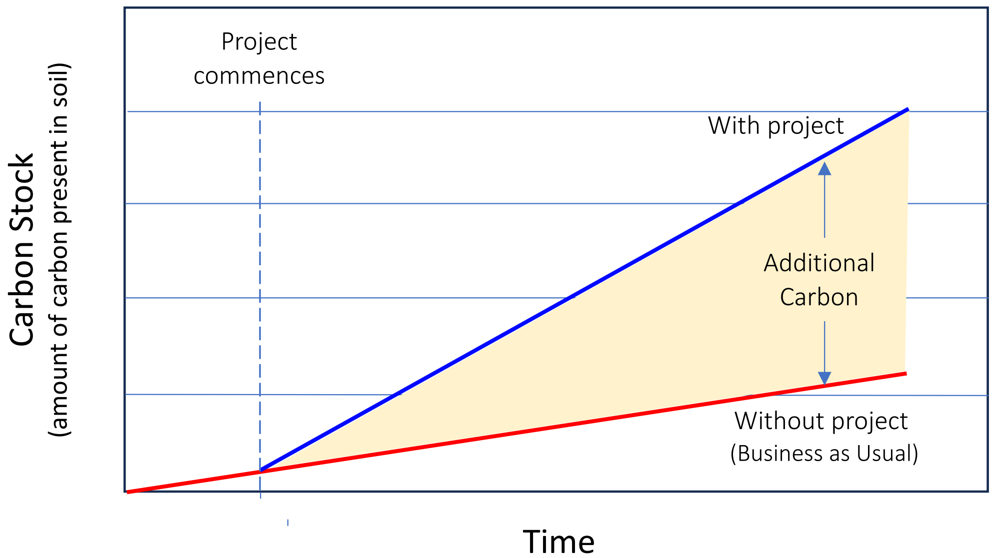


Figure 3 Additionality in blue carbon projects. The diagram shows the amount of carbon which might accumulate at a site over time under two scenarios: at a site with no management action (i.e., Business as Usual (red line); and at the same site following implementation of a blue carbon project (blue line). The difference between the two lines represents the additionality (i.e., the additional carbon sequestered because of the management action).

The second important requirement for any crediting project is that permanence can be demonstrated. Permanence refers to the length of time that the captured carbon will be retained on the site. Many verification schemes require the carbon to be captured for 20 or 100 years, and the number of credits awarded will reflect the level of confidence and the duration of the permanence; project with a high level of certainty of capturing carbon for a long period of time may receive more credits. Demonstrating permanence requires ongoing monitoring of a project site to show that carbon has been captured and retained. However, it is also possible to gain insights into permanence by measuring healthy sites and determining the age of carbon in those sites.

It is apparent from the above that any blue carbon assessment will generate the most versatile outcomes for future application when both healthy and disturbed meadows are assessed. Ideally, the disturbed meadow will be very similar to the healthy meadow in all respects except for the disturbance or interest – e.g., dredging, boat moorings, eutrophication, sediment deposition, fishing.

2.2 NP-identified objectives for BC assessment

In late 2019, at the SES Project Inception meeting held in Manado, each National partner was asked to clarify their objective(s) in undertaking a Blue Carbon assessment. All the National Partners indicated that their primary objective was to:

- Build capacity for the National partner to independently undertake Blue Carbon assessments; and
- Provide data which would demonstrate to policy makers and the broader community the capacity of local seagrasses to sequester and store carbon.

There was less focus on undertaking the assessments to subsequently develop Blue Carbon projects that could generate financial returns through crediting or any other approach.

Following the Manado meeting, ECU worked closely with the National partners to develop a Blue Carbon assessment which would meet their stated objectives. This required the sampling of healthy meadows which could be used to demonstrate the ecosystems service currently being provided. It also required the sampling of disturbed meadows which could, be used to demonstrate any negative effect of those impacts on the ecosystem service. This approach also provided an opportunity to generate baseline data that could inform any future blue carbon project seeking carbon credits.

This report presents the findings of the Blue Carbon assessment in Trang, Thailand, undertaken as part of Work package 1. The assessment incorporated sampling of relatively undisturbed and degraded seagrass ecosystems, focused on C_{org} storage and sequestration. Because the collection of these data added to the database on C_{org} stocks and sequestration rates in Thailand seagrass ecosystems, a review of known information on seagrass blue carbon in Thailand's coastal ecosystems is included.

3 Seagrass Blue Carbon and Blue Carbon Policy in Thailand

Few of the studies of seagrass blue carbon stocks or accumulations rates in Thailand have used a standardised format and consequently, much of work is difficult to compare. Stankovic et al. 2018 and Miyajima et al. 2021 reported seagrass organic carbon stocks over 1 m soil depth, which is an accepted soil depth used in most verification schemes since this represents the soil depth likely impacted by disturbance and, therefore, the potential source of any carbon emissions. That work indicates stocks ranging from 38 to 163 Mg C_{org} ha^{-1} (Table 1), though most measurements were greater than 116 Mg C_{org} ha^{-1}, and included a range of monospecific and mixed-species meadows. These meadows were all on the Andaman coast of Thailand and many contained *Enhalus acoroides*, so the findings are useful for comparison with those of the SAN assessment sites. Only one study (Miyajima et al 2021) has reported carbon accumulation rates for seagrass in the region, with values of around 30 kg C_{org} ha^{-1} y^{-1} at two meadows, both containing *E. acoroides* (Table 1).

Gillis et al. (2018) tested for relationships between the organic carbon content of seagrass soils and a range of environmental variables, including sediment grain size which, elsewhere, has been shown to be a predictor of carbon stocks in some types of meadows. They found no effect of sediment grain size on the soil organic carbon stock but did find significant difference among species of seagrass, with monospecific meadows of *Enhalus acoroides* and *Halophila beccarii* having higher stocks than mixed meadows, though this was only tested in the top 5 cm of soils.

Table 1. Published seagrass soil C_{org} stocks and C_{org} accumulation rates (CAR) for coastal sites in Thailand. CAR = Carbon Accumulation Rate. References: [1]Stankovic et al 2018; [2]Miyajima et al. 2021; [3]Apichanangpool et al 2015

SITE	HABITAT	Sediment depth (cm)	STOCK (Mg C_{org} ha^{-1}) Mean ± s.d.	CAR kg C_{org} ha^{-1} y^{-1}	Ref
Andaman Coast	Mixed seagrass (undefined)	100	123 ± 26.2		1
Andaman Coast	Mixed seagrass (undefined)	100	116 ± 5.3		1
Andaman Coast	Mixed seagrass (undefined)	100	142 ± 40.7		1
Andaman Coast	Mixed seagrass (undefined)	100	134 ± 30.7		1
Andaman Coast	Monospecific (undefined)	100	138 ± 28.6		1
Andaman Coast	Monospecific (undefined)	100	112 ± 19.7		1
Andaman Coast	Monospecific (undefined)	100	163 ± 47.2		1
Andaman Coast	Monospecific (undefined)	100	162 ± 29.6		1
Kuraburi (Andaman coast)	*E. acoroides* (sub-tidal, estuary)	100	120	30.9	2
Trang (Andaman coast)	*T. hemprichii*/*E. acoroides* (subtidal)	100	38	29.7	2
Haad Chao Mai NP, Trang	*Enhalus acoroides* (undisturbed)	15	1.71 ± 0.22		3
Haad Chao Mai NP, Trang	*Enhalus acoroides* (heavily disturbed)	15	0.19 ± 0.02		3
Haad Chao Mai NP, Trang	*Thalassia hemprichii* (75% cover)	15	25.02 ± 4.05		3
Haad Chao Mai NP, Trang	*Thalassia hemprichii* 12% cover)	15	7.58 ± 0.78		3
Haad Chao Mai NP, Trang	*E. acoroides* 75% cover)	15	26.39 ± 2.95		3
Haad Chao Mai NP, Trang	*E. acoroides* 12% cover)	15	6.47 ± 1.01		3

Stankovic et al (2018b) developed regression relationships between seagrass meadow characteristics and the soil organic carbon stocks, an approach which has also been tested in this study to reduce the analytical costs and time associated with blue carbon assessments by estimating organic carbon from more easily measured variables. Stankovic et al. found a weak to moderate relationship between soil organic matter (Loss on Ignition) and soil Organic Carbon (R^2 0.32 to 0.41 for mixed and monospecific meadows, respectively). They found stronger relationships with plant cover and biomass, with R^2 of 0.79 to 0.87 for mixed and monospecific meadows, respectively.

3.1 Seagrass blue carbon policy

Thailand's net GHG emissions in 2016 were 263 Mt CO_{2eq} (including those from LULUCF) with the Energy sector accounting for about 71% of these emissions and the agriculture sector about 15% (UNFCCC, 2021). This placed Thailand among the top 20 countries that emit CO_2, accounting for 0.9% of global emissions.

In 2021 at the United Nation's Climate Change Conference in Glasgow, the Thai government established a goal for the country to be carbon neutral by 2050 and to achieve net-zero GHG emission in 2065 (EIU, 2023). These goals were followed, in 2022, by an update to the country's Nationally Determined Contribution, to reduce GHG emissions by 30-40% compared to the projected business-as-usual level by 2030. Key plans and strategies guiding Thailand's Low Emissions Development Strategy have been summarised by UNFCCC, 2021) and include:

1) Climate Change Master Plan (2015-2050). Prepared by the Office of Natural Resources and Environmental Policy and Planning this aims at low carbon growth and climate change resilience by 2050. The CCMP consists of three key strategies, all of which seagrass blue carbon has the potential to play a role in:
    a. Climate Change Adaptation, which aims to build climate resilience by integrating policies and measures,
    b. Mitigation and Low Carbon Development, which facilitates the development of mechanisms for GHG emissions reduction, and
    c. Enabling Environment for Climate Change Management which aims to enhance potential and awareness of stakeholders and developing database, knowledge, and technology to support climate change adaptation and mitigation.
    d. The mitigation actions include a range of measures intended to reduce emissions across a range of sectors, with short-, medium- and long-term (2050) targets.
2) Thailand's NDC Roadmap (2021-2030; Office of Natural Resources and Environmental Policy and Planning) identifies mitigation measures in energy sector, including renewable electricity and energy efficiency; Measures under the NDC roadmap 2030 are projected to have the potential to reduce GHG emissions by 113 $MtCO_{2eq}$ by 2030.
3) A series of NDC Action Plan specific to the energy, transport, industrial, wastewater and municipal waste sectors.
4) A number of plans regarding energy efficiency and alternative energy development.

Policies with specific relevance to seagrass

The earlier climate change mitigation plans did not specifically address Nature Based Solutions, such as seagrass conservation. However, in 2015, the Office of Natural Resources and Environmental Policy and Planning developed **The National Adaptation Plan for Climate Change Adaptation** (NAP) as a framework for climate change adaptation actions and a guideline for related operations. It covers of focus including 'Natural resources management' where it provides the action's guideline to support conservation, restoration and utilization of natural resources and sustainable biodiversity to support the effects of climate change. The key element of the NAP The key elements in NAP related to mangrove / seagrass are:

1. Conserve and protect marine and coastal resources, including increasing or restoring mangrove forest;
2. Push for the declaration of protected areas in ecologically vulnerable areas and where there are threats to biodiversity outside protected area;
3. Develop a system for tracking and evaluating indicators, measuring the health of the ecosystems; and
4. Prepare an integrated plan for area management of coastlines across the country.

The National Strategy (2018-2037) is Thailand's first national strategy according to the Constitution of the Kingdom of Thailand, with the vision of achieving a "stable, prosperous, sustainable" Thailand. Among its 6 principles, it contains key elements related to mangrove / seagrass:

1. Creating sustainable growth on a green economic society by
   - increasing the value of the bio-based economy in line with the competitiveness strategy;
   - Conservation and restoration of biodiversity in and outside its native places; and
   - Conserving and restoring rivers, canals, and natural water sources.
2. Create sustainable growth on the marine economy society by:
   - increasing the value of the marine bio-based economy;
   - Improve, restore, and rebuild the entire system of marine and coastal resources;
   - Rehabilitation of beaches that are tourist attractions;
   - Coastline protection with integrated coastal management; and
   - Developing and increasing the proportion of marine activities that are environmentally friendly.

Carbon trading

Thailand is among a small number of Asia-Pacific countries that have established carbon trading schemes. The Thailand V-ETS (Voluntary Emission Trading Scheme) was piloted in 2015 by the TGO (Thailand Greenhouse Gas Management Organization) to promote GHG reduction under the domestic voluntary carbon market and to design the measurement, reporting, and verification in accordance with ISO 14064-1, 14064-3 and 14065. The Scheme is explained at: http://carbonmarket.tgo.or.th. Currently there are methods for mangroves through wetland restoration and water flow, and one seagrass method for restoration. One mangrove method includes only C_{org} within biomass (i.e. trees), while the second method also includes soil carbon. The seagrass methodology includes both biomass and soil carbon. Currently, no projects have been implemented.

In late 2022 Thailand launched a voluntary carbon credit exchange, the FTIX, operated by the Federation of Thai Industries. The FTIX will incorporate the government's voluntary emission reduction programme, acting as a carbon credit trading platform for domestic trading. This could potentially offer opportunities for seagrass blue carbon projects to generate financial returns that could be invested into seagrass conservation. The exchange requires projects to be registered to trade carbon credits and according to a report in The Nation news site (https://www.nationthailand.com/thailand/economy/40024038), to date 141 projects are registered to trade about 14 million tonnes of CO_{2eq}, with just over 2 million tonnes currently traded at an average of about 76 baht.

Conclusion

It is clear that nature-based solutions to climate changes are beginning to be recognised in Thailand's policy frameworks. The abatement and adaptation policies as well as the voluntary carbon trading market offer potential to promote seagrass conservation and, possibly, to obtain financing to support those conservation activities. The data generated through the SES project (summarised in the following sections) can be used to argue for the inclusion of seagrass ecosystems into both the policy and trading arenas.

4 Blue Carbon Assessment

4.1 Assessment design

The Blue Carbon Assessment (BCA) was designed to meet the following objectives:

- Build capacity for the National partners (NPs) to undertake Blue Carbon assessments;
- Provide data to demonstrate to policy makers and the broader community the capacity of local seagrasses to sequester and store carbon; and
- Provide data which could inform the development of potential Blue Carbon Projects for financial benefit.

The Blue Carbon assessment was undertaken by SAN in the Province of Trang. To assess the BC potential of the area, SAN assessed four sites (Figure 4; Table 2):

- a Reference site (Mook Island);
- two sites impacted by the predominant disturbances in the area, sediment deposition (Libong Island) and trawl fishing (Sukhon Island); and
- a seagrass restoration site (Boon Kong Island). Globally, there is little knowledge on the effectiveness of seagrass restoration to restore carbon sequestration function, largely due to the lack of accessible restoration sites to sample. A major restoration program has occurred in the Trang region over the past decade, offering a rare opportunity to assess the carbon capture benefits of seagrass restoration in Thailand and South-East Asia.

All four sites had similar geo-morphological settings and water depth and all were occupied by monospecific *Enhalus acoroides* seagrass meadows.

The data for undisturbed meadows can inform government and other decision makers of the value of seagrasses for CO_2 capture and storage. It is also relevant data for the design of BC projects, since these data can identify the 'baseline' or Business as Usual conditions and are relevant to both Avoided Emission and Enhanced Sequestration projects. The data from the disturbed meadows are essential for indicating the extent of carbon which might be lost following disturbance of a meadow and, therefore, the potential amount of carbon loss which could be avoided by conserving this habitat (Avoided Emission) or the additional carbon capture which might be achieved by restoring the meadow (Enhanced Sequestration), by comparison to the undisturbed sites. The restored site provided data on the potential of restoration projects to result in enhanced sequestration.

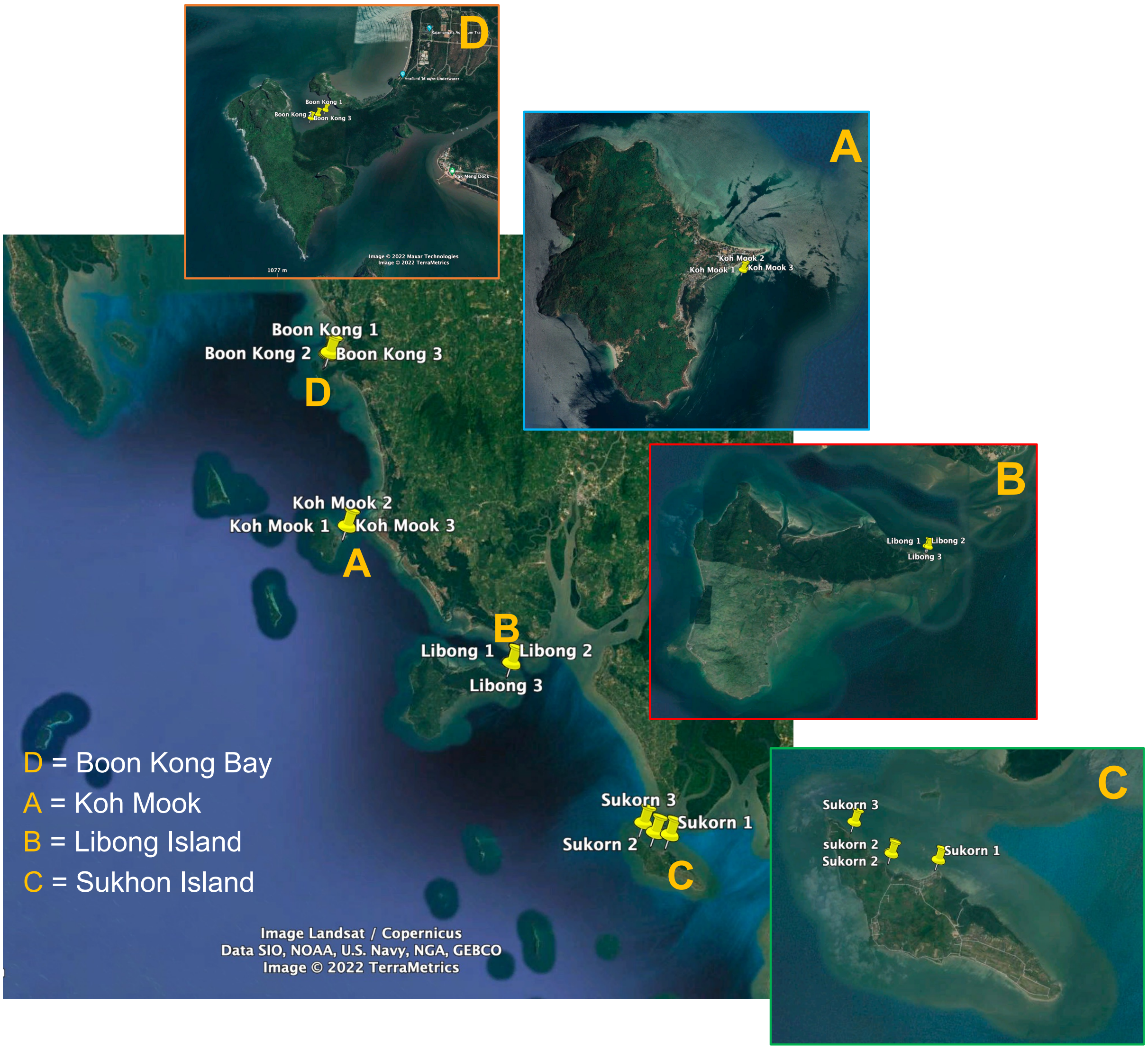


Figure 4. The location of the four sampling sites used by SAN in the Blue Carbon assessment for the Trang region in Thailand. See Table 2 for details of site characteristics and location coordinates.

Table 2. Site details for the blue carbon assessment of seagrass meadows in Trang Province, Thailand.

SITE	DESCRIPTION	Latitude (°N)	Longitude (°E)
Koh Mook	Reference site. The site was dominated by *Enhalus acoroides in* healthy condition and with no obvious disturbance	7°22'40.63”	99°18'28.19”
Libong Island	Unvegetated (dead) previously vegetated with *Enhalus acoroides* lost through sediment deposition which is ongoing	7°14'49.31”	99°27'7.60"
Sukhon Island	Unvegetated (dead) previously vegetated with *Enhalus acoroides* lost through trawling/fishing	7°06'47.38" 7°06'47.49"	99°34'57.74" 99°34'57.81"
Boon Kong Bay	Restored *Enhalus acoroides* meadow (lost in the past but recovered now).	7°30'59.47"	99°17'39.35"

4.2 Site Descriptions

4.2.1 KOH MOOK (MOOK ISLAND)

The site at Koh Mook has relatively low levels of disturbance to the seagrass meadows.

Fishery boat and tourist boat traverse the meadow which is located adjacent to the main pier and the community collect shells from the meadow. However no nets, traps or other fishing gear is allow in the area since it is a protected area in the Chao Mai National Park. The inter-tidal meadow was dominated by *Enhalus acoroides* but nearby areas also supported six other seagrass species: T*halassia hemprichii, Halophila ovalis, Halodule uninervis, Cymodocea rotundata, Halophila minor and Halodule pinifolia*.

Figure 5. Healthy *Enhalus acoroides* seagrass meadow at Mook Island.

4.2.2 LIBONG ISLAND:

The Libong Island site is in an intertidal location which has experienced sediment deposition on the seagrass meadows since about 2019. In that time, it is estimated that there has been a net deposition of in at least 8 cm. Following complaints by local villagers about the degraded seagrass bed, investigations into the source of the sediment have pointed towards the offshore dumping of sand in the sea about 10 km away from the seagrass beds, associated with a river dredging project in the same sub-district. While seagrass remains at the sites around the island, at the study site, on the north-east shore, there has been death of *E. acoroides,* while the remaining seagrass having shorter leaves than prior to the sediment deposition. At some sites around the island there has been seagrass recovery, but this is typically *Halophila ovalis* rather than the original mixed meadows or *E. acoroides* meadows. The site was historically dominated by *E. acoroides* but 10 other species of seagrass have been observed at nearby sites around the island: *Cymodocea rotundata, Thalassia hemprichii, Halophila ovalis, Halophila minor, Halodule pinifolia, Cymodocea serrulate, Halodule uninervis, Halophila beccarii, Halophila decipiens, Syringodium isoetifolium*.

Figure 6. The Libong Island seagrass blue carbon site. The site was previously a healthy *Enhalus acoroides* meadow but is thought to have suffered from the deposition of sandy sediment since 2019, estimated to be as much as 8 cm deep at the site.

4.2.3 SUKHON ISLAND:

The Sukhon Island site previously supported *Enhalus acoroides* seagrass beds but these have been lost from the area in the past 5-7 years, anecdotal evidence suggesting this was due to fishing practice by trawl boats in the area. A recent survey found only sparce patches of *E. acaroides*. Those remaining patches appeared to be healthy, with long leaves 100-120 cm and the sediment appeared to also have good quality, both observations being consistent with the loss of seagrass being due to physical removal by trawling. *Cymodocea rotundata, Halophila minor* and *Halophila ovalis* have also been observed in the area.

Figure 7. The Sukhon seagrass blue carbon site. The site was previously a healthy *Enhalus acoroides* meadow but has suffered from the effects of trawling and other fishing activities at the site.

4.2.4 BOON KONG BAY:

The Boon Kong Bay site is a patchy, intertidal *Enhalus acoroides* meadow. The nearby area also supports five other seagrass species: *Cymodocea rotundata*, *Thalassia hemprichii*, *Halophila ovalis*, *Halophila minor* and *Halodule pinifolia.* The site has been used since 2007 for transplantation of seagrass, mainly *E. acoroides*, using a variety of methods, including placing seeds into plastic cups, bags, or paper cups. Unfortunately, there has been no monitoring activity to track the growth rate or the survival rate of these plantings. Nonetheless, the site now contains *Enhalus acoroides* meadow which is most likely the result of these transplant efforts. As can be seen in Figure 8, the site has muddy sediments and, consequently, turbid waters following any physical disturbance.

Figure 8. The Boon Kong Bay seagrass blue carbon site. The site is believed to have been established through transplantation which commenced in 2007 and is dominated by patchy *Enhalus acoroides*.

4.3 Core collection, processing, laboratory analysis and numerical procedures

Full details of the methods are provided in Appendix A. Prior to core collection, the National partner received training on the field techniques associated with core collection and on the laboratory techniques for subsequent core processing. Initially, it was intended to deliver this training as on-site workshops but COVID-19 travel restrictions prevented this. Instead, ECU prepared instructional videos which explained and demonstrated the process of collecting seagrass soil cores for blue carbon assessment and the laboratory techniques for their subsequent processing. The videos can be accessed at the Vimeo website (Appendix B). ECU ensured the NPs had the necessary sampling equipment and were available via video connection during the sampling event to provide technical support. SAN also contracted blue carbon researchers at a local university (Prince of Songkla University; PSU) to assist in the core collection and subsequent laboratory analysis. PSU accompanied SAN staff on the core collecting field trip and assisted in the collection.

At each site, four seagrass cores were collected to determine the carbon characteristics and allow comparison of undisturbed, disturbed and revegetated sites. The methods used for the collection and processing of the cores and the numerical procedures use to determine carbons tocks and accumulation rates followed published protocols, modified to suit the local circumstances of the national partner. While the protocols were modified, they were designed to provide scientifically robust estimates of carbon stocks and accumulation rates which could be applied in existing carbon verification schemes.

5 Blue Carbon Stocks and Accumulation Rates

5.1 Relationship between %OM and %C_{org}

A key objective of the Blue Carbon assessment was to apply a cost-effective means for NGOs and communities to estimate carbon stocks in seagrass soils. Two common ways to estimate the C_{org} content of seagrass soils are: direct measurement, using an elemental analyser; and indirect estimation based on Loss on Ignition (LoI) (Fourqurean et al 2012; Howard et al. 2014). Elemental analysis is costly and requires access to an analyser. The LoI method is more easily performed but is not a direct measure of carbon content. The SES project combined both approaches, providing a less expensive method which can be performed using readily available laboratory equipment. Globally, a strong relationship has been reported between soil C_{org} and soil organic matter (OM) content, with OM explaining 96% of the variability in C_{org} (Fourqurean et al 2014). Because, OM is inexpensive to measure using the Loss on Ignition (LoI) method, about half the soil sampled were analysed by both methods to develop the relationship for the Trang sites. However, the relationship between LoI and C_{org} was weak for the full data set (R^2 = 0.07) and for each site separately (R^2= 0.01 to 0.13; Figure 9). This starkly contrasts the global analyses (Fourqurean et al 2014) but is consistent with anecdotal reports from researchers in Thailand that the relationship is generally poor at sites sampled in the Andaman coast (Stankovic et al. 2023).

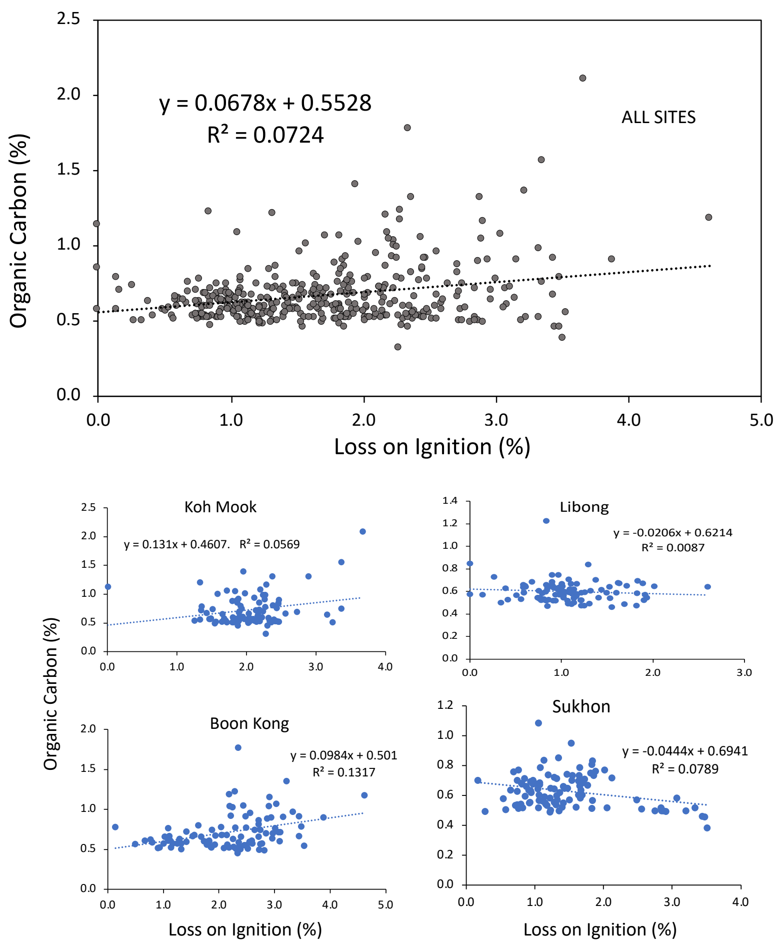


Figure 9. Relationships between soil organic matter (Loss on Ignition) and soil organic carbon for (top) pooled data for all four study sites and (below) for each of the four study sites analysed separately.

The reason for the poor relationship between LoI and C_{org}, in this and other studies, remains unclear but it is well known that while this is a seemingly mundane analysis, it can be challenging in soils with high carbonate content (Serrano et al. 2023), such as those at the assessment sites. A sub-set of samples were re-tested in independent laboratories to confirm the C_{org} and LoI values and, in both cases, showed considerable differences to the original analyses (Appendix B). Consequently, there is a low level of confidence in the data. Stankovic et al (2023) recently published relationships between OC and OM for Thailand seagrass meadows, and reported similarly weak relationship, though stronger than those reported here. Given that the globally accepted relationship between LoI and C_{org} for seagrass soils (Fourqurean et al. 2014) is so much stronger than any of the Thailand relationships, this was applied to the Trang LoI data to estimate soil C_{org} stocks. This finding has two important implications for blue carbon studies in the Trang region and possible beyond. First, while there are significant practical advantages in using LoI to estimate soil carbon (financial and in terms of availability of equipment), the development of a relationship between the two variables is not straightforward and cannot be assumed to be strong. Further studies should be undertaken, ideally by expert laboratories, to build on the work here and by Stankovic et al. (2023), to establish a stronger relationship. Second, the outcome highlights that even relatively straightforward analyses such as LoI require expertise that may not be present in many NGO or community organisation. In this case, the analyses were performed in a university laboratory, increasing the level of confidence that they could be undertaken by the national partner. However, the uncertainty in the outcomes indicates the need for more extensive training in the methods than was able to be provided in the timeframe of the SES project. Finally, it requires strong qualification of the findings of the Trang assessment presented in the following section, since the stock values are based on the global relationship between C_{org} and LoI, and there is a relatively low level of confidence in the LoI data.

5.2 Soil C_{org} stocks and accumulation rates in Trang seagrass ecosystems

Soil C_{org} Stocks

The mean soil C_{org} stocks showed significant differences among sites, with the reference site (Mook) and the restored site (Boon Kong) higher than at both disturbed sites, Libong and Sukhon (Figure 10, Table 3). In the top 100 cm, the Reference meadow had a mean soil C_{org} stock of 84 ± 6 Mg C_{org} ha^{-1}, not statistically significantly different to that in the revegetated Boon Kong site (102 ± 55 Mg C_{org} ha^{-1}) and higher than at Libong and Sukhon, which had 24 ± 8 and 53 ± 22 Mg C_{org} ha^{-1}, respectively. The trends were similar in the top 30 cm of soil (Figure 10).

Assuming the Mook reference site and the Boon Kong restoration site are representative, healthy *Enhalus acaroides* meadows in the region can be assumed to have stocks in the order of 80-100 Mg C_{org} ha^{-1}, similar to those reported for elsewhere on the Andaman coast (see Table 1), though at the lower end. A wide range of factors affect the stocks of soil carbon in seagrass meadows (Mazarassa et al 2018) including hydrodynamic exposure and so it is unsurprising that Koh Mook has slightly lower stocks than other sites on the Andaman coast; the site is relatively exposed on the eastern side of the island and so may be less depositional than at many other embayment sites.

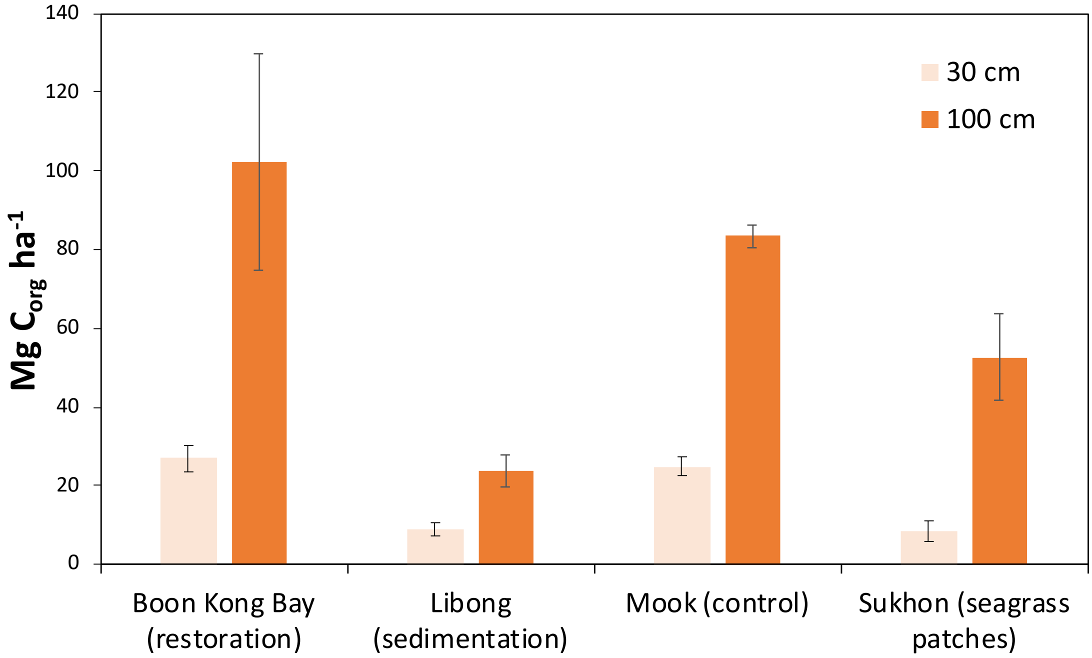


Figure 10. Mean (± SE) organic carbon (C_{org}) stocks in 30 cm and 100 cm-thick soil seagrass deposits collected in Thailand. The organic carbon values were estimated from the Loss on Ignition data by applying the regression in Fourqurean et al. (2014)

Table 3. Soil C_{org} stocks in Trang seagrass ecosystems.

Ecosystem	Location	Species	Soil C_{org} stock. (Mg C_{org} ha^{-1}) 30 cm Mean	30 cm s.d.	100 cm Mean	100 cm s.d.
Reference	Koh Mook	*Enhalus acoroides*	24.8	4.7	78.5	11.0
Disturbed (Sediment)	Libong	*Enhalus acoroides*	8.9	3.2	28.9	12.2
Disturbed (Trawling)	Sukhon	*Enhalus acoroides*	8.4	5.1	52.6	21.7
Transplant	Boon Kong	*Enhalus acoroides*	26.9	6.8	102.2	54.7

C_{org} accumulation rates

For the four seagrass cores analysed, one from each of the four study sites, short-term soil accumulation rates (based on ^{210}Pb) could not be determined. For all cores, there was an absence of excess ^{210}Pb, suggesting a lack of soil accumulation at the sites or the sediment which is accumulating is remobilised, older sediments. Detailed results of the ^{210}Pb analyses are presented in Appendix C.

Long-term sediment and carbon accumulation rates were estimated from the radiocarbon concentrations for each of the four cores (see Appendix D for the age-depth models). Because the surface layers of the soils could not be dated using ^{210}Pb, it was assumed that the surface soil (0 cm) had an age of 0 years, and the long-term accumulation rates were determined from age-depth models based on the most recent ^{14}C age and the surface age of 0 years. Using this approximation, the carbon accumulation rate was similar at all four sites studies with a mean of 0.08 ± 0.02 Mg ha^{-1} y^{-1} (Table 4). These rates of carbon accumulation are low in comparison to most reported rates for seagrasses; for example, the mean across all seagrass sites studies in Australia was 0.36 ± 0.3 Mg ha^{-1} y^{-1} (Serrano et al 2019), about five-times that observed in the Trang meadows. The relatively low rate in comparison to other studies reflects both the relatively low carbon stocks in the soils but could also be due to the use of long-term soil accumulation rates (i.e. thousands of years) which are typically lower than short-term (i.e. last 100 years) accumulation rates. Short-term accumulation rates, reflect the contemporary conditions at a site and, therefore, are more appropriate when estimating current carbon accumulation rates at a site. However, the extremely low concentrations of ^{210}Pb at the sites prevented estimation of short-term accumulation rates, possibly due the absence of soil accumulation or due to accumulation of re-worked material that was depleted of ^{210}Pb. The only other reported carbon accumulation rates for seagrasses in Thailand were also estimated using ^{14}C-dated sediments and, therefore, represent long-term accumulation rates; they are comparable to those reported here, about 0.03 Mg ha^{-1} y^{-1} (Miyajima et al 2021). This provides some confidence in the rates reported here for Trang but, nonetheless, they should be viewed as conservative estimates (i.e. likely under-estimates) given that they were, by necessity, based on ^{14}C, long-term accumulation rates.

Table 4. Estimated mean ± SD long-term C_{org} accumulation rates at the four seagrass sites in Trang. The std errors refer to the uncertainties in the age-depth model, with a single core analysed at each of the four sites.

Ecosystem	Sediment Accumulation Rate ($cm\ y^{-1}$)		C_{org} Accumulation Rate ($g\ C_{org}\ m^{-2}\ y^{-1}$)	
	Mean	s.d.	Mean	s.d.
Koh Mook	0.063	0.001	9.8	2.6
Libong	0.119	0.003	8.9	0.4
Sukhon	0.128	0.001	5.8	0.1
Boon Kong	0.136	0.002	8.2	0.7

The difficulty in obtaining reliable age-depth models from seagrass soils using radionuclide methods is not uncommon (Lafratta et al., 2020), though under appropriate conditions can be successfully applied with the significant benefit of providing immediate rates of soil accumulation that integrate over decades or centuries periods (Arias-Ortiz, 2018). Where the method cannot be applied, an alternative approach is to directly measure soil accumulation using surface elevation tables or, as in this case, elevation rods. While elevation rods have the advantage of providing a direct measure of soil accumulation rates, they have some disadvantages: it may take several years to obtain a reliable estimate of soil accumulation; they are prone to being disturbed; and they can be difficult to establish and to re-sample in sub-tidal seagrass meadows. For these reasons, elevation rods are not commonly applied in seagrass blue carbon studies. Nonetheless, the outcomes of the Trang case study suggests that this approach should be pursued for future blue carbon assessments in the region, with pilot studies to address some of the concerns with the method.

The surface elevation rods were established at all four of the Trang study sites and were measured on the day of installation. At the time of preparing this report there had not been an opportunity to re-measure the rods, and therefore no accumulation rate can be calculated. Re-measuring the rods should be a priority for future activities at the sites, on a 6-monthly to one-year cycle.

5.3 Total soil C_{org} stocks and accumulation rates in Trang seagrass ecosystems

The total soil C_{org} stocks and accumulation rates for seagrass at the Trang sites has been estimated by scaling up the mean C_{org} stock in the top meter of soil to the total area occupied by each ecosystem in the region. This was performed separately for each ecosystem types (i.e. undisturbed, disturbed – Libong and Sukhon, and restored). The estimated total BC stock ranges from 0.32 Mt $C0_{2\text{-eq}}$ in Mook to 0.003 Mt in Sukhon (Table 5). The large differences in stocks at the four sites is due primarily to the differences in total area of seagrass, with less than 0.1 km^2 at Sukhon and Boon Kong compared with about 11 and 23 km^2 at Koh Mook and Libong, respectively.

The total soil accumulation rates were also highest for Koh Mook and Libong, which are accumulating about 400 and 750 t of $CO_{2\text{-eq}}$ per year. The other sites are accumulating only 2-3 $CO_{2\text{-eq}}$ per year, primarily due to the small extent of seagrass at these sites.

Table 5. Total area of blue carbon ecosystems (undisturbed, disturbed and restored) in Trang and their estimated total soil C_{org} stock and short-term accumulation rates. CAR based on long-term accumulation rates calculated from a single point dating of sediment cores with ^{14}C and assuming the core surface was present day sediment.

Ecosystem	Area (km^2)	C_{org} STOCKS: Mean Soil C_{org} stock (kg C_{org} m^{-2})	Total soil C_{org} stock (t C_{org})	Total Soil stock (t $CO_{2\text{-eq}}$)	C_{org} ACCUMULATION RATES*: Soil CAR (long-term) (g C_{org} m^{-2} yr^{-1})	Total soil CAR (t yr^{-1})	Total CAR (t $CO_{2\text{-eq}}$ yr^{-1})
Koh Mook	11.1	7.85	87,135	319,785	9.8	108.8	399
Libong	22.9	2.89	66,181	242,884	8.9	203.8	748
Sukhon	0.1	5.26	526	1,930	5.8	0.6	2
Boon Kong	0.1	10.22	1,022	3,751	8.2	0.8	3

5.4 Potential for carbon abatement

The organic carbon stocks for the Trang seagrass sites have been reported for both the top 1 m and the top 30 cm of soil. Here we use the top 1 m stocks to assess the potential for abatement of CO_2 emissions through management of seagrass habitat. The top 1 m has been used globally as a reference depth to report blue carbon stocks and assess abatement potential on the basis that this captures the depth of soil likely to be disturbed following seagrass canopy loss.

The differences in soil C_{org} stocks between the sites indicates a potential for both avoided greenhouse gas (GHG) emissions and enhanced CO_2 sequestration activities in the seagrass ecosystems. Both impacted seagrass sites, Libong and Sukhon, had lower C_{org} stock than at the undisturbed and revegetated site (Figure 10). The difference in C_{org} stocks between these disturbed sites and the undisturbed Koh Mook site represents the potential emissions which could be avoided by conserving seagrass meadows, while the difference between the disturbed sites and the revegetated site can be used to infer the potential additional carbon which would be sequestered following restoration activities (i.e. enhanced sequestration). Assuming that the difference in stocks between healthy and disturbed meadows represents the losses that would occur on disturbance of a healthy meadow, and assuming that 50% of this loss is ultimately remineralised to CO_2, then the potential avoided emissions associated with management of healthy meadows to prevent their disturbance is estimated to be 48 – 134 t $CO_{2\text{-}eq}$ per hectare of meadow (Table 6).

Estimating the potential for enhanced sequestration through seagrass meadow restoration is more difficult given that the CAR estimated for the sites are long-term rates, covering the past 206-612 years. These rates are unlikely to be representative of contemporary rates in the disturbed meadows. Instead, we assumed that disturbed meadows are likely to have CARs between 0 g C_{org} m^{-2} y^{-1} and those of the undisturbed/restored meadows (Koh Mook & Boon Kong), which averaged 9 g C_{org} m^{-2} y^{-1}, equating to 0 – 9 kg C_{org} ha^{-1} y^{-1} or 0 - 33 kg $CO_{2\text{-}eq}$ ha^{-1} y^{-1}.

Table 6. Estimated potential abatement (Avoided Emissions) for Trang seagrass (*Enhalus acoroides*) meadows. Estimates are based on the difference between healthy and disturbed meadows and assume 50% remineralisation of difference in stock following disturbance.

STOCK ($kg\ C_{org}\ m^{-2}$)				Avoided Emission ($t\ C_{org}\ ha^{-1}$)		Avoided Emission ($t\ CO_{2\text{-}eq}\ ha^{-1}$)	
Healthy		Disturbed					
Koh Mook	Boon Kong	Libong	Sukhon	Min	Max	Min	Max
7.85	10.22	2.89	5.26	13	37	48	134

The data generated through this study, together with previously published estimates of carbon stocks in Thailand seagrass meadows, can be applied to understand the potential carbon stocks and abatement opportunities at a national scale. For illustrative purposes, we have provided a first-order estimate of the potential stocks in Thailand's seagrass meadows and, for the period 2014-2017, the potential annual emissions associated with seagrass loss. For 2017, the Thai government reported a total extent of seagrass in Thailand of 256 km^2, of which 64 km^2 was in good condition, 159 km^2 was in poor condition and 33 km2 had been lost through degradation since the previous survey in 2013 (DMCR, 2019). Assuming (rather boldly) that the stocks for undisturbed meadows reported in this assessment of Trang, and those summarised in Table 1, are representative of good condition meadow, and that the stocks reported for Libong and Sukhon are representative of poor condition meadow, then the seagrass meadows of Thailand are estimated to contain between 0.96 and 1.88 Mt of organic carbon in the top 1 m of their soils, equivalent to 3.5 to 6.9 Mt of $CO_{2\text{-}eq}$ (Table 7). Conservation of these meadows will ensure this carbon is not emitted to the atmosphere and will continue to assimilate an additional 0.02 – 0.06 Mt of $CO_{2\text{-}eq}$ each year. In contrast, the losses of seagrass meadow between 2014 and 2017, estimated at 33 km^2, or 8.25 km^2 per year, could potentially have resulted in an emission of 0.95 to 1.97 Mt per year of CO_2, assuming all the carbon in those meadows were remineralised (Table 8). These estimates clearly indicate the significantly higher abatement gains to be made by avoiding losses of seagrasses meadows through effective management, including conservation, rather than attempting to restore them.

Table 7 Illustrative estimates of potential soil organic carbon stocks and annual sequestration for Thailand's seagrass meadows. Estimates are based on reported extent and condition of Thailand's seagrass meadows and the carbon stocks and CARs reported here. * from DMCR (2019); # from data in Tables 1 and 5.

Status* (2014-17)	Area* (km^2)	Stock# (kg C_{org} m^{-2})	Total Stock ($Mt\ C_{org}$)		Total Stock ($Mt\ CO_2$)		Annual sequestration# ($Mt\ CO_2$-eq y^{-1})	
			Min	Max	Min	Max		
Healthy	64	7.85-16.3	0.50	1.04	1.84	3.83	0.001	0.002
Poor	159	2.89 – 5.26	0.46	0.84	1.68	3.07	0.002	0.003
Total	**223**		**0.96**	**1.88**	**3.52**	**6.90**	**0.002**	**0.006**

Table 8 Potential annual emissions (top) and lost sequestration (bottom) from Thailand's seagrass meadows based on reported losses for 2014-2017. * From DMCR (2019); #from **Table 1** and **Table 5.**

Habitat loss* (km^2 y^{-1})	Stock# (kg C_{org} m^{-2})	C at risk of remineralisation (t C_{org} m^{-2})		Potential CO_2 emissions (t CO_2 m^{-2})			
				50% remineralisation		100% remineralisation	
		Min	Max	Min	Max	Min	Max
8.25	7.85-16.3	260,000	538,000	475,000	987,000	951,000	1,974,000
	Sequestration rates# (g C_{org} m^{-2} yr^{-1})	Lack of sequestration (t C_{org} y^{-1})		Potential lack of CO_2 sequestration (t CO_2 y^{-1})			
		Min	Max	Min	Max		
8.25	5.8 – 9.8	48	81	175	297		

The national-scale estimate presented above necessarily uses values for C_{org} stocks, CAR and seagrass extent which will have significant errors associated with them, given the limited knowledge on all these variables. Furthermore, the above estimates are based on the C_{org} stocks measured at a limited number of locations in Trang, all of which were *E. acoroides* meadows in various states of disturbance. While the values measured in this assessment are comparable to those reported in previous studies (Table 1), it is unclear how representative these are of other seagrass meadows in the region or Thailand as a whole. Therefore, the estimated potential abatement should be taken as first-order estimates provided here for illustrative purposes. As more data are collected for Thailand's seagrasses, these estimates can be improved.

5.5 Methodological issues for BC assessments and methods (Lessons learnt)

The four SES case studies, including that undertaken at Trang, have provided insights into methodological issues associated with determining C_{org} stocks and accumulation rates (CAR), which could affect the capacity to implement future blue carbon projects by NGOs working in the region. These relate to the determination of carbon accumulation rates using either radioisotope methods or SETs, and also to the use of organic matter as a proxy for determining the organic carbon content of soils. Below we outline the findings and consider their implications for future BC assessments and method development.

Determining Carbon Accumulation Rates

Most carbon crediting schemes and inventories require a measure of the change in C_{org} content of a soil (and/or biomass) over time. This typically involves either dating the soil using radioisotope techniques (Arias-Ortiz et al. 2018) or directly measuring accumulation using surface elevation tables (SET) or a similar method (Cahoon & Turner 1989, Webb et al. 2013). Radioisotope dating methods (e.g. ^{210}Pb and ^{14}C) allow relatively rapid assessment of the carbon accumulation rate with a one-off sampling. However, the successful application of these methods depends on the accumulation of radioisotopes within the soil and lack of subsequent mixing of the soil, which does not always occur in dynamic coastal environment. SETs or horizon marker rods are used to directly measure the change in soil height relative to a fixed depth marker. These have the advantage on no dependence of radioisotope accumulation or lack of mixing. On the other hand, it may require years or decades to gain a reliable estimate of the soil accumulation rates using SETs. Furthermore, they are rarely applied in seagrass habitats where it is difficult for divers to take measurements without themselves disturbing the surface.

Here we attempted to apply radio-isotope (^{210}Pb or ^{14}C) methods to determine soil accumulation rates. We had no success in applying the ^{210}Pb method to determine accumulation rates over the past 100 or so years. This poor return on an expensive and time-consuming investment is not uncommon in seagrass ecosystems (Lafratta et al., 2020) and argues for the wider use of direct measurement of sediment elevation. Due to the limited duration of the SES project, it was not possible to determine accumulation rates from the elevation rods which were deployed, but this is something that can be evaluated by the National Partners in the future, following a period of 6-monthly rod measurements. An important finding of the assessment was that, in many sites, the surface elevation rods were removed by locals who saw value in the metal rods (stainless steel or brass). Finding ways to work with the communities to protect the rods will be critical if this approach is to be used in the future.

Our findings lead to three important conclusions:

1. not all sites are suited to the use of radioisotope techniques for estimating carbon sequestration rates; and
2. further trails are required to assess the reliability of using elevation rods to make direct measurements of net sediment accumulation; and
3. current carbon accounting and crediting methods (VERRA, Hiraishi et al. 2013) require demonstration that the GHG emission reductions are real, measurable and permanent, and the inability to calculate rates of carbon accumulation or to date soils can make it difficult to show this. Consequently, careful assessment of potential sites should include an assessment

of the soil accumulation dynamics to determine whether the site is suitable for the intended project method and thereby, management actions can result in carbon abatement.

Methodological issues with determining %C_{org} using %LOI

Loss on Ignition (LOI) is commonly used to estimate the organic content of a soil. It is not uncommon in BC studies to use the relationship between LOI and C_{org} (Fourqurean et al. 2012 and Howard et al. 2014) to estimate the C_{org} content of a soil when only LOI data are available, commonly the situation when financial constraints limit the number of C_{org} analyses that can be performed or when there is no access to an elemental analyser. To estimate soil C_{org} content in the cores based on LOI, we attempted to generate site-specific relationships between LOI and C_{org} (see methods in the appendices). As reported for several of the SES project case study sites, the relationship was weak and there were significant uncertainties for the C_{org} data, forcing the project to rely on the relationship in Fourqurean et al. 2014) in several instances.

The poor relationships could be due to errors in the sample analysis or unusual soil characteristics which introduce artefacts into the analyses of LoI, C_{org}, or both, for example: 1) incomplete removal of carbonates from the sample prior to analysis; 2) the loss of acid-soluble organic matter and the heat generated during carbonate reaction with acid, i.e. hydrolysing organic matter, during acidification can lead to an underestimation of C_{org} content (Roberts et al. 1973, Heath et al. 1977, Froelich 1980); and 3) the loss of inorganic compounds (e.g. carbonates) during the LOI combustion can lead to an overestimation of organic matter, hence C_{org} content (Wang & Li 2011), and could be significant if the soils have high carbonate content.

Our findings indicate that:

- the inclusion of LOI–C_{org} correlations in a BC methodology should be done with caution. The appropriateness of using such relationships should be determined on a site-by-site basis;
- Despite the relatively simple techniques involved in estimating LoI, some National partners had difficulty performing these, either through difficulty in accessing appropriate facilities, or in misunderstanding of the protocol (not helped by the inability to provide face-to-face training due to COVID travel restrictions).
- Some of the laboratories used to conduct elemental analysis of C_{org} returned quite variable results, suggesting some quality assurance issues.

This emphasises the need to use appropriate laboratory facilities to support NGOs for undertaking soil carbon analyses, rather than relying on the NGOs to undertake these analyses themselves. Despite the laudable goal of building capacity within the NGOs, it was clear that none of the partners had the expertise or facilities necessary to undertake the full range of analyses and, in some instances, those facilities were not available within their country to outsource the analyses.

The generation of reliable soil carbon data is central to the blue carbon assessment and the uncertainties regarding the data from some of the sites reduces confidence on the assessments. In future, a more efficient approach will be for NGOs to collect and process the samples but use appropriate laboratories to undertake the chemical analyses and provide the results to the NGO for interpretation.

Permits

Several of the SES Project case study sites experienced significant difficulty in implementing the assessments because of permitting issues. These related either to:

- Permits to undertake field work to collect soil samples; or
- Permits to export soil samples for chemical analysis.

The first issue was typically resolvable but in once instance required several months to gain the permits despite vigorous efforts on the part of the NGO partner. By the time the permit was issued, the field sampling season had been missed, causing about a one-year delay in the assessment.

The second issue is more problematic, in that some governments (e.g. Indonesia) require permits to export either samples or data for analysis. If those countries have analytical facilities that NGOs can use on a collaboration or fee-for-service basis, then this is not a significant issue; the samples can simply be analysed in-country. However, in the case of Indonesia, there were no facilities within the country to conducted either the elemental carbon analyses or the ^{210}Pb analyses. While the samples could easily have been analysed by the Technical Partners, it took almost 3 years to work through the permitting process and, ultimately, this was not resolved by the end of the project. Consequently, there was a much-reduced data set for Indonesia, despite the significant efforts of the NGO partner.

The lesson here is that it is critical to understand the permitting requirements in countries before commencing a blue carbon assessment and that sufficient time needs to be allowed for obtaining those permits. In some countries this is not an issue. In others it can be an almost insurmountable obstacle and, in those cases, establishing relationships with agencies or other NGO's which have the necessary permits may be an effective strategy.

Training delivery

The SES Project was initially structured around in-country, face-to-face training, to build capacity among the NGO partners. COVID-19 travel restrictions prevented several technical partners travelling in 2020-2022, requiring a shift in approach. The Blue Carbon training was provided through a combination of training videos produced specifically for the project, and now available on the CMS's project webpage (https://www.dugongseagrass.org/projects/seagrass-ecosystem-services-project/), and on-line instruction during sampling and laboratory activities.

The on-line training resources proved useful in allowing the NGO partners to collect samples and to undertake initial processing in the laboratory. However, the impact of no face-to-face training became apparent as the project developed: many issues that arose in the field or laboratory were difficult to predict in advance and so were not covered in the instructional videos; other problems were not recognised by the NGOs and so errors were introduced into the various protocols. An illustration of this was the LoI protocol, which relies on accurate measurement of weight loss in sugar standards; several laboratories did not take this measurement, instead making a visual assessment, which unfortunately is often misleading. It also became apparent that interpreting the findings, and considering how the data can be applied in policy or business contexts was a significant hurdle for some NGO. What could effectively be explained face-to-face in two or three hours proved almost impossible to convey using other approaches.

In short, the experience of the blue carbon technical partners and all the NGO national partners was that the lack of opportunity to hold the planned in-person workshops had a detrimental effect on both the efficiency and the quality of the outcomes of the blue carbon assessments. While the outcomes are still valuable, there is no doubt that any future capacity building should prioritise in-person training.

6 Conclusions and Recommendations

- Healthy and restored seagrass meadows in the Trang region were found to have soil C_{org} stocks of 84-102 Mg C_{org} ha^{-1}, comparable to stocks measured in other areas of Thailand and previously in Trang.
- Disturbance appears to reduce the soil C_{org} stocks. The meadows disturbed by sedimentation and fishing activity had stocks of 24 ± 8 and 53 ± 22 Mg C_{org} ha^{-1}, respectively.
- Based on current estimates of the area of seagrass meadows at the four Trang sites, the total stocks ranged from 0.002 to 0.319 Mt of $CO_{2\text{-}eq}$.
- Based on carbon-14 dating, the Trang seagrass meadows have long-term carbon accumulation rates of about 5.8 – 9.8 (mean: 0.08±0.02) Mg C_{org} ha^{-1} y^{-1}. This is larger than, but of similar order of magnitude to, the only other published accumulation rate for seagrasses in the region of 0.03 Mg C_{org} ha^{-1} y^{-1}.
- Based on current estimates of the area of seagrass meadows at the four Trang sites, the total annual organic carbon accumulations ranged from 2 to 748 t of $CO_{2\text{-}eq}$.
- The potential abatement associated with conservation of seagrass meadows in the region was estimated to be 48 – 134 t $CO_{2\text{-}eq}$ per hectare, while restoration of seagrass habitat was estimated to have potential enhanced sequestration of up to 33 kg $CO_{2\text{-}eq}$ ha^{-1} y^{-1}.
- Reported losses of 8.5 km^2 of seagrass meadows per year in Thailand were estimated to represent a potential emission of about 175 – 300 t $CO_{2\text{-}eq}$ y^{-1}.
- The values generated in this assessment for seagrass carbon stocks, carbon accumulation rates and potential carbon abatement through management, can be used to inform decision makers and the broader community about the value of seagrasses, and can be used to make first order estimates of the potential abatement opportunity for seagrass blue carbon project, including those seeking carbon credits.
- The SES Project has successfully achieved the key objectives of:
  - Building capacity in the NGO National Partners to undertake blue carbon assessments,
  - Generating local data for application in local policy contexts and to strengthen any future carbon crediting verification projects, including development of Tier 2 and Tier 3 carbon abatement projects, and
  - Identification of local partner organisations to assist the NGO partners in future projects.
- The blue carbon assessment saw the following activities completed as parts of Work Packages I, II, III and IV of the SES Project:
  - **Activity I.1:** Modify or develop new methodological tools for monitoring seagrass ecosystem services (carbon sequestration);
  - **Activity I.2:** Five trainings (one per site) provided to local stakeholders on assessment of seagrass status (blue carbon status) – the trainings were provided through on-line instructional videos and a face-to-face workshop which all five National partners participated in;

- **Activity I.4**: Data collection (blue carbon) at all five sites, with community participation, to build on and integrate with any existing data concerning the location, extent, conservation, and SES of seagrass meadows and megafauna;
- **Activity II.1**: SES (blue carbon) data collection, analysis, and assessment at four sites to determine the different ways in which seagrass is providing value and what the loss of these services would cost;
- **Activity II.2**: Five workshops (one per site) provided to local stakeholders on understanding assessment and valuation of key SES. Total of ≥50 community members. Due to COVID travel restrictions, the five workshops (one per site) were replaced with a single workshop to which all six of the project's NGOs participated;
- **Activity IV.1**: Training to build capacity of stakeholders (decision-makers, Protected Area managers and NGOs) to utilise SES assessment and valuation. Training for the blue carbon component was provided through a face-to-face workshop (Bogor, 2023) for all six project National Partners.

Recommendations

- **It is recommended that** the findings of this assessment be used to inform policy and seagrass restoration efforts in Thailand.
    - **The** values generated in this assessment for seagrass carbon stocks, carbon accumulation rates and potential carbon abatement through management, can be used to inform decision makers and the broader community about the value of seagrasses, in particular their role in carbon abatement. This can be used to argue for the inclusion of seagrass ecosystems in the NDC, specifically the LULUCF sector. It can also be used to argue for the inclusion of seagrass projects in a range of government strategies that involve the conservation or restoration of marine and other vegetated habitats for climate change mitigation. The data generated in this assessment can also provide an initial indication of the carbon credit potential of seagrass blue carbon projects in the voluntary carbon trading market operating in Thailand.
    - Achieving the above will be made far more possible if the NGO partners in the SES Project are provided ongoing support to consider the outcomes of the blue carbon assessment in the policy context of their countries.

- **It is recommended that future efforts to undertake seagrass blue carbon assessment use the approaches, based on the experience gained during the SES Project:**
    - Further effort be applied to generate more robust Organic Carbon: Organic Matter relationships which can be applied to estimate carbon stocks from Loss on Ignition data;
    - NPs work collaboratively with local university/research partners to implement assessments, in particular the LoI and organic carbon analyses; and

- Direct measurement of soil accumulation rates be made using surface elevation rods, horizon markers or rSETs, rather than relying on radio-isotopic approaches. This will require pilot studies to overcome some of the difficulties associated with the use of rods such as removal by local communities;
- Future efforts to build capacity in seagrass ecosystem service (blue carbon) assessment prioritise the inclusion of face-to-face field and laboratory techniques training.

- **It is recommended that future policies related to Blue Carbon, particularly for seagrass, should consider on the following insights gained from the SES project:**
    - The Blue Carbon assessment has specifically defined characteristics for seagrass ecosystems, not other blue carbon ecosystems, which are known to be different. The development of policies, regulations, and frameworks should be clear to distinguish between different classes of blue carbon resources;
    - The potential implementation of seagrass Blue Carbon projects demands a comprehensive understanding of the inherent nature of seagrass by policy makers and project proponents. This understanding should precede the development of any project framework, enabling the project developers to appropriately inform other stakeholders involved in the Blue Carbon Project;
    - The Blue Carbon Assessment elucidates the steps required to quantify carbon stocks and sequestration and prevent over-claiming of potential carbon abatement. Policymakers and project developers should apply rigorous standards, procedures, and scientifically-grounded monitoring protocols to provide confidence in potential voluntary carbon credits stemming from seagrass projects in the future scenarios; and
    - Most seagrass habitat in Thailand is intricately linked to coastal communities, fostering a symbiotic relationship, where seagrass provides ecosystem services in return for conservation efforts. Consequently, community-driven conservation and active participation in future blue carbon initiatives are pivotal elements for sustainability. While governmental or private sector interventions may yield short-term success, sustained benefits lie in involving the communities which are intimately associated with specific seagrass habitats. Any relevant policies, blue carbon frameworks, or projects should involve communities as key stakeholders, empowering them not only in participation but also in decision-making capacities, to ensures enduring benefits of any blue carbon project.

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Appendix A Methods - core collection, processing, and numerical procedure

Core collection and processing

At each site, four cores were collected using PVC pipes (6.3 – 10.5 cm inner diameter) by manual percussion and rotation. Compression during coring was assessed by measuring the length of the core protruding from the soil surface inside and outside the core (Glew et al. 2001). All results presented in this study refer to the decompressed depths (cm), unless indicated. Following retrieval, cores were sealed at both ends, transported vertically and stored at SAN or PSU until processing.

Figure 11 SAN team members undertaking blue carbon core collection at the four study sites in Trang Province. A) Koh Mook; B) Boon Kong; C) Sukhon; D) Libong; and E) installing surface elevation rods

The cores were sliced at 1 cm-thick resolution for the top 20 cm, and at 5 cm-thick intervals for the remainder (High Resolution, HR). For each soil slice, the wet weight (WW) was recorded prior to drying at 60°C until constant dry weight (DW) to estimate dry bulk density (DBD). The dried samples were homogenized and divided into sub-samples by quartering. The sub-samples were used for C_{org}, Organic Matter (OM) analyses as well as analysis for ^{210}Pb and ^{14}C (radiocarbon) dating.

Organic Matter and Organic Carbon determination

Organic Matter (OM) was determined for every sediment slice while C_{org} was analysed in every second 1 cm-thick slice for the top 20 cm (compressed) and every 5 cm-thick slice for the remainder of the cores. These analyses were performed on one sub-sample of the soil slice which had been ground in a ball mill grinder. For C_{org} analysis, about 1 g of ground sample was acidified with 4% HCl to remove inorganic carbon, centrifuged (3,400 rpm during 5 min), and the supernatant with acid residues carefully removed by pipette, avoiding resuspension. The soil sample was then washed with Milli-Q water, centrifuged and the supernatant again removed. The residual samples were re-dried (60°C until constant weight) and encapsulated in tin capsules. The C_{org} and $\delta^{13}C$ were determined using a Costech Elemental Analyzer interfaced to a Thermo-Finnegan Delta V Isotope Ratio Mass Spectrometer at UH-Hilo Analytical Facilities. The accuracy of the analysis of the Standard reference material NIST 8704 (Buffalo River Sediment) was ≤1%. The C_{org} content (%) is reported for the bulk (pre-acidified) samples.

The OM of the ground soil samples was estimated in each slice of every core, with the intention of using the relationship between %OM and %C_{org} to interpolate the C_{org} values for slices along the core which had not been analysed for %C_{org} content, in order to calculate the accumulated C_{org} stocks (Fourqurean et al. 2012, Howard et al. 2014). OM content was estimated using the LOI method (Heiri et al. 2001, Kendrick & Lavery 2001) at Prince of Songkla University facilities by combusting 4 g of dry sample for 4 hours at 550 °C. All combustions included reference samples of pure glucose to correct for incomplete combustion of OM.

Age-depth chronology

To determine soil and C_{org} sequestration rates, one core from each site was dated by means of ^{210}Pb (short-term accumulation; last ~100 years) and radiocarbon (long-term). Concentrations of ^{210}Pb in the upper 20 cm were determined through the quantification of its granddaughter ^{210}Po activity by alpha spectrometry, assuming radioactive equilibrium between the two radionuclides (Sanchez-Cabeza et al. 1998). When sand content was high (in most seagrass scores), the soil samples were sieved (0.125 mm), and <0.125 mm fraction was analysed for ^{210}Pb. 200 mg aliquots of each sample were spiked with a known amount of ^{209}Po and microwave digested with a mixture of concentrated HNO_3 and HF. Boric acid was then added to complex fluorides. The resulting solutions were evaporated and diluted to 100 mL with 1 M HCl and polonium isotopes were auto-plated onto pure silver disks. Polonium emissions were measured by alpha spectrometry using Passivated Implanted Planar Silicon, PIPS detectors. Reagent blanks were run in parallel and found to be comparable to the detector backgrounds. Supported ^{210}Pb (^{226}Ra) was analysed by ultra-low background liquid scintillation counting (Masque et al. 2002). The concentration profile of excess ^{210}Pb was determined by subtraction of ^{226}Ra from total ^{210}Pb concentrations along the core (Appleby & Oldfield 1978, Masque et al. 2002).

For each dated core, up to 3 depth per core were radiocarbon dated at AMS Direct Laboratory after acid-base-acid treatment, following ISO 17025 and ISO 9001, using bulk soil samples. All raw radiocarbon dates were calibrated with CALIB software v.7.1 (Stuiver et al. 2018), corrected for the marine reservoir effect by subtracting 71 years (Bowman 1985), and expressed as radiocarbon dendro-calibrated years before present (BP, present being AD 2022).

Surface elevation tables (SETs)

Surface elevation rods were deployed at each seagrass sites. At each site, four stainless rods (5 mm-thick 1.8 m long) were driven into the soils to a depth of 1.5 m, leaving 30 cm above the sediment surface. The rods were located along a single line, separated by 5 m from each other. The distance between the top of the rod and the sediment surface was measured (30 cm for all rods on the first occasion). To avoid any influence of depression holes around the edge of the rod, a washer was carefully lowered down around the rod and placed on the sediment surface to provide a flat platform for the rule to sit on.

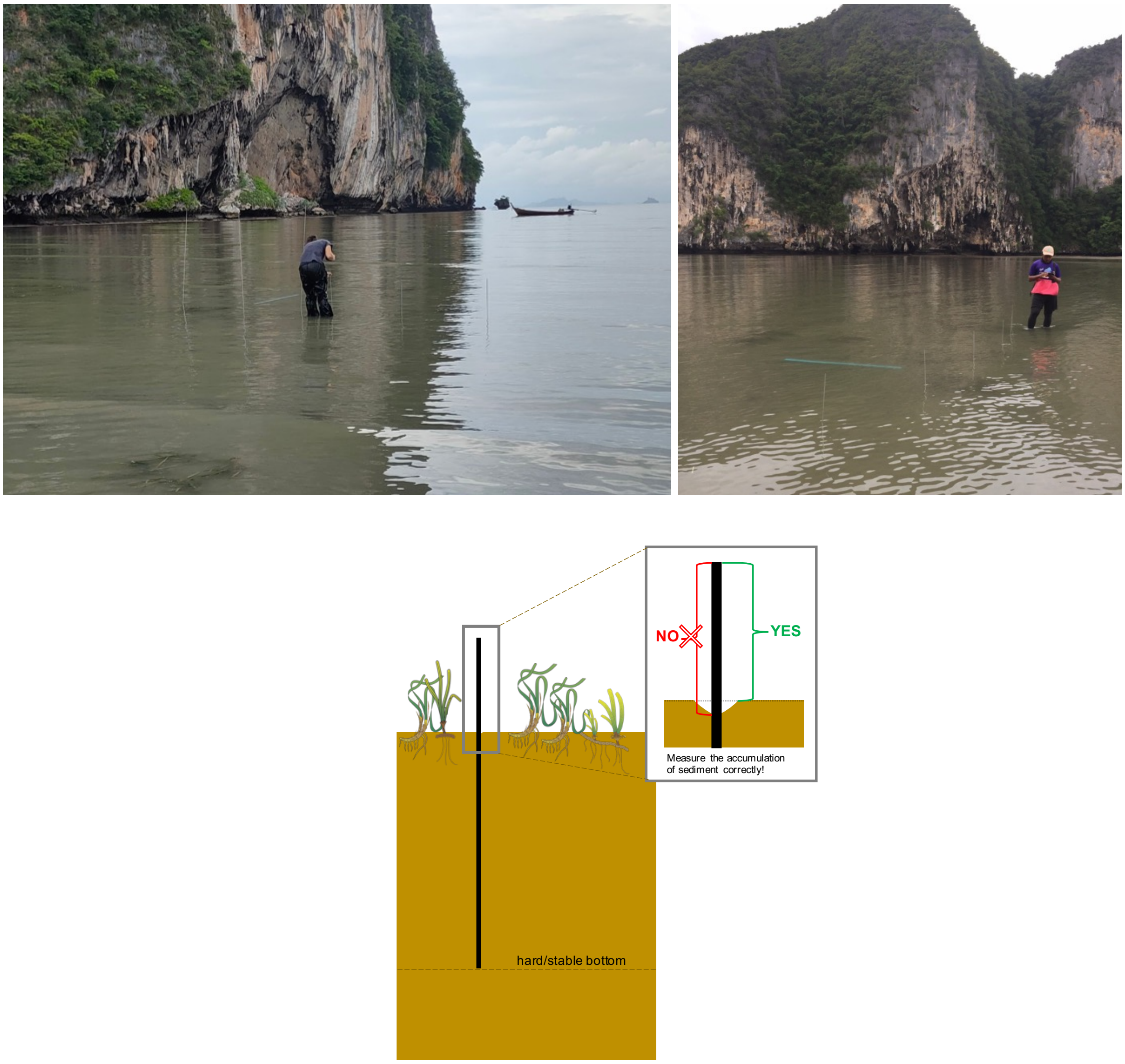

Figure 12 Surface Elevation Rods being installed in seagrass meadows. Schematic diagram at bottom shows the measurement approach.

Numerical procedures.

The CF:CS model (Krishnaswamy et al. 1971) was used to estimate the average soil accumulation rates (SAR) for the last century, where possible (Appendix D for details). When good chrono-stratigraphy of both the radiocarbon-aged section of a core and the ^{210}Pb-derived ages were available , we combined the ages using the R package Bacon, which applies Bayesian statistics as an approach to age-depth modelling to reconstruct accumulation histories (Blaauw & Christen 2011).

Long-term soil accumulation rates (g cm^{-2} yr^{-1}) were calculated averaging the accumulation rates of each depth of the core when an age-depth model was built with rBacon. For cores where only the bottom sample was analysed for ^{14}C, the long-term soil accumulation rate was calculated for that specific depth. Long-term soil accumulation rates have been standardized at >700 cal yr BP.

For cores where accumulation rates (short-term or long-term) could not be determined (i.e. the core was mixed) we applied the accumulation rate of the replicate core, if available, or an average accumulation rate (Mean ± SE) for that specific habitat. When ^{210}Pb analyses revealed no net accumulation of soil (i.e. no excess ^{210}Pb) an accumulation rate was not applied to that particular core.

Accumulated soil C_{org} stocks in each core were calculated for 30 cm and 100 cm thick soil deposits using the DBD (g cm^{-3}) and the %C_{org}. Because C_{org} was not analysed in every sample along the depth of the cores, the missing C_{org} values were interpolated using the C_{org} content of the two adjacent analysed samples in order to calculate the accumulated soil C_{org} stocks. The relationship between %OM and %C_{org} was inconsistent among cores and, in some cases, among sections of the same cores (Figure 9), therefore, we did not apply the relationship to estimate %C_{org}.

For cores shorter than 100 cm we extrapolated the soil C_{org} stock up to 100 cm-thick using a linear correlation between depth and C_{org} stock of the section of the core where the change in soil C_{org} stock with depth was constant. We validated this approach on a number of long (>1 m) cores; for these cores we used the data from the top 50 cm only and then extrapolated the carbon stocks to 1 m using the above approach. We then compared the measured (real) stocks to 1 m with those estimated by extrapolation. In all cases, the correlation between extrapolated and measured C_{org} stocks was significant ($p<0.001$; $r^2 = 0.96$)

Total soil C_{org} stocks in the study area were calculated by multiplying the average ± SD soil C_{org} stocks for each BC ecosystems (reference, Disturbed, Transplanted) by the specific ecosystem area. Area estimates for each habitat type were based on polygon allocation by the National Partner officers familiar with the area.

Sediment C_{org} accumulation rates (g C_{org} m^{-2} yr^{-1}) were calculated by multiplying the C_{org} concentration by the mass accumulation rates (g m^{-2} yr^{-1}). Where possible, short-term C_{org} accumulation rates have been calculated for the last ~100 years (since 1950s) of accumulation (based on ^{210}Pb dating) while the long-term accumulation rates have been reported for accumulation periods older than 700 cal yr BP (based on ^{14}C dating).

We tested for statistically significant differences in %C_{org}, DBD and soil C_{org} stocks (in 30- and 100 cm-thick soil deposits) among BC ecosystems. Because the data were not normally distributed, had outliers and/or the sample size was not homogeneous among groups we applied a Kruskal–Wallis test followed by Dunn's multiple post-hoc test. To test for differences in the soil C_{org} stocks among disturbed and undisturbed sites, we applied a one-way ANOVA (one test for seagrass and a separate test for mangroves), because the data were normally distributed, outliers were absent, and the variances were homogeneous.

Appendix B The Seagrass Blue Carbon toolkit.

The Seagrass Blue Carbon toolkit aims to help particularly who is approaching the blue carbon science for the first time.

The toolkit was developed by Edith Cowan University and includes a series of videos with step-by-step instructions for sampling in subtidal and intertidal environments and processing seagrass sediment cores for subsequent chemical and physical analyses. Links to available manuals are also included in this page to provide background information and context to the training material.

Field work: How to sample sediment cores in seagrass ecosystems (*please see disclaimer below*)

In this section you can find videos on how to sample seagrass sediment cores in both subtidal and intertidal environment. We are providing those videos in both high and low resolution, for easier access when high internet connection is not available.

Intertidal high-resolution: https://vimeo.com/566866993

Intertidal low-resolution: https://vimeo.com/598658572

Subtidal high-resolution: https://vimeo.com/596307784

Subtidal low-resolution: https://vimeo.com/599209697

Laboratory work: How to process a seagrass sediment core (*please read ECU disclaimer below*)

In this section you can find videos on how to open, slice and process the samples of a seagrass sediment core.

Laboratory part 1: https://vimeo.com/679010491

Laboratory part 2: https://vimeo.com/678904546

Data management: examples of datasets and calculation to obtain final data

- Main dataset with initial calculation
- Decompression spreadsheet
- %LOI spreadsheet with organic carbon calculation
- Carbon stocks and carbon accumulation rate
- Avoided CO_2 emissions and Enhanced C_{org} sequestration

Useful references: available Blue Carbon manuals

- Howard, J., Hoyt, S., Isensee, K., Telszewski, M. and Pidgeon, E., 2014. Coastal blue carbon: methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses. (https://www.thebluecarboninitiative.org/manual)

- IUCN (2021). Manual for the creation of Blue Carbon projects in Europe and the Mediterranean. Otero, M. (Ed)., 144 pages (https://www.thebluecarboninitiative.org/manual)
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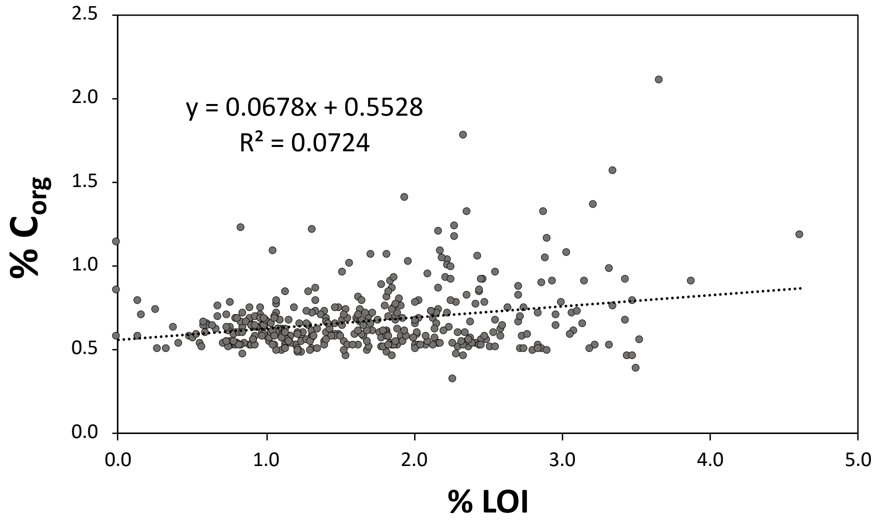
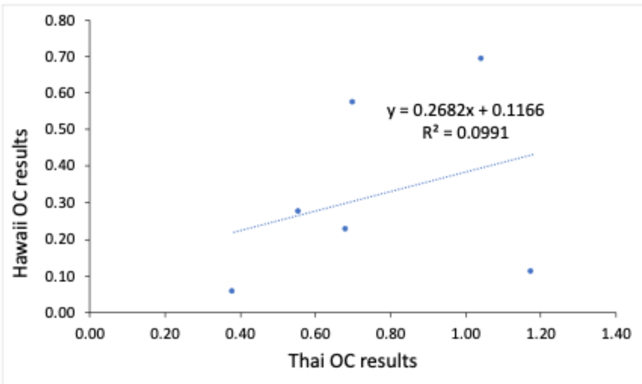
Appendix C Soil Organic Matter v Soil Organic Carbon relationships





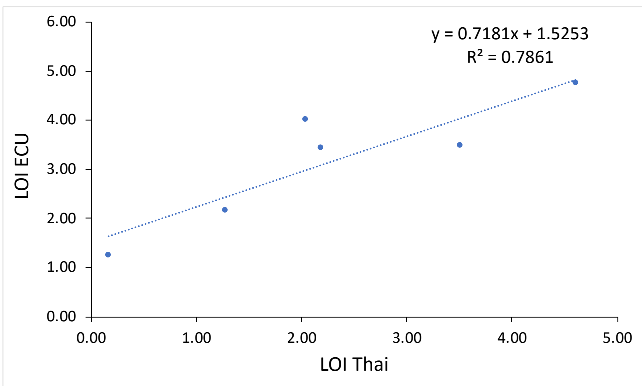


Figure 13 Relationships among soil LoI and soil C_{org} content for the Trang seagrass sites. Top: the relationship for all samples pooled across the four sampling sites; Middle: The relationship between the C_{org} (%) data produced by the PSU laboratory in Thailand and by the University of Hawaii laboratory on a sub-set of soil samples; and Bottom: The relationship between the LoI (%) data produced by the PSU laboratory in Thailand and by the Edith Cowan University laboratory on a sub-set of soil samples.

Appendix D ^{210}Pb dating of sediment cores: IKI-funded SES Project - Thailand

^{210}Pb dating of sediment cores – IKI Project - Thailand

Prof Paul Lavery and Dr Anna Lafratta (Edith Cowan University)

by

Pere Masqué

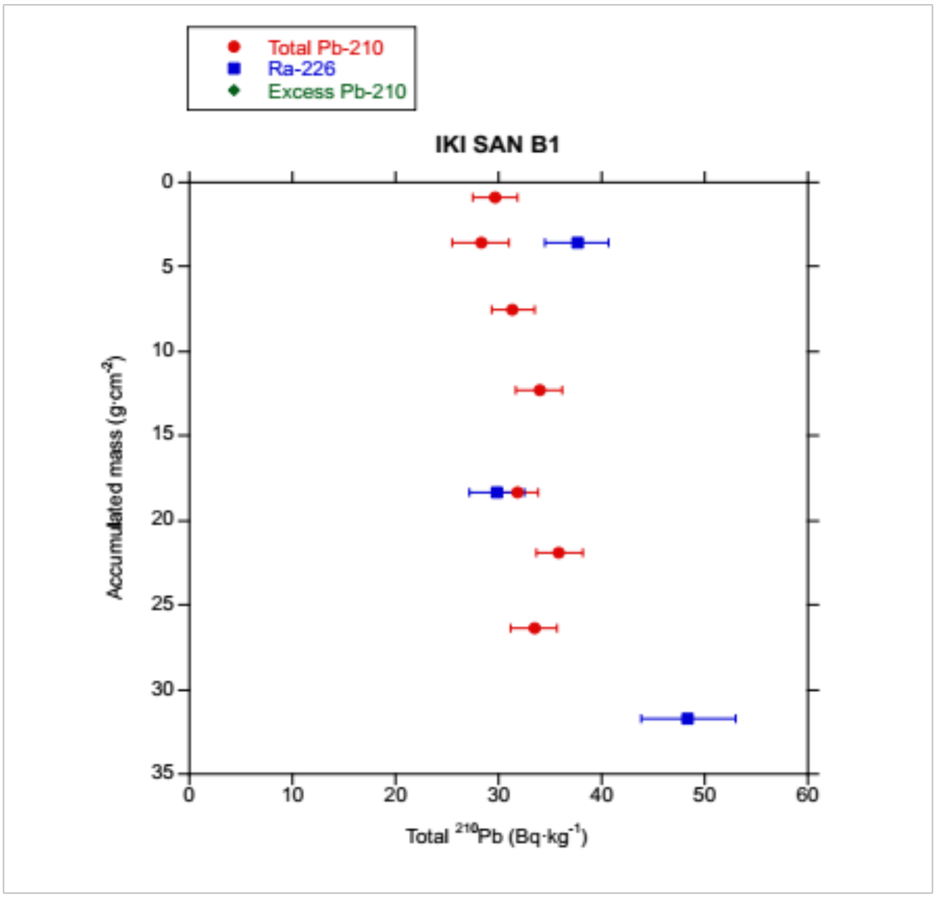
Edith Cowan University (Australia)

June 2023

- We received samples of 4 sediment cores collected in 2022 from several seagrass sites in Thailand for the analysis of Pb-210 to determine the sediment accumulation rates during the last decades/century where possible.
- The sediment cores had been sliced every 1 cm (upper 20 cm) and 5 cm (below 20 cm) and dried.
- ^{210}Pb was determined through the analysis of ^{210}Po by alpha spectrometry after addition of ^{209}Po as an internal tracer and digestion in acid media using an analytical microwave[i]. Some samples from each core were gamma spectrometry to determine the concentrations of ^{226}Ra. The concentrations of ^{137}Cs were determined where detected. The concentrations of excess ^{210}Pb used to obtain the age models were determined as the difference between total ^{210}Pb and ^{226}Ra (supported ^{210}Pb).
- No correction for compression is applied in the following.
- Main observations and estimates of sedimentation rates for each site are provided below. An accompanying file (Report Pb-210 dating IKI Thailand.xlsx) contains all relevant data.

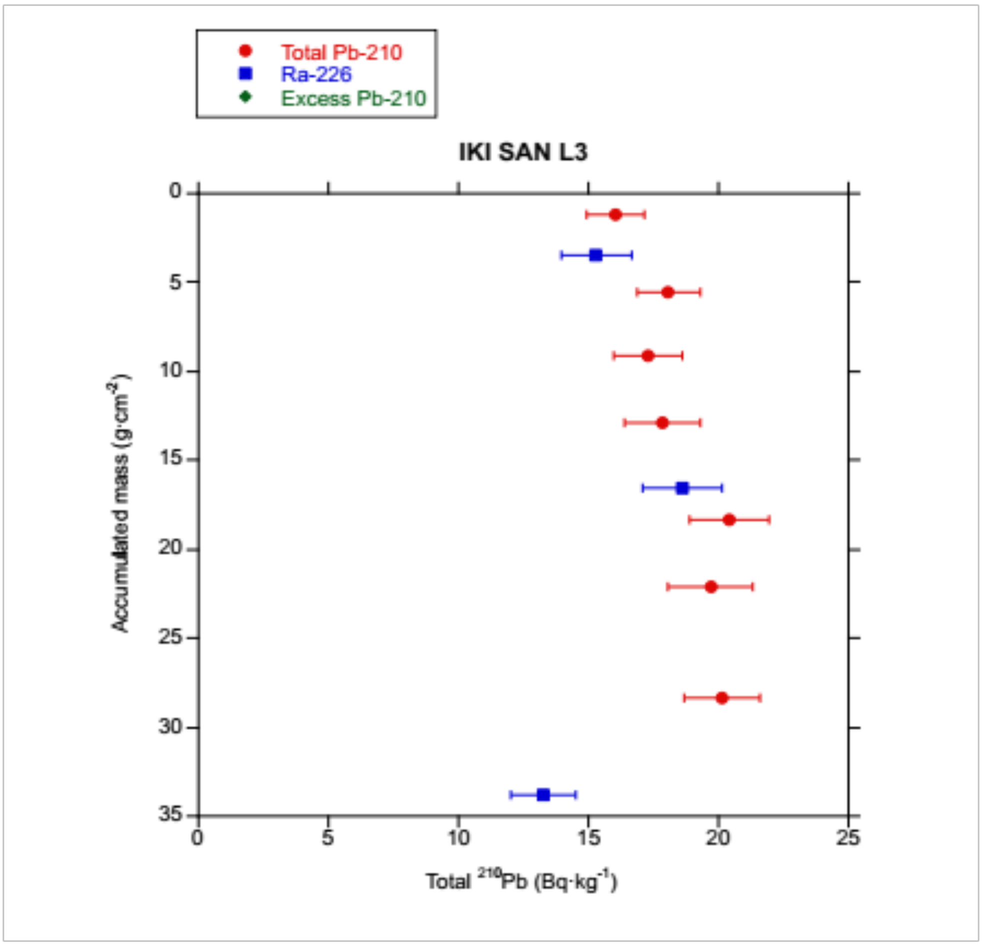
Bong Kong Bay – Core IKI SAN B1

- The core was collected from a restored meadow, described as "mud-sand with highly absorb water. The whole core has the same soil characteristic and contains small pieces of shells. However, soil at the bottom is wetter than at the top".
- Dry bulk density along the core was relatively high, between 1.5 and 2 g·cm^{-3}, with fine contents (<63 µm) of less than 10% only. The analyses were conducted on the finer fraction.
- The concentrations of total ^{210}Pb ranged from 28 to 35 Bq·kg^{-1} along the upper 15 cm, without any decreasing trend with depth. The concentrations of ^{226}Ra measured at several depths averaged 35 ± 6 Bq·kg^{-1}. Therefore, there was no excess ^{210}Pb along the core, suggesting negligible net sedimentation during the last decades at this site.



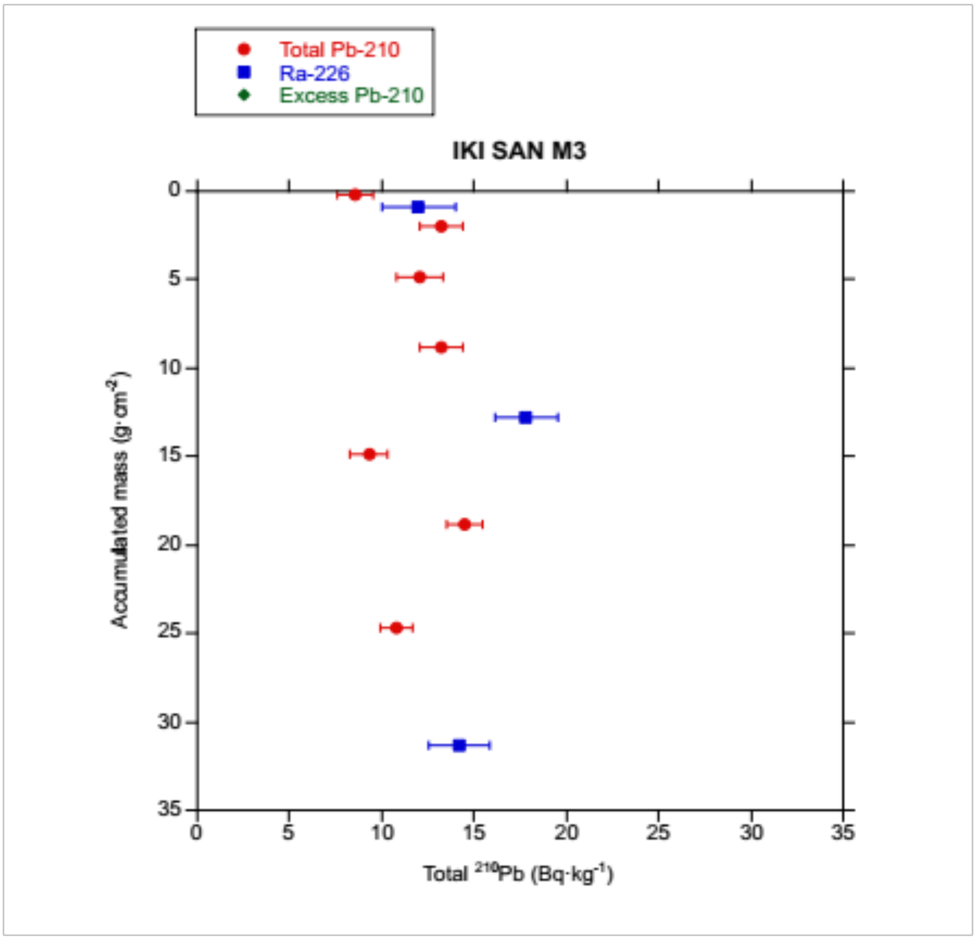
Koh Libong – Core IKI SAN L3

- The core was collected from a site impacted by sedimentation, described as "sandy mud soil and quite absorb water; there are small shells around the core, and the characteristics of the soil are the same along the core".
- Dry bulk density along the core was relatively high, around 2 g·cm^{-3}.
- The concentrations of total ^{210}Pb ranged from 16 to 20 Bq·kg^{-1} along the upper 15 cm, without any decreasing trend with depth. The concentrations of ^{226}Ra measured at several depths averaged 16 ± 3 Bq·kg^{-1}. Therefore, there was no excess ^{210}Pb along the core, suggesting negligible net sedimentation during the last decades at this site.



Koh Mook – Core IKI SAN M3

- The core was collected from a control site (healthy seagrass), described as "sandy mud soil and quite absorb water, and the characteristics of the soil are the same along the core. 17-100 cm: contain small pieces of small shells".
- Dry bulk density along the core was relatively high, around 2 g·cm^{-3}, except from somewhat lower values in the upper 5 cm
- The concentrations of total ^{210}Pb ranged from 9 to 14 Bq·kg^{-1} along the upper 15 cm, without any decreasing trend with depth. The concentrations of ^{226}Ra measured at several depths averaged 15 ± 3 Bq·kg^{-1}. Therefore, there was no excess ^{210}Pb along the core, suggesting negligible net sedimentation during the last decades at this site.



References

Sanchez-Cabeza, J. A., Masqué, P. & Ani-Ragolta, I. ^{210}Pb and ^{210}Po analysis in sediments and soils by microwave acid digestion. (1998). Journal of Radioanalytical and Nuclear Chemistry, 227, 19-22.

Appendix E Core samples used for radiocarbon dating.

Table 9 Radiocarbon dating of cores sampled in Thailand. All radiocarbon dates were calibrated with CALIB software v.8.20. The reservoir effect (RE) affecting the ages was 71 years and was accounted in the corrected ages (Cal years BP) were BP stands for 'before the present' and present was 2022. B= Boon Kong Bay; L= Libong Island; M= Mook Island; S= Sukhon Island. * Cannot calibrate due to nuclear testing ^{14}C

Site	Core ID	cm decomp	Fraction of modern		Raw age		CALIB 8.20 - MARINE20 - 2 sigma					Corrected age (Cal years BP-RE)	Corrected age error		
			pMC	1σ error	year (BP)	age error (±)	cal AD	cal AD	cal BC	cal BC	Median		+	-	±
B	B1	38.9	89.26	0.25	913	22	1327	1585			1410	612	83	-175	129
B	B1	100.0	84.59	0.3	1344	28	820	1223			1021	1001	201	-202	201.5
L	L3	37.5	94.17	0.3	483	26	1649	1950			1804	218	155	-146	150.5
L	L3	101.8	80.09	0.2	1783	20	378	757			569	1453	191	-188	189.5
M	M3	39.6	93.6	0.25	531	21	1590	1950*			1765	257	175	-185	180
M	M3	107.5	57.91	0.2	4388	28			2881	2433	-2657	4679	224	-224	224
S	S2	39.6	94.34	0.28	468	24	1664	1950*			1816	206	152	-134	143
S	S2	101.9	72.52	0.22	2581	24			655	154	-387	2409	268	-233	250.5

Appendix F Summary data for all seagrass cores sampled in Trang.

Table 10 Summary of sampling location data, habitat type and soil C_{org} parameters for all cores collected in South Australian seagrass habitat in 2014 and 2017.

Core ID	Sampling date	Country	Site	Lat	Long	Type of site	Habitat	Species	max core depth	Top 30 cm C_{org} stock	Top 100 cm C_{org} stock	SAR long-term		CAR long-term	
									cm dec	Mg C_{org} ha^{-1}	Mg C_{org} ha^{-1}	g cm^{-2} yr^{-1}	SD	g C_{org} m^{-2} yr^{-1}	SD
B1	Aug-22	Thailand	Boon Kong Bay	7.5167	99.2943	restored	seagrass	E. *acoroides*	106	43.9	155.9	0.10	0.01	8.2	0.7
B2	Aug-22	Thailand	Boon Kong Bay	7.5167	99.2943	restored	seagrass	E. *acoroides*	96	26.0	127.5	-	-	-	-
B3	Aug-22	Thailand	Boon Kong Bay	7.5167	99.2943	restored	seagrass	E. *acoroides*	106	24.3	96.8	-	-	-	-
B4	Aug-22	Thailand	Boon Kong Bay	7.5167	99.2943	restored	seagrass	E. *acoroides*	105	13.5	28.6	-	-	-	-
L1	Aug-22	Thailand	Libong Island	7.2471	99.4520	impacted	bare	-	122	5.3	19.6	-	-	-	-
L2	Aug-22	Thailand	Libong Island	7.2471	99.4520	impacted	bare	-	103	9.8	44.4	-	-	-	-
L3	Aug-22	Thailand	Libong Island	7.2471	99.4520	impacted	bare	-	107	12.8	32.8	0.22	0.01	8.9	0.4
L4	Aug-22	Thailand	Libong Island	7.2471	99.4520	impacted	bare	-	82	7.8	18.8	-	-	-	-
M1	Aug-22	Thailand	Mook Island	7.3781	99.3073	non-impacted	seagrass	E. *acoroides*	119	22.1	85.8	-	-	-	-
M2	Aug-22	Thailand	Mook Island	7.3781	99.3073	non-impacted	seagrass	E. *acoroides*	114	30.2	77.0	-	-	-	-
M3	Aug-22	Thailand	Mook Island	7.3781	99.3073	non-impacted	seagrass	E. *acoroides*	113	22.2	87.6	0.17	0.04	9.8	2.6
M4	Aug-22	Thailand	Mook Island	7.3781	99.3073	non-impacted	seagrass	E. *acoroides*	115	9.6	63.5	-	-	-	-
S1	Aug-22	Thailand	Sukhon Island	7.1132	99.5827	impacted	bare	-	120	4.6	38.5	-	-	-	-
S2	Aug-22	Thailand	Sukhon Island	7.1132	99.5827	impacted	bare	-	114	3.5	38.2	0.22	0.01	5.8	0.1
S3	Aug-22	Thailand	Sukhon Island	7.1132	99.5827	impacted	bare	-	113	11.8	84.3	-	-	-	-
S4	Aug-22	Thailand	Sukhon Island	7.1132	99.5827	impacted	bare	-	115	13.6	49.4	-	-	-	-

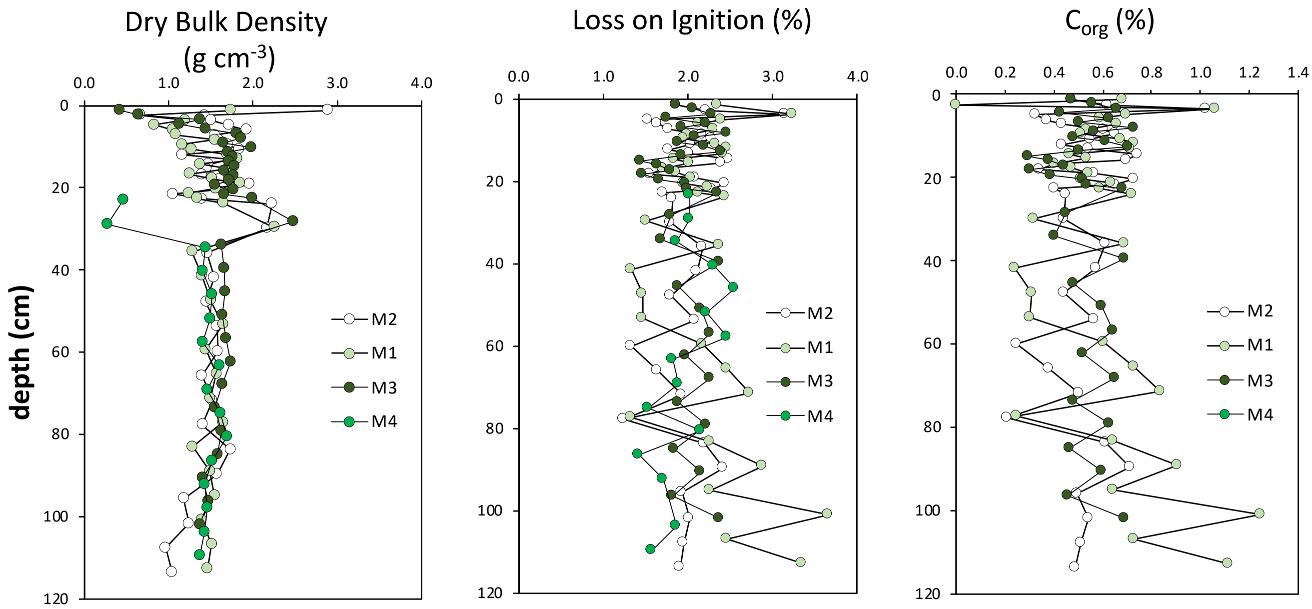
Appendix G Statistical testing for difference in soil characteristics

Table 11 Outcomes of statistical test for significant differences in soil carbon characteristics among the four seagrass blue carbon ecosystems in Trang, Thailand: soil C_{org} content (%), LoI, dry bulk density (DBD) and soil C_{org} stocks in the top 20-, 50- and 100- cm of soils.

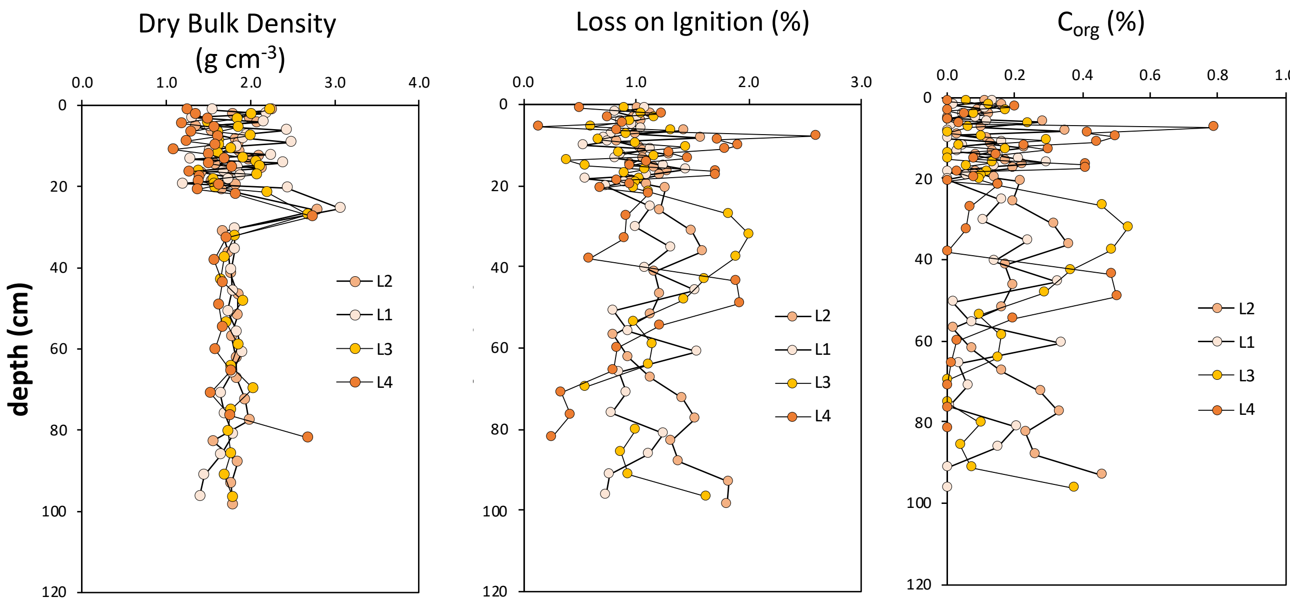
Parameter	K-W Test	Top 30 cm				Top 100 cm			
		B	L	M	S	B	L	M	S
DBD (g/cm^3)	N	84	89	69	86	136	138	115	133
	Mean rank	146	201	150	156	228	332	220	258
	H-value	19				46			
	p-value	**<0.001**				**<0.001**			
LOI (%)	N	84	89	69	86	136	138	115	133
	Mean rank	238	87	238	113	364	138	358	202
	H-value	177				223			
	p-value	**<0.001**				**<0.001**			
Soil C_{org} content (%)	N	84	89	69	86	136	138	115	133
	Mean rank	240	90	230	115	365	136	358	202
	H-value	164				228			
	p-value	**<0.001**				**<0.001**			
Soil C_{org} stock (kg m^{-2})	N	4	4	4	4	4	4	4	4
	Mean rank	13	5.3	11	5	12	4	11	8
	H-value	8.5				7.9			
	p-value	**0.037**				**0.049**			

Appendix H Seagrass soil characteristics profiles at the four Trang sampling sites

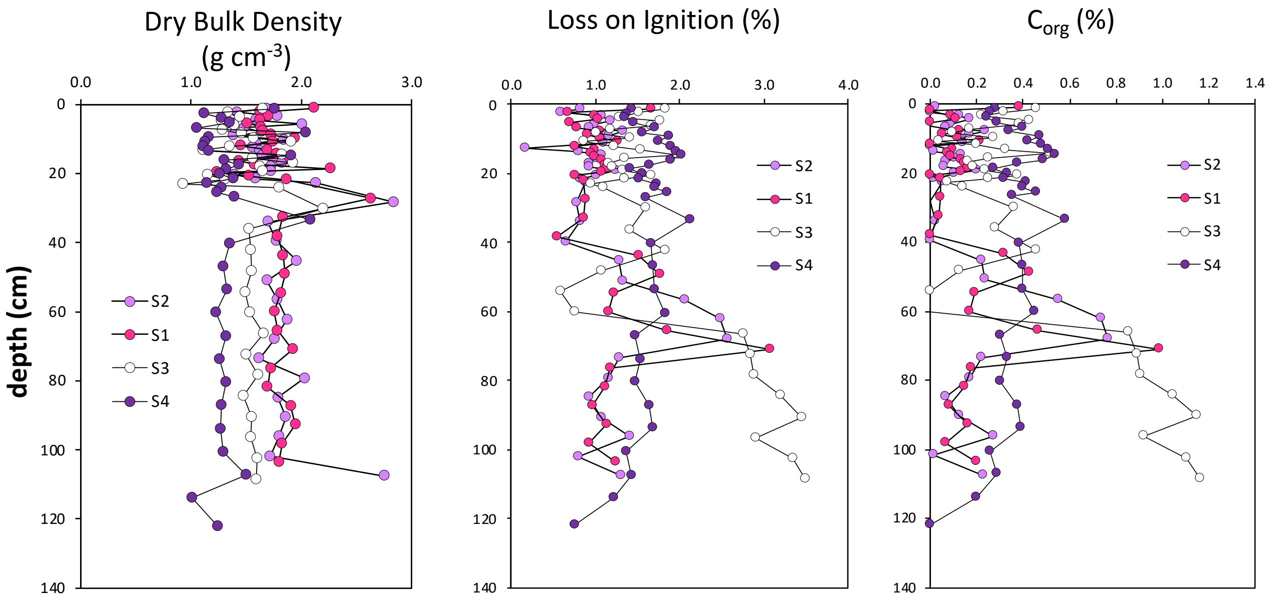
a) Koh Mook: unimpacted seagrass meadow.



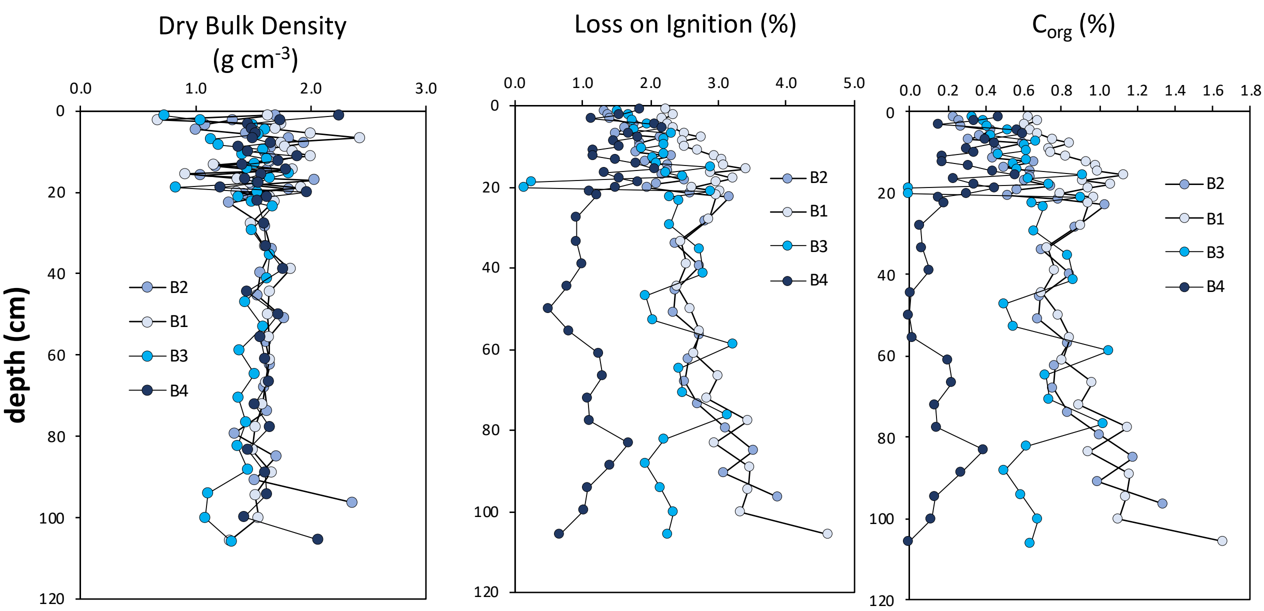
b) Libong: impacted (sedimentation) seagrass meadow.



c) Sukhon: impacted (trawling) seagrass meadow.



d) Boon Kong: transplanted seagrass meadow.



e) Mean data for the four Trang sites

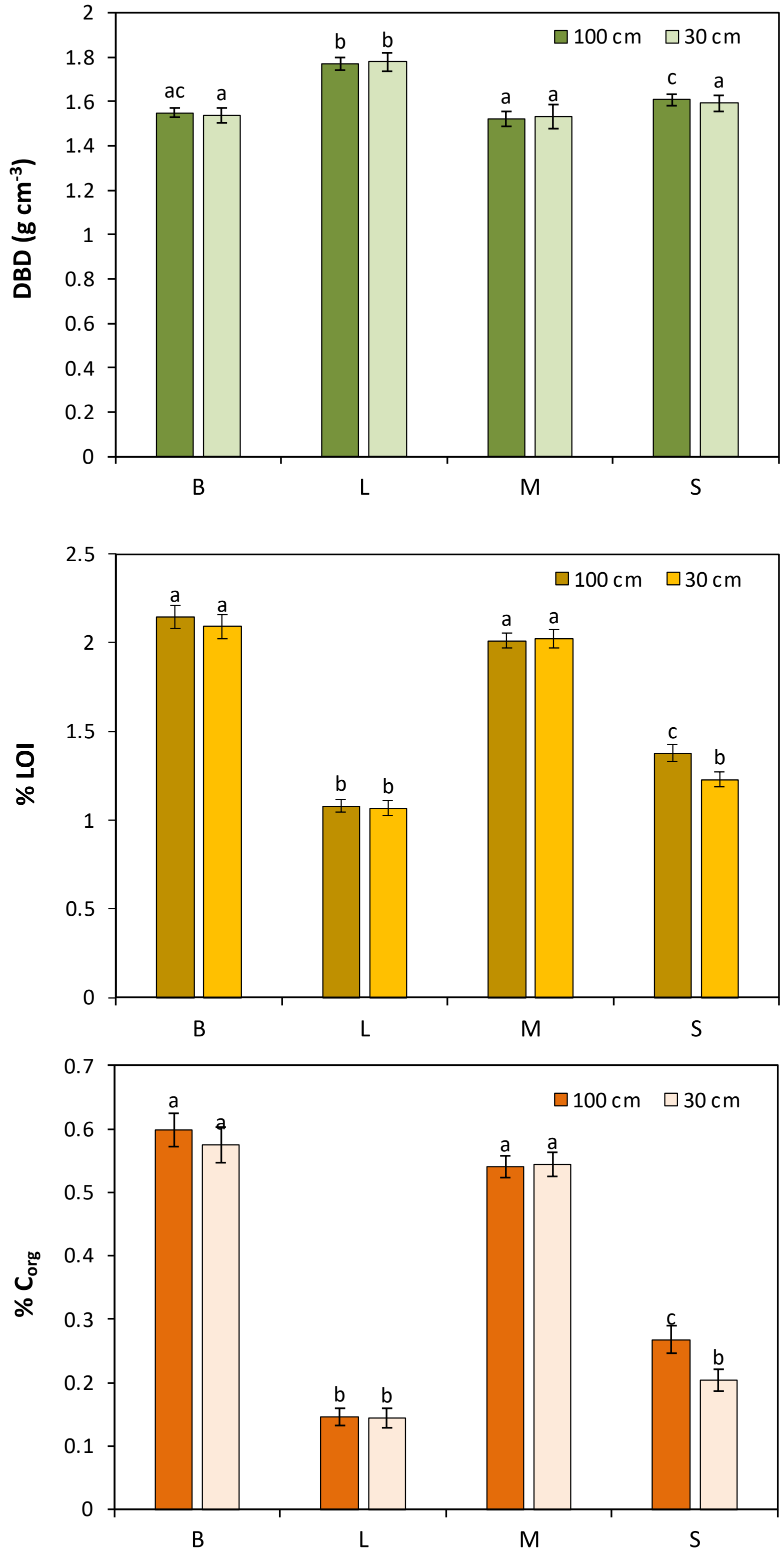


Figure 14 Mean (± s.e.) DBD, % LOI and % C_{org} in the top 30 and 100 cm of seagrass soil in Thailand. B= Boon Kong Bay; L= Libong Island; M=Mook Island; S= Sukhon Island. Shared letters indicate no significant different ($p > 0.05$)