Variation of carbon content in sediments of seagrass ecosystems based on the presence of seagrass species on Mare Island, Indonesia

[1]Irmalita Tahir, [2]Desy M. H. Mantiri, [2]Antonius P. Rumengan, [1]Nurhalis Wahidin, [2]Lawrence J. L Lumingas, [2]Khristin I. F. Kondoy, [2]Roike I. Montolalu, [2]Rene C. Kepel, [1]Zulhan A. Harahap

[1] Faculty of Fisheries and Marine Sciences, Khairun University, Ternate, North Maluku, Indonesia; [2] Faculty of Fisheries and Marine Sciences, Sam Ratulangi University, Manado, Indonesia. Corresponding author: I. Tahir, iermalitha@gmail.com

Abstract. Seagrass has an important role in mitigating climate change, having a role in capturing "blue carbon". Seagrass ecosystems function as effective carbon sinks and stores, most of the carbon being stored in seagrass sediments. This study aimed to investigate variations in sediment carbon content based on seagrass species of seagrass ecosystems in the Mare Island Conservation Area, Indonesia. Data collection of seagrass adopted the "seagrass watch" method. C-org content was determined using the Walkley and Black method and analysis of sediment carbon stores referred to Howard et al (2014). Eight species of seagrass were found. *Thalassia hemprichii* had the highest density value. Research results show that two seagrass species, *Enhalus acoroides* and *T. hemprichii* had the highest carbon storage. The highest average carbon storage was found at the plot adjacent to the mangrove ecosystem. Station 2, which had an average value of sediment carbon stores higher than Station 1, was located between mangrove and coral reef ecosystems. Sedimentary carbon storage on Mare Island is 97676.598±1293 MgC.

Key Words: carbon sediment, carbon storage, Mare Island, seagrass species, sedimentary.

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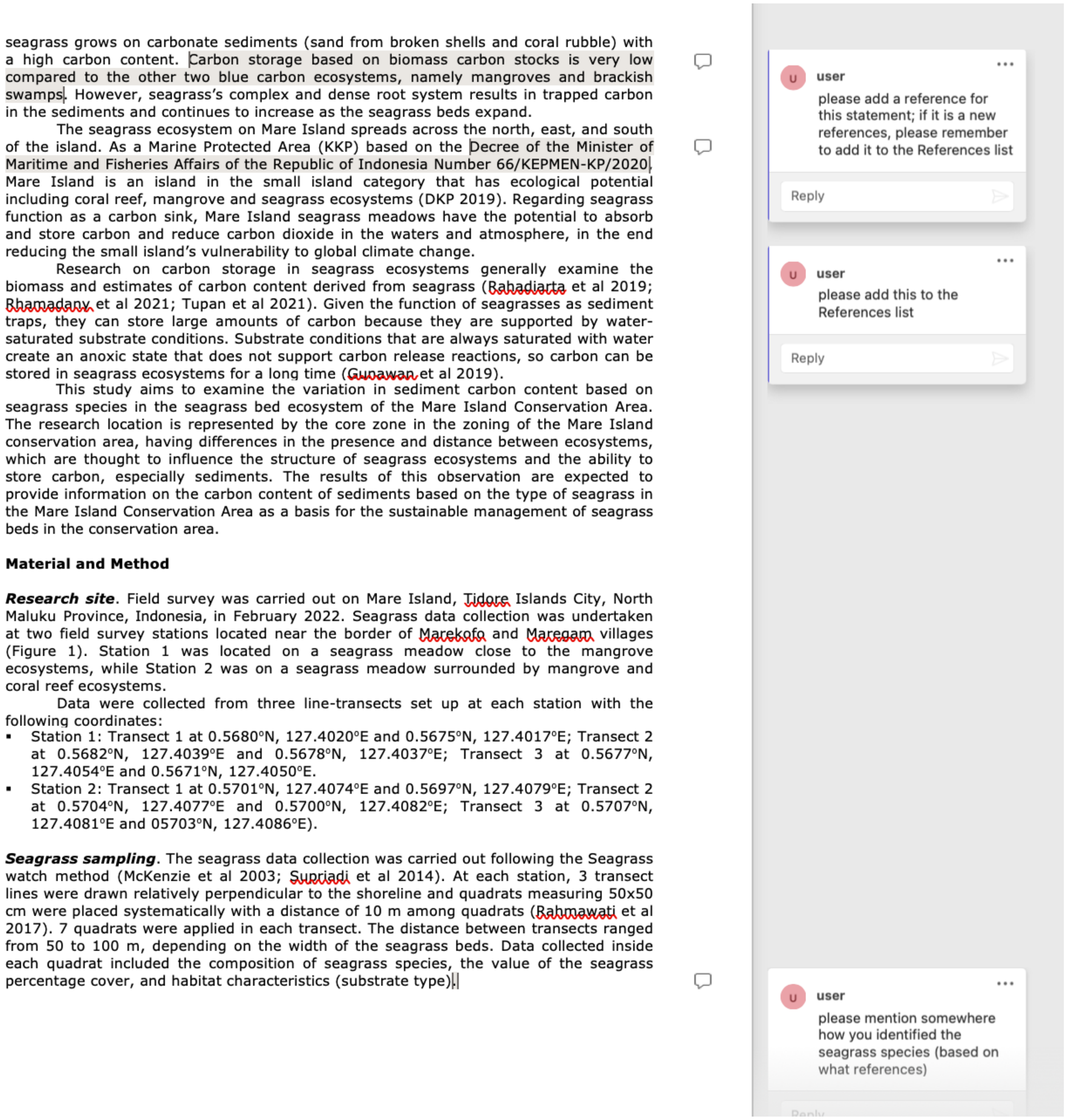
Introduction. Seagrass is a true plant that grows in the coastal areas and can adapt to salinity and tides. The ecological role of seagrass is as food source, spawning area, and rearing area for various marine biota. Seagrass ecosystems provide carbon storage and climate change mitigation (Rattanachot & Prathep 2015; Rodríguez et al 2018; Karlina et al 2022) storing blue carbon. Blue carbon ecosystems consisting of mangroves, seagrasses, and brackish swamps are known to store 3–5 times more carbon than terrestrial ecosystems. Indonesia's blue carbon ecosystem is a vital carbon sink, and at the same time, possesses a global climate threat when released (Ayostina et al 2022). Seagrass ecosystems can absorb and remove large amounts of carbon from the atmosphere every day and deposit it in tissues or sediments for a long time.

The contribution of seagrass vegetation to carbon sequestration starts from the photosynthesis process. Some types of seagrass tend to develop more underground biomass, accumulating more carbon. In addition, below substrate biomass stores photosynthetic products which support seagrass growth if the photosynthesis process does not run optimally (Citra et al 2020). Seagrass biomass will also enter the food web through herbivore's food chain followed by predation at a higher trophic level or through the process of litter decomposition. Carbon storage in seagrass ecosystems is divided into 3 carbon pools, namely: upper seagrass biomass, including sheaths, leaf blades and attached epiphytic biota; lower seagrass biomass, including rhizomes and seagrass roots; and sediments, originating both inside the ecosystem (autochthonous) and outside the ecosystem (allochthonous) (Fourqurean et al 2014).

The carbon content at the bottom of the substrate is higher than at the top, because carbon will accumulate in the sediment (Rahadiarta et al 2019). In general,



seagrass grows on carbonate sediments (sand from broken shells and coral rubble) with a high carbon content. Carbon storage based on biomass carbon stocks is very low compared to the other two blue carbon ecosystems, namely mangroves and brackish swamps. However, seagrass's complex and dense root system results in trapped carbon in the sediments and continues to increase as the seagrass beds expand.

The seagrass ecosystem on Mare Island spreads across the north, east, and south of the island. As a Marine Protected Area (KKP) based on the Decree of the Minister of Maritime and Fisheries Affairs of the Republic of Indonesia Number 66/KEPMEN-KP/2020, Mare Island is an island in the small island category that has ecological potential including coral reef, mangrove and seagrass ecosystems (DKP 2019). Regarding seagrass function as a carbon sink, Mare Island seagrass meadows have the potential to absorb and store carbon and reduce carbon dioxide in the waters and atmosphere, in the end reducing the small island's vulnerability to global climate change.

Research on carbon storage in seagrass ecosystems generally examine the biomass and estimates of carbon content derived from seagrass (Rahadiarta et al 2019; Rhamadany et al 2021; Tupan et al 2021). Given the function of seagrasses as sediment traps, they can store large amounts of carbon because they are supported by water-saturated substrate conditions. Substrate conditions that are always saturated with water create an anoxic state that does not support carbon release reactions, so carbon can be stored in seagrass ecosystems for a long time (Gunawan et al 2019).

This study aims to examine the variation in sediment carbon content based on seagrass species in the seagrass bed ecosystem of the Mare Island Conservation Area. The research location is represented by the core zone in the zoning of the Mare Island conservation area, having differences in the presence and distance between ecosystems, which are thought to influence the structure of seagrass ecosystems and the ability to store carbon, especially sediments. The results of this observation are expected to provide information on the carbon content of sediments based on the type of seagrass in the Mare Island Conservation Area as a basis for the sustainable management of seagrass beds in the conservation area.

Material and Method

Research site. Field survey was carried out on Mare Island, Tidore Islands City, North Maluku Province, Indonesia, in February 2022. Seagrass data collection was undertaken at two field survey stations located near the border of Marekofo and Maregam villages (Figure 1). Station 1 was located on a seagrass meadow close to the mangrove ecosystems, while Station 2 was on a seagrass meadow surrounded by mangrove and coral reef ecosystems.

Data were collected from three line-transects set up at each station with the following coordinates:

- Station 1: Transect 1 at 0.5680°N, 127.4020°E and 0.5675°N, 127.4017°E; Transect 2 at 0.5682°N, 127.4039°E and 0.5678°N, 127.4037°E; Transect 3 at 0.5677°N, 127.4054°E and 0.5671°N, 127.4050°E.
- Station 2: Transect 1 at 0.5701°N, 127.4074°E and 0.5697°N, 127.4079°E; Transect 2 at 0.5704°N, 127.4077°E and 0.5700°N, 127.4082°E; Transect 3 at 0.5707°N, 127.4081°E and 05703°N, 127.4086°E).

Seagrass sampling. The seagrass data collection was carried out following the Seagrass watch method (McKenzie et al 2003; Supriadi et al 2014). At each station, 3 transect lines were drawn relatively perpendicular to the shoreline and quadrats measuring 50x50 cm were placed systematically with a distance of 10 m among quadrats (Rahmawati et al 2017). 7 quadrats were applied in each transect. The distance between transects ranged from 50 to 100 m, depending on the width of the seagrass beds. Data collected inside each quadrat included the composition of seagrass species, the value of the seagrass percentage cover, and habitat characteristics (substrate type).

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Figure 1. Research sites.

Sediment sampling. Sediment samples were collected using a sediment core made of PVC with a length of 50 cm and a diameter of 7.5 cm, which was embedded in the sediment in the square. There were 3 repetitions of sediment collection on each transect, namely the upper quadrats (1st quadrats), middle quadrats (4th quadrats), and lower quadrats (7th quadrats). The collected samples were cut per layer with a length of 15 cm each layer. There were 3 layers in each sediment collection, namely from 15 cm, 30 cm, and 45 cm, with a total of 54 samples of sediment. The sediment samples were then air dried to a constant weight and further analyzed at the Bogor Soil Research Institute, Indonesia. The C-org content was determined using the Walkley and Black method (Rustam et al 2019). Measurement of water parameters included temperature, pH, salinity, and dissolved oxygen (DO) with a water quality checker (Hanna type HI 98194). Measurements were carried out directly *in situ* three times at each field station.

Data analysis. The density of species is the number of individual seagrasses (stands) of a species per unit area. Seagrass density is calculated based on the following equation (Supriadi et al 2014):

Where: D - species density (stands m^{-2}); Ni - number of stands for species i; A - area of quadrat (m^2).

Criteria for seagrass density are presented in Table 1.

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Table 1

Seagrass density criteria

Density	Condition
>175	Very tight
125-175	Meeting
75-125	Rather tight
25-75	Seldom
<25	Very rarely

Seagrass conditions. The assessment of seagrass conditions based on cover was carried out according to Rahmawati et al (2017), being categorized into four ratings, namely: rare (0-25%), moderate (26-50%), dense (51-75%) and very dense (76-100%). The condition of seagrass beds was based on cover according to KMLH (2004), namely: good (rich/healthy: ≥60%), damaged (less rich/unhealthy: 30-59.9%), and damaged (poor: ≤29.9 %).

Analysis of sedimentary carbon content. The data collected were soil density, carbon density, estimated carbon, and total carbon. Before calculating the amount of sediment carbon value, the soil density value (dry bulk density) was calculated using the following equation (Howard et al 2014):

Sediment carbon content in each part of the sediment depths (layers) was calculated by using the equation:

Soil C (MgC/ha) = BD x SDI x %C

Where: Soil C (MgC/ha) - sedimentary carbon storage; BD - soil density (g cm^{-3}); SDI - soil depth interval (cm).

After knowing the sedimentary carbon store in each section of depth (layer) of the sediment, the value of the sediment carbon content in each sediment core was calculated by adding up the parts in the sediment core. The average carbon storage at each study site was determined. The calculation of sedimentary organic carbon storage per hectare was based on the research of Howard et al (2014):

Where: C - total sedimentary carbon store (g cm^{-2}).

After the conversion results were obtained, the total carbon content of the sediments at the study site on Mare Island was calculated using the equation:

Total Seagrass Sedimentary Carbon Content of Mare Island = the average amount of carbon content x the area of the seagrass ecosystem

Results and Discussion

Environmental parameters. The results of environmental parameters measurements at each station included temperature, pH, salinity, and DO and are presented in Table 2. The seawater temperature on Mare Island ranged from 29.3 to 30.2°C. The normal temperature for seagrass growth in tropical waters ranges from 24°C to 35°C. The temperature measured at the study site was feasible for seagrass growth because it was within the tolerance range. Salinity is a factor that influences biota's existence in seawater. Seawater salinity in Mare Island was 32-33$^{o}/_{oo}$. The average value of salinity in Mare Island waters met the quality standard, namely 32-34$^{o}/_{oo}$ (KKLH 2004). The salinity measured at the time of the study was feasible for seagrass growth because it

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was within the tolerance range.

Variations in the degree of acidity (pH) of seawater can be used as an indicator for seawater quality. The pH value of seawater is influenced by various factors including rainfall and influences from the land as well as oxidation processes. A certain range of pH values can indicate a change in water quality. The measurement results show that the pH of seawater in the research location was in the range of 7.3-7.5. These pH values were suitable for seagrass growth, since the optimum pH value for seagrass growth ranges from 7.3-9. DO at the study site ranged from 6–6.4 mg L^{-1}. The DO range was close to the optimum value for seawater quality standards according to KEPMEN LH No. 51 of 2004, which is >5.

Table 2

The average measurement values of environmental parameters

Parameter	*Unit*	*Station*	
		1	*2*
Temperature	°C	29.3	30.2
Salinity	°/oo	32	33
pH	-	7.3	7.5
Dissolved oxygen	mg L^{-1}	6.3	6.4

Substrate type. The type of substrate observed visually at the sampling time consisted of muddy, sandy mud, and sand mixed with shell and coral fragments substrates. The type of substrate affects the uptake of organic carbon. Absorption of organic carbon is also affected by the size of substrate granules, with larger granules lowering the ability of the substrate to absorb carbon.

Seagrass species. There were 8 species of seagrass found in the research location, namely: *Enhalus acoroides, Thalassia hemprichii, Halophila ovalis, Halophila minor, Cymodocea rotundata, Halodule pinifolia, Halodule spinulosa,* and *Syringodium isoetifolium*. *T. hemprichii* and *E. acoroides* were the most common species found on Mare Island research stations. *T. hemprichii* has a morphological structure advantageous in accelerating its distribution and a strong and long rhizome to cover a wider area than other seagrass species. *T. hemprichii* generally dominates mixed seagrass beds and grows together with *E. acoroides*. The presence of seagrass species in quadrats 1, 4, and 7 according to the quadrat sediment samples from each transect, divided into upper quadrats (UQ), middle quadrats (MQ) and lower quadrats (LQ) is presented in Table 3.

T. hemprichii was found in almost all quadrats, followed by *E. acoroides*. Muddy and sandy mud substrates affected the presence of seagrass species *T. hemprichii* and *E. acoroides*. Differences in the composition of substrate types can cause differences in the composition of seagrass species and can also affect the fertility and growth of seagrass. Differences in the grain size composition of the sediment will cause differences in nutrients for seagrass growth and the decomposition and mineralization processes that occur in the substrate. The sediment fraction also plays a role in the seagrass root system. Seagrasses that grow on muddy substrates with fine sediment grain sizes require more roots to bind sediments. On the other hand, seagrass species that live on coral rubble and sand substrates tend to have strong roots. This is due to the large and uniform porosity of coarse sandy substrates. Hence, seagrass roots need to firmly grip the substrate to survive the currents and waves.

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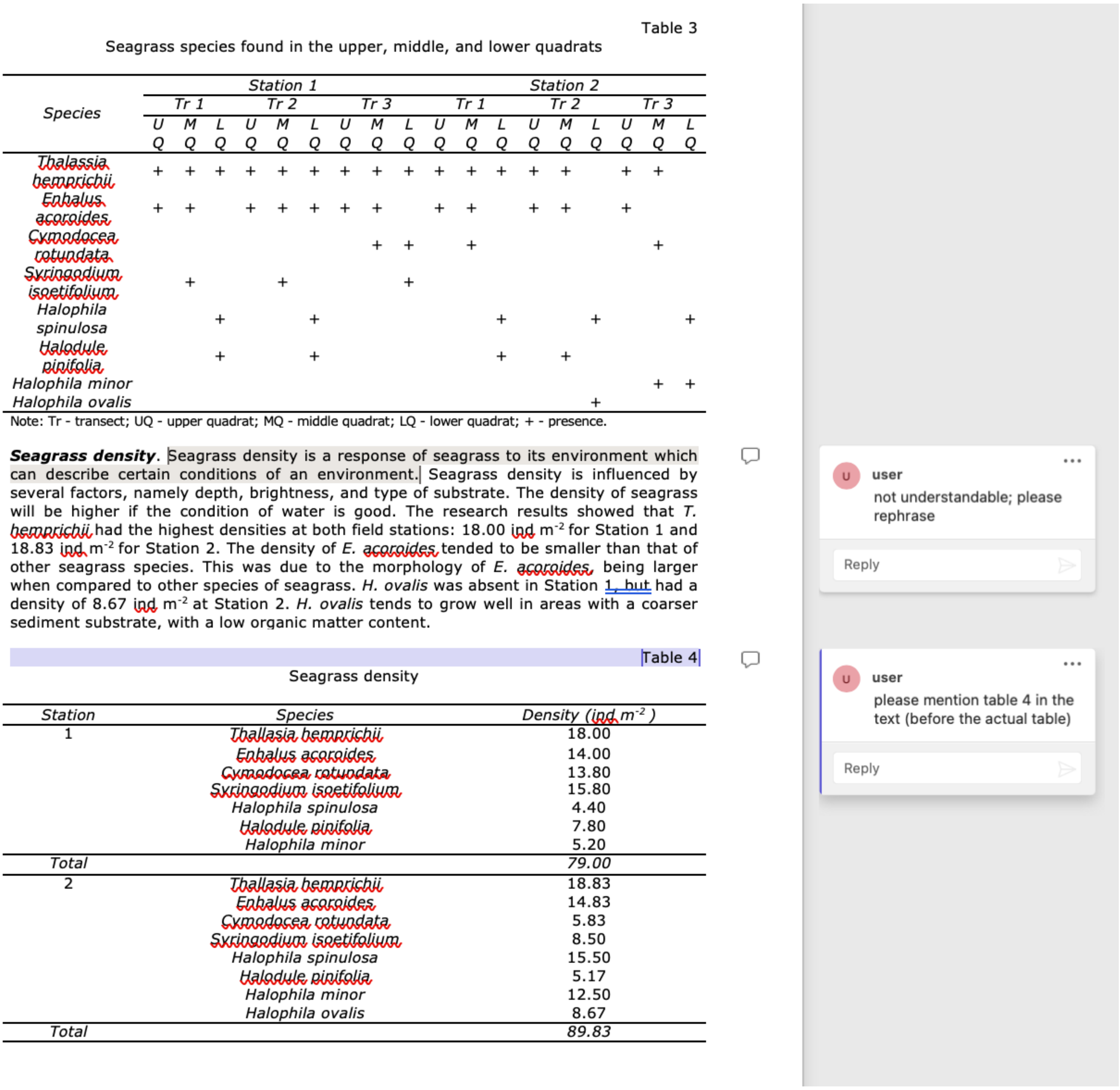

Table 3

Seagrass species found in the upper, middle, and lower quadrats

Species	*Station 1*									*Station 2*								
	Tr 1			*Tr 2*			*Tr 3*			*Tr 1*			*Tr 2*			*Tr 3*		
	UQ	*MQ*	*LQ*	*UQ*	*MQ*	*LQ*	*UQ*	*MQ*	*LQ*	*UQ*	*MQ*	*LQ*	*UQ*	*MQ*	*LQ*	*UQ*	*MQ*	*LQ*
Thalassia hemprichii	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+	+	
Enhalus acoroides	+	+		+	+	+	+	+		+	+		+	+		+		
Cymodocea rotundata								+	+		+						+	
Syringodium isoetifolium		+			+				+									
Halophila spinulosa			+			+						+			+			+
Halodule pinifolia			+			+						+		+				
Halophila minor																	+	+
Halophila ovalis															+			

Note: Tr - transect; UQ - upper quadrat; MQ - middle quadrat; LQ - lower quadrat; + - presence.

Seagrass density. Seagrass density is a response of seagrass to its environment which can describe certain conditions of an environment. Seagrass density is influenced by several factors, namely depth, brightness, and type of substrate. The density of seagrass will be higher if the condition of water is good. The research results showed that *T. hemprichii* had the highest densities at both field stations: 18.00 ind m^{-2} for Station 1 and 18.83 ind m^{-2} for Station 2. The density of *E. acoroides* tended to be smaller than that of other seagrass species. This was due to the morphology of *E. acoroides*, being larger when compared to other species of seagrass. *H. ovalis* was absent in Station 1, but had a density of 8.67 ind m^{-2} at Station 2. *H. ovalis* tends to grow well in areas with a coarser sediment substrate, with a low organic matter content.

Table 4

Seagrass density

Station	*Species*	*Density (ind m^{-2})*
1	*Thallasia hemprichii*	18.00
	Enhalus acoroides	14.00
	Cymodocea rotundata	13.80
	Syringodium isoetifolium	15.80
	Halophila spinulosa	4.40
	Halodule pinifolia	7.80
	Halophila minor	5.20
Total		*79.00*
2	*Thallasia hemprichii*	18.83
	Enhalus acoroides	14.83
	Cymodocea rotundata	5.83
	Syringodium isoetifolium	8.50
	Halophila spinulosa	15.50
	Halodule pinifolia	5.17
	Halophila minor	12.50
	Halophila ovalis	8.67
Total		*89.83*

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The total seagrass density value at Station 1 was 79 ind m^{-2}, while Station 2 had a total density value of 89.83 ind m^{-2}. The two values show that the seagrass density condition at both stations was fairly dense. The lower density value at Station 1 could have been related to its substrate, dominated by muddy to sandy mud sediments. These substrate conditions could have limited the growth of *H. ovalis* at Station 1. Some human activities were observed at Station 1, such as boat mooring and anchoring and sand mining. The existence of human activities may have affected the distribution and growth of seagrass, as was the case observed by Wagey et al (2022), where *E. acoroides*, *S. isoetifolium*, and *T. hemprichii* had high-growth rates in locations protected from disturbances caused by humans (e.g. boat traffic) and showed slow growth rates at areas with physical disturbances from human activities (for domestic and tourism purposes). The high seagrass density at Station 2 could be attributed to the existence of more species and less disturbance from human activities. The total density of seagrass at Stations 1 and 2 was lower than the total density of seagrass in Dompak (103 ind m^{-2}) and Berakit (246 ind m^{-2}) waters, Riau Islands (Hertyastuti et al 2020). This is suspected to relate to a smaller sampling area and to a different beach topography.

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Seagrass condition. Research results showed that seagrass percentage cover at the research stations was in the very dense category, with coverage values of 90.21% at Station 1 and 95.5% at Station 2. Based on the KMLH (2004) standard, seagrass conditions found at the research location belonged to the good (rich/healthy seagrass: ≥60%) category. At all research stations, *E. acoroides* had the highest species percentage cover value among all species, namely 33.85% and 36.92% for Stations 1 and 2, respectively. *T. hemprichii* species percentage cover values were 20.29% and 13.79%. The lowest percentage cover for Station 1 was in the case of *H. spinulosa* (5.50%), and *H. pinifolia* had the lowest percentage cover (6%) for Station 2. Species with the highest value can be said to be the pioneer species in an area (Schaduw & Kondoy 2020).

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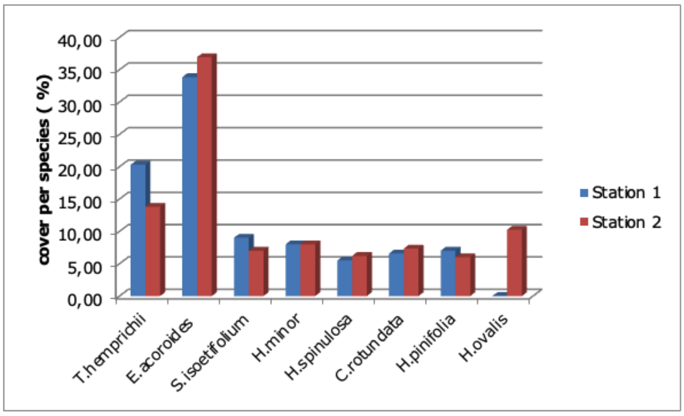

Figure 2. Seagrass species percentage cover.

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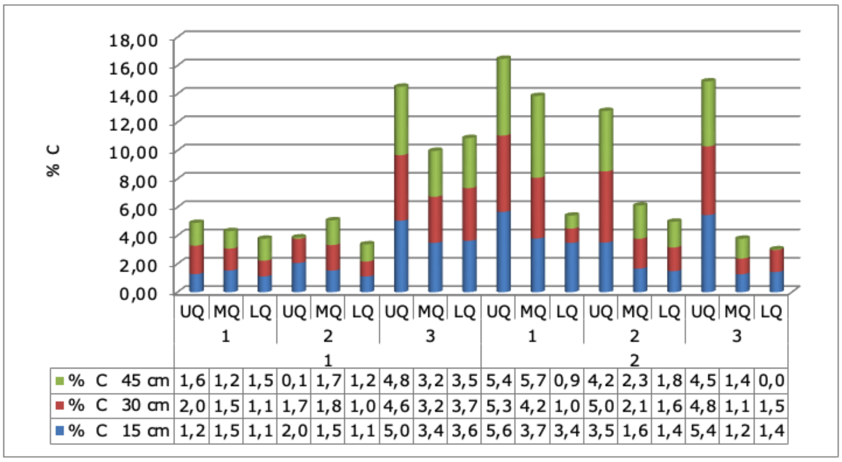
%C sediments. Sediment samplings for organic carbon content were taken from depths of 15, 30, and 45 cm. The %C sediment values found at all sampling points on Mare Island are presented in Figure 3. %C sediment varies with depths. %C at a depth of 15 cm had a range of 1.11–5.67, at a depth of 30 cm the range was 1.02–5.39, and at a depth of 45 cm it was 0.05–5.78. The highest %C at a depth of 15 cm was found at Station 2, Transect 1, upper quadrat, at a depth of 30 cm it was at Station 2, Transect 1, upper quadrat, and at a depth of 45 cm was at Station 2, Transect 1, middle quadrat.

The species of seagrass and the distance from the mangrove ecosystems, coral reefs, and land may influence the level of %C at depth. The quadrat with the highest %C in Station 1 was located close to a dense and old *Rhizophora apiculata* tree colony having roots around 1-2 m high above the ground. The highest %C in Station 2 was found at Transect 1, upper quadrat, with very dense seagrass stands. A higher density and a bigger size of seagrasses will cause more organic matter to be stored in the sediment (Riniatsih 2015). The highest %C at 45 cm depth was 5.78, found at Station 2, Transect 1, upper quadrat. According to Mahasani et al (2016), roots are one of the organic materials that contribute to organic carbon content in the soil. In addition to roots, mud composition and seagrass density also contribute to high carbon storage. The presence of *E. acoroides* is also a contributing factor to high sediment carbon content, because it has a relatively large stand size, with leaves that can grow longer than 1 m.



	UQ	MQ	LQ	UQ	MQ	LQ	UQ	MQ	LQ	UQ	MQ	LQ	UQ	MQ	LQ	UQ	MQ	LQ
	1			2			3			1			2			3		
	1									2								
🟩 % C 45 cm	1,6	1,2	1,5	0,1	1,7	1,2	4,8	3,2	3,5	5,4	5,7	0,9	4,2	2,3	1,8	4,5	1,4	0,0
🟥 % C 30 cm	2,0	1,5	1,1	1,7	1,8	1,0	4,6	3,2	3,7	5,3	4,2	1,0	5,0	2,1	1,6	4,8	1,1	1,5
🟦 % C 15 cm	1,2	1,5	1,1	2,0	1,5	1,1	5,0	3,4	3,6	5,6	3,7	3,4	3,5	1,6	1,4	5,4	1,2	1,4

Figure 3. %C values at three different substrate depths by transect and quadrats; UQ - upper quadrat; MQ - middle quadrat; LQ - lower quadrat.

Sedimentary carbon deposits. The soil density value found in this study ranged from 0.12 to 0.126 g cm^{-3}. It was affected by the depth of the sediment core. The results showed that carbon storage in the sediment ranged from 0.05 g C m^{-2} to 5.78 g C m^{-2}. Carbon storage in each part of the sediment core ranged from 5.591 g C m^{-2} to 31.086 g C m^{-2}. The average conversion value of carbon per core ranged from 186.373 Mg C ha^{-1} to 1036.198 Mg C ha^{-1} (Table 5).

The average value of sediment carbon storage in the upper quadrat was higher than in the middle and lower quadrats, except for Transect 1, quadrat 2, at Station 1. In addition to the presence of *E. acoroides*, the high carbon content of the sediments could have also been related to quadrat distance from the mangrove ecosystem and shoreline. The tidal waves and currents affect the litter and sediment transport over seagrass substrate, which may carry out or carry in materials having organic carbon content. Dense seagrass stands reduce the amount of resuspended sediment and increase suspended particles trapping rates.

Seagrass not only traps and stores organic carbon produced by plants and other sources, but also traps and sinks carbon originating elsewhere (allochthonous carbon). Not all net production in seagrass beds is maintained. Some of the carbon derived from seagrass ecosystems is also exported to other coastal and marine ecosystems where it can be consumed or stored.

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in the figure, what do the numbers 1,2,3 represent under UQ, MQ, LQ?

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Table 5

Average sedimentary carbon stored per square

Station	*Transect*	*Quadrat*	*Carbon storage (Mg C ha $^{-1}$)*
1	1	UQ	301.395
		MQ	271.625
		LQ	227.558
	2	UQ	238.169
		MQ	319.410
		LQ	212.521
	3	UQ	892.499
		MQ	627.503
		LQ	669.835
2	1	UQ	1036.198
		MQ	871.462
		LQ	340.160
	2	UQ	804.814
		MQ	376.436
		LQ	313.123
	3	UQ	936.225
		MQ	227.558
		LQ	186.373

The majority of organic carbon in seagrass ecosystem sediments comes from seagrass litter and the rest comes from the environment around the seagrass ecosystem (Rahayu et al 2019). Litter buried in sediments has the potential to be a source of organic carbon at the bottom of the waters. Organic carbon stored in sediments in seagrass ecosystems can come from the presence of marine snow, both autochthonous and allochthonous (Wahyudi et al 2016).

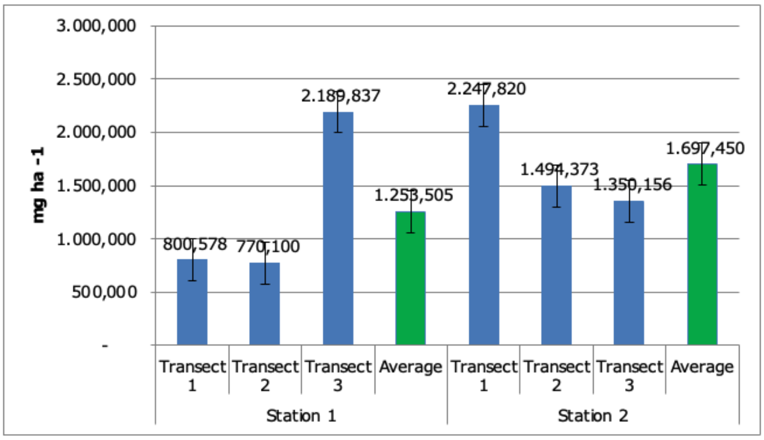
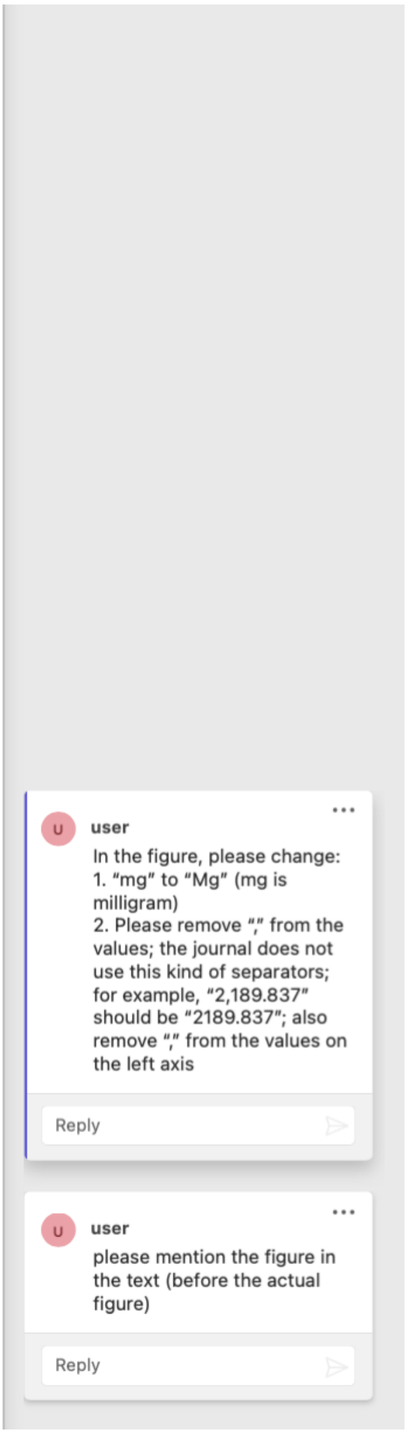


Figure 4. Average sedimentary carbon storage per transect.

The highest sediment carbon storage per transect at Station 1 was found at transect 3 (2189.837 Mg C ha^{-1}) and for Station 2 at transect 1 (2247.820 Mg C ha^{-1}). The average carbon storage at Station 1 was 1253.505±811 Mg C ha^{-1} and for Station 2 it was 1697.450±482 Mg C ha^{-1}. The higher average sediment carbon storage found at Station 2 might relate to the absence of human activity and to the location between mangroves



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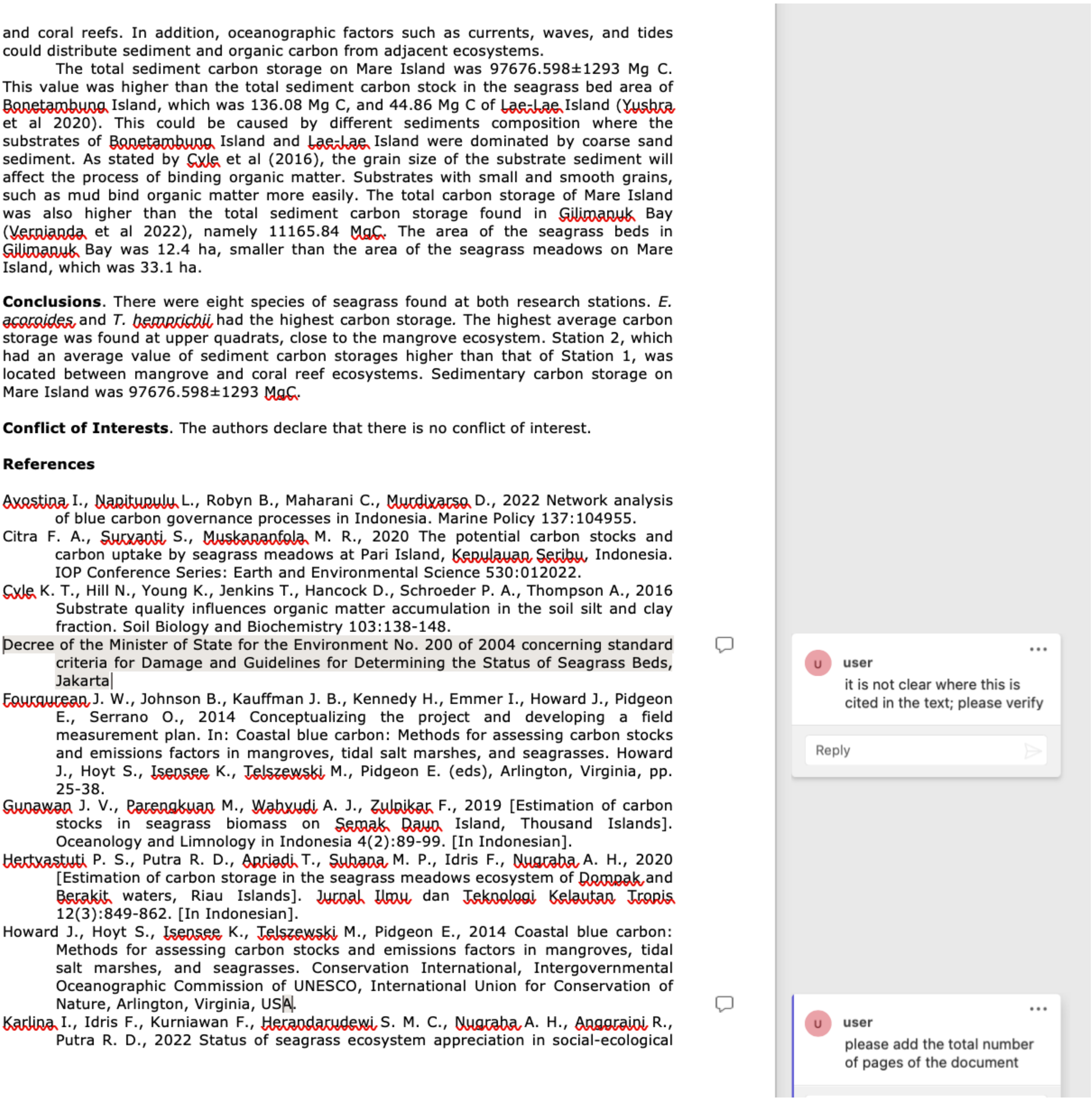

and coral reefs. In addition, oceanographic factors such as currents, waves, and tides could distribute sediment and organic carbon from adjacent ecosystems.

The total sediment carbon storage on Mare Island was 97676.598±1293 Mg C. This value was higher than the total sediment carbon stock in the seagrass bed area of Bonetambung Island, which was 136.08 Mg C, and 44.86 Mg C of Lae-Lae Island (Yushra et al 2020). This could be caused by different sediments composition where the substrates of Bonetambung Island and Lae-Lae Island were dominated by coarse sand sediment. As stated by Cyle et al (2016), the grain size of the substrate sediment will affect the process of binding organic matter. Substrates with small and smooth grains, such as mud bind organic matter more easily. The total carbon storage of Mare Island was also higher than the total sediment carbon storage found in Gilimanuk Bay (Vernianda et al 2022), namely 11165.84 MgC. The area of the seagrass beds in Gilimanuk Bay was 12.4 ha, smaller than the area of the seagrass meadows on Mare Island, which was 33.1 ha.

Conclusions. There were eight species of seagrass found at both research stations. *E. acoroides* and *T. hemprichii* had the highest carbon storage. The highest average carbon storage was found at upper quadrats, close to the mangrove ecosystem. Station 2, which had an average value of sediment carbon storages higher than that of Station 1, was located between mangrove and coral reef ecosystems. Sedimentary carbon storage on Mare Island was 97676.598±1293 MgC.

Conflict of Interests. The authors declare that there is no conflict of interest.

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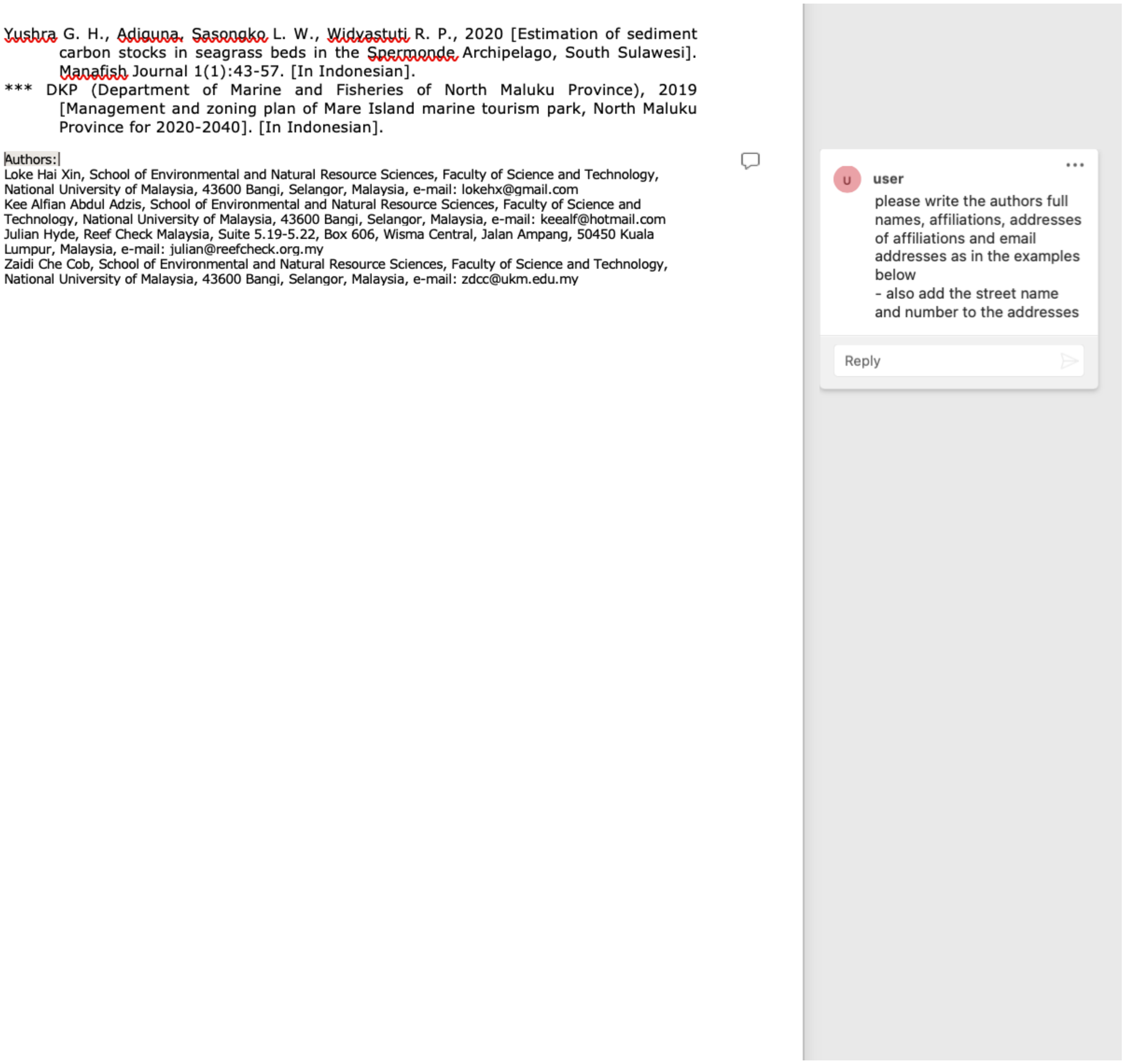

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Authors:
Loke Hai Xin, School of Environmental and Natural Resource Sciences, Faculty of Science and Technology, National University of Malaysia, 43600 Bangi, Selangor, Malaysia, e-mail: lokehx@gmail.com
Kee Alfian Abdul Adzis, School of Environmental and Natural Resource Sciences, Faculty of Science and Technology, National University of Malaysia, 43600 Bangi, Selangor, Malaysia, e-mail: keealf@hotmail.com
Julian Hyde, Reef Check Malaysia, Suite 5.19-5.22, Box 606, Wisma Central, Jalan Ampang, 50450 Kuala Lumpur, Malaysia, e-mail: julian@reefcheck.org.my
Zaidi Che Cob, School of Environmental and Natural Resource Sciences, Faculty of Science and Technology, National University of Malaysia, 43600 Bangi, Selangor, Malaysia, e-mail: zdcc@ukm.edu.my

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