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Carbon Stock and CO_2 Fluxes in Various Land Covers in Karang Gading and Langkat Timur Laut Wildlife Reserve, North Sumatra, Indonesia

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Abstract: Mangrove forests play an important role in coastal areas from an ecological perspective, being able to store large amounts of carbon through sequestration and inhibiting climate change processes by absorbing CO_2 in the atmosphere. In recent years, there have been changes in the land cover of converted and degraded mangrove forests which have resulted in the release of carbon and an imbalance in soil structure, which in turn cause a flux of CO_2 into the atmosphere. This research was conducted at the Karang Gading and Langkat Timur Laut Wildlife Reserve (KGLTLWR) in North Sumatra, Indonesia. The study focused on six different land covers, namely natural forests, restoration, mixed agriculture, paddy fields, oil palm plantation, and ponds. This study aimed to measure the total carbon stock of mangrove forests that have been converted to other land covers and estimate the level of CO_2 flux in the area. A total of three transects and six plots for each land cover were used in this study; for tree biomass, a non-destructive method was used by recording every DBH > 5 cm, and for soil carbon, drilling was carried out, which was divided into five depths in each plot. CO_2 flux was measured using an Eosense Eosgp CO_2 sensor with the static closed chamber method. The highest carbon stock was found at 308.09 Mg ha^{-1} in natural forest, while the lowest 3.22 Mg ha^{-1} was found in mixed agriculture. The highest soil carbon was found at 423.59 MgC ha^{-1} in natural forest, while the lowest 50.44 MgC ha^{-1} was found in mixed agriculture dry land. The highest average CO_2 flux value of 1362.24 mgCO_2 m^2 h^{-1} was found in mangrove restoration and the lowest in ponds was 123.03 mgCO_2 m^2 h^{-1}. Overall, the research results inform how much carbon stock is lost when converted to other land covers so that it can be used as a reference for policy makers to provide future management of mangrove forests and develop mitigation measurements to reduce carbon emissions.

Keywords: carbon stock; CO_2 flux; policy makers; restoration; climate change

1. Introduction

Mangrove forests function as carbon storage and serve as a mitigation process of climate change by absorbing CO_2 in the atmosphere [1,2]. Karang Gading Langkat Timur Laut Wildlife Reserve (KGLTLWR) is a conservation area in the form of mangrove forest with an area of 15,765 ha, marine vegetation dominated by mangrove forest vegetation (more than 11,500 ha or 70% of the area), and a little green forest of at least 37 plant species from 21 families [3]. In recent years, there has been a change in mangrove forest land cover which has been converted, with an area of ±6558 ha in the form of oil palm plantations, fish ponds, permanent shrimp ponds, agriculture land, and community settlements which can result in carbon release and an imbalance in soil structure which in turn causes a flux of CO_2 into the atmosphere [3,4].

Even though mangrove forests have the potential to store very large carbon reserves, they occupy only 0.5% of the global coastal area. Mangroves are able to store 1023 MgC ha^{-1} or three to five times more than other types of terrestrial forests [5]. When a hectare of forest (trees) disappears (dead trees), sooner or later the biomass stored in trees will decompose and the carbon elements bound to the air become emissions [6–8]. This change in carbon form then becomes the basis for calculating emissions [9,10].

The amount of CO_2 gas emitted and absorbed in the atmosphere is considered uncertain. Therefore, it is necessary to analyze the CO_2 transfer process by observing the CO_2 flux. CO_2 flux is the amount of CO_2 gas flowing through the sea surface either from air into the water or from water into the air per a certain area per unit time. The CO_2 solubility function and the CO_2 gas transfer rate that occur at sea level are referred to as the CO_2 flux [11,12]. Soil CO_2 flux is the release of CO_2 gas produced by the respiration of autotrophs (plant roots) and heterotrophs (soil microbes and fauna). CO_2 flux serves as an indicator of the overall production and metabolic activity of living organisms in the soil [13]. The decomposition of soil organic matter can lead to an increase in CO_2 flux into the atmosphere. The two biggest contributors to greenhouse gas emissions today are carbon dioxide (CO_2) and methane (CH_4). The main contributors to these emissions are the energy systems sector (34%), industry (24%), AFOLU (agriculture, forestry, and other land uses) (21%), transportation (14%), and building operations (6%) [3,14]. The average carbon stock in Indonesian mangroves is 950.5 Mg C ha^{-1} [15]. Mangroves in the study areas in Serang (sand mining location) and Angke (adjacent to the deposition location) are estimated to store an average of 203.64 Mg C ha^{-1} and 531.53 Mg C ha^{-1}, respectively [16]. Peak GHG fluxes were observed in rehabilitation (32.8 ± 2.1 $MgCO_2$ $ha^{-1}y^{-1}$) and undisturbed (43.8 ± 4.5 $MgCO_2$ $ha^{-1}y^{-}$) sites as well as dry open aquaculture ponds (30.6± 1.9 $MgCO_2$ $ha^{-1}y^{-1}$) [17].

Changes in land use can affect soil structure. Therefore, it is necessary to analyze land cover change and its impact on CO_2 flux. Research on the impact of changes in land cover in the North Sumatra KGLTLWR is important for planning and implementing coastal management. This study aims to develop a systematic approach to inform how much carbon stock is lost when converted to other land covers, which is then linked to the resulting CO_2 flux value and integrated with land use for an effective emission reduction plan.

2. Materials and Methods

2.1. Materials

This research began in December 2021 at the Karang Gading and Langkat Timur Laut Wildlife Reserve (KGLTLWR), located in the districts of Hamparan Perak and Labuhan Deli, Deli Serdang Regency, and Secanggang and Tanjung Pura districts, Langkat Regency (Figure 1). KGLTLWR is a conservation area consisting of mangrove and coastal forests with flat topography (0–8%), a land elevation of up to 5 m asl, and partly a tidal area [3]. Rainfall ranges from 2010 to 2327 mm/year. Between December and March, northeasterly winds bring dry air and rainfall is generally low (below 100 mm/month in months February and March). From March to September the area is under the influence of the northwestern monsoon, heavy rainfall occurs in May, and August to October has an average temperature of 28–36 °C [3]. The soil in the mangrove forest is dominated by clay, which in several locations is mixed with gravel, fine sand, organic matter, and carbonate bioclastic (especially shell fragments) [3].

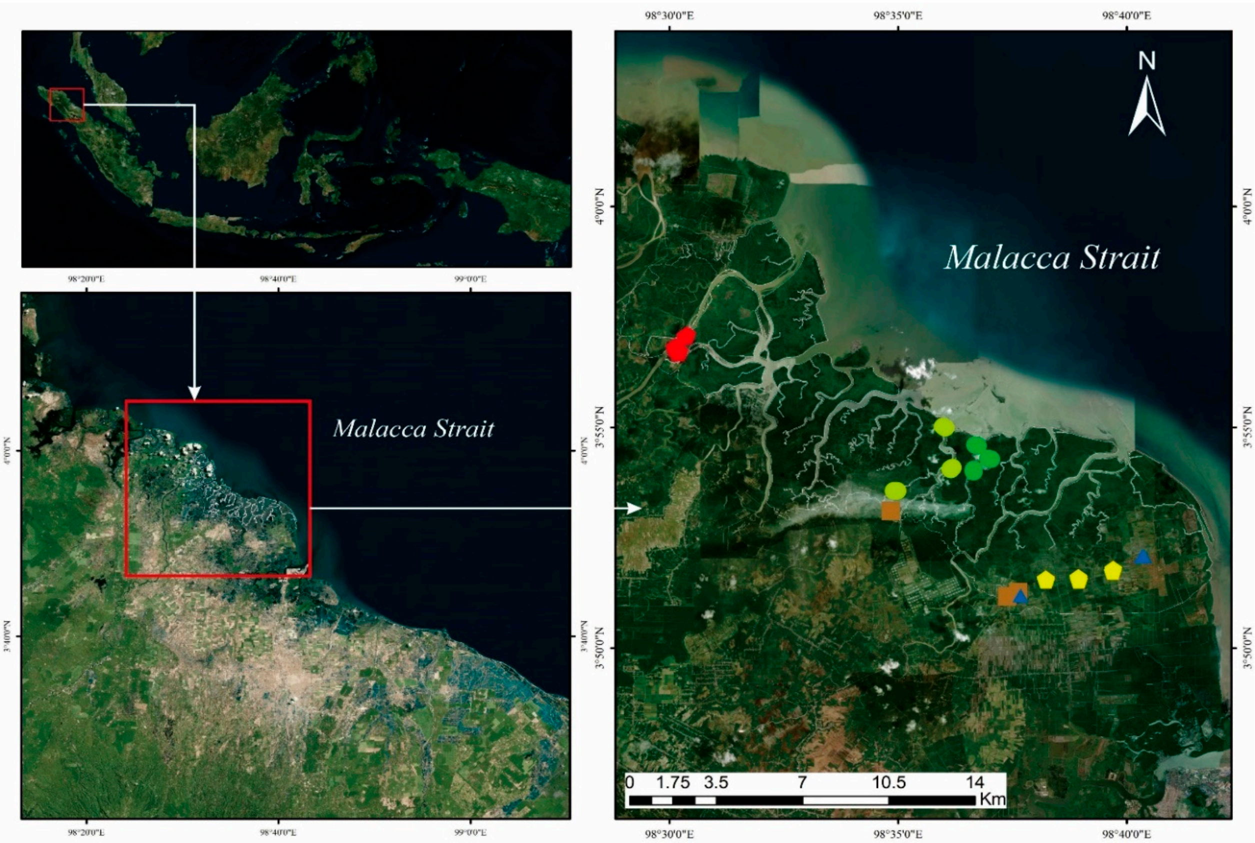

Figure 1. Study sites of six land uses in Karang Gading and Langkat Timur Laut Wildlife Reserve, North Sumatra, Indonesia. Red dot denotes mixed agriculture dry land, dark green shows natural mangrove forest, light green depicts mangrove restoration, brown indicates pond, yellow shows oil palm, and blue represents paddy field.

The data were analyzed by R and RStudio program. An Eosense Eosgp CO_2 sensor was used to measure CO_2 fluxes (Figure 2).

Figure 2. (**a**) Soil sampling was collected in pond (**b**) using Russian peat auger.

2.2. Soil Sampling and Biomass Assessment

Soil sampling for organic carbon content was carried out by collecting sub-samples of 5 cm from the midpoint in each five-depth range, namely at depths of 0–15 cm, 20–30 cm, 30–50 cm, 50–100 cm, and 100–200 cm using a Russian peat corer (Figure 2, [7]). Soil samples were carefully dried at 70 °C until they reached a constant weight and grounded before being sent to the laboratory for organic carbon concentration analysis. Soil carbon stock is the product of bulk density, soil depth, and carbon content. Measurement of the tree biomass was performed non-destructively using the 2019–2022 tree census dataset (planted mangrove at 4, 5, and 7 years old, respectively). We only included trees with a DBH of 5 cm for the total biomass estimation (Table 1, [18]).

Carbon stock estimation in oil palm plantations was calculated using the formula initiated by Dewi [19], where with H (tree height) and p (density) for stem biomass:

$$\text{AGB} = (0.0976 * \text{H}) + 0.0706 \tag{1}$$

The calculation of carbon stock in mixed agriculture dry land uses the formula referring to Kettering [20], namely:

$$\text{Biomassa: } 0.11p\ \text{DBH}^{2.62} \tag{2}$$

Table 1. Allometric equations for calculating mangrove tree biomass used in this study [18].

Above-Ground Biomass (kg)	Below-Ground Biomass (kg)
A. marina Wtop = 0.308DBH2.11, r^2 = 0.97, n = 22, Dmax = 35 cm [21]	*A. marina* WR = 1.28DBH 1.17, r^2 = 0.80, n = 14, Dmax = 35 cm, [21]
Rhizophora spp. Wtop = 0.128DBH$^{2.60}$, r^2 = 0.92, n = 9, Dmax = 32 cm [22] Wtop = 0.105DBH$^{2.68}$, r^2 = 0.99, n = 23, Dmax = 25 cm [23]	*Bruguiera* spp. WR = 0.0188 (D^{2}H)$^{0.909}$, n = 11, Dmax = 33 cm cf, H = D/(0.025D + 0.583) [25]
Rhizophora apiculata Wtop = 0.235DBH$^{2.42}$, r^2 = 0.98, n = 57, Dmax = 28 cm [22]	*R. apiculata* WR = 0,00698DBH$^{2.61}$, r^2 = 0.99, n = 11, Dmax = 28 cm [22]
Bruguiera gymnorrhiza Wtop = 0.186DBH$^{2.31}$, r^2 = 0.99, n = 17, Dmax = 25 cm [23]	*R. stylosa* WR = 0.261DBH$^{1.86}$, r^2 = 0.92, n = 5, Dmax = 15 cm [25]
Bruguiera gymnorrhiza Wtop = 0.186DBH$^{2.31}$, r^2 = 0.99, n = 17, Dmax = 25 cm [23]	*Rhizophora spp.* WR = 0.00974 (D^{2}H)$^{1.05}$, r^2: undefined, n = 16, D max = 40 cm [22]
Bruguiera parviflora Wtop = 0.168DBH$^{2.42}$, r^2 = 0.99, Dmax = 25 cm, n = 16 [23]	*Xylocarpus granatum* WR = 0.145DBH$^{2.55}$, r^2 = 0.99, n = 6, Dmax = 8 cm [26]
Xylocarpus grnatum Wtop = 0.0823DBH$^{2.59}$, r^2 = 0.99, n = 15, Dmax = 25 cm [23]	*Bruguiera exaristata* WR = 0.302DBH$^{2.15}$, r^2 = 0.88, n = 9, Dmax = 10 cm [21]
Common equation: Wtop = 0.251 pD$^{2.46}$, r^2 = 0.98, n = 104, Dmax = 49 cm [24]	Common equation: WR = 0.199 p 0.899 D$^{2.22}$, r^2 = 0.95, n =26, Dmax = 45 cm [24]

2.3. CO_2 Flux Calculation

CO_2 flux sampling was performed using two devices, a CR1000x logger chamber (Campbell Scientific, Logan, UT, USA) and an Eosense Eosgp CO_2 sensor (Eosense, Dartmouth, NS, Canada), by enclosing the chamber on mangrove ecosystem land and water, as displayed in Figure 3. Chambers were randomly placed at each mangrove station with up to 3 points and 3 replications. Then, a gas sample was taken inside the chamber using an Eosense sensor. The chamber serves to measure the accumulation of CO_2 flux. It was closed for 3 min, followed by 2 min with the chamber lid open. This method was repeated three times during the measurement time. The data obtained were monitored on a desktop using the PC1000 application.

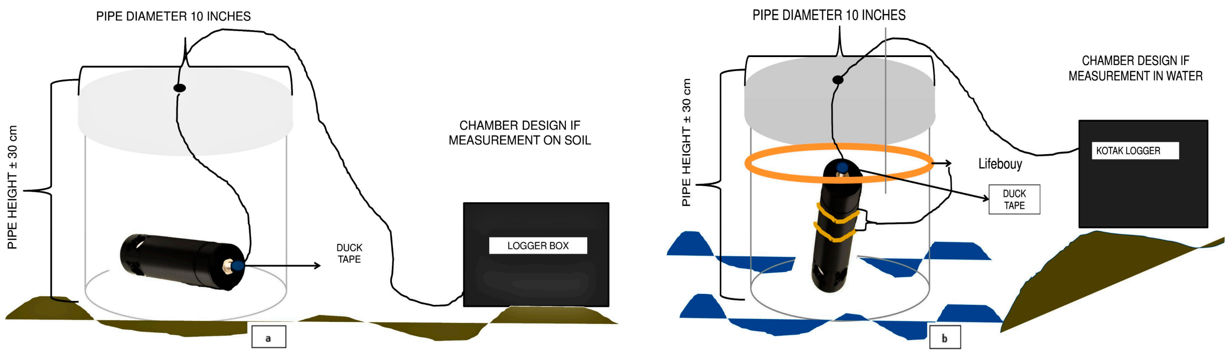

Figure 3. (**a**) Chamber design for flux measurements on the ground, (**b**) chamber design for flux measurements on water [12].

2.4. Data Analysis

Data measurements were processed and analyzed statistically using software applications such as R version 4.1.3, RStudio version 4.2.3, IBM SPSS v26, and Microsoft Excel 2013 The following equation [27,28] was used for this analysis:

$$F = S_{CO_2} \cdot \frac{V}{R \cdot T_{\text{air chamber}} \cdot A} \quad (3)$$

where F = ground-air CO_2 flux (mmol m^{-2} s^{-1});
S_{CO_2} = slope of CO_2 in the chamber over time (atm^{-1} s);
V = total volume of the flux chamber + tube (m^3);
R = ideal gas constant (atm m^3 K^{-1} mol^{-1});
$T_{\text{air chamber}}$ = absolute air temperature in the chamber (K); and
A = ground surface covered by the chamber (m^2).

The slope was calculated using linear regression. Only regressions with an R^2 value of 0.7 and $p < 0.05$ were saved to calculate F. When taking measurements, it is important to consider environmental variables such as air temperature and the number of macrozoobenthos.

2.5. Analysis of CO_2 Flux in Different Land Cover Types

The results of the CO_2 flux calculations were analyzed using descriptive statistical analysis and a one-way ANOVA test at a 95% confidence level. CO_2 flux was compared among different land cover types, such as ponds, oil palm plantations, natural mangrove forests, mangrove forest restoration, mixed agriculture, and rice fields [29].

2.5.1. Analysis of CO_2 Flux in Rainy and Dry Seasons

The mean difference test, specifically the paired sample *t*-test, was used to compare the CO_2 flux between the dry season and the rainy season.

2.5.2. Analysis of the Relationship of Macrozoobenthos with CO_2 Flux

Correlation analysis was used to determine the relationship between macrozoobenthos and CO_2 flux. Macrozoobenthos data were collected in natural mangrove forests and restored mangroves during the rainy season (September 2022) and dry season (July–August 2022).

3. Results

3.1. Standing Structure

There are nine types of true mangroves and 23 associated mangrove species. The highest number of individuals found in the mangrove forest of North Sumatra KGLTLWR was 1787 ind/ha for natural forest, followed by restored mangrove at 1.762 ind/ha, oil palm at 155 ind/ha, and agriculture dry land at 134 ind/ha (Table 2).

Table 2. Number of species (ind/ha) in KGTLWR in North Sumatra, Indonesia.

Species	Natural Forest	Restoration	Oil Palm	Mixed Agriculture
Avicennia officinalis	76	11	Na	Na
Bruguiera gymnorrhiza	101	137	Na	Na
Bruguiera parviflora	379	195	Na	Na
Ceriops tagal	11	33	Na	Na
Excoecaria agallocha	274	119	Na	Na
Rhizophora apiculata	755	1181	Na	Na
Scyphiphora hydrophyllacea	47	Na	Na	Na
Xylocarpus granatum	144	340	Na	Na
Elaeis guineensis	Na	Na	155	Na
Persea americana	Na	Na	Na	7
Artocarpus communis	Na	Na	Na	18
Artocarpus heterophyllus	Na	Na	Na	7
Cocus nucifera	Na	Na	Na	11
Durio zibethinus	Na	Na	Na	7
Psidium guajava	Na	Na	Na	11
Citrus sinensis	Na	Na	Na	15
Calophyllum inophyllum	Na	Na	Na	25
Areca catechu L.	Na	Na	Na	4
Annona muricata	Na	Na	Na	25
Artocarpus altilis	Na	Na	Na	4
Total	1787	1762	155	134

Na = not available.

3.2. Standing Structure, Average Diameter, and Basal Area

The highest average diameter values are found in natural forests, followed by restored forests, mixed agriculture dry land, and oil palm. The highest basal area values are found in natural forests, followed by mixed agriculture dry land, restored forests, and oil palm plantations. This is because the natural forest is typically characterized by dense vegetation and minimal human interference, resulting in a more intact stand structure, greater height and basal area, and better overall quality compared to other land cover types. The values for the stand structure, average diameter, and basal area are shown in Table 3.

Table 3. Stand structure, average diameter, and basal area in KGLTLWR, North Sumatra.

No.	Land Cover Type	Diameter (cm)	Height (m)	Basal Area (m^2)
1	Natural forest	11.83 ± 5.07	11.97 ± 1.78	0.84 ± 0.76
2	Restoration	10.03 ± 4.30	9.83 ± 1.53	0.64 ± 0.94
3	Oil palm	0.80 ± 0.12	4.51 ± 0.93	0.00 ± 0.00
4	Mixed agriculture	9.43 ± 5.45	4.91 ± 1.99	0.66 ± 0.49

3.3. Vegetation and Soil Carbon Stocks in Mangrove Forests and Various Land Covers

Carbon stocks in vegetation are generally influenced by the amount of carbon contained in above-ground biomass. The value of carbon stocks in mangrove forests and various vegetated land cover in KGLTLWR in North Sumatra is shown in Table 4. Specifically for oil palm and agriculture dry land, we only calculated above-ground biomass according to the allometric used, namely Dewi et al. (2009) [19] and Kettering et al. (2001) [20]. In paddy fields and ponds, we only collected soil carbon data due to the absence of woody vegetation.

Table 4. Carbon stocks in mangrove forests and various land covers.

No.	Land Covers	Above-Ground Carbon (MgC ha^{-1})	Below-Ground Carbon (MgC ha^{-1})	Woody Debris (MgC ha^{-1})	Soil Carbon (MgC ha^{-1})	Total Carbon (MgC ha^{-1})
1	Natural forest	242.93	32.51	17.06	423.59	716.09
2	Restoration	145.99	17.69	13.93	356.53	534.14
3	Oil palm	7.29	Na	6.73	65.05	79.07
4	Mixed agriculture	6.95	Na	0.18	50.44	57.45
5	Rice fields	Na	Na	Na	215.79	215.79
6	Pond	Na	Na	Na	303.07	308.07

Na = not available.

Table 4 shows that the highest carbon stock was found in natural forests (716.09 MgC ha^{-1}), while the lowest carbon stock was obtained in mixed agriculture forest areas (57.45 MgC ha^{-1}). This research found that the total carbon stock in oil palm plantations was 79.07 MgC ha^{-1}. This result is much higher than the findings of previous research conducted by Basyuni et al. on oil palm plantations in the KGLTLWR, North Sumatra, namely 22.96 MgC ha^{-1} [4]. The highest soil carbon stock was found in natural forests, with an average value of 423.59 MgC ha^{-1}, while the lowest was found in mixed agriculture land cover, with an average of 50.44 MgC ha^{-1} (Table 4). In this study, it was seen that there was a significant reduction in carbon stock of up to 50% if its function was transferred to other uses. In this study, natural mangrove forests for mixed agriculture will reduce carbon stock by up to 80%.

3.4. Content of CO_2 Flux Values in Various Land Covers

The average flux of CO_2 in mangrove natural forest land cover was found to be 1297 mg CO_2 m^2 h^{-1} during the rainy season and 835 mg CO_2 m^2 h^{-1} during the dry season (Figure 4). CO_2 flux in restored land cover during the rainy season was found to be an average of 1635 mg CO_2 m^2 h^{-1}, while in the dry season, it was 1321 mg CO_2 m^{-2} h^{-1}.

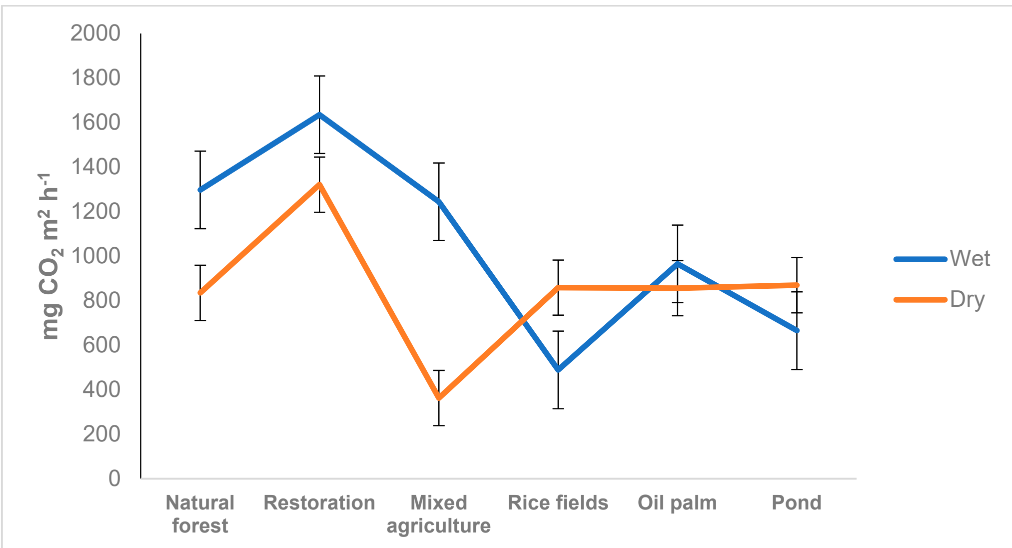

Figure 4. CO_2 flux per land cover in Karang Gading and Northeast Langkat (SE ± n = 6) in the wet and dry season.

3.5. Analysis of the Effect of CO_2 Flux on Various Land Covers

A paired mean difference test (comparing means) was carried out through a paired sample *t*-test. Analysis of the effect of mangrove CO_2 flux was conducted using a paired sample *t*-test to compare means, as shown in Table 5.

Table 5. Paired mean difference test (comparing means): Paired sample *t*-test.

		Paired Differences					T	Df	Sig. (2-Tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Natural forest	−360.547 -	696.503 -	284.346 -	−1091.482	370.88 -	−1.268 -	5 -	0.261 -
Pair 2	Restoration	261.410 -	2617.274 -	1068.498 -	−2485.250	3008.071 -	0.245 -	5 -	0.816 -
Pair 3	Mixed agriculture	264.099 -	1077.378 -	439.838 -	−866.540 -	1394.738 -	0.600 -	5 -	0.574 -
Pair 4	Rice fields	−1391.762	1679.508 -	531.107 -	−2593.210	−190.315 -	−2.620 -	9 -	0.028 -
Pair 5	Pond	−65.137 -	998.099 -	315.627 -	−779.134 -	648.860 -	−0.206 -	9 -	0.841 -
Pair 6	Oil palm plantation	−1302.605	1417.934 -	578.869 -	−2790.636	185.425 -	−2.250 -	5 -	0.074 -

Table 5 indicates that the *t*-tests show that there was no difference in the average amount of CO_2 flux between the dry and rainy seasons in primary forests (Table 5). Similarly, there was no difference in the average amount of CO_2 flux between the dry and rainy seasons in restoration forests, mixed agriculture, rain ponds, and oil palm plantations. However, there was a difference in the average CO_2 flux between the dry season and the rainy season in rice fields (0.03 < 0.05). During the study period, the rainfall varied between the dry season (July–August) and the rainy season (September), as shown in Figure 5.

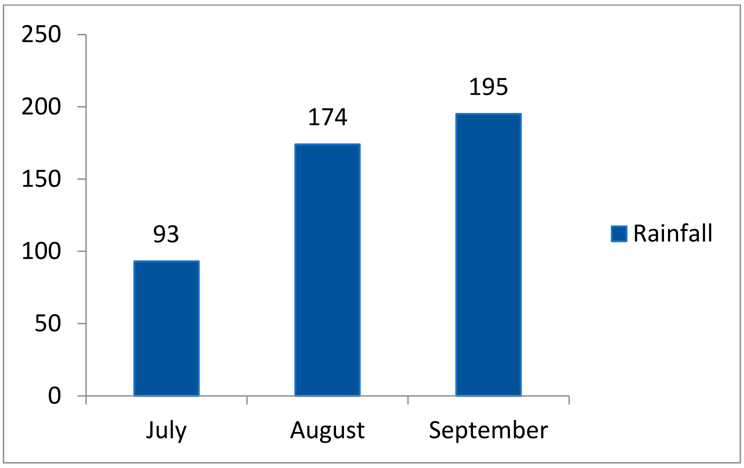

Figure 5. Rainfall Center for Statistics of North Sumatra Province in 2021.

3.6. Correlation Analysis of Macrozoobenthos with CO_2 Flux

3.6.1. Number of Macrozoobenthos Holes and Their Impact on CO_2 Flux Rate

Macrozoobenthos increase oxygen levels in the sediment or substrate by creating holes in the substrate through bioturbation. From this report, it can be inferred that an increase in the number of macrozoobenthos holes leads to a higher population of macrozoobenthos. Consequently, there is a greater reliance on the substrate contained in the soil, resulting in a decrease in the amount of carbon stored in the soil.

Figure 6 shows that the average value of CO_2 flux in the land cover of natural mangrove forests and restoration forests during the rainy season is 551.29 $mgCO_2\ m^2\ h^{-1}$, with a total of 19 benthic holes. As per Figure 7 during the dry season, the average number of benthic holes increased to 59, with a CO_2 flux of 843.324 $mgCO_2\ m^2\ h^{-1}$.

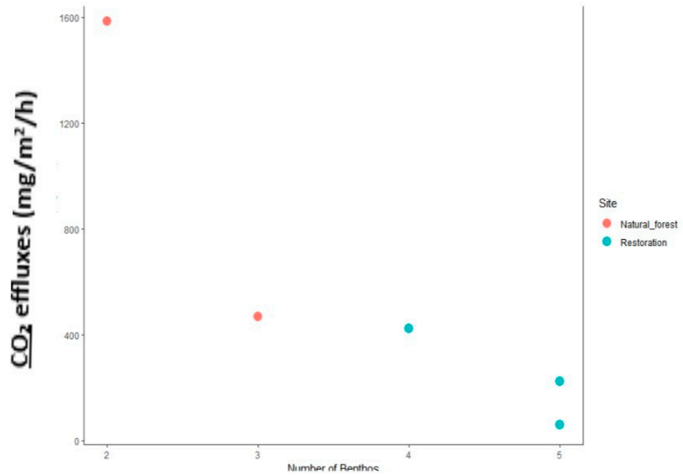

Figure 6. Number of macrozoobenthos holes on CO_2 flux levels in natural and restoration forests during the rainy season.

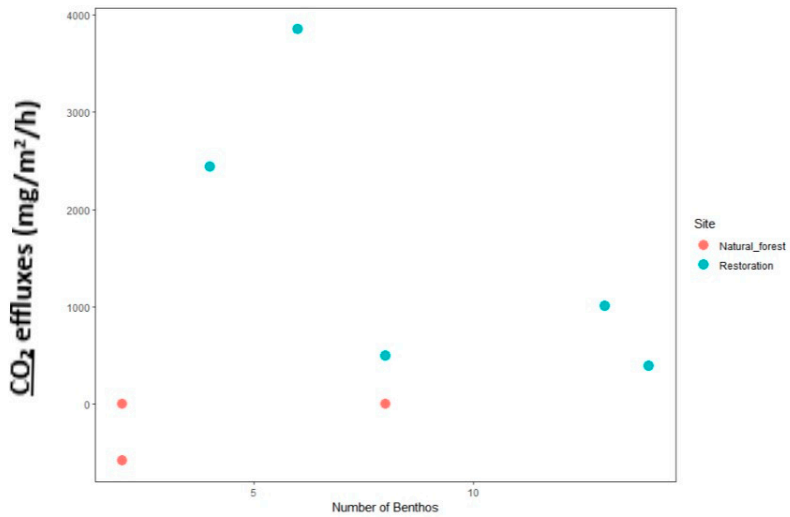

Figure 7. Number of macrozoobenthos holes on CO_2 flux level in natural and restoration forests during the dry season.

Based on the test results in Table 6, the significance value of the Pearson correlation test was obtained as 0.815 (>5% or 0.05). This indicates that there is no significant relationship between the number of holes in macrozoobenthos and CO_2 flux. The results also showed that the correlation coefficient (r) between the number of macrozoobenthos holes and CO_2 flux was 0.815. It suggests that there is no significant relationship between the number of benthos and the value of CO_2 flux (Table 6). The results of the correlation test between the number of macrozoobenthos and CO_2 flux are shown in Table 6.

Table 6. Correlation test results between the number of macrozoobenthos holes and CO_2 flux.

		CO_2 Flux	Number of Macrozoobenthos Holes
CO_2 Flux	Pearson correlation	1	0.069
	Sig. (2-tailed)		0.815
	N	14	14
Number of macrozoobenthos holes	Pearson correlation	0.069	1
	Sig. (2-tailed)	0.815	
	N	14	14

3.6.2. Macrozoobenthos and Their Impact on CO_2 Flux Levels in a Given Area

The average area of benthic holes in the rainy season was 8.1404 cm^2, as shown in Figure 8. In contrast, during the dry season, the average area of benthic holes was 12,905 cm^2, as indicated in Figure 9.

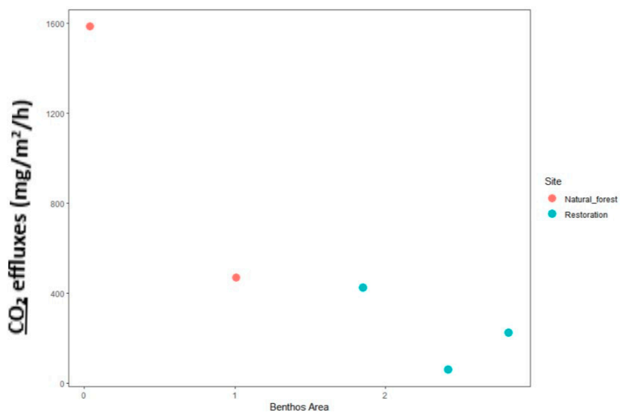

Figure 8. Macrozoobenthos hole area to CO_2 flux level of natural forests and restoration during the rainy season.

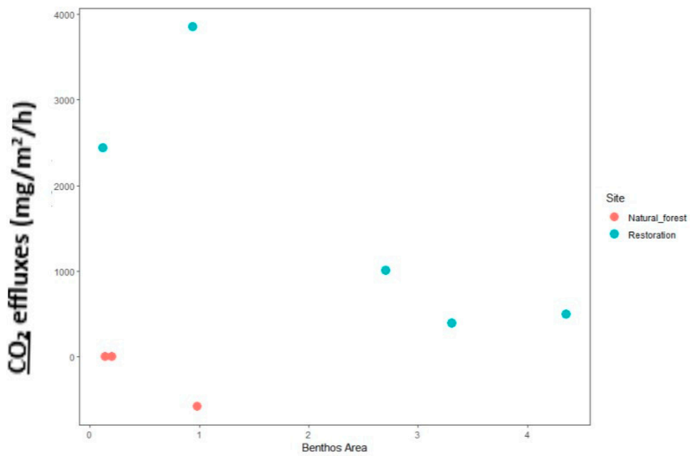

Figure 9. Macrozoobenthos hole area to CO_2 flux level of natural forest and restoration during the dry season.

Based on the test results shown in Table 7, it is evident that there is no significant relationship between the area of macrozoobenthos holes and CO_2 flux. The results also showed that the correlation coefficient (r) between the area of macrozoobenthos holes and CO_2 flux is −0.185. It shows that there is an inverse relationship between the area of macrozoobenthos holes and CO_2 flux. This means that if the area of macrozoobenthos holes is small, the CO_2 flux will be high, and vice versa. Correlation test results between the area of the macrozoobenthos hole and CO_2 flux are shown in Table 7.

Table 7. Correlation test results between macrozoobenthos area and CO_2 flux.

		CO_2 Flux	**Hole Area**
CO_2 flux	Pearson Correlation	1	−0.185
	Sig. (2-tailed)		0.527
	N	14	14
Hole area	Pearson Correlation	−0.185	1
	Sig. (2-tailed)	0527	
	N	14	14

Macrozoobenthos are widely distributed and play an important role in the food chain. Macrozoobenthos are organisms that exhibit a faster response compared to other high-level organisms, making them effective indicators of environmental pollution. From this result, it can be concluded that the area occupied by macrozoobenthos depends on the number of individuals. Therefore, a higher abundance of macrozoobenthos will result in lower values of carbon reserves and CO_2 flux.

4. Discussion

Secondary forests have a less complex vertical structure compared to primary forests. The reduced density and the flat surface of the land decrease the curvature of the plant structure [30,31]. The condition of the stand in each growing place is usually described by the diameter and height of the trees. Tree height is an indicator of soil fertility, while diameter reflects the amount of growing space available [32]. Additionally, natural forests have a significant amount of litter on the soil surface, which contributes to a higher content of active microorganisms involved in decomposition. This makes the soils in natural forests more fertile, with higher carbon stocks compared to other land cover types [19].

Differences in carbon deposits in each land cover are caused by the number and density of trees, tree species [33], and environmental factors, such as sunlight, water content, temperature, and soil fertility, which affect the rate of photosynthesis [34]. Another factor that affects carbon stock is tree diameter. The larger the diameter of the tree, the greater the amount of carbon that can be stored. The lifespan of mangroves can contribute to an increase in the diameter and height of trees within mangrove forests [35].

One of the factors that affects soil carbon stock is the amount of litter in the soil, which is an organic matter obtained from the decomposition process [36,37]. The more fertile, the higher the carbon content in the soils [38]. In addition, the number and the type of vegetation can affect the value of carbon stocks. The amount of carbon deposits is also influenced by the density and stem diameter of each individual [39]. The carbon in the root exudates provides a valuable food source for soil biota organisms. Decomposers (bacteria, fungi, and larger biota) also grow and multiply, consuming soil organic carbon (SOC) and converting it into a more stable form, eventually becoming humus in natural mangrove forests [40]. Soil biota is active in forming and recycling nutrients, while carbon is mineralized into $CO_{2,}$ which is released into the atmosphere [41]. The amount of soil carbon varies by location. This variation is influenced by factors such as soil type, rainfall, types of plants present, plant density, and land management [42]. Soil depth can affect SOC content and is useful in predicting SOC content in soil; with increasing soil depth, SOC content tends to decrease [43,44].

This circumstance exists because during the rainy season, the distribution pattern of CO_2 flux is similar to the distribution pattern of chlorophyll, which is influenced by water. However, in the dry season, it fluctuates; the concentration of chlorophyll, which dominates the waters, is higher and more widely spread than in the rainy season. CO_2 emissions decrease as the amount of solar radiation received decreases due to the soil being covered by the canopy of plants [45]. As a comparison, the resulting soil CO_2 flux in the mangrove swamps of South China was between 10.6 and 1374.1 mg m^{-2} h^{-1} [46]. Variations in CO_2 gas exchange patterns can be influenced by leaf photosynthesis and are strongly affected by high temperatures and light conditions. Nevertheless, there is little influence of temperature on the photosynthesis of leaves in plants from 20 °C to 40 °C. High temperatures can decrease the rate of photosynthesis by 40–60% at various growth stages. The degree of photosynthesis in leaves under light-dependent conditions is strongly correlated with atmospheric CO_2 and also varies with increasing temperature [47].

Ecologically, mangrove ecosystems can play an important role in mitigating climate change through reducing deforestation. In addition, mangrove ecosystems store large amounts of blue carbon, and in the long term, increasing vegetation biomass will increase SOC originating from mangroves in the soil [5,48,49]. Carbon stock in the mangrove forest in the KGLTLWR area is quite high. The results obtained were not significantly different from the mangrove forests in Vietnam, namely 844 $\pm$ 58 MgC ha^{-1} [50]; the total carbon stock in the restored mangrove forests in North Sumatra was 558.07 MgC ha^{-1} [51]. The conversion of mangrove forests into shrimp ponds accounts for at least 75.5% of total carbon loss [52]. Soil carbon stock decreased from native forest to plantations (−13%) and native forest to plantations (−42%) [53].

Even though the land is repaired, it takes quite a long time for it to return to natural forest; based on data from North Sumatra's BBKSDA [3], it has been approximately 20 years since the forest currently being restored was first cleared. Mangroves that are allowed to regenerate for more than 25 years achieve the same level of biomass carbon as compared to undisturbed forests [52]. These data can be used as material for consideration by the Indonesian government in making decisions through combining mangrove conservation and restoration for climate change reduction strategies, in particular to meet the unconditional national carbon emission reduction target of 29% by 2030 as stated in the Nationally Determined Contribution (NDC) as part of the Paris Agreement [54].

Mangroves worldwide can fix 218 $\pm$ 72 Tg C yr^{-1}, which is 50% of coastal carbon sinks and 10% of global ocean CO_2 removal, and thus represents a key term in regional and global carbon budgets [55]. Greenhouse gas production from soil is primarily due to microbiological processes, microbial activity, and greenhouse gas fluxes related to soil properties, including total carbon, total and inorganic nitrogen concentrations, bulk density, salinity, and redox potential [56]. These results suggest that seasonally varying the duration of exposure to the forest floor is important in evaluating annual CO_2 fluxes at a local scale and understanding the role of mangrove ecosystems as regulators of atmospheric CO_2 [57]. Seasonal variations follow the same trend at all sites, and variations in the spatial flux of CO_2 over the canopy are mainly explained by canopy density and the cooling efficiency of mangrove species [58].

The diversity of macrozoobenthos is strongly influenced by changes in the quality of water and the substrate in which they live. One type of macrozoobenthos is crustaceans, which have high movement or mobility which allows them to hide in their holes [59]. The abundance of individual macrozoobenthos represents the number of individuals per unit area [60,61].

5. Conclusions

The conversion of mangrove forests to other land cover, such as mixed agriculture dry land, ponds, rice fields, and oil palm plantations, can lead to a significant decrease in the amount of carbon stored. The present study shows that the conversion of land cover to other types resulted in a reduction of carbon stocks.

The CO_2 flux from various land covers is not necessarily lower in the rainy season. The presence of organic matter in the soil does not have a linear impact on the amount of CO_2 emitted from the soil. The release of CO_2 from various layers of vegetation is determined by the process of respiration, which is influenced by plant conditions and microbial activity.

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