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ORIGINAL RESEARCH PAPER

Sediment organic carbon stocks in tropical lakes and its implication for sustainable lake management

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ABSTRACT

BACKGROUND AND OBJECTIVES: The lakeside has an enormous sediment carbon storage potential; however, it is susceptible to various environmental changes and can easily become a source of carbon emissions. Understanding the amount of carbon storage in lakeside sediments and organic matter sources may provide information about the potential of lakeside zones in climate change mitigation, particularly for sustainable lake management. This study aims to estimate sediment organic carbon stock and the sources of organic matter in the Maninjau Lakeside-West Sumatera, Indonesia.

METHODS: Sediment sampling was performed at five research sites, with a depth of 0–100 centimeters. Sediment samples were divided into 4 subsamples: 0–15; 15–30; 30–50; and 50–100 centimeters. Bulk density and total nitrogen content were analyzed, and the percentage of organic carbon was calculated from the loss of ignition. The sediment organic carbon stock was calculated based on the bulk density and organic carbon content. Carbon per nitrogen ratio was also calculated to determine temporal changes in the sources of organic matter in the lake.

FINDINGS: This study demonstrated that Maninjau Lakeside has an enormous potential sedimentary organic carbon stock range between 284.23–442.59 megagrams per carbon per hectare. The highest total sediment carbon stock was found in Duo Koto (442.59 megagrams per carbon per hectare), with the lowest in Koto Kaciak (284.23 megagrams per carbon per hectare). In addition, the study's results also exhibited significant differences in sediment organic carbon stocks at each location with different land use and cover; in this case, the forest area has a higher carbon stock value than the agricultural and settlement areas. Therefore, it is essential to take initiatives for the restoration and conservation of lakeside areas because of their essential role in mitigating the climate change. The mean ratio of organic carbon and total nitrogen was between 9.96 to 16.91, indicating that phytoplankton, a mixture of floating macrophytes, and submerged vegetation were the sources of organic matter.

CONCLUSION: In general, the value of sediment organic carbon stocks tends to be lower in locations with intensive agricultural settlements than in forest areas. This study emphasizes that restoring lakeside wetland is vital in increasing sediment organic carbon stocks and maintaining lake sustainability.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
97	10	7

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INTRODUCTION

Carbon dioxide (CO_2) emissions are a significant contributor to greenhouse gas (GHG) emissions (accounting for around 74 percent of all GHG), making them the primary driver of global warming and climate change (UNFCCC, 2008). As an impact, global temperature has increased by almost a degree centigrade (°C) from the pre-industrial levels; the current increase is 1.1 °C specifically, and if the current emission rates remain high without any mitigation, the temperature rise is likely to increase by 1.5 °C from 2021 to 2040 (IPCC, 2021). Therefore, burning of fossil fuels, deforestation, and land use changes are some of the primary sources of CO_2 emissions in the atmosphere (Donato *et al.*, 2011). Wetlands, rainforests, and oceans, are among the most productive ecosystem types in the world (Balwan and Kour, 2021). Wetlands develop between the land and water bodies (such as peatlands and swamps), rivers, and lakes, and their capacity for carbon sequestration, particularly that of carbon deposited in sediments, can significantly contribute to climate change mitigation (Comer-Warner *et al.*, 2022). The biogeochemical process in the wetlands sediments affects carbon (C) and nitrogen (N) cycling and may lower the GHG in the atmosphere (Adame *et al.*, 2018). Sediment organic carbon (SOC) stocks in wetlands represent one-third of earth's SOC (500–700 Petagram Carbon, Pg C) despite covering only about 3% of global land (Page and Baird, 2016). However, despite having a high potential for carbon storage, wetland ecosystems are vulnerable to degradation due to various anthropogenic activities. Lakeside is one of the wetland ecosystems that have significant carbon storage potential. However, its sensitivity to environmental changes triggered by land conversion activities, may reverse its function as a source of carbon emissions (Minnick *et al.*, 2021; Lei *et al.*, 2022). Wetland disruption significantly impacts the organic carbon content of sediments, and it is estimated to have increased carbon emissions by 37.5% (Liu *et al.*, 2020). In the last few decades, widespread deforestation and massive land conversion for agriculture, aquaculture, and settlements have significantly threatened the wetland ecosystem and likely exacerbated the impacts of global climate change (Alongi, 2002; Adame *et al.*, 2018). Previous studies have indicated that the conversion of wetlands to other land uses may decrease the SOC stocks (Sakin and Sakin (2011) found a lower SOC value for the agricultural land than the forest land. These findings were supported by Dayathilake *et al.* (2021), who also discovered a significantly higher percentage value of SOC in wetlands with high vegetation cover (Kolonawa wetlands) than those with lower vegetation cover (Thalawathugoda wetland park). The highest SOC was found in the natural forest zone (147,000 kilogram per hectare (kg/ha), while the lowest SOC was found in the grasslands surrounding the lake Victoria Crescent Agro-Ecological Zone, Uganda (65,000 kg/ha) (Akodi *et al.*, 2016). Lei *et al.*, (2022) also reported different SOC values for different land uses, where the restoration zone (20.59 kg/m^2) and the mesophytic farmland rewetting zone (19.51 kilogram per square meter (kg/m^2) have a higher SOC than the lakeside zone without vegetation (3.63 kg/m^2). Meanwhile, wetlands can store carbon stock; therefore, it is essential to conduct research related to the quantification of carbon stocks in such ecosystems. Thus, understanding the SOC stock distribution across the different types of land uses and sediment depths offers a framework for assessing the vulnerability of SOC to disturbances (Uhran *et al.*, 2021). Indonesia has enormous potential for wetlands, with an area of 30.3 million hectare (ha), with various habitats, such as swamps, peatlands, wetlands, rivers, lakes, peatlands, and mangrove forests (Amin, 2016). Therefore, wetlands in Indonesia can play an essential role in mitigating climate change by storing significant carbon amount, especially underground. Despite the importance of wetlands in carbon sequestration, the level of wetland degradation in Indonesia is substantial, mainly due to land conversion, peatland burning, and illegal logging to expand plantations, agriculture, and settlements, contributing up to 50% carbon emissions in Indonesia's total national emissions (Margono *et al.*, 2014). Research on carbon storage estimation in Indonesian wetlands is critical, particularly to establish a database that can be utilized as a reference in wetland management strategies. There has been much research on estimating the carbon stocks in the wetlands of Indonesia, but most studies have only focused on the carbon stocks in peatlands (Basuki *et al.*, 2021; Siregar and Narendra, 2021; Silviana *et al.*, 2021), swamps (Novita *et al.*, 2021; Sufrayogi and Mardiatmoko, 2022; Purwanto *et al.*, 2020), and mangrove forests (Murdiyarso *et* al., 2015; Arifanti et al., 2019; Kusumanigtyas et al., 2019). Meanwhile, research on estimating carbon stocks in lakeside wetland areas is still limited (Sujarwo and Darma, 2011; Priyadi et al., 2014), despite its enormous potential to store carbon and vulnerability to degradation due to land use change and deforestation. Furthermore, knowledge regarding the effect of land use/cover on organic carbon stocks stored in soil or sediments also remains relatively unclear. Meanwhile, the land conversion rate of forest area into plantations and agricultural land continues to expand in Indonesia. This led to the establishment of this research, specifically conducted to determine the potential of SOC stocks in the lakeside wetlands and compare the amount of SOC stocks between locations with different land uses/covers. This study employed Maninjau Lake, a big lake in Indonesia, as the case study location. Lake Maninjau is one of the largest lakes in the West Sumatra Province, Indonesia, which plays a vital role in the local community's economy, including tourist destinations, aquaculture, and agriculture (Syandri et al., 2014). Maninjau Lake has faced heavy eutrophication exacerbated by anthropogenic nutrient inputs regarding the aquaculture and agricultural expansion since 1990. Aside from contributing to water contamination, excessive use of chemical fertilizers in agriculture and feed aquaculture in Lake Maninjau has also seriously harmed the local economy and public health (Tasri et al., 2021). This study particularly aims to determine the SOC stock and composition of sediment variables, including organic carbon concentration (OC), total nitrogen (TN), and bulk density (Bd), as well as compare the SOC stock at each research site with different land uses/covers. This study also aims to determine the source of organic matter in the northern part of Maninjau Lake. This study is essential for the sustainable management of Lake Maninjau and climate change mitigation. This study was conducted at Maninjau Lake, West Sumatra, Indonesia, in 2022.

MATERIALS AND METHODS

Study area description

This research was conducted at Lake Maninjau (0° 19' S 100° 12' E) in Tanjung Raya District, Agam Regency, West Sumatra Province, Indonesia, which lies at an elevation of 461.50 meters (m) above sea level. Maninjau Lake has an elongated shape with an approximate dimension a length of 17 kilometers (km) and a width of 8 km extending from north to south, along with a surface area and volume of 9,737.50 ha and 10,226 x 10^6 cubic meters (m^3), respectively. This lake has a natural outlet, namely the Batang Antokan River, which flows towards the west. The depth of Maninjau Lake increases in the southern part, and the maximum depth reaches ± 165 m. The study area has a wet tropical climate with an average rainfall of 345.58 millimeters (mm) per month and the average humidity of 95.20%. The average temperature of Maninjau Lake is 22.66 °C-31.27 °C (MERI, 2011). Maninjau Lake is located within the physiographical area of the Bukit Barisan Mountains and was formed from the eruption of ancient volcanoes embodying a strato morphology of the surrounding landscape. Topography classes of Maninjau Lake consist of flat (0–8% slope), mild (8–15%), fairly steep (15–25%), steep (25–40%), and very steep (> 40%) areas, with the southern part being steeper than the north-west. The lake's sediment can record the frequency and magnitude of volcanic eruptions, given its proximity to several active volcanoes, namely Mount Marapi, Singgalang, and Talang (De Maisonneuve et al., 2019). Maninjau Lake is an important tourist destination, with a hydroelectric power plant with a capacity of 64 Mega Watts (MW), capturing fisheries, floating net cages, and agriculture (Junaidi et al., 2014). Lake Maninjau is included in the list of National Priority Lakes together with 15 other lakes in Indonesia because of its strategic economic, ecological, socio–cultural, scientific values, and an experience of significant pressure and degradation (Presidential Regulation of the Republic of Indonesia No. 60 of 2021). The catchment area's primary land uses are rice farming, arid land, plantation, settlements, and forest. The water surface of Maninjau Lake covers a sizable portion (75.38%) of the catchment area (24,800 ha). Maninjau Lake is in a heavy eutrophic state due to the rapid expansion of floating net cage-based carp and tilapia, resulting from an influx of nutrients, including N and phosphorus (Syandri et al., 2014).

Field sampling designs

The field sampling was conducted in June 2022. The research sites were determined based on random judgemental sampling, a method that identifies distinct characteristics relevant to the study goals

(Bhardwaj, 2019). The sampling point in this study was determined based on the representativeness and accessibility of the sampling locations. Sediment sampling was limited to five sites in the northern part of the Lake, which is more accessible and sloped than the southern part. The five sampling sites included Koto Malintang (M1), Koto Gadang (M2), Koto Kaciak (M3), Duo Koto (M4), and Koto Maninjau (M5) (Fig. 1 and Table 1). Several sediment variables were measured, including depth, Bd, OC concentration, and TN. Sediment sampling was performed at each site using a D'Section corer, a cylindrical stainless steel tube 50 centimeters (cm) long and 2.5 inches in diameter. The depth of sediment coring at all research sites reached 100 cm. The sediment samples were then divided into several layers according to the depth intervals of 0–15 cm, 15–30 cm, 30–50 cm, and 50–100 cm. A total of 20 sediment samples were obtained from the five research sites.

Laboratory analysis

Analyses of Bd, percentage of SOC content, and TN were performed at the Environmental Engineering Laboratory, Diponegoro University, and the CNH Laboratory, Semarang.

Sediment organic carbon stock (SOC)

Bd (gram per cubic centimeter: g/cm^3) was determined by calculating the ratio of the dry weight and volume of the sample. The sediment sample was oven-dried at 60 ^{o}C for at least 48 hours and later weighted. Dry Bd was calculated using Eq. 1 (Kauffman and Donato, 2012).

Bd (g/cm^3) = Oven-dry sample mass (g) / Volume of the sample (m^3) (1)

The Loss on ignition (LOI) method was used to calculate the percentage of OC content (%OC) (Nelson

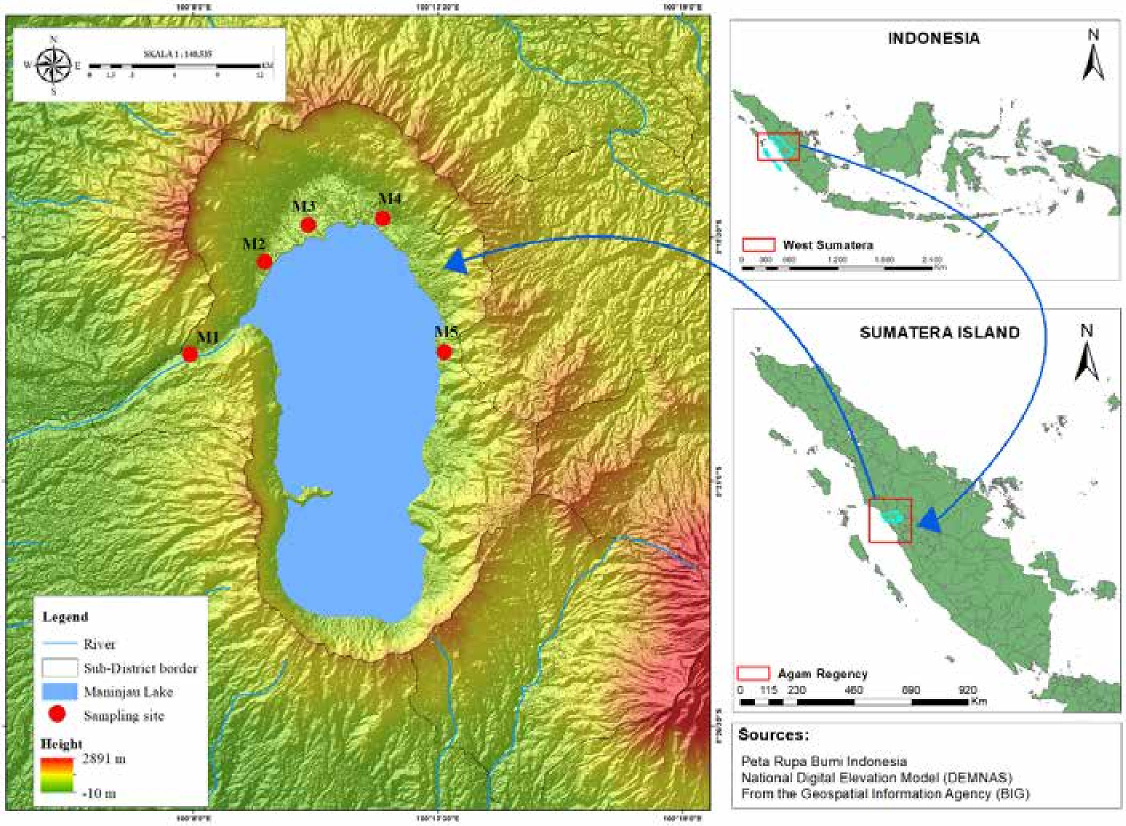


Fig. 1: Geographic location of the study area in the north part of Maninjau Lakeside in Indonesia

Table 1: Description of the study sites

Site	Location	Geographical position	Description
M1	Koto Malintang	-1° 42' 25.6''S 100° 8' 56.5''E	The lake outlet with conservation and tourism areas with sandy substrate types.
M2	Koto Gadang	-1° 44' 18.5''S 100° 10' 26.2''E	An inlet of the lake, with overgrown water hyacinth and sandy-mud substrate type
M3	Koto Kaciak	-1° 44' 41.4''S 100° 10' 59''E	Sloping lakeside, floating net cage, and riparian areas are dominated by agricultural land with muddy substrate types.
M4	Duo Koto	-1° 44' 54.3'' S 100° 11' 40.4''E	Dominated by forest areas with the sandy-mud substrate
M5	Maninjau	-1° 41' 50.2'' S 100° 13' 33.4''E	Near dense settlements with minimal vegetation cover, with several aquaculture activities in the lake's water bodies with a sandy substrate type.

et al., 1996). A total of 20 collected sediment samples were placed in weighted crucibles and oven-dried at 105 °C for 12-24 hours to determine the water loss. After oven-drying, the sample was burned in a furnace at 550 °C for 4 hours, then weighed to define the organic matter. The LOI is calculated using Eq. 2 (Heiri *et al.*, 2001).

$$LOI_{550} (\%) = ((DW_{105} - DW_{550}) / DW_{105}) * 100 \quad (2)$$

Where;

LOI_{550} : percentage of LOI at 550°C

DW_{105} : dry sample weight before combustion

DW_{550} : dry sample weight after combustion (heating at 550 °C)

The total OC content percentage was estimated through LOI at 550 °C (LOI_{550}), which is then transformed by a factor of 0.55 as in Eg. 3 (Hoogsteen *et al.*, 2015), while, the SOC stock was calculated using Eq. 4 (Howard *et al.*, 2014).

$$OC = LOI_{550} * 0.55 \quad (3)$$

$$SOC\ (Mg/C/ha) = Bd \times H \times OC \quad (4)$$

Where;

SOC : Sediment organic carbon stock (Mg/C/ha)

OC : organic carbon concentration (%)

Bd : bulk density (g/cm^3)

H : sediment thickness (cm)

Total nitrogen and carbon/nitrogen (C/N) ratio

TN was determined by indophenol-blue methods, followed by Kai *et al.* (2016). TN analysis commenced with the destruction of the sediment samples. Sediment samples (0.5 g) were digested using 10 mL sulfuric acid (H_2SO_4) and 10 mL hydrogen peroxide (H_2O_2) at 420 °C for 1.5 hours using Kjeldahl. 0.5 g of copper (II) sulfate ($CuSO_4$) catalyst was used to accelerate the destruction reaction. Furthermore, the crude extract was filtered using ADVANTEC Filter Paper number 6. TN content was measured by mixing 1 mL of the extract with 0.6 mL of indophenol solution and 0.4 mL of sodium hypochlorite (NaOCl) solution. The mixture was then incubated at room temperature for 45 min until the solution color changed. The solution absorbance was then measured using a UV-Vis spectrophotometer at a wavelength of 635 nanometers (nm) (Santoni *et al.*, 2001). The C/N ratio was also calculated to determine the temporal changes in the sources of organic matter in the lake. The C/N ratio was calculated based on the OC (%) and TN (%) concentration and then multiplied by 1.167 to obtain the yield atomic mass ratios using Eq. 5 (Fan *et al.*, 2017).

$$C/N\ ratio = (OC/TN) * 1.167 \quad (5)$$

Where;

OC : organic carbon (%)

TN : total nitrogen (%)

1.167 : yield atomic mass ratios

The C/N ratio of fresh algae in lacustrine sediment generally ranges between 3–8, and the C/N ratio of terrestrial vegetation ranges from 14–23 or may reach up to 45–50 (Mayers, 1997).

Statistical analysis

Statistical analysis was performed to determine the difference in the OC and TN between Bd. Sediment carbon concentrations between the research sites and depths were tested with analysis of variance (ANOVA). The relationships between OC and TN (dependent variables) and Bd (independent variables) were examined using linear regression. The Shapiro–Wilk test assessed data normality, and all statistical tests used a significance level of 0.05.

RESULT AND DISCUSSION

Sediment organic carbon stocks

The SOC in the different depth intervals is presented in Fig. 2, and it can be seen that SOC increased with depth. The SOC stock in each depth interval differs significantly with the probability (p= 0.000 <0.05) (Table 2). A remarkable difference was observed between SOCs in the surface and deeper layer (p= 0.000 <0.05). The highest SOC stock of 267.56 Mg/C/ha was noted for the deepest layer of (50–100 cm), and the lowest stock was 43.47 Mg/C/ha at the depth of 15–30 cm.

The findings of this research are in agreement with Wei *et al.* (2022), who found that SOC stocks of 25% at the surface layer and 53% in the deeper sediment layer. A similar pattern was observed by Wang *et al.* (2018) and Jiang *et al.* (2019). They reported the highest SOC at the deepest layer (300 cm). The SOC stocks at five research sites are shown in Fig. 3. The SOC in the Maninjau lakeside ranged between 284.23 (M3)–442.59 Mg/C/ha (M4). The average stock at the Maninjau lakeside (365.54 Mg/C/ha) was lower than that in the urban freshwater wetlands at Kolonawa and Thalawathugoda, Colombo (504 ± 14 and 550 ± 23 Mg/C/ha) (Dayathilake *et al.*, 2021), but higher than the highest SOC stocks in the lakeside of West Mauri Lake, China (313.16 Mg/C/ha) (Lei *et al.*, 2022) and the Lake Victoria, Uganda (147 Mg/C/ha) (Akodi

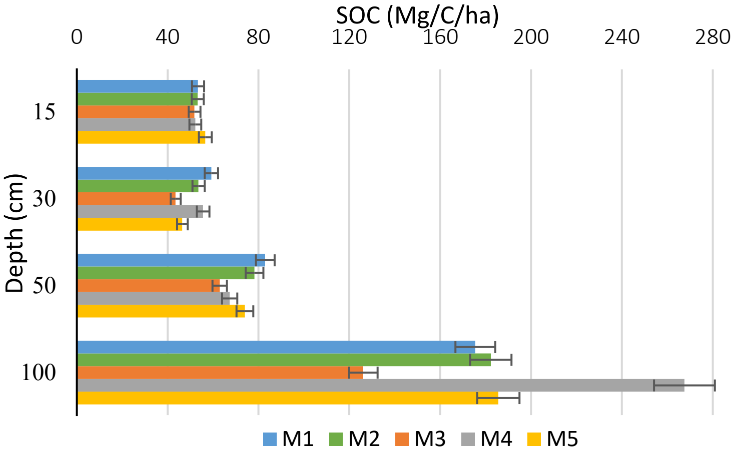


Fig. 2: SOC stock at different sites in various depth intervals

Table 2: Anova test of SOC at each site

Source of variation	SS	df	MS	F	P-value	F crit
Between groups	60349.58	3	20116.53	30.70605	7.16E-07	3.238872
Within groups	10482.12	16	655.1324	—	—	—
Total	70831.7	19	—	—	—	—

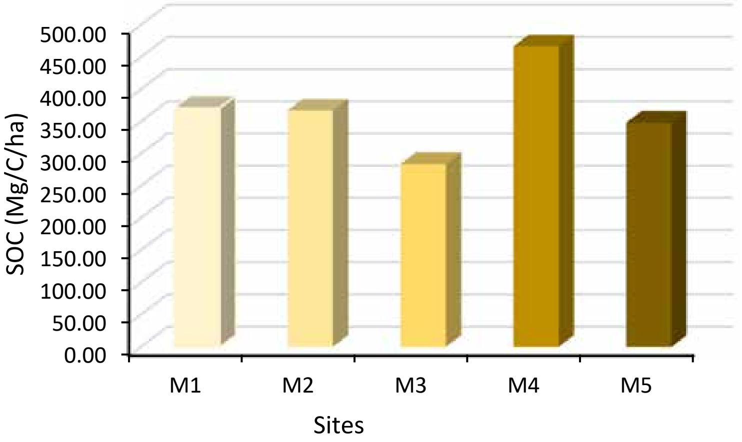


Fig. 3: SOC stocks at five different research sites

Table 3: The type of land use in the catchment area of Maninjau Lake (BPS-SAR, 2015)

No	Village (Nagari)	Forest (ha)	Built-up area (ha)	Plantation (ha)	Rice -field (ha)
1	Tanjung Sani	2,421	154	1773	126
2	Sungai Batang	720	180	279	389
3	Maninjau	560	110	426	205
4	Bayua	692	140	140	524
5	Duo Koto	2,037	75	159	275
6	Paninjauan	58	60	99	145
7	Koto Kaciak	369	110	236	458
8	Koto Gadang	606	64	101	216
9	Koto Malintang	1,431	80	98	174

et al., 2016). The highest SOC was observed at M4 (442.59 Mg/C/ha), with the highest forest area cover, whereas the lowest was noted at M3 (284.23 Mg/C/ha). Based on the data from Syandri *et al.* (2014), the forest area in M4 reaches 2,037 ha. In contrast, the forest area around the M3 constitutes only 369 ha, and land use is dominated by rice fields, causing low SOC stock in comparison to other study sites (Table 3). The SOC and TN amounts in sediments was significantly influenced by land use or cover in the Maninjau Lake catchment area. This suggests that the presence and type of vegetation on the lakeside have a critical impact on the OC storage in sediments. It also emphasizes the importance of the restoration efforts in wetlands, considering that the land use type significantly affects the SOC stocks (Lei *et al.*, 2022).

The land use in the Maninjau Lake area has undergone significant changes, especially in the forest areas. The forest area surrounding the lake has been declining from 1989 to 2020. In 1989, the forest area was 8,228.25 ha; it has declined considerably to 5,190.21 ha in 2020, and it is predicted to continue declining until 3,607.83 ha in 2050 (Antoni *et al.*, 2016). Meanwhile, agriculture, plantations, and built-up area have increased sharply due to the economic and population growth. Land use in the catchment area affects the quality of the environment and water quality. The use of chemical fertilizers on the agricultural and plantation land affected the TN sediment. Meanwhile, reduced forest area will directly reduce the organic inputs and SOC (Akodi *et al.*, 2016). The amount of SOC and other organic elements are also influenced by the topography of the catchment area of Maninjau Lake, which mainly contains steep slopes and is prone to landslides. Landslides and erosion are closely related to the carbon cycle (C) and cause changes in physical, chemical, and biological properties (Shiels and Walker, 2013). Landslides can release carbon into the atmosphere (Lal, 2004). Soil experiencing landslides causes the loss of the topsoil and most of the soil's organic matter (Stalard, 2012). The presence of SOC in the eroded soil is highly dependent on the ecohydrological factors (Quijano *et al.,* 2013), topography, and land cover (Dialynas *et al.,* 2016a). One of the northern parts of the Maninjau catchment areas with a high landslide susceptibility is Koto Malintang (M1), with a slope of 30–45% (Ramanda *et al.,* 2019). Other areas in the northern part of Maninjau Lake are relatively sloping and not prone to landslides. M1 has a relatively large forest area, which can minimize the landslides and loss of SOC stock. This is in line with the results of Dialynas *et al.* (2016b), which showed that the land cover type dramatically affects the extent of SOC loss due to erosion, where the land with forest cover type loses lesser SOC when compared to oil palm plantation areas. Thus, the presence or absence of above-ground vegetation and the density and health of its growth regulate the organic matter input and SOC in the sediment (Zhao *et al*., 2018; Wei *et al*., 2022). Lakeside wetland areas with forest cover have a higher SOC stock than those with minimum vegetation cover; this indicates that vegetation restoration in the lakeside regions may substantially increase the SOC stock (Ji *et al.*, 2020). A similar conclusion was drawn by Adame *et al.* (2018), who found that the restoration of wetlands may help increase the OC stock of sediments in the long term. They found that the SOC stock increased from 1234±18 to 1309±270 Mg/C/ha from 5 to 70 years of restoration. Furthermore, Creed *et al.* (2022) also showed that wetlands from the agricultural land could restore the wetland carbon stock to that of intact wetlands within 40 years or less. Meanwhile, the conversion of forest areas on the lakeside and wetlands into settlements will significantly decrease the SOC stock and potentially contribute to carbon emissions.

Distribution of sediment organic carbon concentration and total nitrogen content

The distribution of OC concentration and TN at different depths and sites is presented in Fig. 4a and b. OC fluctuated significantly, with a trend towards the lower values at the deeper layers. However, an opposite pattern was reported at the M4 site, where high OC was found at the deepest layer (50–100 cm) (35.368%), whereas it was 22.29% in the surface sediment layer (0–15 cm). TN's vertical distribution showed a similar trend, except for sites M3 and

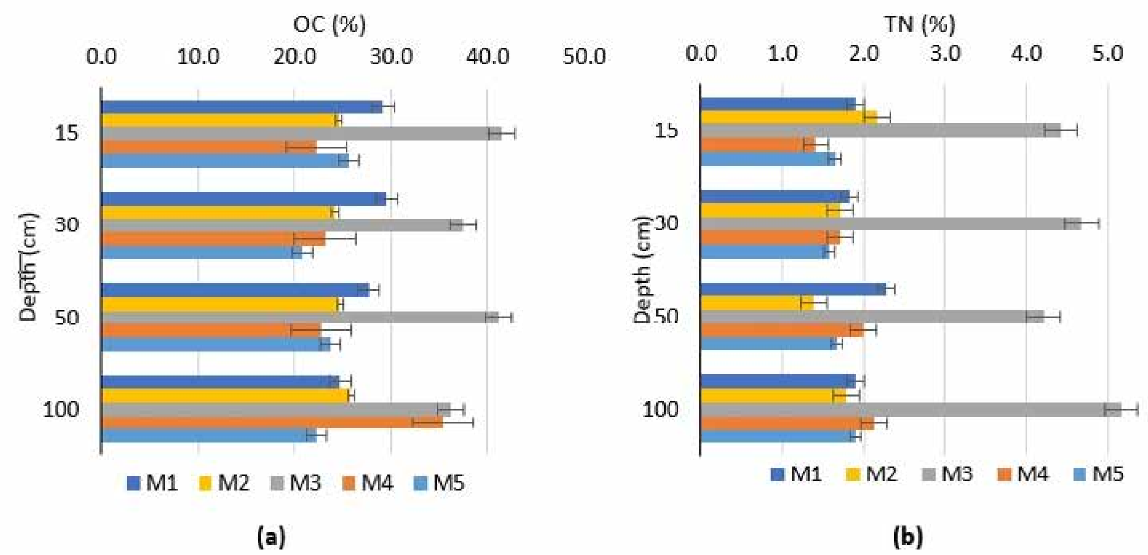


Fig. 4: Vertical distribution of (a) OC in the sediment and (b) TN

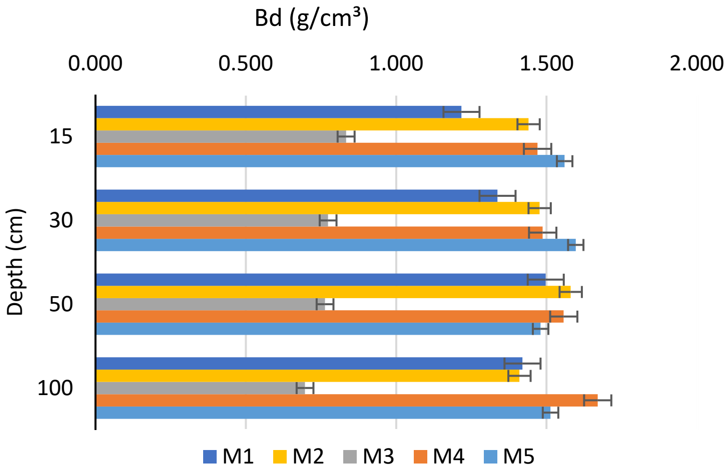


Fig. 5: Vertical distribution of Bd

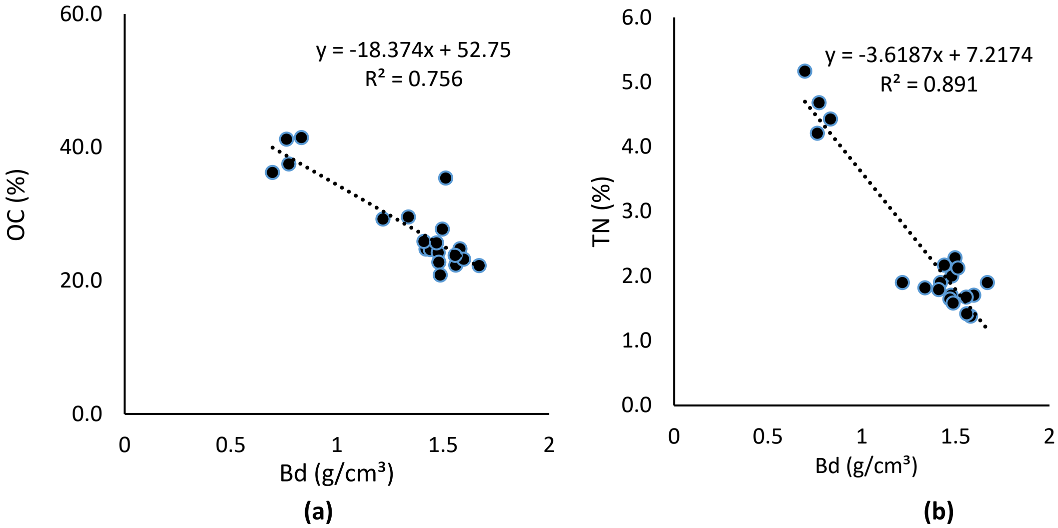


Fig. 6: Correlation between (a) OC and Bd; and (b) TN and Bd

M4, where TN was higher in the deepest layer than the surface layer. There was a significant positive correlation between OC and TN ($y=0.1554x–2.003$, $R^2=0.7342$), which indicated that most of the nitrogen was in the form of organic nitrogen (Yu *et al.,* 2018).

Generally, the vertical distributions of OC and TN varied among the different sediment depth intervals. Thus, the vertical variations in OC and TN were correlated with the Bd of the sediment. The Bd of a sediment increased with its depth. However, the opposite trend was observed in OC and TN at the M3 and M5 sites (Fig. 5), which showed that Bd positively correlates with sediment depth, in agreement with previous studies (Twum and Nii-Annang 2015; Gnanamoorthy *et al.,* 2019). It was also found that sediment Bd has a significant negative correlation with OC and TN ($y= −18.374x + 52.75$, $R^2= 0.756$; and $y= −3.6187 + 7.2174$, $R^2 = 0.891$, respectively) (Fig. 6a and b). Thus, high Bd may indicate lower OC and TN in the sediment. The biological cycles and microbial decomposition restricted to the deeper sediment layers are two complex processes contributing to the declining trend in OC correlated with the increase in the sediment depth (Bhomia *et al.,* 2016; Sasmito *et al.,* 2020).

The mean of OC, TN, and Bd in the sediments differed significantly (*p*=0.000; *p*=0.000; *p*=0.000<0.05, respectively) (Tables 4 to 6) among the research sites. The highest average of %OC was found at M3 (39.07%), while the lowest was noted for site M5 (23.11%) (Fig. 7a). Likewise, the highest average value of TN was also found at M3 (4.62%), with the lowest in M5 (1.69%) (Fig. 7b). A previous study reported that the TN and OC in the sediment of Maninjau Lake ranged from 1.10% to 2.10% and 48.81% to 62.35%, respectively, and the highest values were also found at M3 (Junaidi *et al*. 2014). In this case, the dynamics of TN and OC in sediments are influenced by various biota activities at the lake bottom, which correlated with water quality parameters, including temperature, DO, pH, and others. The waste from the floating net cages strongly influences the quality of the lake waters. There is massive sediment waste at M3 since its topography is relatively sloping compared to other locations and thus, supports waste accumulation. The extensive deposition of organic matter has resulted in water hyacinth blooms in that area (Syandri *et al*., 2014).

Anthropogenic sources, including the use of fertilizers in agricultural activities and runoff from the settlement can also increase the input of organic matter in the lake (Avarimidis *et al*., 2015). Fishery production in Maninjau Lake showed an increasing trend from 2018 to 2019 (from 187.87 to 593.86 tons). Concurrently, agricultural production, especially in the rice field, increased from 35,506 to 38,303 tons (BPS-SAR, 2020). The trend of increasing fishery and agricultural production due to the use of fertilizers also increased the input of organic matter in Maninjau Lake. The highest and lowest Bd were found in M5 (1.546 g/cm^3) and M3 (0.7665 g/cm^3), respectively (Fig. 7c). Bd concentration depends upon the vegetation's roots, which in turn, influences the biological activity, increases water permeability, and decreases sediment compaction (Bhomia *et al*., 2016; Arifanti *et al*., 2019). This condition probably originates from the differences in land use and vegetation density among the research sites. Site M5 is mostly an urbanized area with minimum vegetation coverage and a sandy substrate, while M3 is dominated by agricultural land with a muddy substrate. In addition, sediment texture also significantly affects the OC content. For instance, the finer sediments, such as mud, generally have a higher content of OC than sandy substrates (Musale *et al*., 2015).

Table 4: Anova test of the OC concentration at each site

Source of variation	SS	df	MS	F	P-value	F crit
Between groups	642.9768	4	160.7442	14.19317	5.52E-05	3.055568
Within groups	169.8819	15	11.32546	—	—	—
Total	812.8587	19	—	—	—	—

Tabel 5: Anova test of TN at each site

Source of variation	SS	df	MS	F	P-value	F crit
Between groups	25.43542	4	6.358854	72.51939	1.25E-09	3.055568
Within groups	1.315273	15	0.087685	—	—	—
Total	26.75069	19	—	—	—	—

Tabel 6: Anova test of Bd at each site

Source of Variation	SS	df	MS	F	P-value	F crit
Between groups	1.718473	4	0.429618	63.37768	3.24E-09	3.055568
Within groups	0.101681	15	0.006779	—	—	—
Total	1.820154	19	—	—	—	—

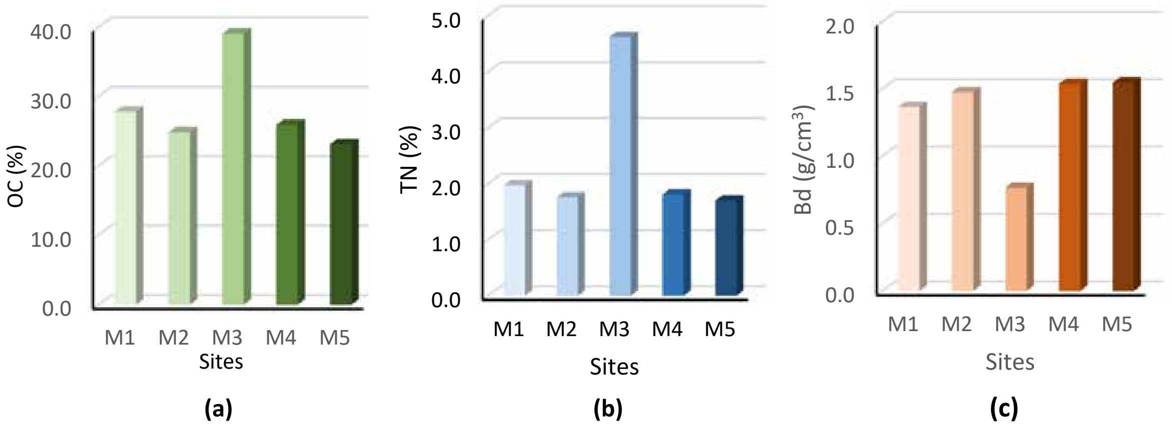


Fig. 7: The differences among (a) OC, (b) TN, and (c) Bd at each site

Table 7: OC and TN concentration in the lake sediments in several countries

Lake	Characteristic	OC (%)	N (%)	References
Maninjau, Indonesia	heavy eutrophic	20.82–41.44	1.37–5.16	This study
Chaohu, China	oligotrophic	0.59–1.02	0.07–0.15	Yu *et al.*, 2018
Balkhash, Kazakhstan	oligotrophic	1.13–1.69	0.16–0.21	Liu *et al.*, 2021
Dali, Mongolia	mesotrophic	1.0–7.3	0.13–0.56	Fan *et al.*, 2017
El Sol, Mexico	oligotrophic	4.6–7.9	—	Alcocer *et al.*, 2020
Towuti, Indonesia	mesotrophic	0.4–4	—	Friese *et al.*, 2021
Sentani, Indonesia	oligotrophic	8.0–16.0	0.33–1.91	Nomosatryo *et al.*, 2021
Tempe, Indonesia	mesotrophic	4.7–5.8	0.30–0.50	Yustiawati *et al.*, 2021
Qinghai, China	mesotrophic	1.4–4.8	0.14–0.72	Chen *et al.*, 2021
Halai, China	—	13.2	—	Xu *et al.*, 2019
Dahu, China	—	48.76	—	Xu *et al.*, 2019
Chapala, Mexico	oligothropic	15–22	—	Xu *et al.*, 2019
Great Ghost, Taiwan	oligotrophic	7.1–22.2	—	Kandasamy *et al.*, 2018
Ovre Bjorntjarn, Sweden	eutrophic	39.9–40.0	—	Gudasz *et al.*, 2017
Solbacka, Sweden	eutrophic	31.5–34.4	—	Gudasz *et al.*, 2017

The concentrations of OC and TN in Lake Maninjau (20.82–41.44% and 1.37–5.16%, respectively) are significantly higher than in several lakes in Indonesia, such as Lake Towuti (0.4–4 %) (Friese *et al.*, 2021), Lake Sentani (8–16%) (Nomosatryo *et al.*, 2021), and Lake Tempe (4.7–5.8 %) (Yustiawati *et al.*, 2021). This is closely related to the trophic level of the lake, where a lake with a trophic level of heavy eutrophic such as Maninjau Lake, will have a higher OC concentration. The result of sediment OC concentration and TN in this study were comparable to the average value reported for eutrophic lakes and significantly higher than the mesotrophic and oligotrophic lakes in several countries (Table 7). The heavy eutrophic status of Lake Maninjau was established in 2013 due to high nutrient inputs, such as nitrogen and phosphorus from aquaculture waste (floating net~~s~~ cages) and agriculture activities on the lakeside. The number of floating net cages in Lake Maninjau shows an increasing yearly trend (Fig. 8), for instance, from 16 units in 1992the number increased to 17,226 units in 2014 (MERI, 2015). The newest 2021 data displayed

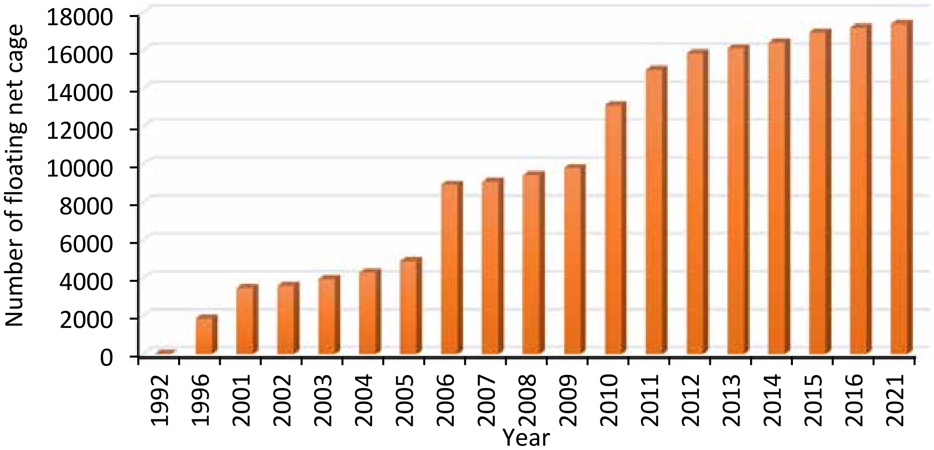


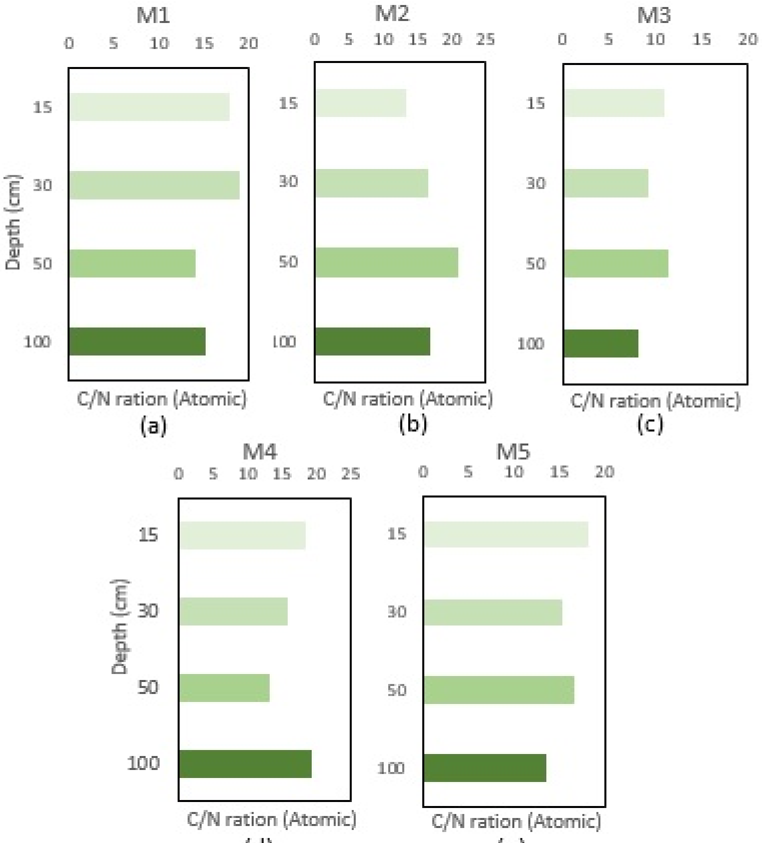
Fig. 8: The number of floating net cages in Lake Maninjau in 1992–2021 (MERI, 2011; Junaidi *et al.*, 2014; MERI, 2015; Soejarwo *et al.,* 2022)

17,441 units of floating net cages in Lake Maninjau (Soejarwo *et al*., 2022).

The additional source of nutrient pollution in Maninjau Lake is associated with the widespread land use transformation in the lakeside area for settlements, rice fields, and other uses. This has led to the occurrence of blue-green algae blooms and the dominance of phytoplanktons, such as the genera Gloeocapsa, Oscillatoria, and Mycrocystis (Sulastri, 2019). Syakti *et al.* (2019) reported that hazardous algae blooms (HABs), and generated by the dynamics of various phytoplankton species, emanated from increased human activity.

Sources of organic matter in lakeside sediment

The organic matter in lake sediments originate from the internal primary production (autochthonous) and terrestrial materials introduced into the lake (allochthonous) (Lin *et al.,* 2022). The source of organic matter in the lake sediment is commonly determined by the ratio of OC and TN (C/N ratio) (Mayers, 2003; Barus *et al*., 2019). The vertical distribution of C/N atomic ratios at each site is presented in Fig. 8. The general trend in C/N atomic ratios decreased from the surface towards the deeper sediment layers. The exceptions constitute sites M2 and M4, where the C/N atomic ratios increased with the sediment depth. The C/N atomic ratio varies depending on the organic matter source. Values between 3 and 8 are typically noted when the allochthonous sources dominate. A C/N ratio greater than 20 indicates that allochthonous material is the main source of organic matter. Considering this, a decreasing trend in the C/N ratio with the sediment depth may indicate an increasing share of autochthonous sources. In contrast, an increasing trend in the C/N ratio may relate with a higher allochthonous proportion (Yu *et al*., 2018). The result of the C/N atomic ratio in this research showed that at the sites M1, M3, and M5, the organic matter mainly originates from autochthonous sources, while allochthonous sources and terrestrial input dominate at sites M2 and M4. These results indicate that the organic matter in Maninjau Lake sediments is dominated by autochthonous material, especially from the floating net cage waste. The average C/N atomic ratio of all research sites (M1–M5) ranged from 9.96 to 16.75 (Fig. 9), with the lowest and highest ratios found at M3 and M4, respectively. These values were in the range typically noted for phytoplanktons (4–10) and were close to the range reported for submerged and floating macrophytes (10–20), but were significantly less than those of terrestrial plants (greater than 20) (Tyson, 1995; Sasmito, 2020). The average value of the C/N ratio at M3 was below 10 (9.96) (Fig. 10), indicating that the main source of the organic matter is phytoplankton or endogenous aquatic organism. The C/N value is inversely proportional to the intensity of land use by humans. (Enters *et al.*, 2006). M3 is located in Koto Kaciak and is the most polluted site by organic matter—reflected by the high concentration of OC and TN in the sediment of the



(a) (b) (c)

(d) (e)

Fig. 9: The vertical variation of C/N atomic ratios at each site

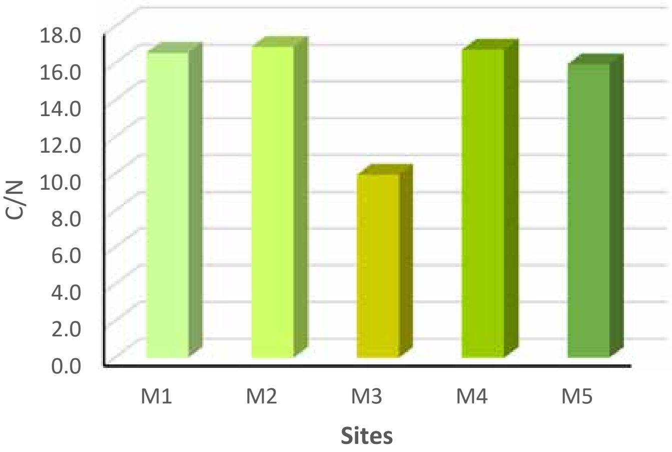


Fig. 10: The average C/N atomic ratio at each site

Maninjau Lakeside. The relatively sloping topography of M3 causes a significant waste accumulation in the surface sediments. The high expansion of organic matter has caused a phytoplankton bloom in that area (Barus *et al*., 2019). Consequently, a low C/N ratio was reported for Koto Kaciak. The mean atomic C/N ratios at the remaining sites, including M1, M2, M4, and M5, ranged from 15.95 to 16.91, indicating that the primary source of organic matter in these locations is a mixture of floating macrophyte derivatives and submerged vegetation. Furthermore, these results also illustrate that the high OC value in these locations mainly results from terrestrial plant material (forest litter) from the forested catchment and the impact of anthropogenic terrestrial activities (Mahapatra *et al.,* 2012). This is in agreement with the characteristics of each site: site M1 (Koto Gadang) is an outlet area and a conservation forest; M2 (Koto Malintang) is an inlet area overgrown by water hyacinth; M4 (Duo Koto) is dominated by forest; M5 (Koto Maninjau) is a settlement area. The mean atomic C/N ratios at the remaining sites, including M1, M2, M4, and M5, ranged from 15.95 to 16.91, indicating that the primary source of organic matter in these locations is a mixture of floating macrophyte derivatives and submerged vegetation.

Implication for sustainable management of lake

The lakeside area is a type of wetland ecosystem vulnerable to environmental changes, mainly caused by human interference. The significant land use change in the lakeside, primarily for agriculture, plantations, and settlements, has transformed this area into a carbon source because of its sensitivity to changes in the nutrient content, temperature, pH, etc (Mitra *et al*., 2005). The findings of this study have demonstrated that SOC stocks are higher in the lakeside area with a dense vegetation cover, such as conservation forest areas, than within agricultural land and settlements with a sparse vegetation cover. This suggests that restoration and conservation efforts of lakeside wetlands may enhance the SOC stock. SOC stock has continued to rise as the lakeside vegetation succession stage has been developed (Li *et al*., 2018). The presence of land vegetation in the lakeside area essentially reduces the erosion susceptibility of environments within sandy soils, such as in M1. Restoration initiatives in the lakeside area, such as converting agricultural land to wetlands may thereby reduce human disturbance, which is beneficial for ecosystem recovery and SOC accumulation (Lei *et al*., 2022). In addition, the condition of the catchment area along the lakeside significantly affects the state of Maninjau Lake. Agricultural activity contributes to sewage ingress and nutrient input into the lake, thus contaminating lake waters and settling as sludge sediment (Mahapatra, 2012). The high nutrient load released from floating net cage waste further pollutes the waters of Maninjau Lake. Additionally, it is generally recognized that anthropogenic activities increase the nutrient inputs into the lakes and affect their trophic state (May *et al*., 2021). Lake Maninjau is characterized as being heavily eutrophic, thus substantially influencing ecological degradation (Syandri *et al*., 2014). Therefore, a proper management strategy is required to reduce the pollution load in Maninjau Lake. The potential management actions to improve the lake water quality encompass the following: developing sewage treatment plants, raising industrial waste disposal standards, limiting industrial and domestic sewage disposal, preventing regional sources of pollution from agricultural irrigation, and lowering fertilizer and pesticide usage in the lakeside area (Qing *et al*., 2007; Yu *et al*., 2020). Additionally, the self-purification of water bodies may be significantly boosted with sufficient restoration efforts in the riparian zone along the lakeside. These initiatives may also enhance the biodiversity, protect soil quality, and limit eutrophication (Chen *et al.,* 2019). Hence, to improve the sustainability of the water and lakeside environment of Maninjau Lake, it is essential to invest restoration efforts by considering the suitable type of vegetation in the lakeside area. Following this, the ecosystem's total carbon stock could be significantly increased by planting local plant species and maintaining plant biodiversity. Moreover, the water balance must be considered to ensure the effectiveness and sustainability of the ecological restoration efforts in the lakeside area (Jiang *et al.,* 2019). Regarding the global climate change mitigation, restoring and protecting the sustainability of Maninjau lakeside may significantly reduce carbon emissions, increase carbon storage capacity in sediments, and improve the local community's livelihoods. It is also necessary to have early detection of pollutants dissolved in Maninjau Lake; referring to the research of Kamyab *et al.,* (2022), carbon-based molecularly-imprinted polymers

(MIPs) can be effectively used to detect harmful pollutants. Since carbon-based nanomaterials are sensitive to molecular identification, they are widely used to assess the environmental quality. Agricultural waste, aquaculture, and water pollution in Maninjau Lake are also caused by household waste, which is generally discharged into rivers before eventually entering the lake. To overcome those problems, initiatives are needed in managing household waste, such as converting waste into compost that can be reused by the community. Based on the research study by Kamyab *et al.,* (2015), the management of waste into compost can provide considerable benefits from an economic perspective and help reduce the greenhouse gas emissions by 90%.

CONCLUSION

This study has indicated that the lakeside wetlands have a relatively large capacity to store carbon stocks, especially in sediments. In general, SOC stocks show an increasing trend with the increasing sediment depth, which confirms the findings of previous studies. The estimated SOC stocks in the lakeside also significantly differ among the research sites, indicating that environmental conditions, land use, and land cover can affect the SOC stock. The highest SOC stock (442.59 Mg/C/ha) was found at site M4, a lakeside area dominated by forest cover. In contrast, the lowest stock (284.23 Mg/C/ha) was found at site M3, dominated by the agricultural land. Our results support the assertion that vegetation cover plays an essential role in the SOC stock. Furthermore, the land use differences also affect the distribution of OC, TN, and Bd. The spatial variations in the OC and TN content display a tendency towards higher values in locations close to the agricultural land. In contrast, Bd tends to be high in areas with minimal vegetation, such as settlements. Moreover, Maninjau Lake has a heavy eutrophic state with a much higher OC and TN contents compared to several other Indonesian lakes and eutrophic lakes in other countries. The primary source of organic matter in the sediments of Maninjau Lakeside is phytoplankton, a mixture of floating macrophyte and submerged vegetation. The unregulated increase of floating net cages and widespread change of land use into extensive agricultural and settlements are the main contributors to water pollution and ecological degradation in Maninjau Lake. This study's results confirm the relationship among the anthropogenic activities (land use), SOC stocks, and the lake's trophic state. It was also found that the restoration efforts of the lakeside wetlands are important for maintaining the sustainability of the water and lakeside environment. The preserving and protecting lakeside wetlands may support global climate change mitigation through sequestration processes that can reduce carbon emissions in the atmosphere.

AUTHOR CONTRIBUTIONS

T.R. Soeprobowati, the corresponding author, has contributed to the sediment carbon stock analysis, interpreted the results, and prepared the manuscript. N.D. Takarina performed sediment analysis. P.S. Komala designed the field experiment, L. Subehi prepared all the maps and figures; M. Wojewódka-Przybył participated in the interpretation of the results and manuscript preparation, J. Jumari prepared related text and R. Nastuti conducted field data acquisition and contributed to the data analysis.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and falsification, double publication and submission, and redundancy, have been ultimately observed by the authors.

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ABBREVIATIONS

%	percent
°C	centigrade
ANOVA	Analysis of variation
Bd	Bulk density
C	carbon
C/N	Organic carbon and total nitrogen ratio
cm	Centimeter
CO_2	Carbon dioxide
$CuSO_4$	Copper (II) sulfate
df	degree of freedom
DW_{105}	A dry weight of the sample before combustion
DW_{550}	dry weight of the sample after combustion
E	East
Eq.	Equation
F	Freedom
F crit	Freedom critical
Fig.	Figure
g	Gram
g/cm^3	Gram per cubic centimeter
GHG	Greenhouse Gas
H	The thickness of sediment
H_2O_2	Hydrogen peroxide
H_2SO_4	Sulfuric acid
ha	Hectare
HABS	Hazardous algae blooms
kg/m^2	Kilogram per square meter
Km	Kilometer
LOI	Loss of ignition
LOI_{550}	percentage of LOI at 550°C
M1	Koto Malintang
M2	Koto Gadang
M3	Koto Kaciak
M4	Duo Koto
M5	Koto Maninjau
m.a.s.l	Meter above sea level
mm	millimeter
m	meter
mL	Milliliter
m^3	Cubic meter
Mg/C/ha	Mega gram per carbon per hectare
MIPs	molecularly-imprinted polymers
MS	Mean square
nm	nanometer
OC	Organic carbon
pH	Power of Hydrogen
p	probability
Pg C	Petagram Carbon
R^2	Determination coefficient
S	South
SOC	Sediment organic carbon
SS	Sum of square
TN	Total nitrogen
y	Dependent variable

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