RESEARCH PAPER

SEAGRASS CARBON STOCKS AND SEQUESTRATION IN HABITAT IMPACTED BY TIN MINING ACTIVITIES IN BANGKA BELITUNG, INDONESIA

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ABSTRACT. Seagrass meadows are important blue carbon ecosystems. They are threatened by various anthropogenic activities, including mining, which affect the ecological health. This study investigates the impact of sea-based tin mining activities on the carbon storage capabilities of seagrass meadows in Bangka Belitung, Indonesia. The objective of the study is to quantify carbon stocks and sequestrations in these ecosystems and understand how mining influences these critical natural resources. The research was conducted at various seagrass sites with different levels of mining impacts. Carbon stocks and sequestration were measured using the Loss on Ignition method, and net primary productivity was calculated. Remote sensing data from Landsat 7 and Sentinel-2A satellites were used to monitor changes in seagrass cover over time. Sedimentation rates and total suspended solids were measured to assess environmental impacts. Statistical analysis, including correlation and cluster analysis, examined the relationship between mining activity and seagrass health. The findings indicate a significant decrease in seagrass coverage and carbon storage in areas with high levels of tin mining. Specifically, areas with intensive mining showed higher rates of sedimentation and total suspended solids, which correlated with reduced seagrass biomass and carbon sequestration. This decrease compromises the ecological role of seagrass meadows as effective carbon sinks, highlighting the destructive impact of mining activities on these ecosystems.

KEYWORDS: carbon stock, carbon sequestration, seagrass, tin mining

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INTRODUCTION

Seagrass ecosystems play a crucial role in carbon sequestration, representing essential components of the marine environment. Although they cover a small fraction of the ocean floor, seagrasses contribute significantly to oceanic carbon storage, accounting for up to 20% of the ocean's carbon (Khairunnisa et al. 2023; McHenry et al. 2023). This capacity for carbon storage indicates their critical role in global carbon cycles and climate change mitigation efforts (Wahyudi et al. 2020; Mashoreng et al. 2021). Seagrasses can store carbon in their bodies and in the soil by creating biomass and trapping carbon particles that settle from the water. (Harahap et al. 2021; Hartoko et al. 2021). Although seagrass meadows can release small amounts of methane (CH_4) into the atmosphere, recent studies indicate that CH_4 emissions from these ecosystems are minimal and offset less than 2% of the carbon sequestered in their sediments (Yau et al. 2023). Incorporating seagrass ecosystems into the blue carbon framework further emphasizes their importance in mitigating anthropogenic CO_2 emissions (Marbà et al. 2015).

Despite their crucial roles, seagrass habitats and ecological conditions have declined due to human activities, including mining. This poses a serious threat to their carbon sequestration potential (Fourqurean et al. 2012; Unsworth et al. 2019; McKenzie and Yoshida 2020). In Bangka Belitung, Indonesia, tin mining significantly impacts coastal waters. Water turbidity from mining activities impedes seagrass growth by reducing essential sunlight penetration for photosynthesis (van Katwijk et al. 2011; Adams et al. 2016; Yamamoto et al. 2019). Offshore tin mining, initiated in 2001, has expanded annually, escalating environmental pressure on coastal ecosystems (Ibrahim et al. 2018; Irzon 2021).

Previous studies has highlighted the importance of conserving seagrass ecosystems as global carbon sinks, with Indonesia's seagrass meadows offering valuable insights into their carbon storage potential (Alongi et al. 2016; Wahyudi et al. 2020; Hernawan et al. 2021). Seagrasses are known for their ability to sequester carbon and store it as organic carbon in underwater sediments, making them one of the vital blue carbon ecosystems for climate change mitigation (Wahyudi et al. 2020; Stankovic et al. 2021). Human activities can cause the release of carbon that has been in sediments for hundreds of years, which may lead to higher greenhouse gas emissions (Fourqurean et al. 2012; Luo et al. 2022). Effective conservation and management strategies are needed, given the ability of seagrasses to store carbon and act as significant marine carbon sinks (Dewi et al. 2021; Hernawan et al. 2021). This study hypothesizes that tin mining significantly affects seagrass carbon storage. To test the hypothesis, it assessed the carbon stock and sequestration in three mining-affected areas in Bangka Belitung.

Data on seagrass carbon storage in Bangka Belitung remains limited, despite their acknowledged important role. Previous studies have primarily focused on seagrass distribution and the environmental consequences of mining (Syafutra et al. 2018; Haryati and Dariah 2019; Nopiansyah et al. 2021; Akhrianti et al. 2023). This study seeks to fill the gap by examining the effects of tin mining on seagrass carbon dynamics to inform conservation efforts and sustainable management practices. This study aims to assess seagrass meadows' carbon storage and ecological condition in tin-mining-impacted coastal waters in Bangka Belitung, Indonesia. It specifically focuses on how tin mining affects seagrass carbon dynamics, an area previously underexplored. By quantifying seagrass meadows' carbon storage capacity in mining-impacted regions, this study contributes to understanding their role in climate change mitigation and the effects of anthropogenic activities on their function. The study was conducted on two islands, Bangka and Belitung, Indonesia, over two years, 2022 and 2023 (Fig. 1). Sampling focused on marine seagrass beds affected by tin mining activities near Bangka and in non-impacted areas around Belitung.

MATERIALS AND METHODS

Grouping and Mapping of Tin Mining Impacts

Sampling areas were initially categorized based on the intensity of mining impacts. This involved creating a map highlighting the potential impacts of tin mining based on the Bangka Belitung Islands Provincial Regulation No. 3 of 2020 on Coastal and Small Island Spatial Zoning. The spread of Total Suspended Solids (TSS) can reach 16 miles from mining sites (Pamungkas and Husrin 2020), and TSS levels over 20 mg/L can harm seagrass ecosystems, according to Government Regulation of the Republic of Indonesia No. 22 of 2021 on Environmental Protection, Organization, and Management. These factors were important in making this classification..

Seagrass Area Mapping

For temporal comparison, Landsat 7 ETM+ imagery was used to assess water conditions in 2000, a year before offshore tin mining began, while Sentinel L2A imagery from 2022 was employed for depicting the latest conditions. Landsat 7 ETM+ has a spatial resolution of 30 m, while Sentinel-2 offers a higher spatial resolution of 10–20 m with 13 spectral bands, making it particularly effective for seagrass mapping in shallow coastal waters (Traganos et al. 2018; Bannari et al. 2022). Sentinel was selected as its operation began in 2016, rendering it unsuitable for earlier assessments. Previous studies showed that Sentinel-2 can effectively map seagrass using its multispectral images to identify different seagrass species and the algae that grow with them (Nur et al. 2021; Bannari et al. 2022). Landsat, while operating at a lower spatial resolution, has been invaluable for its long-term data continuity, enabling researchers to assess seagrass dynamics and temporal changes over decades (Carpenter et al. 2022; Rosalina et al. 2023). Image processing, including unsupervised classification, was performed using QGIS software to determine changes in seagrass coverage over time. The satellite image acquisition dates are presented in Table 1.

Seagrass, Sedimentation, and Carbon Measurement

At the seagrass meadow research site, quantified species diversity, density (shoots/m^2), and coverage (%) at the seagrass meadow research site using three 100 m line transects and 50×50 cm quadrat transects (Hernawan et al. 2021). The amount of seagrass (measured in g/m^2) and the organic carbon stock (measured in tC/Ha) were calculated using the Loss on Ignition (LOI) method (Fourqurean et al. 2012). Carbon Sequestration (CS) is defined as net primary productivity measured using the Eq. (1): CS = 1.743 + 0.087 (seagrass coverage), with units of tC/ha/year (Wahyudi et al. 2020). This Eq. (1) was chosen because it was developed using seagrass data from Indonesia, making it highly applicable to this study. The sedimentation rate was measured to assess the rate of sediment accumulation over time at the site, expressed in g/m^2/day (Roswaty et al. 2014). The Total Suspended Solids (TSS) were measured gravimetrically, with results reported in mg/l (Wisha and Ondara 2017).

Statistical analysis

The statistical analyses provided a robust framework for understanding the impacts of tin mining on seagrass ecosystems by quantifying the relationships between mining activities and seagrass health metrics. These

Table 1. Satellite data related to the impact of tin mining

Location	Sentinel L2A, Acquisition Date	Landsat L7 ETM+, Acquisition Date	Tin Mining Impact
Bakit	27/05/2022	23/05/2000	High
Tukak	08/06/2022	14/04/2000	Moderate
Tanjung Kerasak	18/07/2022	14/04/2000	Moderate
Pegantungan	08/06/2022	06/03/2000	Low
Tanjung Kelayang	08/06/2022	03/12/2000	Low

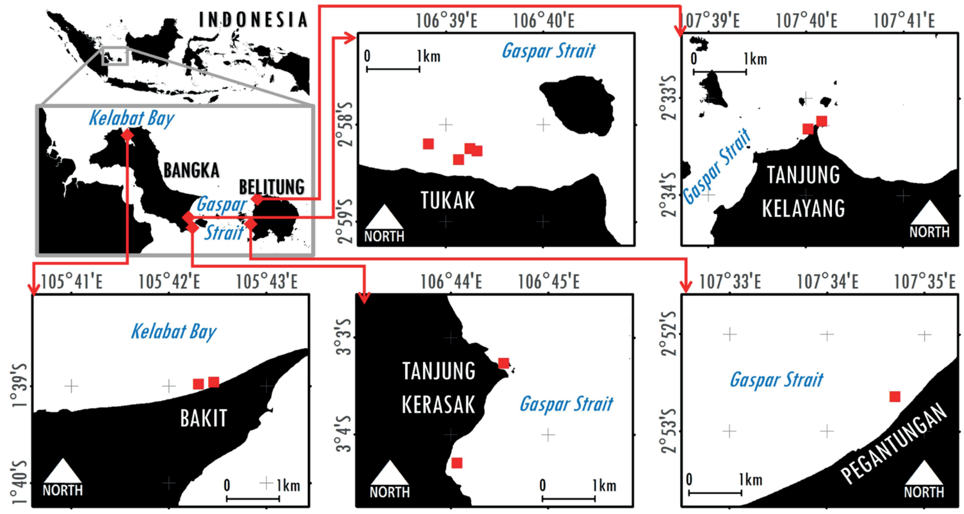

Fig. 1. Study sites in Bangka Belitung, Indonesia. Red boxes indicate sampling sites

relationships were analyzed using PAST 4.03 (Hammer et al. 2001), a program made for statistical and graphical analysis, particularly in paleontological studies. The analysis used correlation and clustering methods to understand how different factors relate to each other and to group research locations based on their environmental traits.

RESULTS AND DISCUSSION

Seagrass Coverage Decline

The study of seagrass meadows at five locations showed a big decrease in seagrass coverage, linked to the level of tin mining nearby (Fig. 2). Over the 22-year study period, the most significant decline was observed in Bakit. In this high-mining impact area, seagrass coverage decreased by 41.46 Ha/year (Fig. 2, Fig. 3, and Table 2). In contrast, Tukak, with a moderate mining impact, showed the least decline (0.27 Ha/year). These results highlight the harmful impact of mining on seagrass habitats, which matches the loss of seagrass reported in other studies (Brodie et al. 2020; Supriyadi et al. 2021; Sjafrie et al. 2022; Nugraha et al. 2023). The seagrass meadows at the study included nine types of seagrass: *Thalassia hemprichii, Enhalus acoroides, Cymodocea rotundata, Cymodocea serrulata, Halodule uninervis, Halodule pinifolia, Halophila ovalis, Halophila minor, and Syringodium isoetifolium.* The decline in seagrass coverage diminishes the ecosystem's ability to perform essential functions such as carbon sequestration and threatens marine biodiversity.

Sedimentation Rates and Water Turbidity

The results indicate significantly higher sedimentation rates in areas with high mining activities (Table 2 and Fig. 3). Bakit, the area with the highest mining impact, recorded a sedimentation rate of 146.93 g/m^2/day, which is nearly double that observed in areas with lower mining impacts. These elevated Higher sedimentation rates are linked to more Total Suspended Solids (TSS), which makes the water muddier (Samper-Villarreal et al. 2016). The negative correlation between sedimentation rates and seagrass canopy coverage suggests that increased sediment deposition obscures light penetration, which is essential for seagrass health and productivity (Ahmad-Kamil et al. 2013).

Seagrass Biomass and Carbon Dynamics

Analysis of seagrass biomass revealed that areas with lower mining impacts exhibited significantly higher biomass (e.g., Pegantungan and Tanjung Kelayang averaging 104.66 g/m^2) compared to highly impacted areas like Bakit (3.4 g/m^2) (Fig. 4 and Table 2). The reduction of biomass in areas with high mining activities directly impacts the ecosystem's carbon storage capacity. These findings align with Greiner et al. (2013), highlighting the role of healthy seagrass meadows in enhancing carbon sequestration.

Furthermore, an inverse relationship was observed between mining impact intensity, carbon stock, and

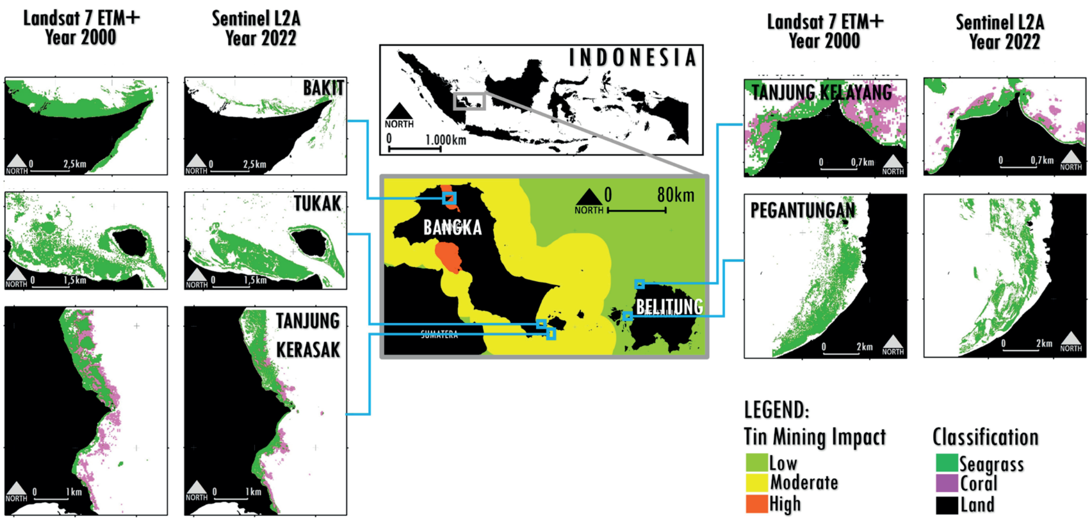

Fig. 2. Potential Impacted Areas of Tin Mining and Changes in Seagrass Area (2000-2022)

	High	Moderate	Low
Seagrass Cover (%)	5.33	21.895	48.72
Seagrass Loss (Ha/Year)	-41.46	-4.525	-1.95
Seagrass Loss (%)	-82.79	-16.065	-12.145
Sediment Rate (g/m²/day)	146.93	132.075	77.87
TSS (mg/l)	26.29	19.655	15.885

Tin Mining Impact

Fig. 3. Seagrass and Sedimentation in Tin Mining Impacted Areas

Table 2. Seagrass Condition

	Location				
	Bakit	Tanjung Kerasak	Tukak	Pegantungan	Tanjung Kelayang
Tin Mining Impact	High	Moderate	Moderate	Low	Low
Sedimentation and Total Suspended Solid (TSS)					
Sedimentation Rate (g/m²/day)	146.93	135.11	129.04	61.59	94.15
TSS (mg/l)	26.29	17.3	22.01	16.53	15.24
Seagrass Mapping					
Total Station	2	2	4	1	2
Seagrass Species	3	10	8	3	8
Seagrass Cover (%)	5.33	17.66	26.13	73.28	24.16
Seagrass Area in 2000 (Ha)	1,101.72	183.43	669.32	865.72	65.23
Seagrass Area in 2022 (Ha)	189.66	177.46	476.05	790.03	55.08
Seagrass Loss (Ha/Year)	-41.46	-8.78	-0.27	-3.44	-0.46
Seagrass Loss in 22 years (%)	-82.79	-28.88	-3.25	-8.74	-15.55
Seagrass Biomass and Carbon					
Total Sampel	16	32	109	14	36
Biomass, Above Ground (g/m²)	1.03	18.51	15.37	33.82	16.75
Biomass, Below Ground (g/m²)	2.37	46.54	74.51	102.99	55.76
Total Biomass (g/m²)	3.4	65.06	89.88	136.81	72.51
Organic Carbon, Below Ground (tC/Ha)	0.006	0.138	0.216	0.262	0.122
Organic Carbon, Above Ground (tC/Ha)	0.003	0.055	0.045	0.101	0.047
Standing Stock Carbon (tC/Ha)	0.009	0.193	0.261	0.363	0.169
Carbon Sequestration (tC/Ha/Year)	5.33	17.66	26.13	73.28	24.16
Sediment Carbon					
Total Sampel	35	9	34	44	79
Organic Carbon Stock (tC/Ha)	57.36	80.12	110.53	173.05	151.56

sequestration in seagrass meadows. In high-impact areas, the carbon sequestration was as low as 5.33 tC/Ha/year, whereas, in low-impact areas, it averaged 162.31 tC/Ha/year. This inverse correlation supports the hypothesis that physical disturbances such as sedimentation impair the seagrass meadows' ability to sequester carbon effectively (Mazarrasa et al. 2018).

The detrimental effects of mining on seagrass ecosystems have been demonstrated by several studies indicating a decline in seagrass area and health due to various mining activities. Rosalina et al. (2019) and Adi et al. (2024) described how mining waste affects seagrass ecosystems. This includes metal accumulation and altered seagrass dynamics, leading to less biomass and disrupted ecological functions seen in this study. Studies on Bintan Island and Taka Bonerate National Marine Park also report significant seagrass area reductions and health declines due to increased turbidity from mining activities (Supriyadi et al. 2021; Nugraha et al. 2023). Moreover, the broader decline of seagrass meadows in Indonesia, as noted by Sjafrie et al. (2022), reflects a trend where development and mining operations, including dredging and land cover changes, exacerbate the vulnerability of these ecosystems.

Statistical Analysis

Employing the Unweighted Pair Group Method with Arithmetic Mean (UPGMA) and Euclidean distance, the cluster analysis revealed significant spatial differences among the sampling locations (Fig. 5). Bakit, experiencing the highest impact of mining, displayed the greatest differences. In contrast, Tanjung Kerasak and Tukak, areas with moderate mining impacts, showed close similarities. This analysis supports the spatial differentiation of the study sites into three distinct groups based on the degree of mining impact.

Pearson's r correlation statistics were used to examine the connections between sedimentation rates, seagrass canopy cover, and carbon stocks (see Fig. 5). The results indicate a significant negative correlation ($p<0.05$) between sedimentation rates and both seagrass canopy cover and sediment carbon. This means that higher sedimentation from mining harms seagrass and reduces carbon stored in sediments. On the other hand, there were positive correlations found between seagrass cover, biomass, and above-ground organic carbon stock, indicating that areas with healthier seagrass canopies tend to have higher biomass and carbon storage capabilities. These findings are crucial for understanding the dynamic interactions within seagrass ecosystems under stress from anthropogenic activities.

These statistical findings not only reinforce the visual and descriptive observations made during the study but also provide a quantitative basis for the conclusions drawn concerning the impacts of tin mining on seagrass ecosystems. The significant correlations and spatial distinctions highlighted by the analyses underscore the complex nature of the interactions between environmental disturbances and ecological responses in these critical marine habitats.

Ecological and Conservation Implications

The degradation of seagrass meadows due to tin mining activities poses significant risks to marine biodiversity and the livelihoods dependent upon these

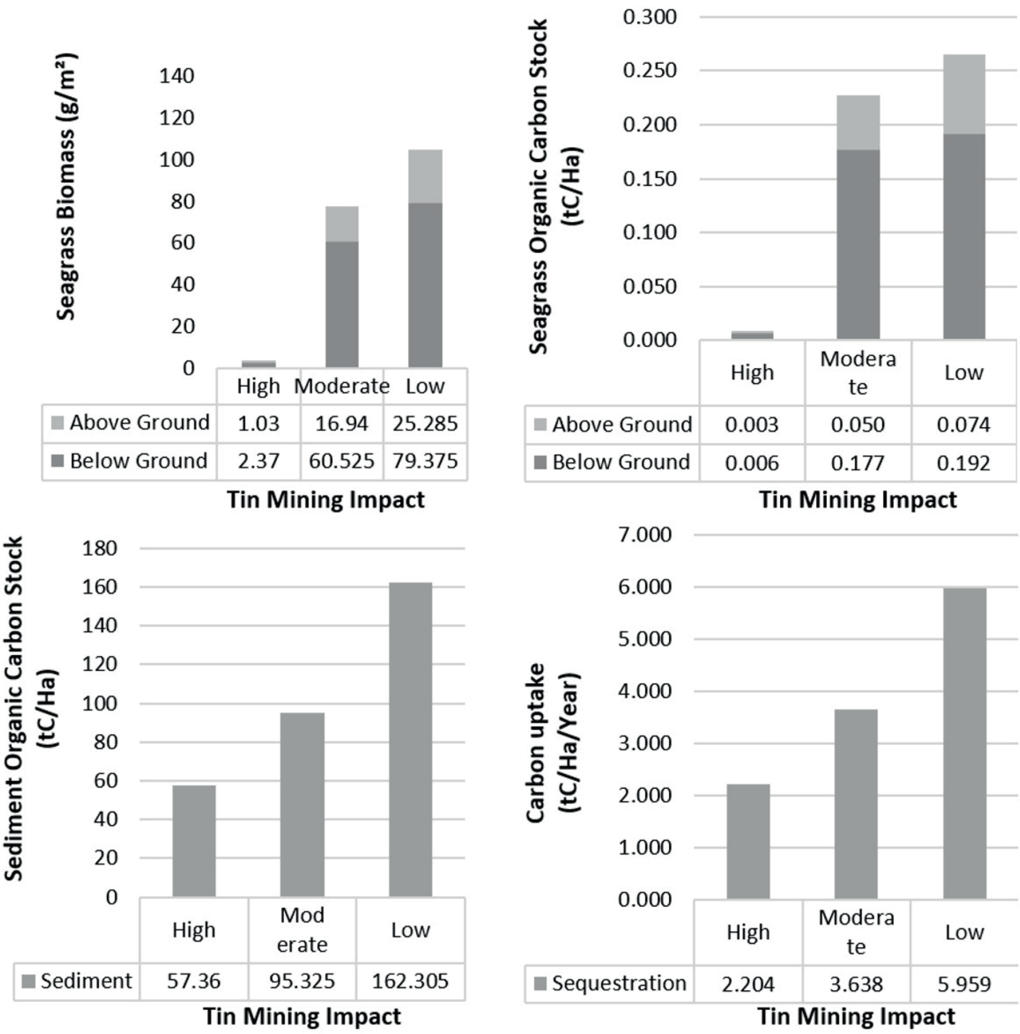

Fig. 4. Biomass, Carbon Stock, and Sequestration in Tin Mining Impacted Areas

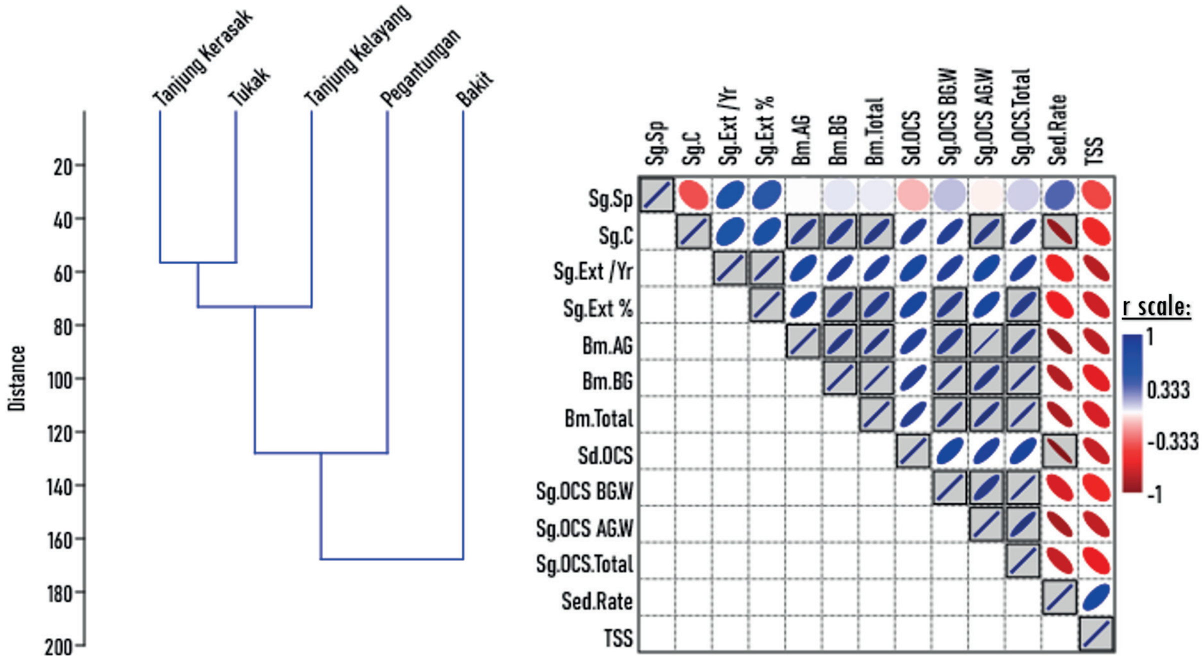

Fig. 5. Cluster Analysis of research location (left) and correlation between research variables (right), significance (P<0.05) shown in a square box. Sg.Sp= Seagrass Species; Sg.C= Seagrass Cover; Sg.Ext/Yr= Seagrass Changes (Ha/Year); Sg.Ext = Seagrass Change in 22 year (%); Bm.AG= Biomass Above ground; Bm.BG= Biomass Below ground; Bm.Total = Biomass above ground + below ground; Sd.OCS= Carbon Organic Sediment; Sg.OCS.BG.W= Seagrass Carbon Organic Stock Below Ground; Sg.OCS.AG.W= Seagrass Carbon Organic Stock Above Ground; Sg.OCS.Total Seagrass Standing Stock Carbon; Sed.Rate Sedimentation Rate; TSS Total Suspended Solid

ecosystems. Our findings emphasize the urgent need for conservation strategies that mitigate the impacts of such anthropogenic activities. Establishing protected marine areas and regulating mining practices near critical habitats are potential measures that could be taken to preserve these valuable ecosystems (Sugianti and Mujiyanto 2020; Tebaiy et al. 2021; Rifai et al. 2022).

Seagrass conservation and restoration in turbid waters present unique challenges and require tailored strategies to ensure ecosystem health and sustainability. Turbidity, influenced by factors such as water depth, canopy complexity, and sediment resuspension, plays a crucial role in shaping seagrass habitats and their associated ecosystem services (Samper-Villarreal et al. 2016). The stability of seagrass ecosystems, particularly in shallow coastal lagoons, relies heavily on feedback processes linked to the stirring up of sediments and the reduction of light (Adams et al. 2016; Park et al. 2016; Lanuru et al. 2018). Understanding these interactions is essential for effective conservation and restoration efforts.

Restoration initiatives have shown their potential to recover the health of coastal ecosystems rapidly. Programs such as the establishment of marine protected areas have been effective in maintaining ecosystem health and enhancing organic carbon storage in seagrass meadows (Adams et al. 2016; Stankovic et al. 2021; Tanner et al. 2021). In Asia, where seagrass beds are a critical component of marine biodiversity, conservation efforts are crucial for protecting these valuable habitats and the services they provide. The work by Sudo et al. (2021) highlights the importance of understanding the distribution, temporal changes, and conservation status of tropical seagrass beds to inform and tailor conservation strategies effectively.

Using advanced techniques like remote sensing to map how much seagrass there is can give important information that helps improve conservation and management efforts in turbid waters (Koedsin et al. 2016). These techniques are useful not only for monitoring the current state of seagrass meadows but also for predicting their responses to environmental changes and human impacts.

CONCLUSIONS

The study shows that in areas affected by mining, there are major decreases in seagrass growth and the ability to store carbon. This was determined by looking at data on biomass, sediment rates, total suspended solids (TSS), and organic carbon levels.

The strong association between mining intensity and the degradation of seagrass meadows, which are vital for carbon sequestration and marine biodiversity, suggests the need for immediate conservation efforts and a re-evaluation of mining practices to protect the seagrass ecosystem from continuously degrading. Management actions should prioritize protection, particularly in areas heavily affected by mining activities. The findings of this research have significant implications for policy-making and environmental management, particularly in promoting sustainable mining practices that consider the ecological value of seagrass meadows. This study calls for protective measures to safeguard the role of seagrass ecosystems as critical carbon sinks and biodiversity reservoirs. These actions are essential not only for the preservation of marine ecosystems but also for contributing to global climate change mitigation efforts. In addition, this study also fills a knowledge gap regarding the impact of tin mining on seagrass carbon dynamics while providing a foundation for future research and conservation strategies to ensure the sustainability of seagrass habitats in Bangka Belitung amidst increasing anthropogenic pressures.

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