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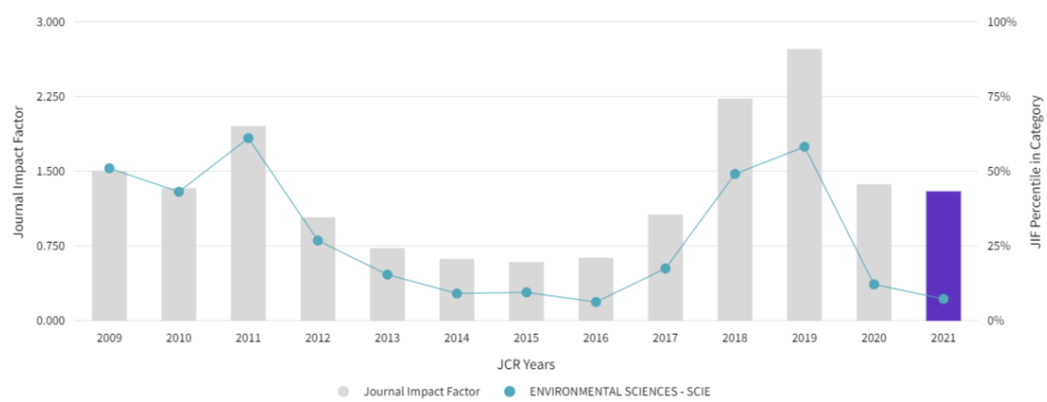

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THE POTENTIAL SOIL ORGANIC CARBON STOCKS IN MANGROVE AREAS OF SINJAI DISTRICT, SOUTH SULAWESI, INDONESIA

Abdul MALIK[1*], Muhammad ICHSAN ALI[2], Suwardi ANNAS[3], Abdul Rasyid JALIL[4], Restu Utami MULYA[1], Konstantina GRAVANI[5]

[1]*Department of Geography, Faculty of Mathematics and Natural Sciences, Universitas Negeri Makassar, Makassar, South Sulawesi, Indonesia*
[2]*Department of Civil and Planning, Faculty of Engineering, Universitas Negeri Makassar, Makassar, South Sulawesi, Indonesia*
[3]*Department of Statistics, Faculty of Mathematics and Natural Sciences, Universitas Negeri Makassar, Makassar, South Sulawesi, Indonesia*
[4]*Department of Marine Science, Faculty of Marine Science and Fisheries, Universitas Hasanuddin, Makassar, South Sulawesi, Indonesia*
[5]*Department of Geosciences and Natural Resource Management, Faculty of Science, University of Copenhagen, Copenhagen K, Denmark*

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Highlights

- Soil organic carbon (SOC) stocks were estimated in disturbed mangroves of South Sulawesi.
- The mean values of the SOC stock are 413.10±12.37 Mg C ha^{-1}.
- Promoting restoration may preserve remaining mangroves and increase SOC stocks.

Abstract. The soil pool is the primary sink for carbon in mangrove wetlands and plays a major role in mitigating climate change. However, aquaculture pond expansions go further to disrupt carbon storage in mangroves. The aim of this study is to estimate the stock of soil organic carbon (SOC) in the mangrove area of South Sulawesi, Indonesia. The mangroves of Sinjai District in South Sulawesi are a disturbed region with no previous study on SOC stock. We implemented a line transect method at five study sites, collected 15 soil cores at a depth of 0–15 cm, 15–30 cm, and 30–50 cm, and performed soil analysis using the Loss on Ignition method. We find that the mean value of SOC stock is 413.10±12.37 Mg C ha^{-1}. More attention to the conservation and restoration of lost mangrove areas is a high priority. It may also increase the stock of SOC to mitigate climate change. This study will help to preserve the remaining mangroves.

Keywords: coastal blue carbon, climate change mitigation, disturbed mangroves, mangrove soil properties.

Introduction

Climate change mitigation is one of the essential ecosystem services provided by mangroves (Duncan et al., 2016; Soper et al., 2019; Malik et al., 2020). Although mangroves cover only a small portion of the planet, they store considerable organic carbon (Hopkinson et al., 2012; Nóbrega et al., 2015). Mangroves are one of the most carbon-rich forests (Donato et al., 2011), with a global average total forest stock of 738.9 Mg C ha^{-1} (Alongi, 2020). Therefore, they represent a critical component in carbon sequestration for climate change mitigation (Intergovernmental Panel on Climate Change, 2014; Murdiyarso et al., 2015).

Mangroves can store carbon in plant materials and soil pools (Howard et al., 2014). However, most of the carbon is in soil pools, which account for up to 50–90% of the total carbon stock of mangroves (Donato et al., 2011; Kauffman et al., 2011; Sharma et al., 2020).

Hamilton and Friess (2018) demonstrated that 70.65% of global mangrove carbon is deposited in mangrove soils. Alongi et al. (2015) and Murdiyarso et al. (2015) both reported that the mean proportion of organic soil carbon

*Corresponding author. E-mail: *abdulmalik@unm.ac.id*

storage in several mangrove areas of Indonesia was about 78%. Abino et al. (2014) revealed that the sediment carbon stock in the natural mangrove forest in Palawan, Philippines was 50%. Besides, Nam et al. (2016) demonstrated that the percentage of soil organic carbon stores from two different mangrove areas (natural and restoration area) in Mekong Delta, Vietnam was similar and reached 90%, respectively. It is also confirmed by Hong Tinh et al. (2020) results in northern Vietnam, who found that the SOC stock of 20–25 years of restored and intact mangroves was not significantly different.

The significant carbon content in soil is due to rapid rates of net primary production from autochthonous (in the form of litterfall and belowground fine root growth) and sedimentation from allochthonous (supply from upstream rivers and sea) (Donato et al., 2011; Alongi, 2012). However, the autochthonous have a higher contribution than allochthonous in soil carbon production (Chen et al., 2017; Kusumaningtyas et al., 2019; Sasmito et al., 2020b; Jennerjahn, 2020).

Unfortunately, mangrove soils might become a significant source of CO_2 emissions if disturbed by land-use change activities, such as conversion into settlements, agricultural lands, and aquaculture ponds (Donato et al., 2011; Murdiyarso et al., 2015; Sharma et al., 2020). In Indonesia and other Southeast Asian countries, the conversion of mangrove forests into aquaculture ponds is the primary land-use activity within the mangrove area (Richards & Friess, 2016). It has occurred rapidly in recent decades (Pendleton et al., 2012) and contributed to about 0.08–0.48 Pg CO_2, translating to 10% of the total global emissions (Donato et al., 2011). Moreover, Hamilton and Friess (2018) have shown that the annual rate of mangrove deforestation (0.26%) since 2000 has emitted between 5.76 Tg CO_2e and 13.95 Tg CO_2e due to conversion to aquaculture ponds in Indonesia (Sidik & Lovelock, 2013).

When mangrove forests are being cleared, and the soil is being excavated, the soil carbon is exposed to air, and subsequently, the accelerated microbial activity releases large amounts of CO_2 and other GHGs into the atmosphere (Howard et al., 2014). Consequently, conversion to aquaculture has become one of the primary sources of CO_2 emissions (Sidik & Lovelock, 2013).

The mangrove area in South Sulawesi province is one of Indonesia's most important areas for the blue carbon program (Malik et al., 2020). Mangroves are distributed in the districts of East Luwu, Luwu, Bone, Sinjai, Takalar, Barru, Pangkep and Pinrang (Rahardian et al., 2019). However, aquaculture development has been the primary driver of mangrove deforestation in the past decades (Malik et al., 2017, 2020). It can be declined the potential carbon stock of the mangrove area and increase a significant CO_2 emission to the atmosphere. Giesen et al. (1991) estimated that the mangrove forests of South Sulawesi accounted for a total area of 100 thousand hectares during the 1950s. However, approximately 10 thousand mangroves were deforested in 2017 due to woodcutting, primarily for aquaculture pond expansion (Rahadian et al., 2019), with annual deforestation rates between 1% and 5% (Malik et al., 2017). Furthermore, the policymakers related to climate change mitigation policies often overlook the significant amount of carbon stocks in this region's case of mangrove deforestation (Malik et al., 2020).

Global climate negotiations have promoted mangroves' potential contribution and conservation in mitigating GHG emissions (Sasmito et al., 2020a). Many countries that own mangroves are interesting in blue carbon programs or fund mangrove protection and restoration through forest carbon programs (Bukoski et al., 2020). One critical step to developing a blue carbon program is data availability and accurate estimates of baseline carbon stocks (Bukoski et al., 2020). This area's soil carbon stock will be lower than other studies done in the region or Indonesia because of the disturbance. Therefore, this research aims to estimate soil organic carbon stocks in the disturbance mangrove area of South Sulawesi, Indonesia, for helping mitigate climate change.

1. Materials and methods

1.1. Study area

The study area is situated in the mangrove area of Sinjai District, South Sulawesi, focusing in East Sinjai sub-District (latitudes 5°7′00″–5°14′00″ and longitudes 120°15′00″–120°19′00″, Figure 1).

The area of East Sinjai Sub-District covers 7,188 ha and is bordered by North Sinjai Sub-District to the north, Bone Bay to the east, Tellu Limpoe Sub-District to the south, and North Sinjai and Central Sinjai Sub-Districts to the west. The population was 30,550 people in 2016, and most of the inhabitants live in the coastal area and work as fishermen and shrimp farmers (BPS Kabupaten Sinjai, 2017).

The coastal area is covered by mangroves, seagrass beds, coral reefs, aquaculture ponds, settlements, and ecotourism areas (Malik et al., 2020). The area covered by mangroves in 2017 was 761 ha (which is about 77% of the total mangrove area in Sinjai District) and distributed among five villages, including Samataring (StV), Tongketongke (TtV), Panaikang (PkV), Pasimarannu (PrV), and Sanjai (SjV) (Malik & Rahim, 2017). Mangroves in these areas grow in a fringing hydrogeomorphic environment, and the tidal regime in this area is semi-diurnal (On most days, there are two tidal cycles, often with not significantly different amplitudes), with the tidal range being about 122 cm (Malik & Rahim, 2017). Mangroves soils are mostly clayey with rich organic matter content and are associated with dominant mangrove vegetation from *Rhizophora* sp. (Suharti et al., 2016; Malik et al., 2020). Moreover, the climatic situation in these areas is characterized by the average annual rainfall of 2697 mm with 211 rainy days in 2017, whereas the mean daily air temperature is between 21 °C and 32 °C (BPS Kabupaten Sinjai, 2017).

However, the expansion of aquaculture ponds through the clearing mangroves in these areas began in the 1930s

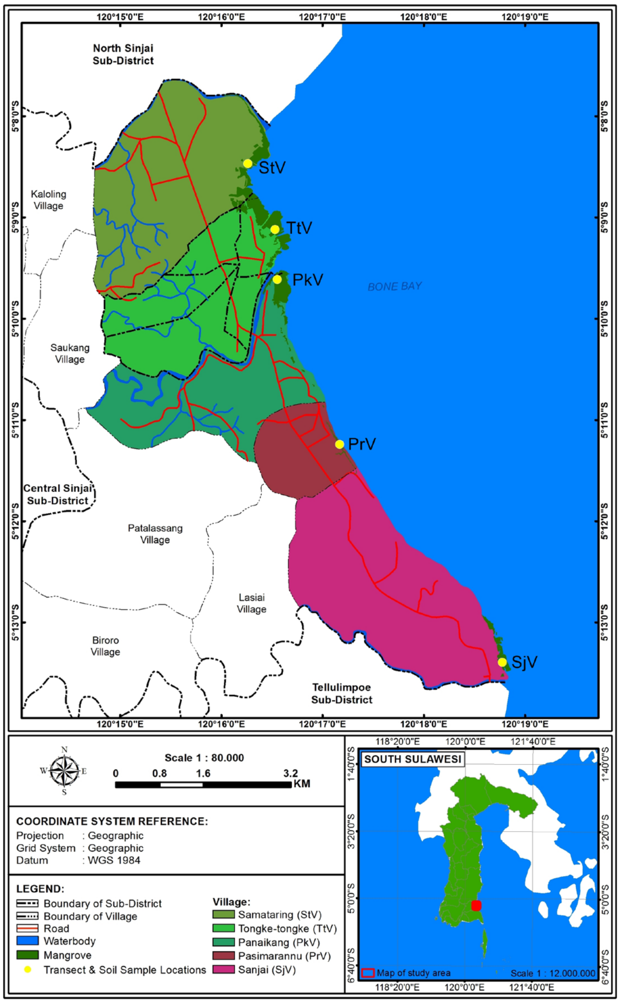

Figure 1. Study area: Sinjai District, South Sulawesi, Indonesia
The distance to the capital of South Sulawesi, Makassar City, is 220 km

(Amri, 2008), but the most significant development occurred in the last three decades (Malik & Rahim, 2017). The mangrove reforestation began in 1984 at the initiative of the local community (Amri, 2008). Since the early 2000s, this action has flourished to protect the area from coastal erosion and storms and provide land for the ecotourism area. However, the disturbances to the mangrove area continue, mainly due to the expansion of aquaculture ponds (Malik & Rahim, 2017).

1.2. Data collection

Fieldwork was conducted in April 2017 in five mangrove areas (StV, TtV, PkV, PrV, and SjV). We used a transect line method (Malik et al., 2015), the length of which depended on the thickness of the mangrove forest from seaward to landward at each site. We established three 10×10 m sampling plots for each transect using a tape measure and plastic ropes (Malik et al., 2015). Within each plot, we collected 15 soil cores at depth of 0–15 cm, 15–30 cm, and 30–50 cm. We inserted the sediment core (stainless steel Eijkelkamp gouge auger) vertically into the soil until the top of the sampler was level with the soil surface. When the soil core was extracted, we measured the depth of the gathered samples using a measuring tape and collected a sub-sample with a length of 5 cm from the midpoint each of intervals depth. Soil samples were extracted, stored in labeled plastic bags, and taken to the laboratory for soil analysis (Kauffman & Donato, 2012).

1.3. Sample analysis

Soil analysis was performed using the Loss on Ignition (% LOI) method by burning the soil sample at high temperatures (Kauffman & Donato, 2012). We placed a 118.73 cm^3 soil sample from different depths in each plot in a pre-weighed ceramic crucible and put them in the drying oven at a temperature of 60 °C for 72 hours to maintain a constant dry matter. The soil samples were carefully broken into smaller pieces to accelerate the drying process. The value of oven-dried soil samples was weighed and subtracted from the net weight of the ceramic crucible. We also placed 20 g of oven-dried sub-sample from each sample in a muffle furnace at 540 °C for five hours to ignite it (Kauffman & Donato, 2012).

To calculate the bulk density of mangrove soil (SBD), we divided the mass of the oven-dry soil sample by the volume of the pre-dried sample (Equation (1)) (Kauffman & Donato, 2012):

$$\mathrm{SBD}\left(\mathrm{g\ cm^{-3}}\right)=\frac{\text{oven-dry sample mass}\left(\mathrm{g}\right)}{\text{pre-dried soil sample volume}\left(\mathrm{cm^{3}}\right)}, \quad (1)$$

where: volume of pre-dried soil sample = 118.73 cm^3.

The % LOI, which indicated the soil organic matter content, was estimated by using Equation (2) (Kauffman & Donato, 2012):

$$\%\,\mathrm{LOI}=\frac{\left[\text{dry mass before combustion}\left(\mathrm{mg}\right)-\text{dry after combustion}\left(\mathrm{mg}\right)\right]}{\text{dry mass before combustion}\left(\mathrm{mg}\right)}\times 100. \quad (2)$$

To calculate the soil organic carbon concentration/SOCC (% C_{org}), we also used Equation (3) as proposed by (Kauffman et al., 2011):

$$\mathrm{SOCC} = 0.415 \times \%\,\mathrm{LOI} + 2.89. \quad (3)$$

To determine the soil organic carbon density (SOCD) and the soil organic carbon (SOC) stocks at each sampled depth, we used Equations (4) and (5), respectively (Kauffman & Donato, 2012):

$$\mathrm{SOCD}\ (\mathrm{g\ C\ cm^{-3}}) = \mathrm{SBD}\ (\mathrm{g\ cm^{-3}}) \times (\%\,C_{org}/100); \quad (4)$$

$$\mathrm{SOC}\ (\mathrm{Mg\ C\ ha^{-1}}) = \mathrm{SBD}\ (\mathrm{g\ cm^{-3}}) \times \text{soil depth interval (cm)} \times \mathrm{SOCC}. \quad (5)$$

Finally, statistical tests using One-Way Analysis of Variance (ANOVA) were performed to compare different soil properties within depth intervals and carbon stock at different sites.

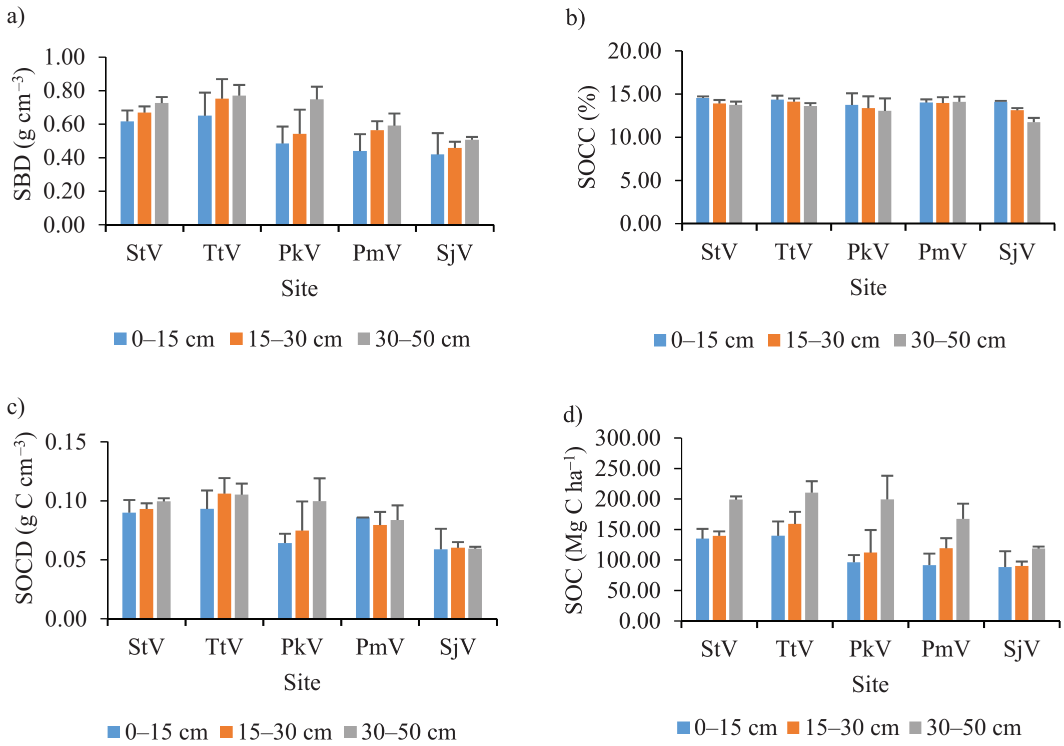

Figure 2. Soil properties: a) SBD, b) SOCC, c) SOCD, and d) SOC in the mangrove forests of Sinjai District, South Sulawesi

2. Results

Soil property values and trends (SBD, SOCC, SOCD, and SOC) of mangrove areas of Sinjai District, South Sulawesi, Indonesia, are summarized in Figures 2a–2d and Table S1.

We found that the SBD value across sites and soil depths ranged from 0.42±0.13 g cm^{-3} at a depth of 0–15 cm at the SjV site to 0.77±0.06 g cm^{-3} at a depth of 15–30 cm at the TtV site, or the mean value of all ranges was 0.60±0.05 g cm^{-3}. The SBD value with interval depth had an increasing trend at all sites and showed a significant difference ($p < 0.05$) (Figure 2a, Table S1).

The lowest SOCC value of 11.74±0.50% was observed at a depth of 30–50 cm at site SjV, whereas the highest value of 14.54±0.20% was observed at the 0–15 cm at site StV, resulting in the mean SOCC of all sites 13.70±0.22%. The SOCC value of each site tended to decrease with depth but did not differ significantly ($p = 0.18$) (Figure 2b, Table S1). The mean SOCD value of soil depth was significantly different at all sites ($p < 0.05$), ranging from the mean value of 0.06±0.0004 at site SjV to 0.10±0.0004 at site TtV (Figure 2c, Table S1).

In addition, we estimated the total SOC stock at the five study sites to be 2,065.50 Mg C, resulting in a mean SOC stock of 137.70±12.37 Mg C ha^{-1}, with the lowest value at 0–15 cm depth at site SjV (88.28±26.14 Mg C ha^{-1}) and the highest SOC stock at a soil depth of 30–50 cm at site TtV (210.35±18.80 Mg C ha^{-1}). The mean of SOC stock between sites was not significantly different ($p = 0.26$) (Figure 2d, Table S1).

3. Discussion

The mean value of SBD (0.60±0.05 g cm^{-3}) in this area was lower than the SBD values of mangroves in many mangrove areas in the world (0.73 g cm^{-3}–1.42 g cm^{-3}, Hossain & Nuruddin, 2016), but higher than in Indo-Pacific and several mangrove areas in Indonesia (0.35–0.55 g cm^{-3}) as reported by Donato et al. (2011) and in Can Gio Mangrove Biosphere Reserve (CGMBR), Mekong Delta, Vietnam (0.52 g cm^{-3}) as detected by Nam et al. (2016). The value of SBD increased with increasing soil depth at all sites and was significantly different ($p = <0.05$) (Figure 2a, Table S1). It is due to lower organic matter content, soil accumulation, and compaction due to the weight of the overlying layer. The trend showed similarities with other mangrove areas in Indonesia (Donato et al., 2011) and in the Mekong Delta, Vietnam (Nam et al., 2016), as well as in Shenzhen Bay, China (Lunstrum & Chen, 2014). However, the SOCC tended to decrease with increasing depth (Figure 2b), which attributes to the high SBD that indicating higher soil density and small soil pores (Lunstrum & Chen, 2014). A similar trend was also observed in the Indo-Pacific and several mangrove areas in Indonesia, as reported by Donato et al. (2011) and consistent with Kauffman et al. (2014) in the Dominican Republic.

SOCD was determined by multiplying the value of SBD and organic carbon content (% C_{org}) at each soil depth. Dorji et al. (2014) stated that SOCD is required for carbon accounting, accumulation, budgeting, and developing carbon sequestration strategies. The mean SOCD (0.08±0.01 g C cm^{-3}, Table S1) in this area was higher compared to several mangrove areas in the world, including the western and eastern Atlantic and Pacific coasts, the Indian Ocean, the Mediterranean Sea, and the Gulf of Mexico (0.055±0.004 g C cm^{-3}), as demonstrated by Chmura et al. (2003). However, this value was lower than the mangrove rehabilitation site in Bali (0.13 g C cm^{-3}), as Mahasani et al. (2016) reported. SOCD tended to increase along with soil depth (Figure 2c) and influenced SBD and SOCC content (Dariah et al., 2012). In contrast, Dorji et al. (2014) and Cuc et al. (2009) found that SOCD decreases with soil depth. The inconsistent trend of SOCD values with the soil depth is due to the fact that SBD and SOCC values may vary with soil depth and location (Howard et al., 2014).

The mean SOC stock was 413.10±12.37 Mg C ha^{-1} in this area (Table S1). With a total mangrove area of 761 ha in 2017 (Malik & Rahim, 2017), the total stock of SOC in this area is estimated to be approximately 0.31 Tg C. Being a mangrove fringe area, the accumulation of autochthonous SOC in this mangrove area is influenced by tidal hydrodynamic which includes biogeochemical and physical processes. Tidal inundation brings abundant sediment, encouraging lateral deposition of mud due to reduced water flow within the mangroves (Rovai et al., 2018). Besides, warm temperatures and abundant rainfall in the area are associated with primary productivity and decomposition can affect the levels of SOC (Ontl & Schulte, 2012). However, the mean SOC stocks in this area were lower compared to other mangrove areas in Indonesia, such as Java and Kalimantan (Donato et al., 2011), Sumatra (Alongi et al., 2015), and West Papua and Papua (Taberima et al., 2014). The loss of mangroves, mainly due to aquaculture development, affects the decline of SOC in the area. Converting mangroves to aquaculture ponds can reduce biomass carbon stocks by an average of 83% and soil carbon stocks by 52% (Sasmito et al., 2019; Friess et al., 2020).

Based on the soil depth layer per site, the mean SOC stock tended to increase from the topsoil (Figure 2d). This pattern was similar to mangrove areas in West Papua and Papua, and Micronesian mangrove forests, as demonstrated by Taberima et al. (2014) and Kauffman et al. (2011), respectively. The mean SOC stock value difference between soil layers was continuously high throughout the soil layer (Kauffman et al., 2011).

Almost half of the total values of SOC at each site are at the 30–50 cm depth (Figure 2d, Table S1). Donato et al. (2011) showed that 49–98% of the carbon is stored at a depth of 0.5 m to 3 m. Taberima et al. (2014) found that most SOC in West Papua and Papua were found at depth 10 cm to 200 cm, but the highest value was above 100 cm. Mangrove root growth at a depth of 50 cm plays a significant role in accumulating SOC (Nguyen et al., 2004). Ontl and Schulte (2012) found that the levels of SOC are primarily derived from root biomass and litter deposited by plants. Plant roots contribute SOC directly and indirectly through root growth and death and the transfer of carbon-rich compounds from roots to the soil.

Conclusions

The study has demonstrated the potential stock of soil organic carbon (SOC) from the mangrove area in Sinjai District, South Sulawesi, Indonesia. The mean SOC stock was 413.10±12.37 Mg C ha^{-1}. However, the observed mean stock of SOC from this area was lower than that studied in several mangrove areas in Indonesia due to human-induced exploitation, mainly for aquaculture expansion.

Promoting wise use and restoration of mangroves is a top priority for sustainable management, preserving SOC presently held, and rebuilding SOC lost during exploitation occurs. In addition, a better understanding of mangrove carbon stocks and human-induced pressures by stakeholders and decision-makers in this region will help them conserve and manage this vital ecosystem and mitigate climate change.

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Conflicts of interest

The authors declare no conflicts of interest.

Author contributions

All authors wrote the manuscript.

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Supplementary information

THE POTENTIAL SOIL ORGANIC CARBON STOCKS IN MANGROVE AREAS OF SINJAI DISTRICT, SOUTH SULAWESI, INDONESIA

Abdul MALIK, Muhammad ICHSAN ALI, Suwardi ANNAS, Abdul Rasyid JALIL, Restu Utami MULYA, Konstantina GRAVANI

Table S1. Soil properties and carbon stock in the mangrove area of Sinjai District South Sulawesi Indonesia

Site	Depth	n	SBD (g cm^{-3})		SOCC (%)		SOCD (g C cm^{-3})		SOC (Mg C ha^{-1})	
			Mean	SE	Mean	SE	Mean	SE	Mean	SE
StV	0–15	3	0.62	0.07	14.54	0.20	0.09	0.01	134.87	16.11
	15–30	3	0.67	0.04	13.92	0.40	0.09	0.005	139.56	7.32
	30–50	3	0.73	0.04	13.74	0.39	0.10	0.003	199.00	5.30
	Mean	–	0.67	0.03	14.06	0.24	0.09	0.003	157.81	20.64
	Total	9	–		–		–		473.43	
	p-value		0.34		0.29		0.64		0.01	
TtV	0–15	3	0.65	0.14	14.34	0.47	0.09	0.02	139.65	23.48
	15–30	3	0.75	0.12	14.12	0.37	0.11	0.01	159.13	19.77
	30–50	3	0.77	0.06	13.61	0.35	0.11	0.01	210.35	18.80
	Mean	–	0.72	0.04	14.02	0.22	0.10	0.004	169.71	21.08
	Total	9	–		v		–		509.13	
	p-value		0.62		0.46		0.74		0.12	
PkV	0–15	3	0.48	0.10	13.74	1.36	0.06	0.01	96.20	11.85
	15–30	3	0.54	0.14	13.36	1.38	0.07	0.02	112.08	37.06
	30–50	3	0.75	0.08	13.05	1.45	0.10	0.02	199.37	38.79
	Mean	–	0.59	0.08	13.38	0.20	0.08	0.01	135.88	32.07
	Total	9	–		–		–		407.65	
	p-value		0.28		0.94		0.44		0.12	
PmV	0–15	3	0.44	0.10	14.03	0.37	0.09	0.00	91.53	18.93
	15–30	3	0.56	0.05	13.96	0.68	0.08	0.01	119.15	16.68
	30–50	3	0.59	0.07	14.10	0.60	0.08	0.01	167.36	24.90
	Mean	–	0.53	0.05	14.03	0.04	0.08	0.002	126.01	22.16
	Total	9	–		–		–		378.04	
	p-value		0.40		0.99		0.89		0.10	

End of Table S1

Site	Depth	n	SBD (g cm^{-3})		SOCC (%)		SOCD (g C cm^{-3})		SOC (Mg C ha^{-1})	
			Mean	SE	Mean	SE	Mean	SE	Mean	SE
SjV	0–15	3	0.42	0.13	14.10	0.12	0.06	0.02	88.28	26.14
	15–30	3	0.46	0.04	13.13	0.25	0.06	0.005	90.22	7.28
	30–50	3	0.51	0.02	11.74	0.50	0.06	0.002	118.75	3.27
	Mean	–	0.46	0.03	12.99	0.68	0.06	0.0004	99.08	9.85
	Total	9	–		–		–		297.25	
	p-value		0.74		0.01		1.00		0.37	
p-value			0.02		0.18		0.002		0.26	
Grand mean		–	0.60	0.05	13.70	0.22	0.08	0.01	413.10	12.37
Grand total		45							2065.50	

Note: StV: Samataring village; TtV: Tongke-tongke village; PkV: Panaikang village; PmV: Pasimarannu village; SjV: Sanjai village; n: number of soil sample; SBD: soil bulk density; SOCC: soil organic carbon concentration; SOCD: soil organic carbon density; SOC: soil organic carbon.