Estimation of soil carbon storage under mono-specific Enhalus acoroides meadows in Pari Island, Indonesia

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Abstract. Large seagrass meadows in Indonesia are predicted to have a significant ability in capturing and storing carbon and are useful to mitigate global climate change. However, most of the available data are derived from short-term carbon storage of living biomass, whereas data on long-term carbon storage in the soil is still limited. This study, therefore, aims to measure soil carbon storage in mono-specific Enhalus acoroides meadows in Pari Island. A total of nine soil cores was collected in a 100x100 m² area. The parameters were soil depth, dry bulk density (DBD), and C<sub>org</sub> content. We applied a PVC corer with 7.4 cm in diameter and 80 cm in length to collect the soil. The length of the soil core varied between 8 and 67 cm. The mean (±SE) of soil dry bulk density is 0.98±0.04 gr/cm³ and the median is 1.1 gr/cm³, while C<sub>org</sub> content is 2.1±0.1% soil DW (mean±SE) and 1.9% (median). E. acoroides vegetation in Pari Island stores around 63 Mg Corg/ha organic carbon in 8-67cm or 34cm (mean depth) of topsoil. Carbon storage of these mono-specific meadows is comparable to soil carbon storage in the seagrass ecosystems per hectare areas on national, regional, and global levels.

Keywords: blue carbon, climate change, organic carbon, seagrass, the sediment of seagrass

1. Introduction
Seagrass meadows, a blue carbon habitat, significantly contribute to climate change mitigation and adaptation [1]. Seagrass ecosystem provides regulation services, capturing organic carbon from other systems and storing it for long periods (centuries or even millennia), mainly in their sediments [2, 3]. Carbon storage of this ecosystem has been estimated at 194.2 ± 20.2 Mg C/ha and 121.95 ± 76.11 Mg C/ha at global and regional (Southeast Asia) levels, respectively. However, information on carbon storage in seagrass meadows at a national level, for example in Indonesia, is limited [3, 4]. The lack of carbon storage data would hinder the development of climate change mitigation policies, particularly in Indonesia, home to the second largest seagrass area in the world [5] and globally significant blue carbon habitats [6].

Seagrass ecosystems in Indonesia are predicted to contribute significantly to global carbon storage and sequestration. [7] estimate that seagrass meadows in Indonesia store carbon around 368 Tg C or almost 2% of the world’s marine value in both living biomass and sediment. A more recent study using a single proxy of seagrass coverage showed that seagrass meadows in Indonesia could fix C<sub>org</sub> for about 1.6 to 7.4 Mg C<sub>org</sub>/year [6]. Since the first report of Blue Carbon by UNEP in 2009 [2], the study of seagrass meadows as blue carbon habitats has developed in Indonesia, estimating the potential carbon storage in living seagrass biomass and sediment. Most studies measured carbon storage on living...
biomass [6, 8–10] which has short-term carbon storage. Recently, there has been available data on soil carbon storage in some areas across Indonesia [11–13]. Yet, it did not provide comprehensive information such as compaction factor and Dry Bulk Density (DBD), so the results may present an over/under-estimated value. Assessment of carbon storages in seagrass soil is vital as more than 90% of organic carbon is deposited in the soil [4, 14], making soil carbon the main component of blue carbon projects [14–16].

Pari Island is in the south part of Thousand Islands, North Jakarta. Seagrass meadows in this area are distributed all over the reef and the condition has been relatively stable in the last three decades [17]. Studies of seagrass as blue carbon habitat in the mono-specific *Enhalus acoroides* meadows in Pari Island were conducted in 2012 [18], yet it was only based on the standing carbon storage. This study aims to assess soil carbon storages in mono-specific *E. acoroides* meadows in Pari Island. The results of this study are expected to contribute to existing soil carbon storage database at national, regional, and global levels, which is of importance for seagrass conservation, management action of climate change mitigation and adaptation.

2. Materials and Methods

The study was carried out in the northwest of Pari Island (106.609110° BT-5.862870° LS) in February 2021. The site is a relatively closed area with soil types dominated by muddy sand. The seagrass meadow is mono-specific *Enhalus acoroides* that always submerge in the water along the season with different water depths across the reef and occur in shallow and low-wave energy areas. This kind of vegetation is only found on the north side of the island.

As the protocol, we followed “Blue Carbon in Seagrass Ecosystem: Guideline for the Assessment of Carbon Storage and Sequestration in Southeast Asia” [19]. We measured three main parameters: soil depth, dry bulk density (DBD), and soil organic carbon content. The measurements were carried out in the Botany Laboratory, Research Center for Oceanography, Indonesian Institute of Sciences. We also estimated the seagrass coverage to assess the seagrass condition, as well as seagrass density.

Three 100 m transects were laid seaward with an interval of 50m. In each transect, we estimate seagrass cover in every 10m interval starting from 0m to 100m and seagrass density in every 30m; in total, we have 33 plots of seagrass coverage data 12 plots of seagrass density within the study area. At the same transect, we collected three sediment cores at 0m, 50, and 100m making nine cores. The core, 80 cm of PVC and 7.4cm in diameter, was pushed into the sediment by hand and a hammer when it hit a more rigid substratum. Hammering can cause sediment compaction, so we calculated the correction factor by measuring the core’s depth (inside and outside) (formula 1, table 1) when the core cannot penetrate the sediment any longer. Once a sediment core was collected, it was transported to the laboratory.

| Table 1. List of formulas to estimate soil carbon storage in seagrass ecosystems. |
|---|---|---|
| No. | Parameters | Formula |
| Formula 1 | Compaction correction factor | Length of sediment sample/ Depth of core |
| Formula 2 | Dry Bulk Density (gr/cm³) %LOI | Mass of dry sediment/ Original volume sampled [(Mass before combustion – Mass after combustion)/ Mass before combustion ] *100 |
| Formula 3 | C_{org} content (% soil dry weight) | Conversion factor for %LOI < 0.2 (r²=0.96) %C_{org} = 0.4*%LOI – 0.21 |
| Formula 4 | C-storage (gr C_{org}/cm²) or (Mg C_{org}/ha) | Dry Bulk Density * C_{org} |

Each sediment core was split by 5cm in the laboratory to know the stratification of bulk density and organic carbon content. The soil core was dried using an oven, 60 °C, for around 72 to 96 hours until it reached a constant dry weight. The dry sediment core was weighed to calculate the dry bulk density (Formula 2, Table 1). In this step, the volume of soil core was calculated by the length of original sample.
After that, the sediment was homogenized using a grinder, and a subsample of 5gr was collected to measure \( C_{\text{org}} \) by LOI (Loss on ignition) at 550°C for 12 hours [20]. The \( C_{\text{org}} \) calculation followed formula 3 (Table 1). The carbon storage was estimated by multiplying bulk density and \( C_{\text{org}} \) in each sample column (Formula 4, Table 1).

### 3. Results and Discussion

The mono-specific meadow of *E. acoroides* in Pari Island is in good condition. The mean coverage was around 27±3.2%, measured in high tide conditions which means the coverage could reach about 70% in low tide, and seagrass density was 176 shoots/m². Soil depth in the study area had a wide variation, while bulk density and \( C_{\text{org}} \) value are generally similar to the core depth (Figure 1). The total carbon storage in the meadows reached 63 Mg \( C_{\text{org}} \)/ha in 8-67 cm upper soil (mean depth=34cm) or 312 Mg \( C_{\text{org}} \)/ha in 1 m topsoils (Table 2). This value was much higher than the national, regional, and global carbon storage estimation.

#### 3.1. Soil depth profile

Based on the soil core, soil depth varied across the study area between 8 and 67 cm (original length) (Figure 1). Due to hammering, soil compaction has occurred in each sediment (less than 25%). Each transect showed a different depth profile from the coastline to the seaward area. The second transect had a short soil depth, while the third transect had deeper soil than the other transects. The soil depth near the coastline (plot-0m) was relatively shorter than in the middle (plot-50m) and seaward (plot-100m) plots, except the 2nd transect. Replication of soil core collection in a unit area (1 ha in this study) was conducted to capture soil depth variability in the seagrass ecosystem. Therefore, it is essential to follow a standard method in measuring soil carbon storage to obtain a comparable national blue carbon database.

#### 3.2. Soil Dry Bulk Density (DBD) and \( C_{\text{org}} \) content

The mean(±SE) of DBD was 0.98±0.04 gr/cm³, while the median was 1.1 gr/cm³ (Table 2). Most of the core had DBD around 0.8-1.2 gr/cm³, except the soil core in the 3rd transect (plot-0m and 50m), which had small DBD (< 0.8 gr/cm³). It may be because this section had finer sediment (e.g., higher mud proportion). Soil in the study meadows had lower density than global estimation (1.03±0.02 gr/cm³). The dominant soil type in this area is muddy sand, particularly in the middle of the meadows. Despite, seagrass ecosystems in Indonesia are dominated mainly by sandy soil [7, 21–25]. Unfortunately, in this study, there is no quantitative data of soil characteristics to support DBD data.

| Table 2. Soil properties in mono-specific *E. acoroides* meadow in Pari Island. |
|---------------------------------|--------|--------|--------|
| Soil DBD (gr/cm³)               | 0.4–1.4 | 0.98±0.04 | 1.1     |
| LOI (% soil DW)                | 3.8–14.9 | 5.8±0.3 | 5.4     |
| \( C_{\text{org}} \) (% soil DW) | 1.3–5.8 | 2.1±0.1 | 1.9     |
| Soil \( C_{\text{org}} \) storage (gr/cm³) | 0.01–0.06 | 0.02±0.001 | 0.02 |
| Soil \( C_{\text{org}} \) storage (Mg \( C_{\text{org}} \)/ha) (original dept) | 63±6.4 |       |        |
| Soil \( C_{\text{org}} \) storage (Mg \( C_{\text{org}} \)/ha) at 1m topsoil | 312±76.2^a | 230   |        |

This value is an extrapolation from the available data using formula by Fourquereau [3].

Organic carbon content in the soil estimated based on LOI was 5.8±0.3 % soil DW (mean±SE) and 5.4% (median) (Table 2). By applying the statistical relationship between %LOI and \%\( C_{\text{org}} \) [3], the mean(±SE) of \( C_{\text{org}} \) was 2.1±0.1 % soil DW, and the median was 1.9%. There is a possibility that \( C_{\text{org}} \) in this study has a higher value because \( C_{\text{org}} \) content from the LOI tends to have less value than direct measurement using an elemental analyzer [3]. The \( C_{\text{org}} \) content in the soil was generally around 1.9%, except for the soil core in the 2nd transect (plot-50m), showing a high carbon content (around 5%) in the 10cm upper soil.
Both DBD and C\textsubscript{org} content mainly performed a slightly fluctuated vertical profile (Figure 1). The DBD was ranged from 0.4 to 1.4 gr/cm\textsuperscript{3}, while C\textsubscript{org} content was from 1.3-5.8% soil DW (Table 2). DBD and C\textsubscript{org} are inconstant with depth [3]. A study in Indonesia showed C\textsubscript{org} content in the soil decreased along with the 50cm soil depth [7], this pattern similar to seagrass meadows in temperate regions [26]. In contrast, The same study by [26] showed some tropical seagrass meadows (mono-specific \textit{H. ovalis}; mix meadows of \textit{C. rotundata T. hemprichii S. isoetifolium H. uninervis}) have a positive trend of C\textsubscript{org} toward the depth, C\textsubscript{org} content is increasing with the depth. The vertical profile of C\textsubscript{org} in seagrass soil may be site-specific, and further study is needed to depict the factor driving soil C\textsubscript{org} profile in seagrass ecosystem.

![Figure 1. Profile of Dry Bulk Density (Left) and C\textsubscript{org} (Right) of soil at each transect and plot. (a). Transect-1, (b). Transect-2, (c). Transect-3.](image_url)
3.3. Estimation of C$_{org}$ storage in mono-specific E. acoroides meadows

The seagrass meadows in this study had relatively high soil carbon storage. The total organic carbon was 63±6.4 Mg C$_{org}$/ha in 8-67 cm upper soil. Compared to other locations in Indonesia, this study area had a large C$_{org}$ pool (table 3). Unavailability data of DBD, actual depth, and C$_{org}$ content of other studies make it hard to assume the differences in each value of soil carbon storage. To compare the soil carbon storage to other studies, we extrapolated carbon storage into 1 m depth by following the formula of Fourqurean [3], resulting in 312±76.2 Mg C$_{org}$/ha in meter topsoil (table 3). The extrapolation value is higher than the national, regional, and global estimations. The extrapolation may overestimate the actual organic carbon storage in the study area because the depth of each core is known; the core hit the base reef, as illustrated in Figure 1. The large C$_{org}$ stored in the E. acoroides meadows in Pari Island may be due to its morphological and habitat characteristics that are appropriate for soil accumulation, such as E. acoroides is a large and persistent species. It forms a continuous meadow. The meadow is in a sheltered and submerged intertidal. Also, the waters in the area have a low wave energy and moderate turbidity [27,28]. Further study may be needed to clarify the amount of soil carbon storage using direct measurement and determine factors controlling the soil accumulation in the species-specific of E. acoroides meadows.

Table 3. Carbon storage and its features in different sites on locals, regional, and global levels.

| Locations/levels          | Soil DBD (gr/cm³) | %LOI$^a$ (% soil DW) | C$_{org}$ (% soil DW) | Depth (cm) | Soil C$_{org}$ storage (Mg C$_{org}$/ha) | Ref.            |
|---------------------------|-------------------|----------------------|-----------------------|------------|----------------------------------------|-----------------|
| Pari Island, Indonesia    | 0.98 ± 0.04       | 5.8 ± 0.3            | 2.1 ± 0.1             | 8-67 (mean=34) | 63 ± 6.4 (312±76.2)$^b$               | this study      |
| Seribu Island, Indonesia  |                   |                      |                       |            |                                        |                 |
| Lembeh strait, Indonesia  |                   |                      |                       |            |                                        |                 |
| Indonesia (National)      |                   |                      |                       |            |                                        |                 |
| Southeast Asia            |                   |                      |                       |            |                                        |                 |
| Global                    | 1.03 ± 0.02       | 0-48.2               |                       | 100        | 194.2 ± 20.2 (312±76.2)               | [3]             |

$^a$LOI= Loss on Ignition
$^b$this number is the extrapolation of the actual value following Fourqurean [3]

3.4. Soil carbon storage in species-specific of E. acoroides

Mono-specific E. acoroides meadows are a reliable system to store and keep organic carbon in the soil. The soil under E. acoroides meadows in Pari island shows a relatively high organic carbon (2.1±0.1% soil DW) (Table 4).

Table 4. Carbon organic in different types of meadows and species.

| Locations          | C$_{org}$ (% soil DW) | Species                          | Ref.   |
|--------------------|-----------------------|----------------------------------|--------|
| Pari Island        | 2.1±0.1               | E. acoroides                     | this study |
| Thailand           | 0.72±0.37             | E. acoroides                     | [29]   |
|                   | 0.70±0.5              | T. hemprichii                    |        |
|                   | 0.43±0.21             | H. ovalis                        |        |
| Tropical Australia | 0.28±0.1              | Mix C. rotundata/H. uninervis    | [26]   |
|                   | 0.3±0.1               | Mix T. hemprichii/C. rotundata   |        |
|                   | 0.6±0.48              | H. uninervis                     |        |
| South Australia    | 2.24±0.05             | Posidonia australis              | [30]   |
| Mediterranean Sea  | 0.7±0.3 - 5.8±0.5     | Posidonia oceanica               | [31]   |

In Thailand, mono-specific E. acoroides preserves 0.72±0.37% (Mean±SE), higher than other species in the study location [29]. Other seagrass communities in tropical Australia, mono-specific Halodule
uninervis meadows, and mixed species of C. rotundata/H. uninervis or T. hemprichii/C. rotundata also show a lower organic carbon content in the soil, ranging from 0.28 to 0.62 % soil dry weight [26]. This value is almost similar compared to Posidonia australis meadows in South Australia and Posidonia oceanica in the Mediterranean sea, which have a high capability to accumulate organic carbon [30,31]. The carbon storage in the soil varies depending on site and seagrass species [26,31,32]. In tropical regions, E. acoroides as a large species may contribute significantly to carbon storage in living biomass and soil [29].

3.5. The Implication for conservation management
This finding may have several contributions to national blue carbon database and seagrass conservation and restoration effort:
1. The information is a baseline for the Indonesian blue carbon database, which lacks carbon storage data in the soil,
2. This finding emphasizes the potential soil carbon storage as a crucial parameter in conservation for seagrass ecosystems amid the high rate of seagrass degradation [33, 34],
3. For restoration efforts, this finding reassures the potential of E. acoroides as target species for a restoration project aiming to mitigate climate change and enhance the capacity of the seagrass ecosystem as blue carbon habitat.

Besides, this finding may give additional value for seagrass ecosystem in conservation strategies in Pari Island, facing various anthropogenic pressures [35–37]. Conservation and protection action, particularly in this study area, are crucial to increase seagrass ecological health and prevent seagrass degradation and CO2 emission back to the atmosphere due to the remineralization of deposited Corg in the sediment.

4. Conclusion
Mono-specific E. acoroides meadows in Pari Island have a considerable capacity of soil carbon storage, 63 Mg Corg/ha in 8-67 cm soil depth. There is a high variability of soil carbon storage and its sequestration regarding the habitat characteristics on large and small scales across the region, such as seagrass structural complexity, seagrass species, water depth, turbidity, hydrodynamic, soil characterization, biotic and abiotic factors of the study area. Further investigation is indispensable to depict the drivers controlling the carbon storage in the mono-specific meadows, the sources of carbon, and the sedimentation rate, which will give an insight into potential carbon storage in the meadows. Also, in the future, we need to assess the soil carbon storage on other sides of the island with an adequate replication of core samples and standard methods to reflect soil carbon storage and its characterization across the island.

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Authors Contribution
Husen Rifai and Susi Rahmawati: Conceptualization, data collection, sample analysis, writing - original draft, writing–review and editing. Doni Nurdiansah: writing the original draft and analyzing the sample. Afdal: writing the original draft, funding acquisition, and project administration.
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