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Blue Carbon Opportunities: seagrass carbon storage and accumulation rates at North Minahasa and Sangihe Island, Indonesia

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Blue Carbon Opportunities: seagrass carbon storage at North Minahasa and Sangihe Island, Indonesia.

TECHNICAL REPORT

For the IKI Seagrass Ecosystem Services Project

Paul Lavery, Anna Lafratta, Akbar Ario Digdo, Abie Ariyo Dandoro, Citra Septiani, Topan Cahyono, Oscar Serrano, Pere Masque.

Report prepared as a contribution to the Seagrass Ecosystem Services 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 SES Project is a partnership between the CMS, Edith Cowan University, Yapeka, Project Seagrass, Seagrass Watch, Murdoch University, MRS, Blue Ventures, SAN, C3, ZSL, and MareCet. 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.

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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

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. carbon contained within living and dead organisms)
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}

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 North Sulawesi region in Indonesia, and addressed a range of seagrass ecosystem services, including carbon sequestration (or Blue Carbon). The Indonesia NGO Yapeka, 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 two priority sites in North Sulawesi – North Minahasa and Sangihe Island. The assessment was implemented with the following goals:

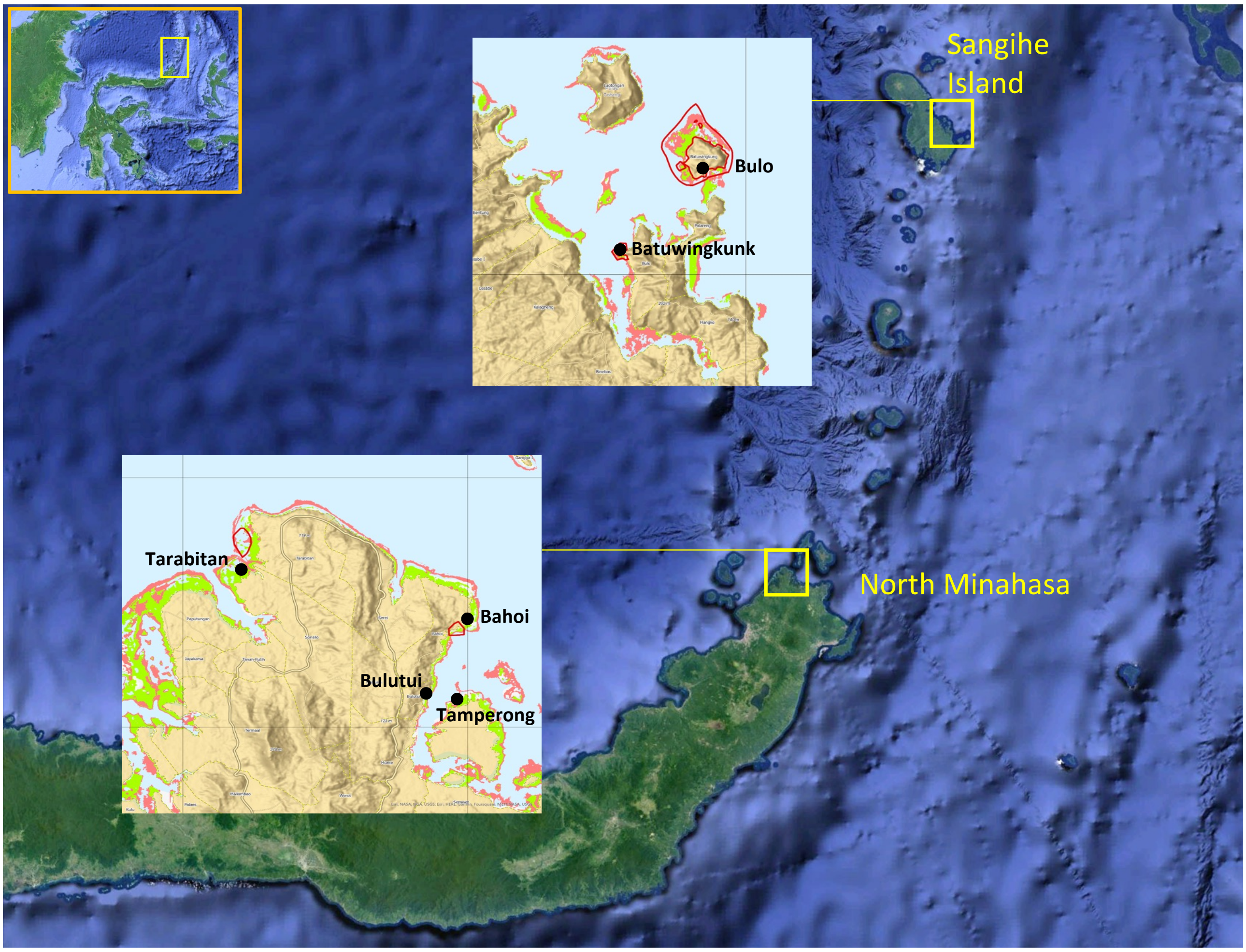
- Obtain information that can be used to inform decision makers of the value of seagrasses for CO_2 capture and storage, and to inform the design of BC projects;
- Build the capacity of local NGO and communities to undertake Blue Carbon SES assessments;
- Collect data to undertake a Seagrass Blue Carbon 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 sites in North Minahasa and at two sites at Sangihe Island (ES Figure 1). The sites comprised:

- In North Minahasa, two relatively undisturbed Reference sites (Tarabitan and Tamperong) and two Impacted sites (Bahoi and Bulutui) where coastal development, extraction and anchoring had affected the seagrass;
- At Sangihe Island, one Reference site (Bulo), considered to be representative of healthy seagrass in the Sangihe Islands region; and one impacted site (Batuwingkung) subject to gleaning and fishing activity.

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. The assessment suffered a major constraint when an export permit could not be obtained to allow the seagrass soil samples to be analysed in overseas laboratories. At the same time, no Indonesian laboratory was equipped to perform the analyses. Consequently, some aspects of the method could not be completed, specifically the direct analysis of carbon content of the souls through elemental analysis and the dating of the soils to determine carbon accumulation rates (CAR). An indirect method was used to estimate the carbon content of the soils, but CAR could not be estimated.



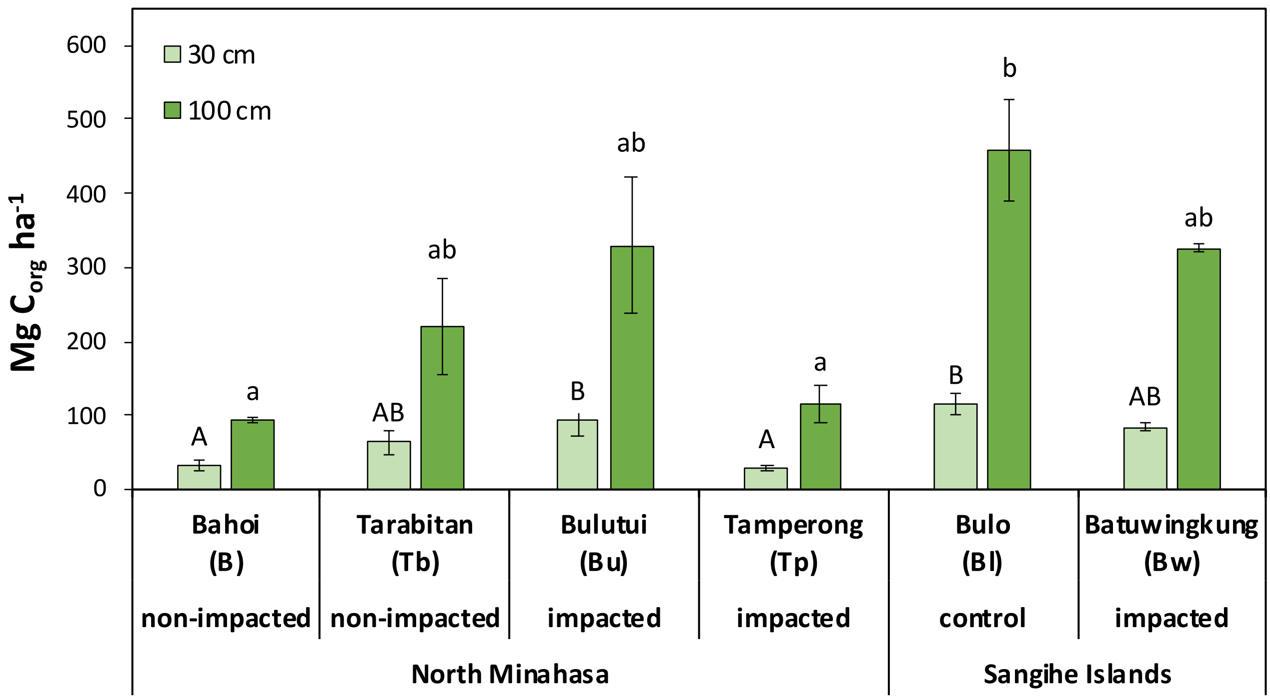
ES Figure 1. The location of the two sampling regions, North Minahasa and Sangihe Island, used by YAPEKA in the Blue Carbon assessment. Insert figures shows the individual sampling locations within each priority region.

1.3 Seagrass soil C_{org} stocks in North Minahasa and Sangihe

On average, the top 100 cm of seagrass soil had stocks ranging from 93 ± 3.6 to 458 ± 68 Mg C_{org} ha^{-1} (1 Mg = 1 tonne). The Sangihe reference site (Bulo) had the highest mean stock and the impacted Bahoi site had the lowest, almost a five-fold difference (ES Figure 1).

At Sangihe Island, the mean soil C_{org} stocks at Bulo and Batuwingkung were exceptionally high at 458±69 and 326±6 Mg C_{org} ha^{-1}, respectively, placing the two sites among the highest recorded, globally. These two sites also provided one of the first opportunities to examine the effect of gleaning on seagrass carbon sequestration, since Batuwingkung experiences gleaning while Bulo does not. Statistically there was no difference between the sites, meaning it is not possible to conclude that gleaning has resulted in a loss of soil organic carbon, though the 30% lower stock at the 'disturbed' Batuwingkung site suggest that further investigation may be warranted.

Assuming the Bulo and Tamperong reference sites are representative, undisturbed seagrass meadows in the region can contain C_{org} stocks in the order of 200-450 Mg C_{org} ha^{-1}, among the very highest recorded in Indonesia and well above the global mean reported for seagrasses of about 140 Mg C_{org} ha^{-1} (Duarte et al. 2013).



ES Figure 2. Mean (± SE) organic carbon (C_{org}) stocks in 30 cm and 100 cm-thick soil seagrass deposits collected in North Minahasa and Sangihe. The organic carbon values were estimated from the Loss on Ignition data by applying the LoI v O.C. regression from Fourqurean et al. (2014)

1.4 Total soil C_{org} stocks and accumulation rates in Minahasa and Sangihe seagrass ecosystems

The total soil C_{org} stocks for seagrass at the seagrass sites were estimated by scaling up the mean C_{org} stock in the top meter of soil to the total area occupied by seagrass. Across the six sites assessed, the total BC stocks ranged from about 13,000 t CO_{2-eq} at Bahoi to 39,500 t in Batuwingkung (ES Table 1).

ES Table 1. Total area and organic carbon stocks in top 100 cm of seagrass carbon ecosystems in the North Minahasa and Sangihe Island sampling sites. 1 Mg = 1 tonne

Ecosystem	Area (ha)	Mean Soil C_{org} stock (Mg C_{org} ha^{-1})	Total soil C_{org} stock (Mg C_{org})	Total Soil stock (Mg CO_{2-eq})
North Minahasa				
Tarabitan	52	219	11,400	41,860
Bahoi	39	93	3,630	13,340
Tamperong	44	115	5,070	18,600
Bulutui	33	330	1,0850	39,920
Sangihe Island				
Bulo	7	458	3,210	11,770
Batuwingkung	33	326	10,760	39,480

The differences in soil C_{org} stocks between the sites was used to make first-order estimates of the potential for avoided greenhouse gas (GHG) emissions in the seagrass ecosystems. Using two different approaches, the potential emissions resulting from loss of the top 100 cm of the meadows would range from as low as 20 to as much as 1200 Mg CO_{2-e} ha^{-1}, though most likely between 20 and 350 Mg CO_{2-e} ha^{-1} (ES Table 2). While this range is high, it captures a number of assumptions which range from less to more conservative, which are detailed in the main report.

ES Table 2. Estimated potential abatement (avoided emissions) for North Minahasa and Sangihe seagrass sites.

*Minimum estimates are based on the difference between the disturbed site and the undisturbed site with the lowest stock and assumes 25% of disturbed carbon is remineralised. **Maximum estimates are based on the difference between the disturbed site and the undisturbed site with the largest stock and assumes 75% of disturbed carbon is remineralised

Region	Mean Soil C_{org} stock (Mg C_{org} ha^{-1})			Total soil C_{org} stock (Mg C_{org} ha^{-1})		Total Soil stock (Mg CO_{2-eq} ha^{-1})	
	Healthy		Disturbed	Min*	Max**	Min*	Max**
North Minahasa	Tarabitan	Tamperong	Bahoi				
	219	115	93	5.5	94.5	20.2	346.8
Sangihe	Bulo		Batuwingkung				
	438		326	28	84	102.8	308.3

1.5 Methodological issues for BC assessments (Lessons learnt)

The four SES case studies, including that undertaken at North Minahasa and Sangihe, 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, however, there is an absence of CAR measurements for Indonesia, forcing a reliance on global means or estimates from other places in SE Asia (e.g. Miyajima et al. 2022). 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 CARs. In Indonesia this was due to legal constraints on exporting the samples for isotope analysis and the absence of a laboratory within the country to perform them. In other sites, the soil characteristics prevented CAR being determined, a problem not uncommon in seagrass sites. Efforts to establish SETs were also unsuccessful due to the theft of the measuring rods.

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 Indonesia, experienced difficulty in obtaining permits needed to undertake the blue carbon assessments. These issues related either to:

1. Permits to undertake field work to collect soil samples; 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

- Relatively undisturbed seagrass meadows in the North Minahasa and Sangihe regions have soil C_{org} stocks of 220-460 Mg C_{org} ha^{-1}, among the greatest stocks measured elsewhere Indonesia and globally.
- Disturbance appeared to reduce the soil C_{org} stocks at some sites by 30% to 60%.
- The potential abatement associated with conservation of seagrass meadows in the region was estimated to be 20 – 346 t $CO_{2\text{-eq}}$ per hectare.
- 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,
    - Identification of local partner organisations to assist the NGO partners in any 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 in which all five National partners participated;
    - **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;
    - **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 in which all six of the project's NGOs participated; and

- **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 information generated in this assessment should be used to inform decision makers and the broader community about the value of seagrasses in carbon abatement. This can be used to argue for the inclusion of seagrass ecosystems in the NDC for the inclusion of seagrass projects in government strategies that involve the conservation or restoration 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 Indonesia.

- **It is recommended that** the CMS assist YAPEKA in completing the analysis of the seagrass soil samples collected during the SES for C_{org} (through elemental C analysis) and for dating of the cores and estimating Carbon Accumulation Rates, when the opportunity arises. The un-analysed samples held by YAPEKA represent an extremely valuable opportunity to fill several key knowledge gaps regarding Indonesian blue carbon resources, with benefit well beyond the SES Project. The cost of implementing this recommendation would be modest compared to the investment already made in obtaining high-quality samples but would yield highly significant data for Indonesia.

- **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;
    - 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.

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2 Introduction and Aims

This report summarises the activities and findings of a Blue Carbon (BC) assessment undertaken by YAPEKA 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 North Minahasa and Sangihe Island regions of Indonesia, 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 sites in North Sulawesi, Indonesia. The assessment was implemented by YAPEKA, 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), Sections 1 and 2 of the report provides 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.

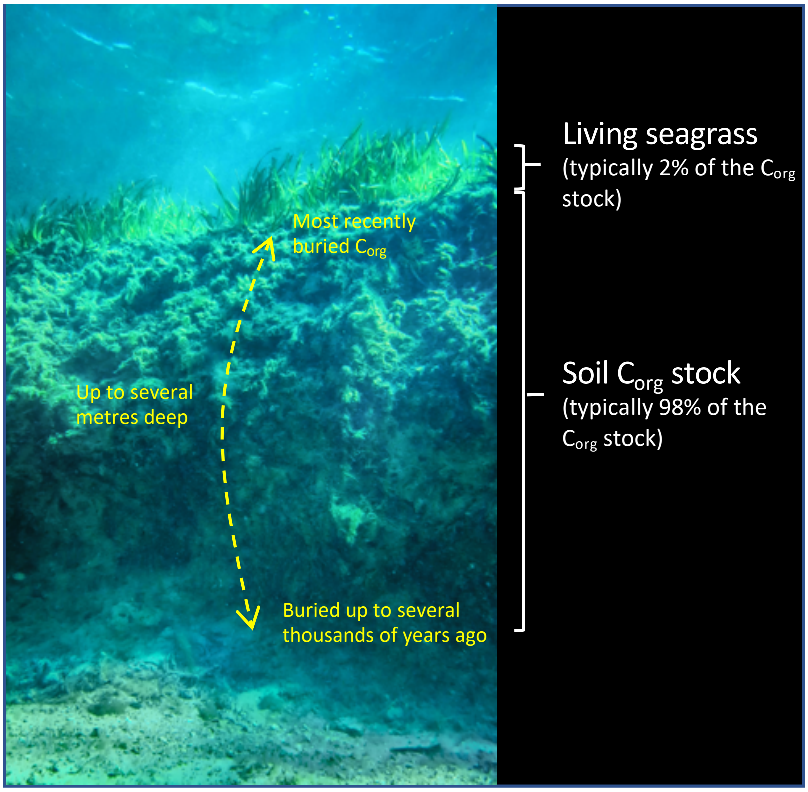

Figure 1 A profile through a seagrass meadow made possible by the erosion of an escarpment wall and revealing the large amount of organic carbon-rich soil below the relatively thin living layer. Numbers in the figure are based on Serrano et al. (2019) for Australian seagrass ecosystems.

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. 2016b). 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.

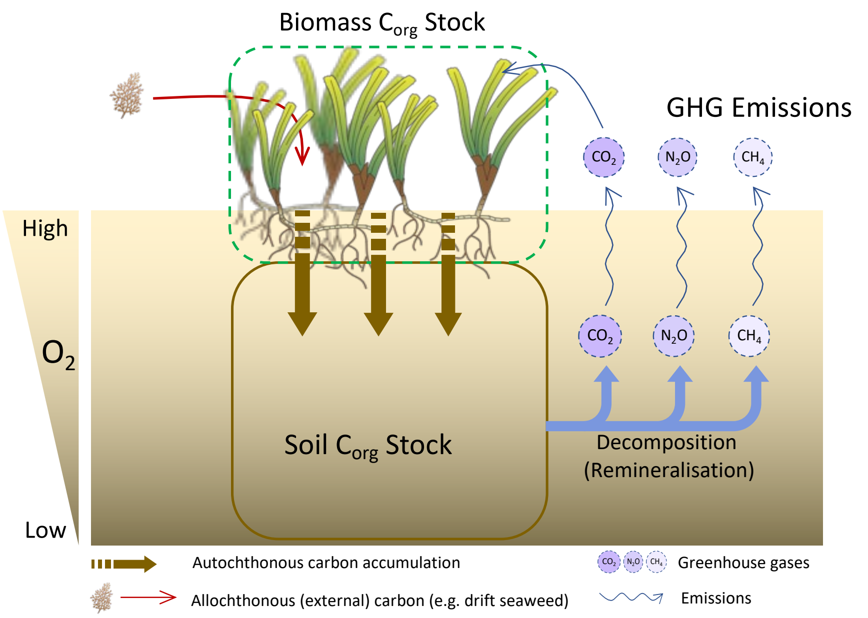

Figure 2 Carbon stocks, accumulation and greenhouse gas emissions in seagrass meadows

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.

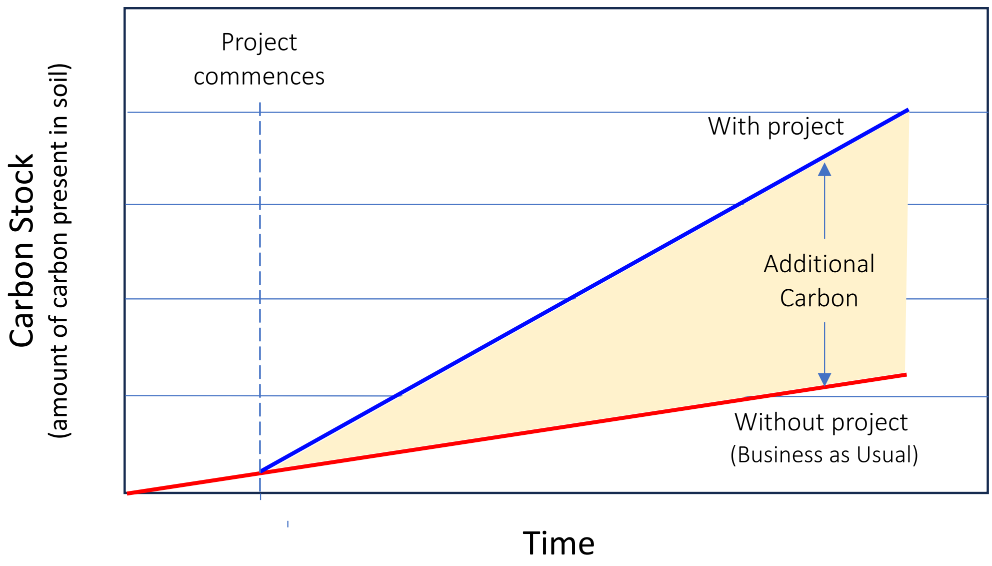

Figure 3 Additionality in blue carbon projects. The diagram shows the amount of carbon which might accumulate at a site over time under two scenarios: at a site with no management action (i.e., Business as Usual (red line); and at the same site following implementation of a blue carbon project (blue 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 two locations in North Sulawesi: North Minahasa (4 sites) and Sangihe Island (2 sites), undertaken as part of Work packages 1 and 2. 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 Indonesian seagrass ecosystems, a review of known information on seagrass blue carbon in Indonesia's coastal ecosystems is included.

3 Seagrass Blue Carbon and Blue Carbon Policy in Indonesia

Seagrass blue carbon stocks in Indonesia have been reported for a variety of different soil depths (Table 1), making comparisons difficult. A number of those studies did report 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 about 36 to over 240 Mg C_{org} ha^{-1} (Table 1) and include monospecific and mixed-species meadows. These meadows were largely at coastal sites in Sulawesi, though national averages and values from Bali (Nusa Penida) fall comfortably within the range. At the time of writing, there were no published carbon accumulation rates for seagrass meadows in Indonesia.

Fourqurean et al. (2014) developed relationships between the organic matter content of seagrass soils and the organic carbon content of seagrass soils, 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. Extracting only data for the latitudes and longitudes encompassing Indonesia (which also includes some Malaysian and Philippines seagrass sites) from Fourqurean et al. (2014), there is a moderate relationship between soil organic matter (Loss on Ignition) and soil Organic Carbon (R^2 0.727), however, this relationship is driven strongly by three sites (in the Philippines and Malaysia).

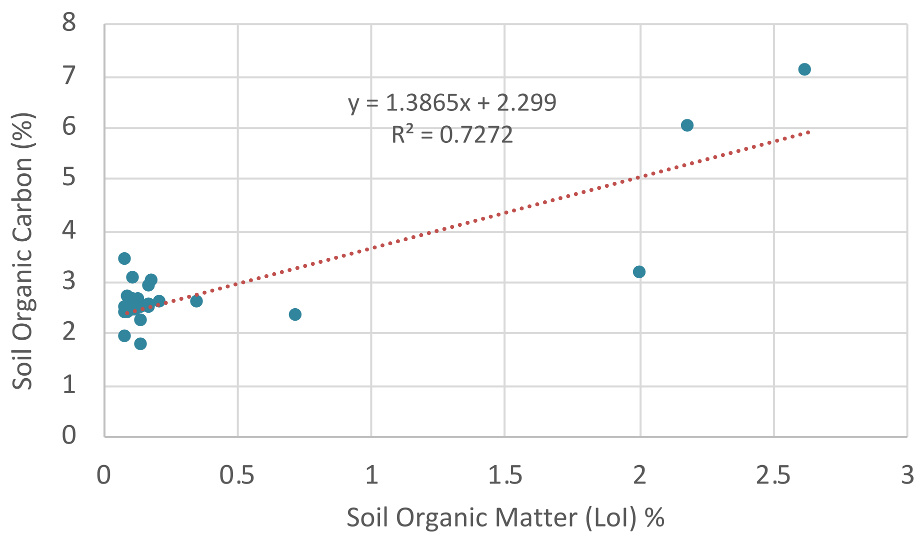

Figure 4 Relationship between seagrass soil organic matter and organic carbon content for Indonesian and Malaysian seagrass meadows, based on data from Fourqurean et al 2012.

Table 1. Published seagrass soil C_{org} stocks for coastal sites in Indonesia.

SITE	SITE	HABITAT	Species	Sediment depth (cm)	STOCK (Mean ± s.d.) (Mg C_{org} ha^{-1})	Ref
INDONESIA	National average	All		100	129.9±9.6	8
INDONESIA	National average	All		100	251	9
Java	NW		Ea, Cr, Hu	100	62±12	1, in 2
Sulawesi	South		Th, Ea	100	31±2	3, in 2
	South		Ea	100	148±22	3, in 2
Sulawesi	SW		Ea	100	239±45	4 in 2
	SW		Cr	100	103±29	5, in 2
	SW		Cr	100	88±28	5, in 2
Kalimantan	East	Coastal	Hu	100	243±30	6, in 2
	East	Mid-offshore	Hu	100	121±15	6, in 2
	East	Offshore	Hu	100	80±10	6, in 2
Sulawesi	South		Ea, Th, Cr	100	214±49	7, in 2
N. Sulawesi	Lembeh	Coastal		100	21.9±0.3	10
Bali	Nusa Lembongan	Coastal		100	77.2±1.4	10
N. Sulawesi	Sangihe Is	Coastal		100	36.1	10
SE Sulawesi	Tinanggea (MPA protection)	Coastal		80	364±37	11
	Tinanggea (Outside MPA)	Coastal		80	422±20	11
South Sulawesi	Spermonde Is, (Barranglompo Is.)	Intertidal	Ea, Th, Hd, Ho, Cr, Hu, Hp, Si)	55	18.8 ± 4.1	12
South Sulawesi	Spermonde Is (Bauluang is.)	Intertidal	Ea, Th, Hd, Ho, Cr, Hu, Hp, Si)	22	20.3 ± 5.3	12
South Sulawesi	Spermonde Is (Sarappokeke Is.)	Intertidal	Ea, Th, Hd, Ho, Cr, Hu, Hp, Si)	30	11.9 ± 3.3	12
South Sulawesi	Spermonde Is (Kapoposang Is.)	Intertidal	Ea, Th, Hd, Ho, Cr, Hu, Hp, Si)	32	32.1 ± 13.4	12
North Sulawesi	Bitung, Kema Lagoon	Subtidal, lagoon	Ea + Th	20-30	8.12	13
North Sulawesi	Manado, Wori	Subtidal, coastal	Hp, Cr, Th	20-30	11.22	13
North Sulawesi,	Bitung, Kema beach	Subtidal, coastal	Ea + Th	20-30	5.23	13
North Sulawesi	Bitung, Tanajung Merah	Subtidal, coastal	Hp, Cr, Th	20-30	14.22	13
North Sulawesi	Bitung, Kema Lagoon	Subtidal, lagoon	Ea + Th	20-30	4.64	13

North Sulawesi	Manado, Wori	Subtidal, coastal	Hp, Cr, Th	20-30	8.55	13
North Sulawesi,	Bitung, Kema beach	Subtidal, coastal	Ea + Th	20-30	5.17	13
North Sulawesi,	Bitung, Tanajung Merah	Subtidal, coastal	Hp, Cr, Th	20-30	2.96	13
North Sulawesi,	Bitung, Kema Lagoon,	Subtidal, lagoon	Ea + Th	20-30	2.87	13
North Sulawesi,	Manado	Subtidal, coastal	Hp, Cr, Th	20-30	13.13	13
North Sulawesi,	Bitung, Kema beach	Subtidal, coastal	Ea + Th	20-30	5.78	13
North Sulawesi,	Bitung, Tanajung Merah	Subtidal, coastal	Hp, Cr, Th	20-30	5.53	13
Riau Archipelago	Bintan Island, Dompak	Coastal	Ea, Th, Ho, Hu	20	103.8	14
Riau Archipelago	Bintan Island, Berakit	Coastal	Ea, Th, Ho, Hu	20	91	14
South Sulawesi	Spermonde Is, Pl. Lae-Lae	Coastal	Ea	0-15	9.4±3.1	15
	Spermonde Is, Pl. Lae-Lae	Coastal	Ea	15-30	8.6±1.6	15
South Sulawesi	Spermonde Is, Pl. Bonetambung	Coastal	Ea	0-15	10.4±2.9	15
	Spermonde Is, Pl. Bonetambung	Coastal	Ea	15-30	8.5±1.2	15
ADDITIONAL STUDIES**						
Riau Archipelago	Bintan Is. Busung	Coastal	Th		3269	16
Riau Archipelago	Bintan Is. Teluk Bakau	Coastal			2400	16
Java	Kepaluan Seribu, Pl Pari	Reef	Ea, Th, Cr	surface	123±39	17
NMR Karimunjawa	Pulau Nyamuk	Coastal	Ea		13048±6699	18
Karimunjawa NMR	Pokemon beach	Coastal	Ea		10640±2216	18
Karimunjawa NMR	Kemujan island	Coastal	Ea		9944±9944	18
Jakarta Bay	Rambut Island (SW)	Coastal	Cs, Th, Cr	10	122.3±0.8	19
Jakarta Bay	Rambut Island (N)	Coastal	Cs, Th, Cr	10	108.8±1.0	19
Bintan Island	Bakau Bay	Coastal	Ea, Th	10	75.01	20
Bintan Island	Pengudang	Coastal	Ea, Th	10	100.1	20

Ea = *Enhalus acoroides*; Th = *Thalassia hemprichii*; Hd = *Halophila decipiens*; Ho = *Halophila ovalis*; Cr = *Cymodocea rotundata*; Hu = *Halodule uninervis*; Hp = *H. pinifolia*; Si = *Syringodium isoetifolium*.

** These studies stocks which are exceptionally large, globally, and so are separated from the rest of the table. These estimates warrant further investigation before being applied

[1]Kiswara (1992); [2]Alongi et al. 2015; [3]Erftemeijer & Middelberg (1993); [4.]Priosambodo (2006); [5]Alongi et al. (2008); [6.] Van Katwijk et al (2011); [7.] Supriadi et al (2014); [8.] Alongi et al (2015); [9.] Thorhaug et al. (2020); [10.] Rahayu et al. (2023); [11.] Analuddin et al 2023; [12.] Rahayu et. al 2019; [13.] Chen et al. 2017; [14.] Hertyastuti et al 2020; [15.] Yushra et al. 2020; [16.] Ansari et al (2020); [17.] Citra et al (2020); [18.] Aji et al. 2020; [19.] Rustam et al. 2020; [20.] Idriani et al. 2017

3.1 Seagrass blue carbon policy

In its country and development report, The World Bank mentioned that Indonesia contributes around 3.5 percent of global greenhouse gas emissions, with annual emissions of 1.457 Gg $CO_{2\text{-}e}$ in 2016 (Govt Indonesia, 2021). Indonesia's total energy supply has increased by nearly 60% from 2000 to 2021. As energy demand has risen, coal has been used to fill the energy gap. The energy sector now emits one-third more CO_2 than in 2000 (WBG, 2023).

Total energy sector emissions have grown faster than energy demand, more than doubling over the last two decades. In 2021, energy sector emissions in Indonesia were around 600 million tonnes of carbon dioxide (Mt CO_2) – making Indonesia the world's ninth-largest emitter, and yet, per capita energy CO_2 emissions are only 2 tonnes, half the global average (IEA, 2023). This number, however, is expected to rise to around 1,669 MtCO2 equivalent in 2030 under the business-as-usual scenario, and will be the largest Carbon emission source in Indonesia (WBG, 2023).

Seagrass Blue Carbon Policy

Indonesia's Nationally Determined Contribution (NDC) outlines the country's transition to a low carbon and climate-resilience future. The NDC describes the enhanced actions and the necessary enabling environment during the 2015-2019 period that has laid the foundation for more ambitious goals beyond 2020, contributing to the concerted effort to prevent $2^{o}C$ increase in global average temperature and to pursue efforts to limit the temperature increase to $1.5^{o}C$ above pre-industrial levels.

By 2030, Indonesia envisions achieving archipelagic climate resilience due to comprehensive mitigation and adaptation and disaster risk reduction strategies. Indonesia has set ambitious goals for sustainability related to the production and consumption of food, water, and energy. These goals will be achieved by supporting empowerment and capacity building, improved provision of basic services in health and education, technological innovation, and sustainable natural resource management, in compliance with principles of good governance. Beyond the 2030 NDC target, Indonesia has committed to progress towards the transformation to a *long-term low-carbon and climate resilience development strategy.*

Indonesia, in its 1st NDC (2016), committed to unconditionally reducing 29% of its greenhouse gas emissions against the business-as-usual scenario by 2030 which will increase to 31.89% in enhanced NDC (2022). To achieve the GHG emission reduction target, Indonesia focuses its program on five sectors, i.e., Energy, Waste, IPPU, Agriculture, and FOLU (Forest and Land Uses). Mangroves, one of the blue carbon ecosystems, are classified as FOLU sectors in Indonesia (Table 2).

Table 2. Indonesia's Nationally Determined Contribution (NDC): Projected BAU and emission reduction from each sector category

Sector	GHG Emission level 2010* (Mton CO2-eq)	GHG Emission Level 2030 (M Ton CO_2-eq) BaU	First NDC		Update NDC		Enhance NDC		GHG Emission Reduction (M Ton CO_2-eq) First NDC		Update NDC		Enhance NDC		Annual Average Growth BAU (2010-2030)	Average Growth 2000-2012
			CM1	CM2	CM1	CM2	CM1	CM2	CM1	CM2	CM1	CM2	CM1	CM2		
Energy*	453.2	1669	1355	1271	1355	1223	1311	1223	314	398	314	446	358	446	6.7%	4.5%
Waste	88	296	285	270	285	256	256	253	11	26	11	40	40	43.5	6.3%	4.0%
IPPU	36	69.6	66.85	66.35	67	66	63	61	2.75	3.25	3	3.25	7	9	3.4%	0.1%
Agriculture	110.5	119.66	110.39	115.86	110	116	110	108	9	4	9	4	10	12	0.4%	1.3%
Forestry and other Land Uses (FOLU)**	647	714	217	64	217	22	214	-15	497	650	497	692	500	729	0.5%	2.7%
TOTAL	**1334**	**2869**	**2034**	**1787**	**2034**	**1683**	**1953**	**1632**	**834 (29%)**	**1081 (38%)**	**834 (29%)**	**1185 (41%)**	**915 (31.89%)**	**1240 (43.20%)**	**3.9%**	**3.2%**

Note:

First NDC: 2016
Update NDC: 2021
Enhance NDC: 2022
CM1: Counter Measure 1 (unconditional mitigation scenario)
CM2: Counter Measure 2 (conditional mitigation scenario)
*) Including fugitive
**) Including emission from estate and timber plantations

Indonesia proposed an enhanced NDC in 2022, aimed at increasing the unconditional emission reduction target of 31.89% which will be implemented through effective land use and spatial planning, sustainable forest management which includes a social forestry program, restoring functions of degraded ecosystems including wetland ecosystems, improved agriculture productivity, energy conservation, and the promotion of clean and renewable energy. Indonesia can increase its contribution up to 43.20% reduction of emissions in 2030 conditionally, compared to 41% in the 1st NDC, subject to the availability of international support for finance, technology transfer and development, and capacity building. Presidential regulation 98/2021 addressed Blue Carbon regulations for supporting the updated NDC in 2021, in two ways:

1. Mitigation (article 8)

- Climate Change Mitigation for other ocean sectors or blue carbon is carried out by ministries that organize government affairs in the marine and fisheries sector.
- The policy for the ocean sector or blue carbon as referred to in paragraph (1) is implemented by the development of science and technology and can be considered in climate change mitigation actions in other sectors for the marine sector or blue carbon to achieve NDC targets.

2. Adaptation (article 32)

- Climate Change Adaptation in other fields for the ocean or blue carbon is carried out by the ministry that organizes government affairs in the marine and fisheries sector.
- The policy for the ocean sector or blue carbon is implemented by the development of science and technology and can be considered in Climate Change Adaptation Action in other fields for the marine sector or blue carbon to achieve NDC targets.

In the enhanced NDC 2021, the key programs, strategies, and actions to achieve climate resilience targets (adaptation) will be achieved by increasing the resilience of the economic, social and livelihood, and ecosystem and landscape. Of these three resilience targets, only one included coastal ecosystems in its strategy (ecosystem and landscape resilience). There are five strategies to protect and sustain these environmental services by taking an integrated, landscape-based approach to managing its terrestrial, coastal, and marine ecosystems; however, only two strategies focus on coastal and marine ecosystems by protection and restoration activities. Mangrove is the only ecosystem included in the actions, by the implementation of integrated management of the mangrove ecosystem and the restoration of degraded mangroves and peatland.

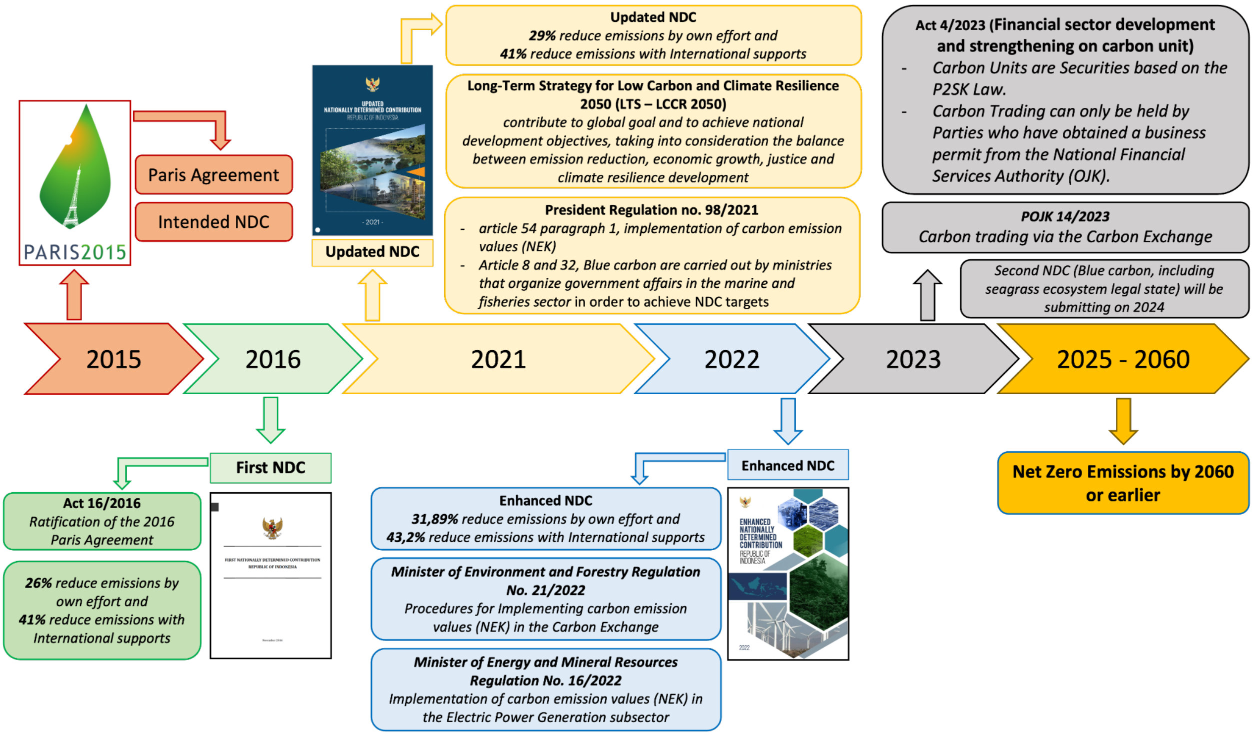

Figure 5. Roadmap of Indonesian Carbon Policy toward Blue Carbon Policy in Second NDC

Policies with specific relevance to seagrass

Since 2020, Indonesia has begun to address ocean-climate mitigation; through the **National Development Plan (RPJMN 2020-2024)**, Indonesia has developed a Policymaker's Summary about Low Carbon Development: A Paradigm Shift Towards a Green Economy in Indonesia and Climate Resilience Development Policy 2020-2025.

Indonesia is currently preparing its second NDC, which will be submitted in 2024 and will be coordinated by the Minister of Marine Affairs and Fisheries (MMAF), who is responsible for formulating Indonesia's submission on ocean climate and coordinating adaptation and mitigation actions in ocean sectors. In addition, MMAF is also responsible for the national geospatial data custodian for thematic geospatial information, including seagrass extent which was estimated at 1,844,442 Ha (11.5% of total world seagrass meadow). In the first NDC, seagrass was not yet counted but the measurements are in progress and will be included in the second NDC.

Despite this, data on seagrass in Indonesia is still limited. Based on the research by Pusat Riset Oseanografi-BRIN (PRO-BRIN), only 293,464 hectares of seagrass meadows across Indonesia have been studied (16-35% of the total area). The need for seagrass mapping is critical for Blue Carbon Policy (second Indonesian NDC) to enhance carbon sequestration, especially in seagrass meadows.

For seagrass ecosystems, MMAF will develop a national seagrass map, revise the national standard (SNI) for seagrass mapping, seagrass blue carbon estimation, MRV mechanism, MRV app systems, and national standard for seagrass carbon measurement. The challenges are the wide range of seagrass ecosystems across the Indonesian archipelago, improvement of the measurement method by implementing the IPPC wetland supplement including emission factors representing various data activities, inclusion of blue carbon in NDC, and implementation of the voluntary carbon trading market, NEK, for blue carbon.

As a non-governmental organization, YAPEKA is helping the MMAF in establishing blue carbon, especially in seagrass ecosystems. Through the cooperation agreement (PKS) of YAPEKA-MMAF (2024-2026), Yapeka is supporting the demonstration plot to calculate the seagrass blue carbon in North Sulawesi as one of the YAPEKA's site project which will be integrated into MMAF's database (Figure 6).

Figure 6. Discussion of the cooperation agreement (PKS) YAPEKA-MMAF, which includes the blue carbon scope in its agreement

Yapeka is contributing to enhancing seagrass mapping, especially in North Sulawesi, through the development of the RZWP3K (Zoning Plan for Coastal Areas and Small Islands). Since 2021, Yapeka has succeeded in advocating for seagrass meadows in some villages across North Sulawesi to be included as "*Kawasan Pencadangan Konservasi di Laut"* (KPL) in the RZWP3K. The document is the foundation to develop the *Rencana Tata Ruang Wilayah* (RTRW) or Spatial Plans for North Sulawesi which can be expanded in governance regulation at the province level. Hopefully, the seagrass meadows inside the KPL zone will be protected from future coastal development.

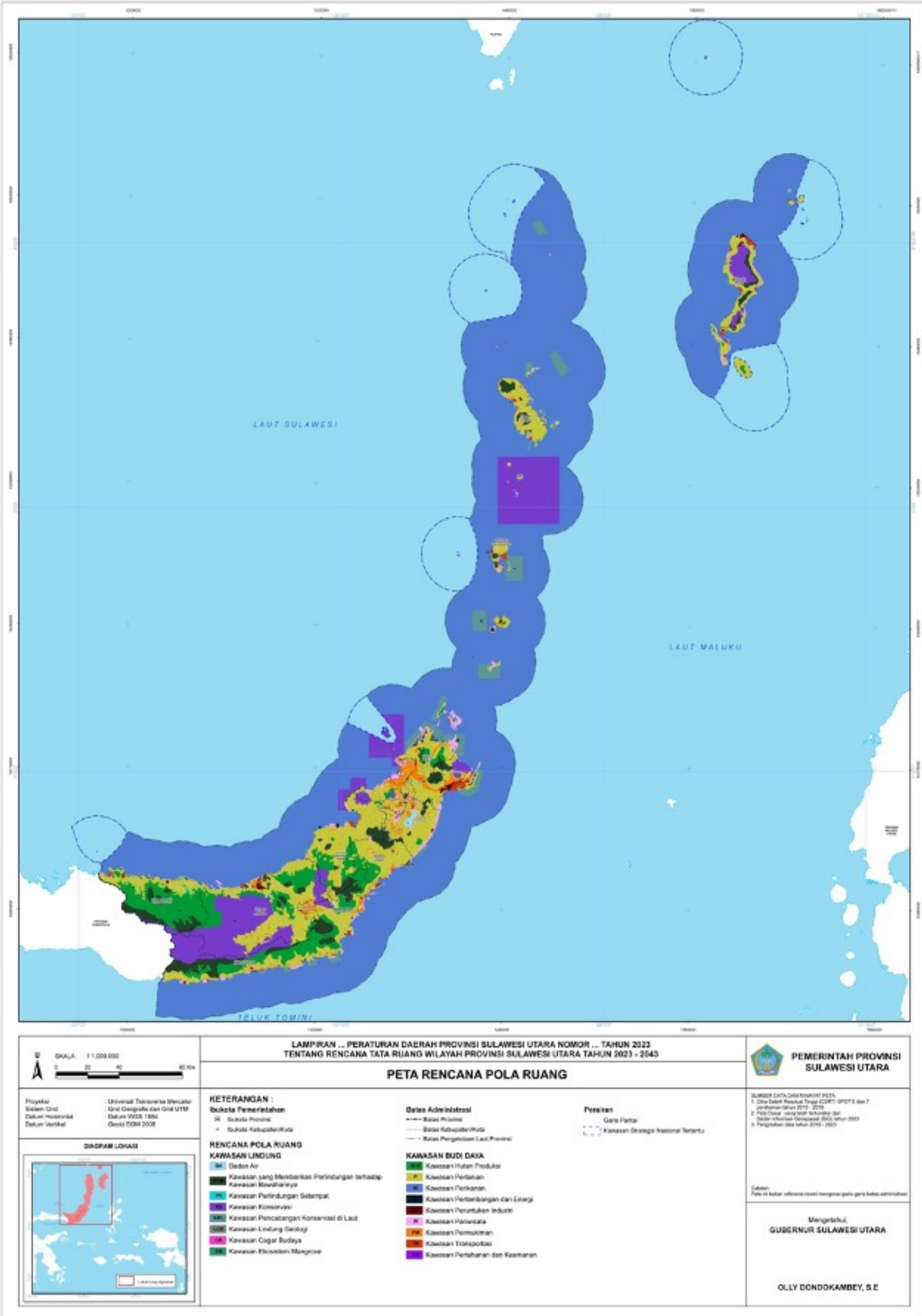

Figure 7. Map of RZWP3K for the development of RTRW North Sulawesi Province which accommodates the seagrass meadows protection efforts by Yapeka.

Carbon Trading

Strengthening NDC in Indonesia is assisted by the implementation of carbon emission values (NEK), as stated in Presidential Decree No. 98/2021 article 54 paragraph 1: *"Domestic and/or foreign*

Carbon Trading is carried out using a carbon market mechanism via the Carbon Exchange; and/or direct trading." This is further supported by the Minister of Environment and Forestry Regulation No. 21/2022 on Procedures for Implementing NEK in the Carbon Exchange. The carbon trading program is also backed by policies from the energy unit, such as Minister of Energy and Mineral Resources Regulation No. 16/2022 on the implementation of the NEK in the Electric Power Generation subsector. Currently, the Carbon Exchange is still linked to the Bursa Efek Indonesia (BEI) and includes five major emission reduction sectors; energy, waste, IPPU, agriculture, and FOLU (Forest and Land Uses).

Some examples of carbon trading in Indonesia are:

- Carbon sales from the FOLU sector resulted from the implementation of the Greenhouse Gas Emission Reduction Programme from Deforestation, Forest Degradation, and Peatlands (October 2018). East Kalimantan has been validated in the first stage to collect 110 million USD from 22 million t CO_{2e} valued at $5/ton through the Forest Carbon Partnership Facility - Carbon Fund program by the end of 2022 (Antara Kaltum, 2023; PPKT, 2023)
- When the first carbon exchange was released on September 26, 2022, Pertamina NRE carbon from the Lahendong Geothermal Power Plant Units 5 and 6 released carbon worth 864.000 tCO2e, which was produced between 2016 and 2020, and has been sold out at a price of IDR 77,000/tCO2e, which is equivalent to 4.9 USD/Ton $CO_{2\text{-}e}$ (CNBC, 2023).
- On October 23, 2023, 500,000 t $CO_{2\text{-}e}$ from PLTGU Muara Karang might be traded on the Carbon Exchange (BEI) in the first stage, followed by 400,000 t $CO_{2\text{-}e}$ in the second stage (Bisnis.com, 2023).

After the announcement of Indonesia's second NDC, which is expected in 2024, Blue Carbon should be included in Indonesia's carbon trading regulations.

In September 2023, Indonesia's Financial Service Authority (OJK) implemented the Financial Service Authority Regulation (POJK) no. 14 tahun 2023, marking the operational start of Indonesia's carbon exchange - IDXcarbon. This regulates the terms and framework for the carbon exchange in Indonesia including the terms and conditions, organizational and capital assets, carbon exchange's operational framework, and the carbon exchange's oversight principles (OJK, 2023).

In the IDXcarbon, traded carbon units are classified as Indonesia Nature Based Solution (IDNBS), Indonesia Nature Based Solution International Standard (IDNBSI), Indonesia Technology Based Solution (IDTBS), and Indonesia Technology Based Solution International Standard (IDTBSI).During the first opening day of the IDXcarbon, 459,9543 t CO_2 were traded in 27 transactions, with a total value of 29.20 Billion IDR (1.8 Million USD). However, in the following days the transactions were very limited and intermittent. This indicates that there is still a lot of work to be done to sustain the uptake of carbon trading.

Conclusion

Indonesia committed, through its 1st NDC in 2016, to unconditionally reduce, by 29%, its greenhouse gas emissions against the business-as-usual scenario by 2030 and later increased this to 31.89% in the enhanced NDC. To achieve this GHG emission reduction target, Indonesia focuses its program on five sectors, i.e., Energy, Waste, IPPU, Agriculture, and FOLU (Forest and Land Uses).

Currently in the FOLU sector, only two strategies focus on protection and restoration of coastal and marine ecosystems, and mangrove is the only coastal ecosystem included in the action plan. In 2024, Indonesia will submit a 2nd NDC that will add seagrass ecosystems to achieve GHG emission reduction targets as part of the forestry and energy sectors. The addition of seagrass blue carbon in the 2nd NDC will increase the adaptation strategy as it provides a wide range of ecosystem services. However, some key challenges such as the lack of accurate seagrass national map and the national standard to measure its coverage and carbon, should be improved to strengthen the implementation of seagrass ecosystems into the carbon sequestration scheme in Indonesia.

This proposed inclusion of the seagrass ecosystem into the next NDC is an important update in Indonesia, where most people live in coastal areas and small islands. The adaptation strategy can be achieved by the implementation of integrated management of coastal ecosystems (mangrove and seagrass), increasing the protection and restoration which leads to sustainable fisheries and tourism in coastal communities for their socio-economic resilience, and enhancing the coastal protection, carbon sequestration, conservation, and disaster risk reduction for the ecosystems and landscape resilience.

Conclusion

Nature-based solutions to climate changes are beginning to be recognised in Indonesia's policy frameworks, and specifically seagrass ecosystems. The abatement and adaptation policies as well as the voluntary carbon trading market offer potential to promote seagrass conservation and, possibly, to obtain some 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. However, these developments are still in their early stages and it will require dedicated effort to insert seagrass blue carbon knowledge into the policy frameworks to achieved effective conservation and climate change mitigation projects.

4 Blue Carbon Assessment

4.1 Assessment design

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

- Build capacity for the 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;
- Provide data which could inform on the potential effects of coastal development practices gleaning and preserving connected ecosystems on blue carbon function; and.
- Provide baseline data for the future development of Blue Carbon Projects to generate carbon credits.

The Blue Carbon assessment was undertaken by YAPEKA North Minahasa in North Sulawesi and at Sangihe Island. To assess the BC potential of the area, Yapeka assessed six sites, four in Minahasa, which were sampled between 26 – 31 July 2022, and two at Sangihe Is., sampled between (Figure 8; Table 3):

- two Reference sites in North Minahasa (Tarabitan and Tamperong), considered to be representative of healthy seagrass ecosystems in the region;
- two Impacted site in North Minahasa, Bahoi and Bulutui;
- One Reference site at Sangihe Island (Bulo), considered to be representative of healthy seagrass in the Sangihe Islands region; and
- One impacted site at Sangihe Island (Batuwingkung) subject to gleaning and fishing activity.

In each location (Minahasa and Sangihe) the sites had similar geo-morphological settings and water depth and all were occupied by mixed species seagrass meadows dominated by either *Thalassia hemprichii* or *Halodule pinifolia* but with five or six other species also present.

The data for undisturbed meadows can inform government and other decision makers of the value of seagrasses for CO_2 capture and storage under baseline, healthy conditions, informing NDC and other greenhouse gas accounting. It is also relevant data for the design of BC projects, since these sites can represent 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. Here, the two disturbed sites were chosen to represent the main activities that currently impact seagrass meadows in the region, coastal development, and gleaning, though it was unclear whether gleaning has a negative effect on blue carbon dynamics.

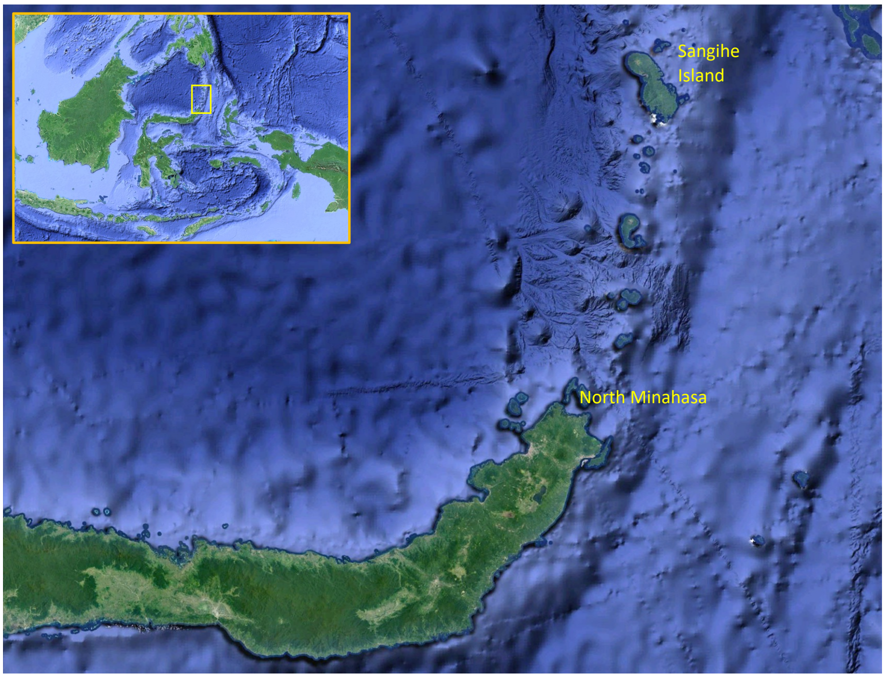

Figure 8. The location of the two sampling regions, North Minahasa and Sangihe Island, used by YAPEKA in the Blue Carbon assessment. Insert figure shows the broader Indonesian region with the box indicating the area of the main map. See Table 3 and subsequent sections for details of site characteristics and location coordinates.

Table 3. Site details for the blue carbon assessment of seagrass meadows in North Minahasa and Sangihe Is., Indonesia. Hp= *Halodule pinifolia*, Ea =*Enhalus acoroides, Th = Thalassia hemprichii, Cs = Cymodocea serrulata, Cr =Cymodocea rotundata, Hu = Halodule uninervis, Si = Syringodium isoetifolium*, Ho = *Halophila ovalis*, *Tc = Thalassodendron ciliatum.*

SITE	DESCRIPTION	Area (ha)	Latitude (°N)	Longitude (°E)
North Minahasa				
Tarabitan	Reference site. A healthy, intertidal seagrass meadow with no obvious disturbance. The site was dominated by *Thalassia hemprichii* but seven other species are also found in the bay.	52	1.735008	124.97842
Bahoi	Impacted – An inter-tidal, mixed-species meadow impacted by gleaning, fishing boat traffic and anchoring. The meadow was dominated by *Halodule pinifolia* but with Ea, Th, Cs, Cr, Hu, Si present	39	1.720555	125.02083
Tamperong	Relatively unimpacted control site for Bulutui. A sub-tidal, mixed-species meadow in about 3 m water depth, dominated by *Thalassia hemprichii* but with Ea, Cs, Cr, Hu, Hp Si present. Some low intensity fishing and gleaning but very little in comparison to Bulutui and Bahoi.	44	1.704891	125.02314
Bulutui	Impacted. A sub-tidal, mixed species meadow in about 3 m of water, comparable to Tamperong but higher levels of disturbance from urban development, sewage, anchoring, fishnet cages. The meadow contains Ea, Th, Hp, Si and Ho	33	1.706138	125.01664
Sangihe Island				
Batuwingkung	Impacted – Fishing, gleaning, household waste disposal, including sewage (though this is a low density village). This is a sub-tidal meadow in about 1.5 m water depth, dominated by *Halodule pinifolia* but with Ea, Th, Cr, Cs, Hu, Si and Tc also present	33	3.527777	125.65806
Bulo	Unimpacted - MPA since 2019. A sub-tidal (1.5 m water depth), multi-species meadow dominated by *Enhalus acoroides* with Th, Cr, Cs, Ho, Hu, Hp, Si and Tc also present	7	3.511666	125.64111

4.2 Study Sites

NORTH MINAHASA

Four sites were assessed in North Minahasa: Tarabitan, Bahoi, Tamperong Island and Bulutui (Figure 9). Tarabitan and Tamperong were classified as undisturbed sites while Bahoi and Bulutui have experienced impacts from coastal development. The climate in this region is generally hot and humid, with an average temperature ranging from 21° to 31° Celsius. Since hurricanes do not pass through the region, the monsoon pattern is primarily responsible for seasonal effects. The rate of rainfall is heaviest during November to February (considered the rainy season), and the lowest during July to September (considered the dry season).

Seagrass beds in North Minahasa are impacted by human activity at varying intensities. The most common anthropogenic impacts are through gleaning, usually using relatively less destructive methods, such as hands, spears (including spear guns), and machetes. Artisanal fisheries use small boats, with or without outboard motors, usually using handlines, cast nets, and fixed gillnets. Static traps are common, targeting crabs and several types of seagrass-associated fish, such as Siganidae, Labridae. Boat scars are less evident and are not an important detrimental factor. Due to their proximity to relatively dense settlements, inadequate solid waste management might contribute to the influx of plastic debris and organic matter to the seagrass meadows.

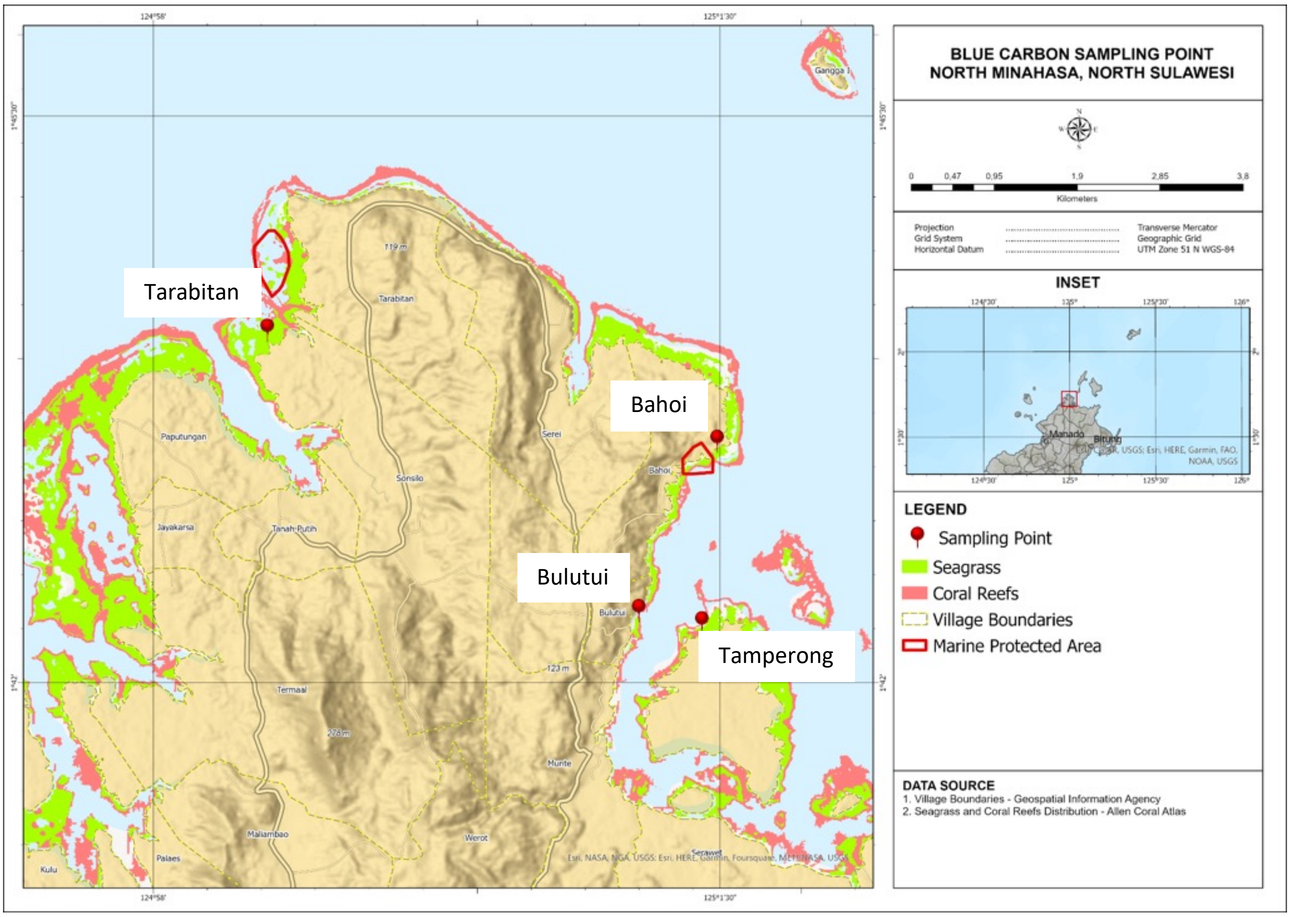

Figure 9 The location of the four blue carbon sampling sites in North Minahasa. Tarabitan, Bahoi and Tamperong were classified as 'undisturbed' sites, while Bulutui was considered a 'disturbed' comparison site for Tamperong.

Tarabitan

Tarabitan is classified as a reference (low-disturbance) site. The embayment adjacent to Tarabitan village contains 52 ha of inter-tidal and sub-tidal seagrass meadow and much of the shoreline contains intact mangroves (Figure 10). The sampling site was in an intertidal zone of the meadow, with mostly sandy gravel substrate and dominated by *Thalassia hemprichii* but with other species also present: *Enhalus acoroides, Cymodocea serrulata, Cymodocea rotundata, Halodule uninervis, Halodule pinifolia, Syringodium isoetifolium*, and *Halophila ovalis*.

The seagrass beds are scattered along the embayment up to the reef crests, often forming large patches. Sampling was carried out in a controlled area (control site), which is located close to the community based Marine Protected Area (CB-MPA) and close to the bay and mangrove ecosystem. Surrounding the sampling point, low-intensity anthropogenic activities occur, such as artisanal fishing and gleaning. The low level of community activity in this area is due to the distance from settlements and because the local communities prefer to fish in coral reefs or open seas.

Figure 10. Healthy seagrass meadow at Tarabitan. Top: seagrass at the sampling location; bottom (L): mangrove forests at Tarabitan Island adjacent to the sampling site; (R)) low-intensity artisanal fishing at the site.

Bahoi

The site, near Bahoi village, is a mixed species seagrass meadow of 39 ha (Figure 11). The site contains inter-tidal and sub-tidal seagrass meadow dominated by *Halodule pinifolia* but also contains *Enhalus acoroides, Thalassia hemprichii, Cymodocea serrulata, Cymodocea rotundata, Halodule uninervis, Syringodium isoetifolium*, and *Halophila ovalis*. The sampling was conducted in an area of the bay close to residential areas, and impacted by several community activities that occur directly within the meadow, including gleaning, fishing, boat traffic, and anchoring of small boats.

Figure 11. The Bahoi seagrass blue carbon site. Top (L): Seagrass meadows in front of the village settlement in Bahoi. (R): Sampling point for blue carbon offshore from Bahoi Village. Bottom: seagrass in close proximity to mangrove.

Tamperong Island and Bulutui

Tamperong Island is a marine protected area, opposite Bulutui village, with a healthy fringing mangrove forest (Figure 12). This unimpacted site, about 1 km from Bulutui village had about 44 ha of seagrass. The sampling site was in about 3 m of water with a mixed-species meadow dominated by *Thalassia hemprichii* but with *Enhalus acoroides, Cymodocea serrulata, C. rotundata, Halodule uninervis, H. pinifolia, Syringodium isoetifolium,* and *Halophila ovalis* also present. The site has some low-intensity fishing and gleaning.

Bulutui Village is located between Bahoi and Munte - a large transit hub and inter-island port. A 33 ha., sub-tidal seagrass meadow occurs in front of the village, impacted by boat traffic, anchoring and floating fishnet cages (**Error! Reference source not found.**). Some houses are built above the s ea and dispose household waste directly to the sea, including untreated sewage The sampling site was in about 3 m depth of water with similar seagrass to Tamperong Island, but lower density and with a thick, fine sand-muddy substrate.

Figure 12. The Tamperong Island and Bulutui sampling sites, which served as unimpacted and impacted comparison sites. TOP: The unimpacted site at Tamperong Island, adjacent to protected stands of mangrove forest. Bottom: The meadow offshore from Bulutui village, showing muddier sediments and community-owned fishnet cages.

SANGIHE ISLAND

Sangihe Island is an active volcanic island, roughly halfway between North Sulawesi and the Philippines. Relatively isolated compared to North Minahasa, Sangihe is under less anthropogenic pressure. Gleaning and other small-scale fishery practices are similar to those in North Minahasa, but much less intense. Small-scale gold mining activities might pose threats in some areas due to sedimentation, particularly in the south-east part of the island.

The climate in Sangihe is similar to North Sulawesi, the rainy season starting from November to February and the dry season from June until September. The average temperature is 27° centigrade, and the weather is humid with plenty of orographic rain. Slightly outside the typhoon zones, Sangihe's weather is often affected when tropical hurricanes hit the Philippine area.

Two sites were sampled at Sangihe Island (Figure 13; Table 3). Bulo, was relatively undisturbed and acted as the control condition. Batuwingkung had similar geomorphological and biological characteristics but has been subject to some human disturbance. It was included as the disturbed counterpart to assess any effect of gleaning and other activities on blue carbon.

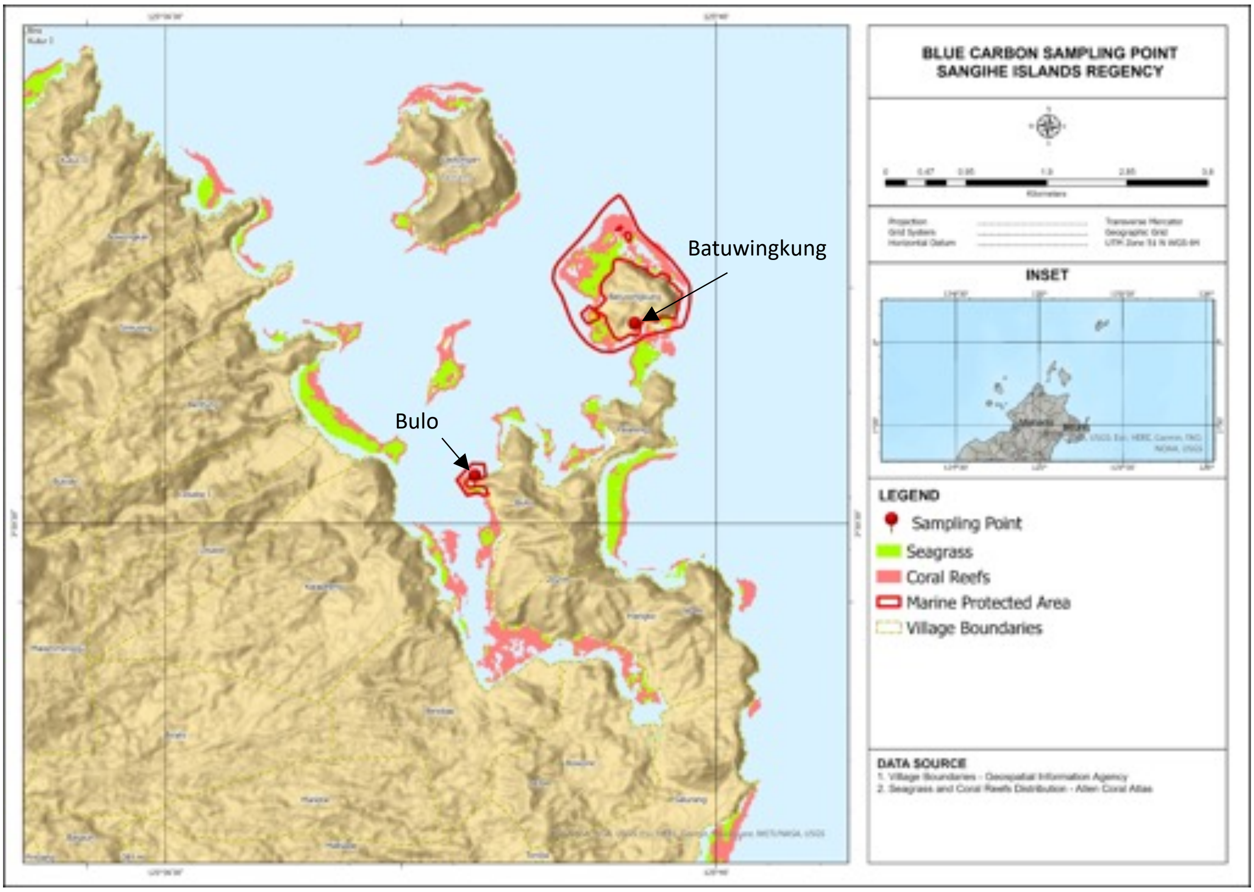

Figure 13. The location of the two blue carbon sampling sites at Sangihe Island. Bulo was classified as 'undisturbed' site, while Batuwingkung was considered a 'disturbed' comparison site**.**

Batuwingkung

The Batuwingkung site was close to Batuwinkung village and has experienced disturbance from a high intensity of fishing, gleaning, and boat traffic (Figure 14). Currently, the village dumps household waste directly to the sea, including cooking waste, sewage and plastics.

The seagrass meadow at Batuwingkung is about 33 Ha in area, on a sand substrate and dominated by *Halodule pinifolia.* but with *Enhalus acoroides*, *Thalassia hemprichii, Cymodocea rotundata, Cymodocea serrulate, Halophila ovalis, Halodule uninervis, Halodule pinifolia, Syringodium isoetifolium, and Thalassodendron ciliatum* also present. The sampling site was sub-tidal, in 1.5 m water depth.

Figure 14. The Batuwingkung sampling site at Sangihe Island. Top: Seagrass meadow close to Batuwingkung village. Bottom: The sampling location, showing an inserted blue carbon corer.

Bulo

The blue carbon sampling point in Bulo Village was located inside the no-take zone of the community-based-Marine Protected Areas (CB-MPA). Since the development of this CB-MPA in 2019, fishing activities have not been permitted inside the designated area and no motorboats are allowed to operate there, therefore this location was defined as the control sampling location. Seagrass covers about 7 ha of the MPA. The core sampling was done in the mud/sand substrate dominated by *Enhalus acoroides* (Figure 15). However, other seagrass species are found in this location: *Thalassia hemprichii, Cymodocea rotundata, Cymodocea serrulate, Halophila ovalis, Halodule uninervis, Halodule pinifolia, Syringodium isoetifolium and Thalassodendron ciliatum*. The sampling site was sub-tidal, in 1.5 m water depth.

Figure 15. The Bulo sampling site at Sangihe Island, was considered a control (baseline) site for comparison with Batuwingkung. Top: Seagrass meadow inside the community-based-MPA. Bottom: The Blue carbon sampling point.

4.3 Core collection, processing, laboratory analysis and numerical procedures

Prior to core collection, the National Partner YAPEKA received training on the field techniques for core collection and the laboratory techniques for 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. ECU ensured the NPs had the necessary sampling equipment and were available via video connection during the sampling event to provide technical support.

At each site, four seagrass cores were collected to determine the carbon characteristics for comparison of undisturbed and disturbed sites. The methods used for collecting and processing the cores, and the numerical procedures used to determine carbon stocks and accumulation rates, followed published protocols, modified to suit the local circumstances of the national partner while providing scientifically robust estimates of the stocks and accumulation rates. Full details of the methods are provided in Appendix A. and the instructional videos can be accessed at websites provided in Appendix B.

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 the carbon stocks in their seagrass soils. Two common ways to estimate the C_{org} content of seagrass soils are by direct measurement, using an elemental analyser, and by indirect estimation based on Loss on Ignition (LoI) measurements (Fourqurean et al 2012; Howard et al. 2014). Elemental analysis is costly and requires access to an analyser, which is not always available whereas the LoI method is more easily performed but is not a direct measure of the carbon content. In the four countries where the SES project's blue carbon assessments were conducted, a combination of the two approaches was used, providing a method to estimate the soil C_{org} content which is less expensive and can be performed using readily available laboratory equipment. Globally, a strong relationship has been reported between seagrass soil C_{org} and soil organic matter (OM) content, with OM explaining about 96% of the variability in C_{org} (Fourqurean et al 2014). Furthermore, OM is relatively inexpensive to measure using the Loss on Ignition (LoI) method. In the SES project, about 50% of the soil sampled were analysed by both methods to develop the relationship for each region as a whole and for each study site independently.

In the case of Indonesia, it was not possible to develop a regional relationship between seagrass soil OM and soil OC. Samples were successfully collected form all sites and were analysed for soil organic matter (LoI). However, it was not possible to analyses the soil samples for C_{org} on an elemental analyser. Despite considerable effort it was not possible to locate a laboratory within Indonesia which could perform the analyses. The major laboratories which routinely perform these analyses were all unavailable due to equipment breakdown. The alternative was to export the samples to ECU where the analyses could be performed, however this was not possible due to the inability to obtain a soil export permit from the Indonesian government. This had been identified as a potential risk early in the project and it was unfortunately that the considerable efforts to obtain a permit and associated agreements to export the samples could not mitigate the risk. Nonetheless, the sample remain available for analysis should an export permit be obtained, or an Indonesia laboratory is able to perform the analyses. Given the relatively low number of seagrass blue carbon studies in Indonesia but the extensive seagrass blue carbon habitat that exist s in the country, it is recommended that the sample are analysed in the future should the resources be available, as they will be a significant addition to the national dataset.

Due to the absence of a region-specific conversion factor, the global conversion factor developed by Fourqurean et al. (2014) for seagrass soils was used to convert the OM data into estimates of soil organic carbon content (%), where:

$$C_{org} = (0.0678.\,OM) + 0.5528$$

Where C_{org} is soil organic carbon content (%), and OM is the soil organic matter content, estimated from the Loss on Ignition (%).

The full Fourqurean et al. (2014) data set was used rather than data only for the Indonesian/Malaysian region sub-set of data since the full relationship was stronger. Consequently, these C_{org} estimates, and the stock estimates which are based on them, should eb considered Tier 1 estimates.

5.2 Soil C_{org} stocks in North Minahasa and Sangihe seagrass ecosystems

Soil C_{org} Stocks

The mean soil C_{org} stocks in the top 100 cm of soil differed significant among sites. The Sangihe reference site (Bulo) had the highest mean stock of 458 ± 68 Mg C_{org} ha^{-1}, and the impacted Bahoi site had the lowest, at 93 ± 3.6 Mg C_{org} ha^{-1}, almost a five-fold difference (Figure 16; Table 4; see Appendix C for statistical testing). Assuming the Bulo and Tamperong reference sites are representative of healthy mixed-species meadows in the region, undisturbed seagrass meadows are capable of containing C_{org} stocks in the order of 200-450 Mg C_{org} ha^{-1}, among the very highest recorded in Indonesia (Table 1) and well above the global mean reported for seagrasses of about 140 Mg C_{org} ha^{-1} (Duarte et al. 2013).

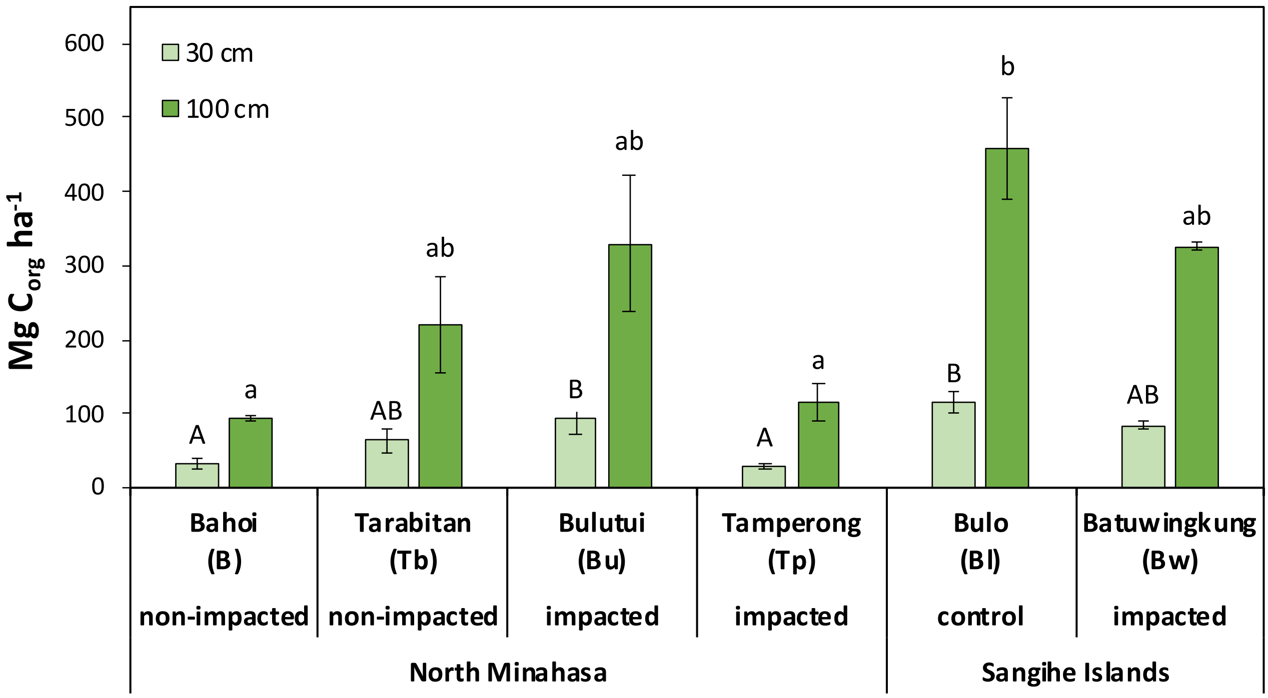

Figure 16. Mean (± SE) organic carbon (C_{org}) stocks in 30 cm and 100 cm-thick soil seagrass deposits collected in North Minahasa and Sangihe. The organic carbon values were estimated from the Loss on Ignition data by applying the LoI v O.C. regression from Fourqurean et al. (2014)

Table 4. Soil C_{org} stocks in North Minahasa and Sangihe Island seagrass ecosystems.

Location	Site type	Soil C_{org} stock. (Mg C_{org} ha^{-1})			
		30 cm		100 cm	
		Mean	s.d.	Mean	s.d.
North Minahasa					
Tarabitan	Control	63.54	16.37	219.34	64.28
Bahoi	Disturbed (gleaning, fishing, anchoring)	32.07	6.69	93.21	3.65
Tamperong	Control	28.02	4.34	115.21	26.59
Bulutui	Disturbed (sewage, fish cages, anchoring)	92.89	19.71	329.62	92.41
Sangihe Island					
Bulo	Control	113.64	14.35	458.12	68.63
Batuwingkung	Mildly Disturbed (gleaning)	84.21	4.59	326.01	5.70

Within the North Minahasa region, the greatest top 100 cm stocks were found at Bulutui and the least at Bahoi, however, the stocks were not statistically significantly different, despite the 3.5-fold range in means. Tarabitan served as the undisturbed control for comparison against the disturbed Bahoi site and had a mean C_{org} stock of 219 Mg C_{org} ha^{-1} more than twice that measured at Bahoi (93 Mg C_{org} ha^{-1}), those these differences were not statistically significant. This difference may well represent the effect of disturbance on the seagrass soil C_{org} stocks. In contrast, the highest stocks in this region occurred at Bulutui, the most impacted site, which had almost three-fold higher stocks that at its control site, Tamperong (329 and 115 Mg C_{org} ha^{-1}, respectively). The organic-rich sediments observed at Bulutui may reflect either terrestrial soil inputs and/or the reported discharges or organic waste into the bay from the village. Stable isotope analysis of the sediments would help to confirm this, and while originally planned to be part of the study, could not be completed due to the inability to export the samples for analysis prevented this. Again, the samples are still held by Yapeka and could be analysed in the future. The findings prevent any conclusions being drawn on how the development at Bulutui is affecting the sequestration of carbon by seagrasses, though future analysis of the samples could assist with this. However, the comparison of the Tarabitan and Bahoi sites does provide insight into the potential effect of coastal development on seagrass carbon sequestration, indicating a loss of more than 50% of carbon storage.

At Sangihe Island, the mean soil C_{org} stocks were higher at the Bulo control site than at Batuwingkung, though were exceptionally high at 458±69 and 326±6 Mg C_{org} ha^{-1}, respectively (Figure 16). The differences were not statistically significant. These stocks place the two sites among the highest recorded, globally (Fourqurean et al. 2014; Serrano et al. 2019). They also provide one of the first opportunities to compare seagrass locations where the only major difference is the presence of gleaning at one. Given the lack of statistically significant difference between the sites, it is not possible to conclude that gleaning has resulted in a loss of soil organic carbon, though the 30% lower stock at the 'disturbed' Batuwingkung site suggest that further investigation may be warranted.

The stocks in the top 30 cm of the seagrass soils likely reflect the effects of recent conditions at the sites. Here, the trends in the top 30 cm stocks were almost identical to those in the 100 cm stocks and so they are not described separately, though the results are presented in Table 4 in case future studies are more focused on the upper soil layers, as may be the case for carbon crediting projects.

C_{org} accumulation rates

It was not possible to develop estimates of the carbon accumulation rates at any of the sites. While samples were collected for radioisotope analysis and dating, it was not possible to obtain an export permit from the Indonesian government to allow the samples to be analysed overseas. The BRIN laboratory had been equipped to perform the analyses prior to the beginning of the SES project, but due to equipment and staff issues was unable to perform the analyses during the period of the SES project. Without the ^{210}Pb or ^{14}C analyses it was not possible to stablish a sediment accumulation rate or a carbon accumulation rate.

The inability to establish carbon accumulation rates for the sites was frustrating given that the samples had been collected and processed. This was made even more disappointing given that there are no other published accumulation rates for seagrass ecosystems in Indonesia and these rates are important for the development of any carbon crediting projects. Any accumulation rate estimates for seagrasses within Indonesia will have immense value not only for YAPEKA and the SES project communities but, given the absence of any estimates for elsewhere in the country, they will inform projects in other locations. YAPEKA is in a strong position to produce these estimates if they can identify a partner in Indonesia who can perform the laboratory analyses (e.g. BRIN once they overcome the current technical issues) or if they can obtain an export permit and send the samples to ECU or any other certified laboratory to perform the analyses and provide an age-depth model.

Surface elevation rods were established at all six of the study sites, as an alternative means of obtaining carbon accumulation rates. Four replicate rods were installed at each site and measured on the day of installation. However, all rods at all sites were subsequently stolen and so could not be re-measured. It is believed that the stainless-steel rods are valued by local spearfishermen for making spears. Surface elevation measurements remain the most appropriate methods for obtaining CARs at the Indonesian study sites but an alternative approach will need to be developed. Installing full Relative Surface Elevation Tables (RSETs; see USGS, 2023) would likely overcome any issues associated with theft but would require more significant establishment costs and the purchase of an elevation table for repeat measurement. It is recommended that this approach be used should future blue carbon assessments be undertaken.

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

The total soil C_{org} stocks for seagrass at the seagrass sites has been estimated by scaling up the mean C_{org} stock in the top meter of soil to the total area occupied by seagrass. This was performed separately for each ecosystem types to account for differences due to disturbance intensity and type. The estimated total BC stock ranged from about 13,000 t $C0_{2\text{-}eq}$ at Bahoi to 39,500 t in Batuwingkung (Table 5). The total stocks have slightly different rankings to the earlier stocks due to the differences in the area of seagrass at each site, in particular Bulo has only 7 ha of meadow and so the total stock is the lowest of all sites, though it has the highest stocks per m^2 of meadow.

Table 5. Total area and organic carbon stocks in top 100 cm of seagrass carbon ecosystems in the North Minahasa and Sangihe Island sampling sites. 1 Mg = 1 tonne.

Ecosystem	Area (ha)	Mean Soil C_{org} stock (Mg C_{org} ha-^{1})	Total soil C_{org} stock (Mg C_{org})	Total Soil stock (Mg CO_{2-eq})
North Minahasa				
Tarabitan	52	219	11,400	41,860
Bahoi	39	93	3,630	13,340
Tamperong	44	115	5,070	18,600
Bulutui	33	330	1,0850	39,920
Sangihe Island				
Bulo	7	458	3,210	11,770
Batuwingkung	33	326	10,760	39,480

5.4 Potential for carbon abatement

The organic carbon stocks for the North Minahasa and Sangihe Island 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 avoided greenhouse gas (GHG) emissions in the seagrass ecosystems. Due to the absence of any carbon accumulation rates, it is not possible to estimate the potential abatement through enhanced sequestration (e.g. restoration or creation of a seagrass site). The potential for avoided emissions was estimated in two ways. First, we took the total stock of organic carbon in the top 100 cm of soil at a site and then assumed that any disturbance causing this carbon to be lost from the site would result in its exposure to oxygen and a portion of it would be remineralised. This approach has been used previously and is heavily dependent on the assumed proportion of carbon which is remineralised, which typically has been estimated to range between 0 and 100% (Pendleton et al. 2012; Ariaz-Ortiz et al. 2018; Serrano et al. 2019; Salinas et al. 2020). Here, to be conservative, we assumed that 25% and 75% of the carbon is ultimately remineralised and present the potential emissions as a range. The second approach was to compare the stocks at an undisturbed site and an appropriate disturbed comparison site, assuming that the undisturbed site was representative of the original condition of the disturbed site. The difference in stocks was used as an estimate of the potential emissions, again applying a remineralisation factor of 25-75%.

Using the first approach, the undisturbed sites Tarabitan and Bulo had mean soil C_{org} stocks of 219 and 438 Mg C_{org} ha^{-1}, respectively. Assuming all this stock were lost due to disturbance and subsequent soil erosion, and that 25-75% of the lost carbon was then remineralised, the potential emissions would range from 54 to 328 Mg C_{org} ha^{-1} (or 200 – 1200 Mg CO_{2-e} ha^{-1}). Using the second approach, the estimated potential emissions ranged between 20 and 346 Mg CO_{2-e} ha^{-1} (Table 6).

The data generated through this study, together with previously published estimates of carbon stocks in Indonesian seagrass meadows, can be applied to understand the potential carbon stocks and abatement opportunities at local and national scales. The stocks of carbon contained in the seagrass meadows in North Minahasa and Sangihe are high in comparison to global estimates. This information can be used to demonstrate to decision-makers and local communities the significant ecosystem service being provided by healthy seagrass ecosystems, and to argue for their conservation. The values can also inform accounting for land use and land use change in policy, including for the NDC accounting if or when seagrass ecosystems are included. The potential abatement values should be viewed as first-order estimates but have been made using explicit and conservative assumptions. These estimates can inform potential blue carbon projects, in terms of the potential abatement to be gained through the conservation of seagrass meadows which might otherwise be impacted. The estimates developed here indicate a particularly large abatement potential on a per hectare area. The abatement has not been expressed in financial terms because the carbon credit price in global and national voluntary markets is highly variable. Instead, the abatement potential has been expressed in tonnes (Mg) of CO_2 equivalent, to allow easy calculation of the potential financial benefit.

Table 6. Estimated potential abatement (avoided emissions) for North Minahasa and Sangihe seagrass sites. *Minimum estimates are based on the difference between the disturbed site and the undisturbed site with the lowest stock and assumes 25% of disturbed carbon is remineralised. **Maximum estimates are based on the difference between the disturbed site and the undisturbed site with the largest stock and assumes 75% of disturbed carbon is remineralised

Region	Mean Soil C_{org} stock (Mg C_{org} ha^{-1})			Total soil C_{org} stock (Mg C_{org} ha^{-1})		Total Soil stock (Mg CO_{2-eq} ha^{-1})	
	Healthy		Disturbed	Min*	Max**	Min*	Max**
North Minahasa	Tarabitan	Tamperong	Bahoi				
	219	115	93	5.5	94.5	20.2	346.8
Sangihe	Bulo		Batuwingkung				
	438		326	28	84	102.8	308.3

There is a growing awareness of the potential benefits of seascape management, whereby the focus is on a range of connected ecosystem types, such as seagrass, mangroves and reefs, rather than treating the ecosystems separately. One such connection is that between seagrass meadows and nearby mangrove forests, which potentially supply carbon into the meadows through exported leaf litter. Understanding the importance of fringing mangroves in seagrass carbon sequestration may reveal possibilities for integrated, multi-habitat blue carbon projects. One objective of the Indonesian case study was to assess whether the amount of soil carbon in seagrass ecosystems, and the proportion that was allochthonous, was affected by the proximity to mangrove forest. This was addressed by comparing sites with healthy mangrove forest adjacent to them (Tarabitan and Tamperong) with sites had impacted mangroves impacted (Bahoi and Bulutui), using stable isotope analysis. Stable isotopes have been used to estimate the proportion of allochthonous carbon in seagrass soils (e.g. Kennedy et al. 2010), including mangrove carbon. Unfortunately, this analysis could not be completed due to the inability to export the samples for stable isotope analysis and the absence of a laboratory within Indonesia to perform the analyses. The samples collected as part of the North Minahasa assessment remain available to investigate this aspect of seagrass blue carbon dynamics. It is strongly recommended that the samples be retained until resources or permits allow their analysis, and that CMS explore option to fund these analyses.

5.5 Methodological issues for BC assessments (Lessons learnt)

The four SES case studies, including that undertaken at North Minahasa and Sangihe, have provided valuable insights into methodological and permit issues associated with determining C_{org} stocks and accumulation rates (CAR), which could affect the capacity to implement the current, and 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 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, that is Carbon Accumulation Rates, or CAR. There is an absence of CAR measurements for Indonesia, forcing a reliance on global means or estimates from other places in SE Asia (e.g. Miyajima et al. 2022). As explained previously, any accumulation rate estimates for seagrasses within Indonesia will be extremely valuable, informing projects throughout the country.

Determining CARs 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, radioisotope (^{210}Pb or ^{14}C) methods to determine soil accumulation rates could not be implement due to legal constraints on exporting the samples for isotope analysis. This would normally be overcome by performing the analyses in an Indonesia laboratory but, as explained previously, that capability was not available within Indonesia during the timeframe of the SES project.

Yapeka attempted the alternative approach of using surface elevation rods to determine sediment accumulation rates at each site to. However, in all cases the rods were taken by fishers, even though we the use of these sticks for research had been announced to them. Relative Surface Elevation Tables (RSETs) are an alternative form of elevation measurement and are less likely to be removed but more costly to install. Given the potential and broad usefulness of CARs generated for seagrasses within Indonesia, it is recommended that YAPEKA retain the soil samples they have collected and work with CMS to find the resources to analyse these once an export permit can be obtained or when an Indonesia laboratory establishes the capacity to perform ^{210}Pb analyses and provide age-depth models. Meanwhile, it is recommended that the use of RSETs be explored, which would be relatively straightforward in intertidal meadows but would require some method development in sub-tidal situations.

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.

Relationships between OM and C_{org} could be established due to due to legal constraints on exporting the samples for C_{org} analysis and the absence of a laboratory within Indonesia which could perform the analyses during the period of the SES project. As for the sediment dating, it is recommended that YAPEKA retain the soil samples they have collected and work with CMS to find the resources to analyse these once an export permit can be obtained or when an Indonesia laboratory establishes the capacity to perform the elemental carbon analyses.

Permits

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

1. Permits to undertake field work to collect soil samples; or
2. 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 sessions, for the technical partners to build capacity among the NGO partners. COVID-19 travel restrictions prevented several technical partners travelling during 2020-2022, requiring a shift in approach. For the Blue Carbon assessments, training was provided through a combination of training videos produced specifically for the project and now available as on-line resources through the CMS's project webpage, and through on-line instruction during sampling and laboratory activities.

The on-line training resources proved useful in allowing the NGO partners to collect the necessary 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 small 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. Some examples of this, provided by the National partners, are:

- Failure to currently implement the LoI protocol, which relies on accurate measurement of weight loss in sugar standards; several of the laboratories did not take this measurement, instead making a visual assessment that all the sugar was gone, which unfortunately is often misleading.
- Breakages of the PVC corers due to inappropriate sampling site selection on hard (coral) substrate; and
- Towards the end of the project, it became apparent that the interpretation of the findings, and considering how the blue carbon data can be applied in the policy or business context was a significant hurdle for some NGO. What could effectively be explained face-to-face in a two- or three-hours discussion proved almost impossible to convey using other approaches. The Regional workshop held in August 2023 assisted the NPs in this regard but they felt that the time limitations (one week) did not allow them to fully understand the data analysis, and most expressed the hope that follow-up workshops could be arranged to fill the knowledge gaps.

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

- Relatively undisturbed seagrass meadows in the North Minahasa and Sangihe regions have soil C_{org} stocks of 220-460 Mg C_{org} ha^{-1}, among the greatest stocks measured elsewhere Indonesia and globally.
- Disturbance appeared to reduce the soil C_{org} stocks at some sites. In Sangihe, the disturbed site had about a 30% lower stock than the undisturbed site. In North Minahasa one disturbed site had 60% lower stock than the undisturbed site, but a second disturbed site had higher stocks than the undisturbed site, possibly due to the input of organic-rich materials for the adjacent town and rivers.
- Based on current estimates of the area of seagrass meadows at the four North Minahasa sites, the total stocks ranged from about 13,000 to 40,000 t of CO_{2-eq}., with a total of 114,000 t CO_{2-eq} across all four sites. At Sangihe Island, the two sites contained a total stock of about 107,000 t CO_{2-eq}. Conservation of these meadows will avoid emission of this carbon and may enhance stocks at the disturbed sites.
- The potential abatement associated with conservation of seagrass meadows in the region was estimated to be 20 – 346 t CO_{2-eq} per hectare.
- The values generated in this assessment for seagrass carbon stocks 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 any 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 in which all six of the project's NGOs participated; and
- **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 Indonesia.
  - The values generated in this assessment for seagrass carbon stocks, and potential carbon abatement through management, should 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 Indonesia.
  - 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** the CMS assist YAPEKA in completing the analysis of the seagrass soil samples collected during the SES for C_{org} (through elemental C analysis) and for dating of the cores and estimating Carbon Accumulation Rates. This could be achieved by having the analyses performed at one or more Indonesian laboratories within Indonesia, should the capability be established, or by exporting the samples to an overseas laboratory. Similarly, CMS should explore opportunities to fund the establishment of RSETs at the Indonesian sites. The cost of the analyses and establishing RSETs will be relatively modest compared to the investment already made in obtaining high-quality samples, and it would fill significant information gaps on Indonesian seagrass blue carbon, specifically OM:OC relationships, providing the first Indonesian CAR estimates and improving the estimates of stocks. This improved knowledge would deliver benefits well beyond the SES project, informing policy and projects nationally.

- **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;
    - The National partner 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 solely on radio-isotopic approaches. This will likely overcome some of the difficulties associated with the use of rods such as removal by local communities but will require specialist equipment and the development of suitable methods for sub-tidal sites;
    - Future efforts to build capacity in seagrass ecosystem service (blue carbon) assessment prioritise the inclusion of face-to-face field and laboratory techniques training.

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

Following are the standard methods which were applied across all four SES Project sites. In some cases, some components of the protocol could not be applied, as detailed in the individual site Blue Carbon technical reports. In the case of the Indonesian sites, elemental C_{org} analysis and core dating using ^{210}Pb and ^{14}C could not be completed due to in the inability to obtain an export permit for the samples and the lack of availability of any laboratory within Indonesia to undertake the analyses. Consequently, all carbon stock estimates are based on Organic Matter data, using the relationship in Fourqurean et al. (2012) and carbon accumulation rates (CAR) could not be estimated.

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 to Institute Pertanian Bogor University (IPB) where they were stored in airconditioned facilities until processing.

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 stored for subsequent Organic Matter (OM) and organic carbon (via elemental analysis) analyses and for dating using ^{210}Pb and ^{14}C (radiocarbon).

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 intended to be determined using a Costech Elemental Analyzer interfaced to a Thermo-Finnegan Delta V Isotope Ratio Mass Spectrometer at UH-Hilo Analytical Facilities. However, this was not possible for reasons explained above.

Figure 17. YAPEKA team members undertaking blue carbon core collection at study sites in North Minahasa.

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 Institute Pertanian Bogor 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

It was intended to determine soil and C_{org} sequestration rates for one core from each site by means of ^{210}Pb (short-term accumulation; last ~100 years) and radiocarbon (long-term). For re4asons explained above, this was not possible. The method is described below in order that any future studies can apply methods comparable to those used in the other SES project sites.

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 (Figure 18). At each site, four stainless rods (5 mm-thick 1.6 m long) were driven into the soils to a depth of 1.2 m, leaving exactly 60 cm above the sediment surface. The rods were located along a single line, separated by 5 m from each other. 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 when measuring the height of the rod above the sediment.

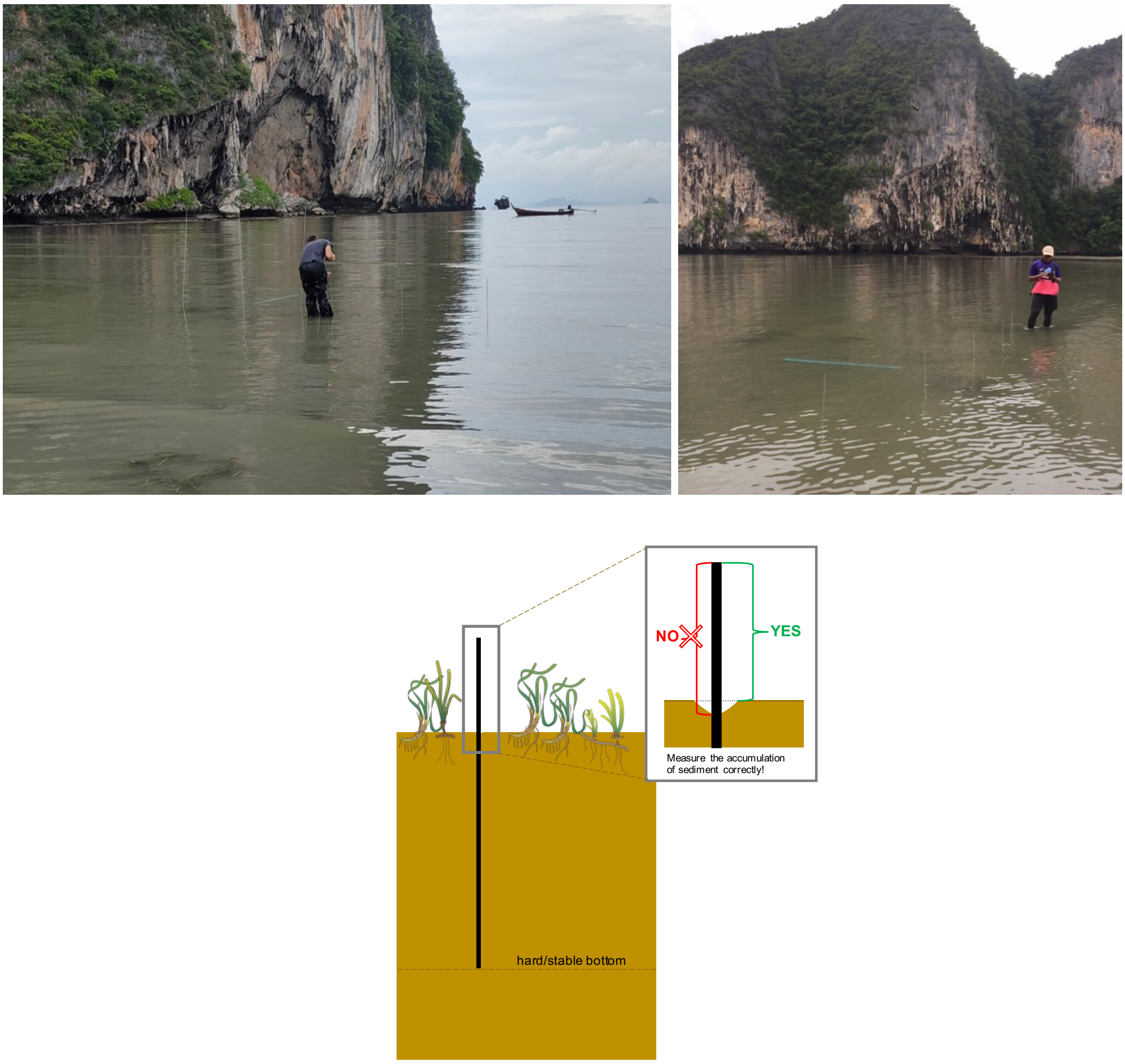

Figure 18 Surface Elevation Rods being installed in seagrass meadows. Schematic diagram at bottom shows the measurement approach.

Numerical procedures.

While carbon accumulation rates could not be determined for the Indonesian sites, the methods, which were applied at the other SES Project sites are provided here, to allow consistency across sites should an opportunity arise in the future to analyse the Indonesian soil samples.

The CF:CS model (Krishnaswamy et al. 1971) was used to estimate the average soil accumulation rates (SAR) for the last century, where possible. 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 $\%C_{org}$ estimated from LoI. 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 several 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 seagrass BC site (Undisturbed and Disturbed) by the area of seagrass at the site. Area estimates for each habitat type were based on previous mapping by the National Partner officers familiar with the area.

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 Summary data for North Minahasa and Sangihe seagrass cores

Table 7. Summary of habitat type and soil C_{org} parameters for all cores collected in North Minahasa and Sangihe. Hp= *Halodule pinifolia*, Ea =*Enhalus acoroides, Th = Thalassia hemprichii, Cs = Cymodocea serrulata, Cr =Cymodocea rotundata, Hu = Halodule uninervis, Si = Syringodium isoetifolium*, Ho = *Halophila ovalis Tc = Thalassodendron ciliatum*

Core ID	Site	Type of site	Sampling date	Species	Max core depth cm decompressed	Top 30 cm C_{org} stock Mg C_{org} ha^{-1}	Top 100 cm C_{org} stock Mg C_{org} ha^{-1}
B1	Bahoi	non-impacted		**Hp** + Ea Th, Cs, Cr, Hu, Si	70	19.2	95.1
B2	Bahoi	non-impacted		**Hp** + Ea Th, Cs, Cr, Hu, Si	65	35.4	86.2
B3	Bahoi	non-impacted		**Hp** + Ea Th, Cs, Cr, Hu, Si	70	41.6	98.4
Bu1	Bulutui	impacted		**Ea** + Th, Hp, Si and Ho	54	76.9	246.6
Bu3	Bulutui	impacted		**Ea**, Th, Hp, Si and Ho	55	69.7	228.1
Bu4	Bulutui	impacted		**Ea**, Th, Hp, Si and Ho	58	132.1	514.1
Tb1	Tarabitan	non-impacted		**Th** + Ea Th, Cs, Cr, Hu, Si, Ho	58	62.5	344.4
Tb2	Tarabitan	non-impacted		**Th** + Ea Th, Cs, Cr, Hu, Si, Ho	58	92.4	182.6
Tb4	Tarabitan	non-impacted		**Th** + Ea Th, Cs, Cr, Hu, Si, Ho	58	35.7	131.0
Tp1	Tamperong	impacted		**Th** + Ea, Cs, Cr, Hu, Hp Si	60	30.2	164.8
Tp2	Tamperong	impacted		**Th** + Ea, Cs, Cr, Hu, Hp Si	57	34.2	107.0
Tp4	Tamperong	impacted		**Th** + Ea, Cs, Cr, Hu, Hp Si	58	19.7	73.8
BL2	Bulo	non-impacted		**Ea** + Th, Cr, Cs, Ho, Hu, Hp, Si, Tc	97	98.3	345.0
BL3	Bulo	non-impacted		**Ea** + Th, Cr, Cs, Ho, Hu, Hp, Si, Tc	72	142.3	582.0
BL4	Bulo	non-impacted		**Ea** + Th, Cr, Cs, Ho, Hu, Hp, Si, Tc	76	100.3	447.4
BW1	Butuwingkung	impacted		**Hp** + Ea, Th, Crt, Cs, Hu, Si, Tc	68	75.6	322.5
BW2	Butuwingkung	impacted		**Hp** + Ea, Th, Crt, Cs, Hu, Si, Tc	69	91.3	318.4
BW4	Butuwingkung	impacted		**Hp** + Ea, Th, Crt, Cs, Hu, Si , Tc	75	85.8	337.2

Appendix D Statistical test for difference in soil characteristics among seagrass sites

Table 8. Outcomes of statistical test for significant differences in soil carbon characteristics among the seagrass blue carbon sites in North Minahasa and Sangihe Island: (A) soil C_{org} content (%), LoI, dry bulk density (DBD) (Kruskal-Wallis Test; A) and soil C_{org} stocks (ANOVA test; (B) in the top 30- and 100- cm of soils.

A)

Parameter	K-W Test	Top 30 cm						Top 100 cm					
		B	Tb	Bu	Tp	Bl	Bw	B	Tb	Bu	Tp	Bl	Bw
DBD (g/cm^3)	N	56	62	58	58	62	66	73	74	71	71	86	88
	Mean rank	58	146	208	190	196	275	80	182	248	242	248	364
	H-value	143.9						192.3					
	p-value	0						0					
LOI (%)	N	56	62	58	58	62	66	73	74	71	71	86	88
	Mean rank	110	169	263	51	306	180	127	211	333	67	393	231
	H-value	240.76						321.0					
	p-value	0						0					
Soil C_{org} content (%)	N	56	62	58	58	62	66	73	74	71	71	86	88
	Mean rank	110	169	263	51	306	180	127	211	333	67	393	231
	H-value	240.76						321.0					
	p-value	0						0					

B)

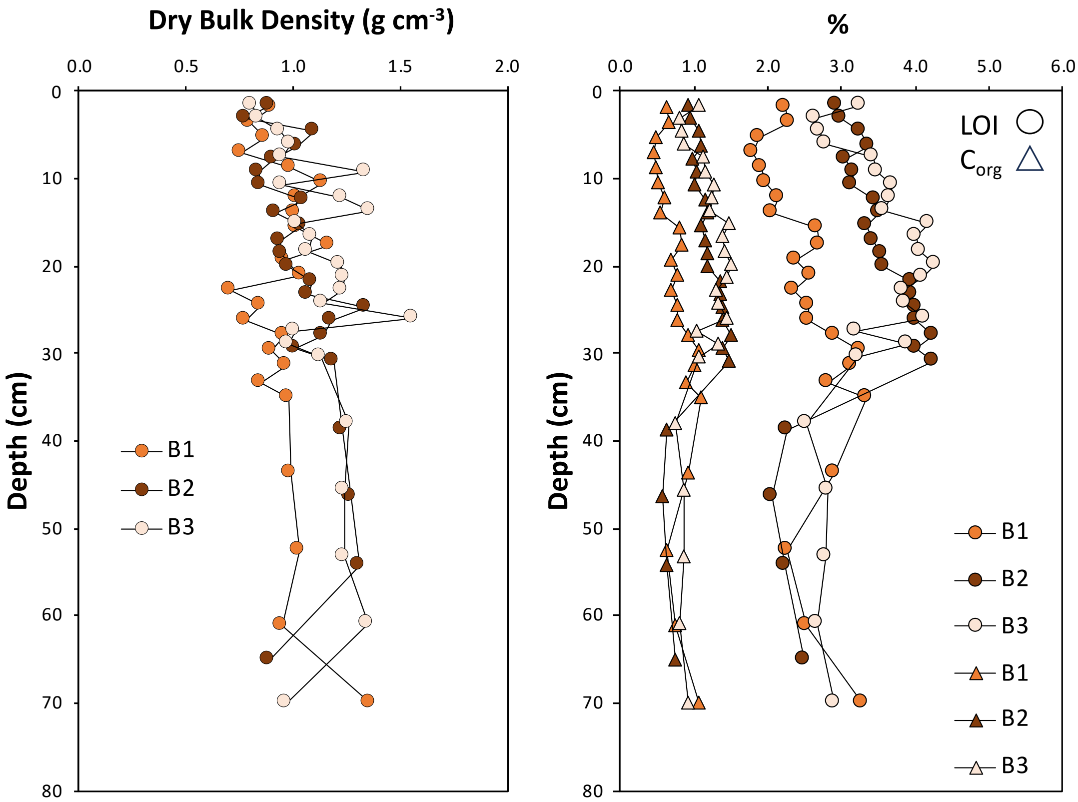
Parameter	core section	one-way ANOVA				
		Sum of Square	df	Mean Square	F	*p* value
Soil C_{org} stock (Mg OC ha^{-1})	top 30 cm	17606	5	3521	7	0.002
	top 100 cm	296499	5	59300	7	0.004

Appendix E: Seagrass soil characteristics at the North Minahasa and Sangihe Island sites

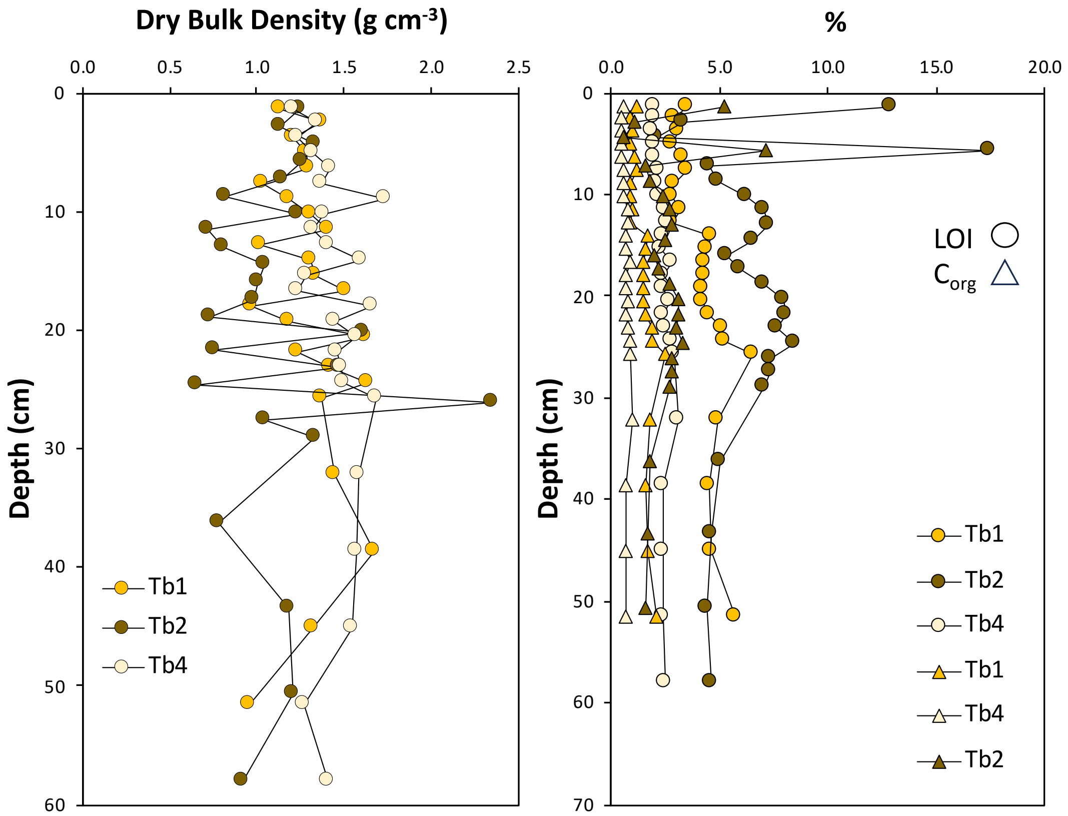
Dry Bulk density, LoI and Organic Carbon.

LoI and Organic Carbon are presented in the same graphs as Organic Carbon was calculated from the LoI values using the regressions provided by Fourqurean et al. (2012)

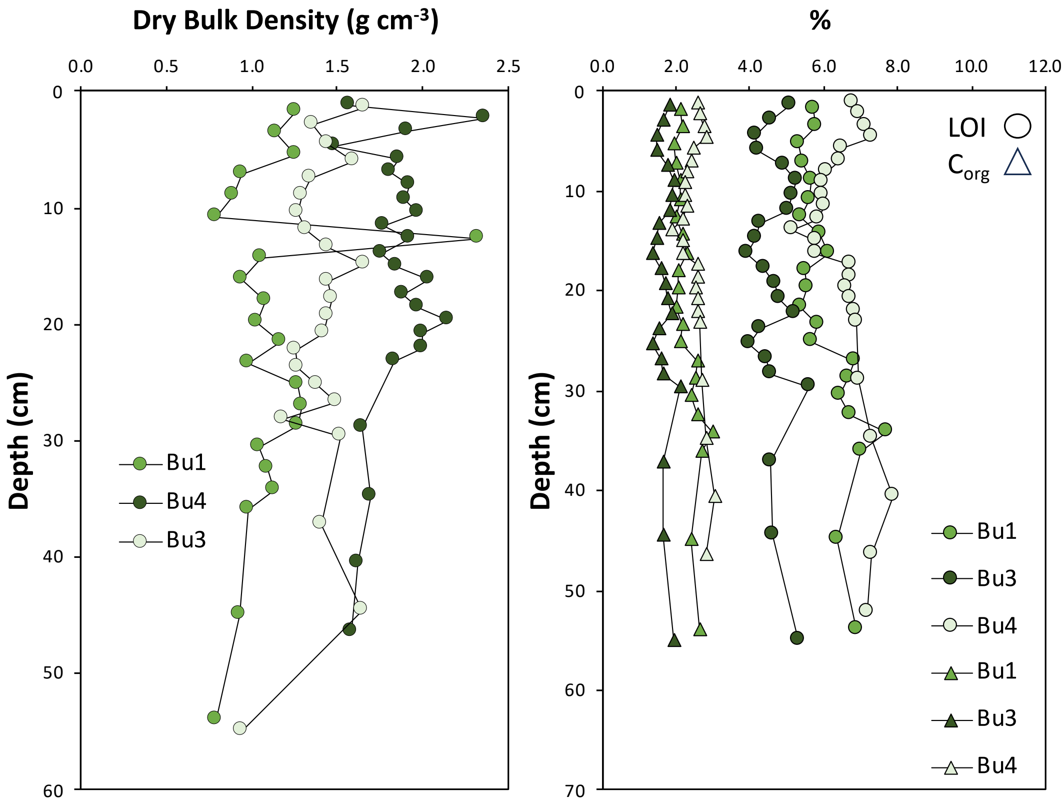
a) Bahoi: impacted seagrass meadow (coastal development, anchoring, organic pollution).



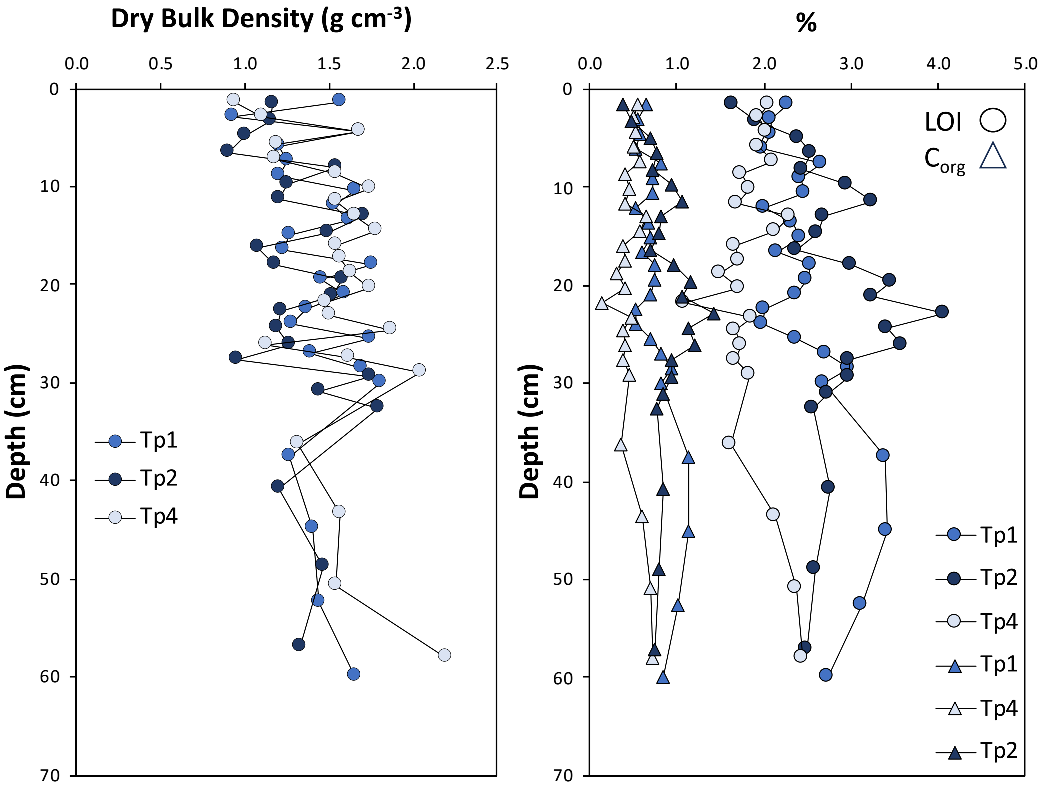
b) Tarabitan Island: unimpacted seagrass meadow.



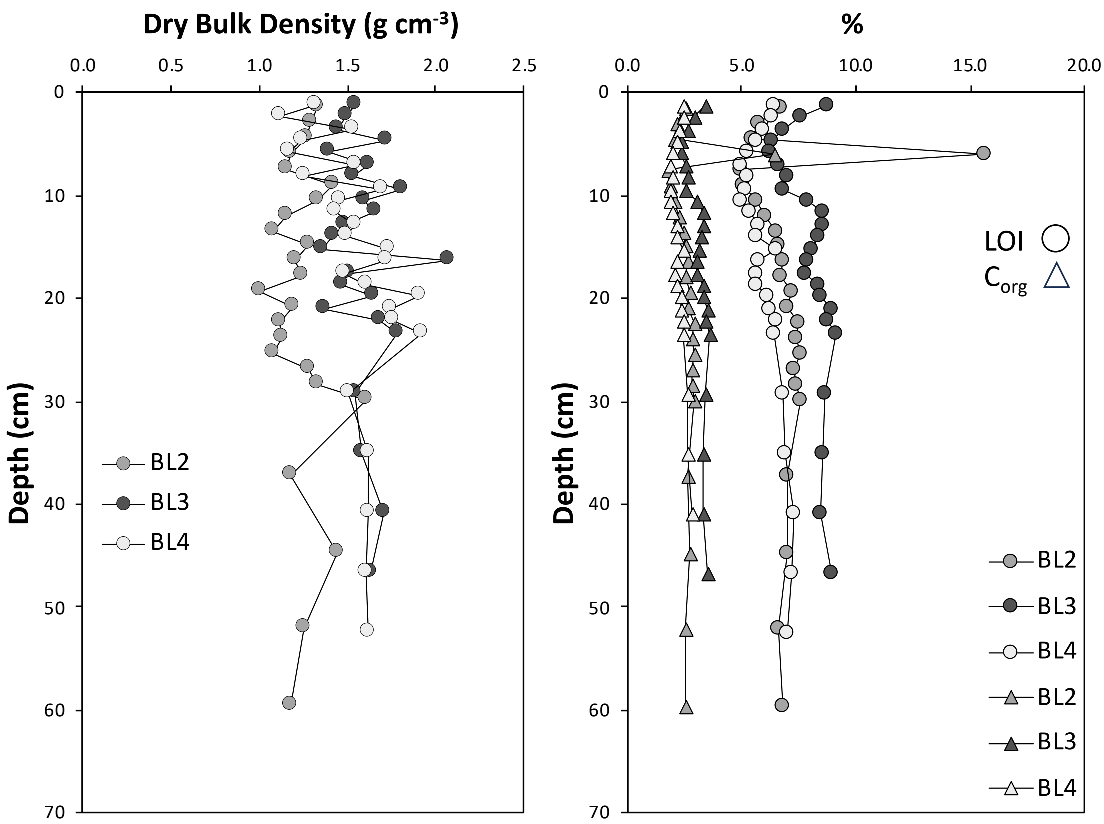
c) Bulutui: impacted (coastal development, sewage, fishnet cages) seagrass meadow.



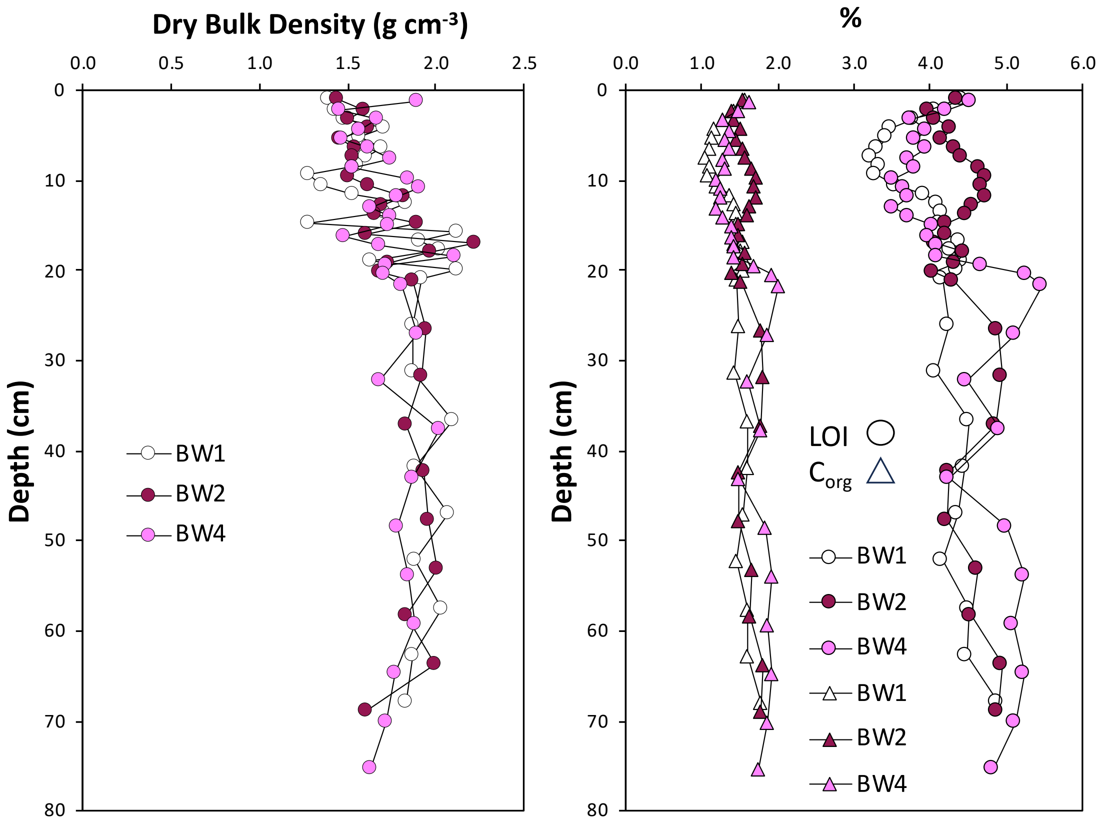
d) Tamperong: Unimpacted (control) seagrass meadow.



e) Bulo: Unimpacted (control) seagrass meadow.



f) Batuwingkung: Impacted (gleaning) seagrass meadow.



e) Mean data for the four North Minahasa and two Sangihe Island sites

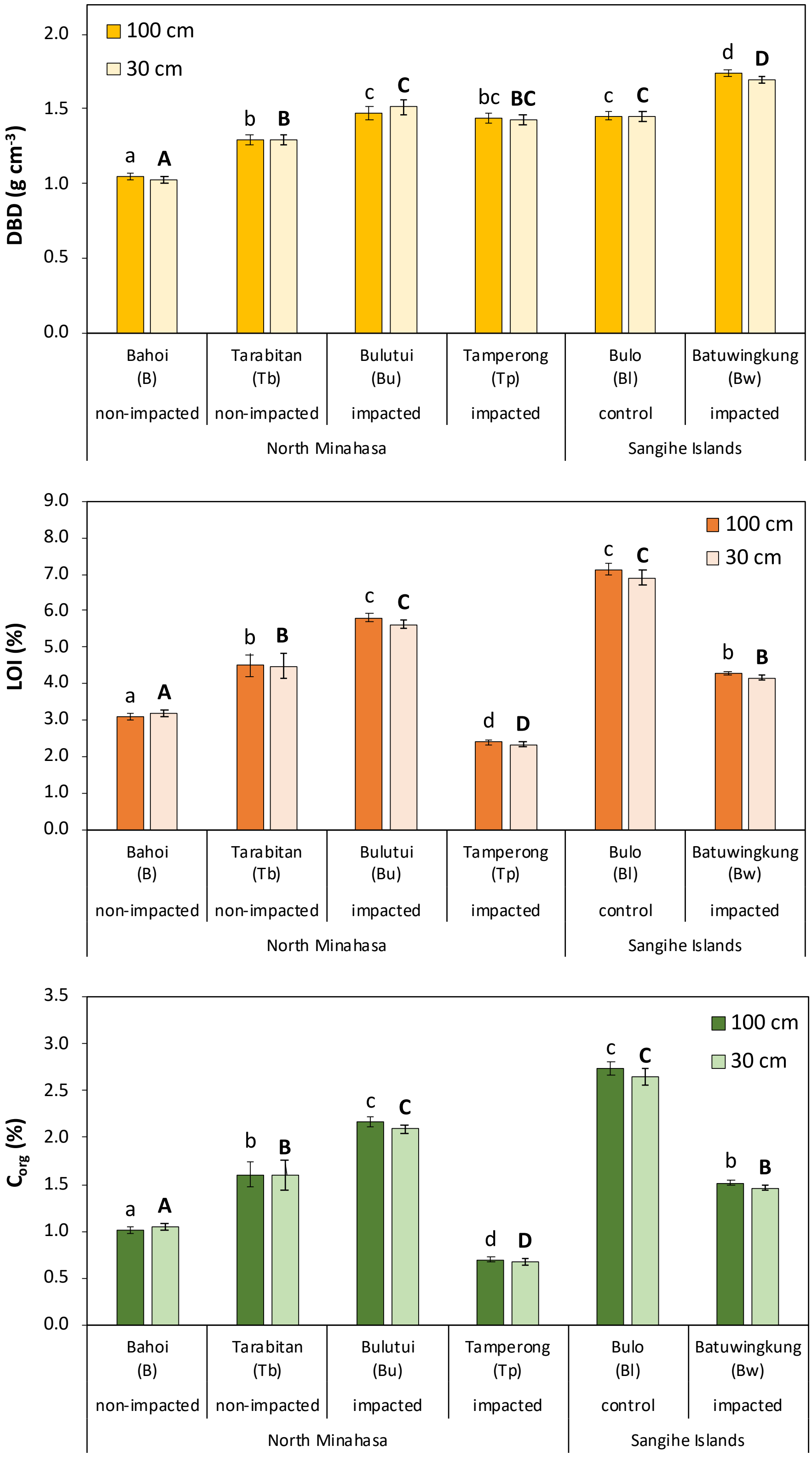


Figure 19 Mean (± s.e.) DBD, % LOI and % C_{org} in the top 30 and 100 cm of seagrass soil in Thailand. Shared letters indicate no significant different ($p > 0.05$)

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