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Article

Evaluation of Plant Growth and Potential of Carbon Storage in the Restored Mangrove of an Abandoned Pond in Lubuk Kertang, North Sumatra, Indonesia

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Abstract: Mangrove forest in Lubuk Kertang Village, West Brandan sub-district has been converted around 20 ha annually (1996–2016) into various non-forest land use. Rehabilitation can be a solution to restore the condition of the ecosystem so that it can resume its ecological and economic functions. This paper discusses the evaluation of mangrove rehabilitation carried out by planting 6000 propagules in December 2015 and 5000 seedlings in May 2016 with *Rhizophora apiculata* species in abandoned ponds. Monitoring was carried out every 6 months from 2016 to 2022. In the restored area, 11 true mangrove species and 3 associated mangrove species were found. The percentage of plants that survived after seven years was 69.42% for planting using propagules and 86.38% for planting with seedlings. The total biomass carbon stocks stored by 7-year-old plants using propagules was 51.18 Mg ha^{-1}, while the carbon stored by planting using seedlings was 56.79 Mg ha^{-1}. Soil carbon stocks at the planted site with propagules were 506.89 ± 250.74 MgC ha^{-1}, and at the planted site with seedlings were 461.85 ± 102.23 MgC ha^{-1}. The total ecosystem carbon stocks (including aboveground carbon) in the planted site using propagules were 558.07 MgC ha^{-1}, while planting using seedlings were 518.64 MgC ha^{-1}. The dataset and findings on the carbon storage evaluation of mangrove rehabilitation will be useful for blue carbon research community and policymakers in the context of the climate change mitigation strategy for Indonesia.

Keywords: mangrove forest; *Rhizophora apiculata*; carbon storage; species diversity; restoration

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1. Introduction

Mangrove forests are coastal habitats that dominate the intertidal zone in tropical and subtropical coastal areas [1,2]. Mangroves have highly important roles for coastal ecological functions and economic source for coastal livelihoods, and their high carbon stocks are substantial for climate change mitigation. In this regard, although mangroves constitute only 0.5% of the global coastal area, this ecosystem can store three to five times more carbon than other types of terrestrial forests or about 300 Mg ha^{-1} to over 1023 Mg ha^{-1} [3–6].

In 2020, Indonesia had 2.7 Mha of mangrove forests that are spread over 34 provinces [7]. Mangrove forests in Indonesia, which are located in Sumatra, are generally found in the areas of Asahan, Batubara, Deli Serdang, Tangjung Balai, Nias, Labuhanbatu, and Serdang Bedagai to Langkat Regency. In 1990, the area of mangrove forests in North Sumatra was 59,645.79 ha, where the deforestation rate was 1.51% per year [8]. Recent data shows that the area of mangroves in North Sumatra was recorded to be 66,873 ha in 2000, to 57,010 ha in 2022 [7]. Specifically, the mangrove forest located in Lubuk Kertang Village, Brandan Barat District, continues to experience degradation and forest conversion. The area of the damaged mangrove forests in this area reached 740 ha of a total of 1200 ha, with area of critical degraded mangrove forest status was up to 528 ha.

Previous restoration studies have showed the impact of mangrove restoration on carbon stocks; for example, in the iconic Westgate bridge restoration forest in Melbourne in southeastern Australia, the age of the mangroves had a significant effect on carbon stocks ranging from 30 $\pm$ 5 MgC ha^{-1} in the youngest stands (13 years) to 94 $\pm$ 4 MgC ha^{-1} in the oldest forest (35 years) [9]. In the restored mangrove forest of Hau Loc, North-Central Vietnam, the average above and below-ground C stock of this forest ranges from 12.7 $\pm$ 2.4 Mg ha^{-1} to 107 $\pm$ 10.7 Mg ha^{-1} [10]

Carbon dioxide and methane (CH4} emissions from the conversion or degradation of mangroves are a major contributor to global greenhouse gas emissions [11–13]. Thus, preventing mangrove loss and restoring degraded mangroves are valuable strategies for climate change mitigation [14,15]. Most of the current mangrove restoration and rehabilitation programs in Indonesia including in Lubuk Kertang landscape are commonly implemented for the carbon storage benefit, despite many past restoration initiatives implemented for coastal protection including from coastal erossion and tsunami impacts [16,17]. During and after the 2004 tsunami, mangrove restoration received much attention in Indian Ocean countries (Sri Lanka, Thailand and Indonesia) because of the strong link between mangrove loss and tsunami damage [18–21].

The degradation of mangrove forests have a negative impact on the livelihoods of fishermen around the area of Lubuk Kertang, including the decrease of fish and shellfish stocks and water pollution increase. Therefore, efforts are needed to rehabilitate the degraded mangroves, especially at the unproductive and abandoned ponds. Restoring the degraded mangrove lands may become one of the potential solutions to enhance ecosystem recovery in this landscape [22,23].

The present work was aimed to evaluate mangrove growth and to monitor the forest structure and carbon stocks of rehabilitated mangrove forests in the abandoned ponds in Lubuk Kertang, North Sumatra, Indonesia. Overall, our data set will be important and assist policymakers in Indonesia via the incorporation of mangrove conservation and restoration for climate change mitigation strategies, in particular to meet the unconditional national carbon emission reduction target of 29% by 2030 as stated in the Contribution Nationally Determined (NDC) as part of the Paris Agreement [24].

2. Materials and Methods

2.1. Study Area

This research was conducted in a mangrove forest rehabilitation area at the Center of excellence for Mangrove (PUI-*Pusat Unggulan Iptek Mangrove*), Universitas Sumatera Utara, in Lubuk Kertang Village, West Brandan District, Langkat Regency, North Sumatra Province, which is located between 4°3′10″–4°3′35″ N; 98°15′30″–98°15′55″ E (Figures 1 and 2). Planting was carried out in two stages on abandoned pond land with an area of 1.6 ha. The first stage was conducted in December 2015, with a direct seeding method of 6000 propagules. The second stage was conducted in May 2016, using a total of 5000 seedlings planted. The plant *Rhizophora apiculata* was chosen because around the restored area, there is a secondary forest that is dominated by *R. apiculata*, making it easier to collect propagules. *R. apiculata* is a pioneer species with a fairly high survival rate [25].

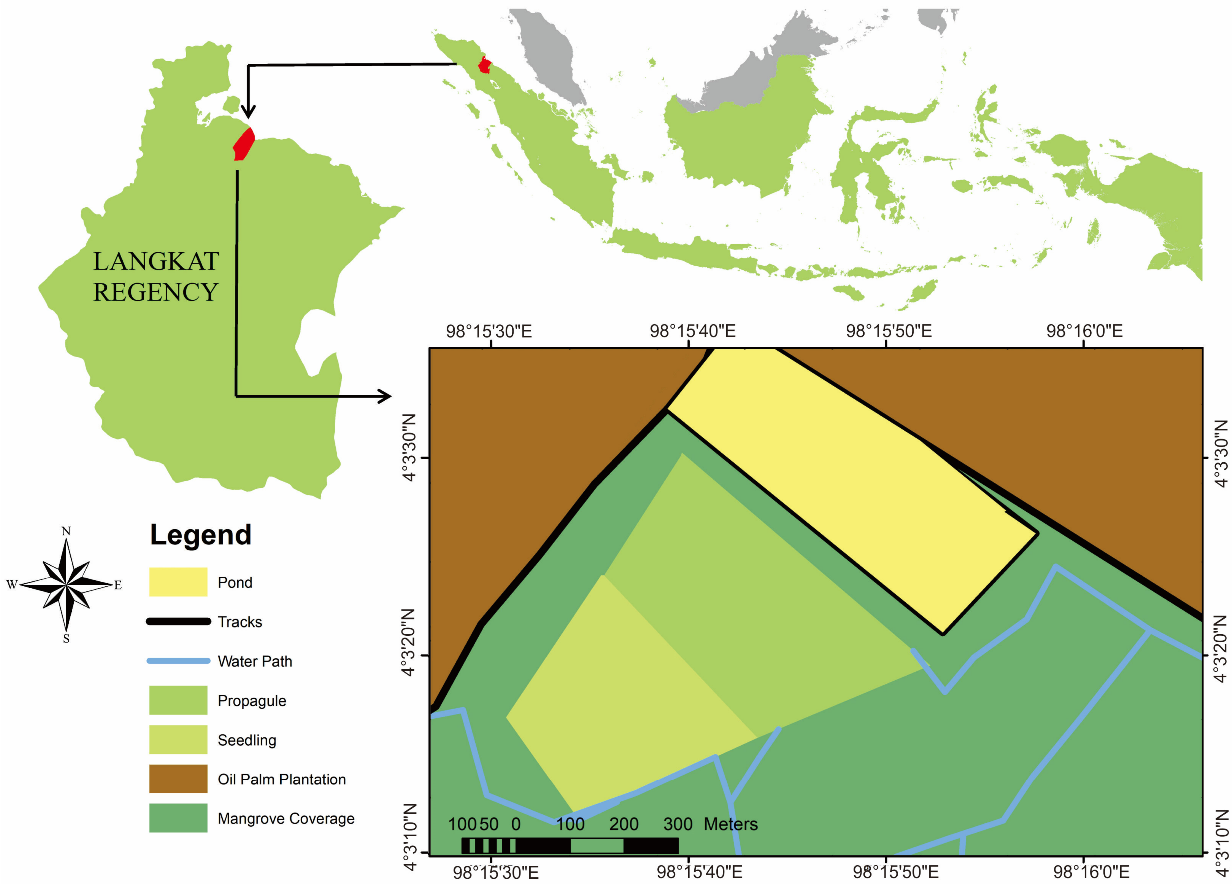

Figure 1. Map of study location of mangrove restored area in Lubuk Kertang Village, West Brandan District, Langkat Regency, North Sumatra, Indonesia.

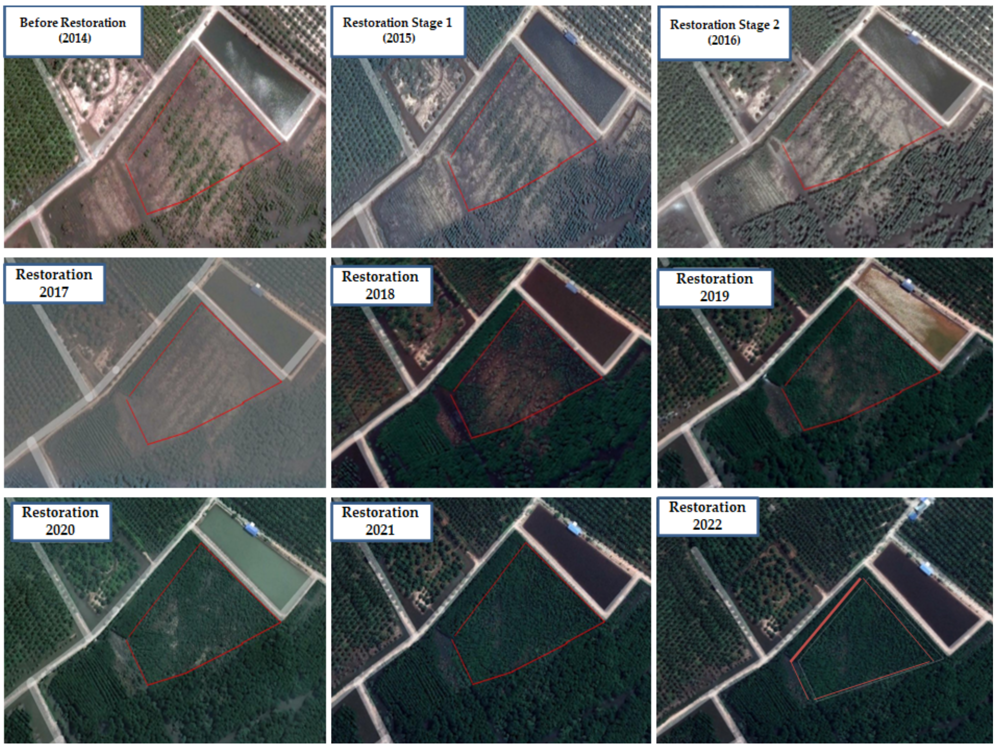

Figure 2. The picture of mangrove growth condition in the planting location obtained from Google Earth satellite images between 2014 and 2022.

2.2. Data Collection

Data collection was carried out using two methods as follows: (1) making sample plots and (2) conducting a census by taking an inventory of all restoration areas. Data collection was conducted in eight sample plots (four plots using plants from propagules and four plots from nurseries) of 10 × 10 m in each sample plot with a total of 800 plants. The first measurement was carried out when the plants were 6 months old, and subsequent measurements were carried out every six months until the plants turned 48 months old (Figure 3). The parameters observed included diameter, which was calculated 10 cm from the ground level for the first measurement (marked for each plant sample, so that it is consistent every time the next diameter measurement is taken); height; leaf thickness, which was measured using a caliper by measuring the first 3 leaves on each branch; number of leaves, percentage of life; pests; and diseases. In the fourth, sixth, and seventh years (2019–2022), the census method was employed by measuring all plants in the rehabilitation area, and the parameters observed were the plant species, diameter at breast height (DBH), and height. Individual characteristics were classified into seedling (1.5 m height), sapling (height > 1.5 m, DBH < 5.0 cm), and tree (DBH > 5 cm) [26]. However, in 2021, census measurements could not be carried out due to an increase in the cases of the Delta COVID-19 variant in Indonesia, including in North Sumatra.

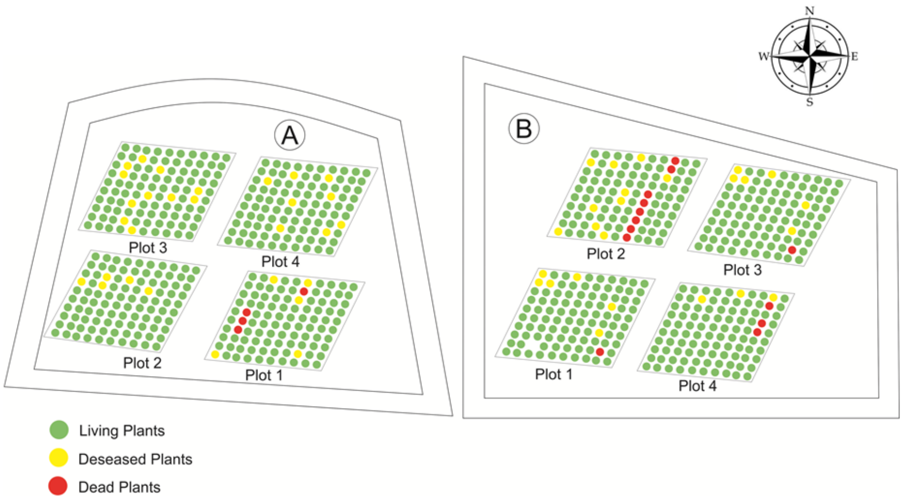

Figure 3. The layout of the sampling plots of the planting (100 planting for each plot with a total of 800 planting); (**A**). Planting using seedlings, (**B**). Planting using propagules. The green circle represent health mangroves, the yellow are pest-affected mangroves, while the red were indicated mortality.

2.3. Vegetation Structure

2.3.1. Diversity Index (H′)

To show structural diversity, the Shannon–Wiener diversity index (H′) was used:

$$H' = -\sum_{i=1}^{s} \text{Pi } \ln \text{ Pi} \tag{1}$$

where, Pi is n_i/N (Ni is the number of individuals of a species, and N is the total number of individuals of a species). When the value of H′ is 0–1, it indicates low/little species diversity. When the value of H′ is 1–3, it indicates medium species diversity, and when the value of H′ is greater than 3, it indicates high species diversity. According to Shannon Wiener, the higher the value of diversity indicates higher quality and functionally of the ecosystem [27].

2.3.2. Evenness Index (E)

Evenness is the composition of the number of individuals of each genus in the community. The Evenness index used in this study is based on the Shannon-Wiener function, which to obtain the distribution of macrozoobenthos species in the plantation area [27].

To uniformity index (E) was calculated by using the following formula:

$$E = \frac{H'}{H\ max} \tag{2}$$

where E is the number of types; H′ is the Shannon–Wiener diversity index; and Ln is the experience logarithms. The value of Evenness in the population ranges from 0 to 1 with the following criteria [16]: E > 0.6 indicates high Evenness; 0.4 < E < 0.6 indicates medium Evenness; and E < 0.4 indicates low Evenness.

2.3.3. Dominance Index (D)

The dominance index is used to obtain information about the dominant family in a community, and it is calculated using Simpson's formula as follows [27]:

$$D = \sum_{i=1}^{s} \left(\frac{n_i}{N}\right) 2 \tag{3}$$

where, n_i is the number of individuals of a species, and N is the number of individuals of all species. The criteria for this index are as follows [24]: when the value of D is close to 0, it indicates that no type is dominant, and when the value of D is close to 1, there is a dominant type.

2.4. Survival and Mortality Plants

To determine the level of damage to mangrove stands, the calculation of the intensity of attacks was carried out as follows:

$$\text{Attack intensity} = \frac{\sum(n_i \times V_j)}{NZ} 100\% \tag{4}$$

where, n_i is the number of infected plant seeds in a certain classification, V_j is the value in a certain classification, N is the number of plant seeds observed in one sample plot, and Z is the highest classification. The criteria for damage to mangrove plants are divided into five classifications, namely: namely: namely: a value of 0 (healthy) is given if the tree planting is not damaged or 100% live; a value of 1 (mild) if small parts (0–25%) of the tree planting are died from pest attack; a value of 2 (moderate) if 26–50% of the tree planting are died from pest attack; a value of 3 (heavy) if 51–76% of the tree planting are died from pest attack; a value of 4 (very heavy) if 76–100% of the tree planting are died from pest attack [28].

2.5. Soil Sampling

Soil sampling was carried out to test the texture and chemical properties of the soil (pH, N-total, Na, K, Mg, Ca, CEC, and salinity) using a purposive sampling method by taking a soil sample of 0.5 kg each in 3 plots representing mangrove rehabilitation soils based on planting method: propagule and seedling. Soil sampling for organic carbon content was carried out by collecting sub-samples of 5 cm from the midpoint of the extracted core at 0–15 cm, 20–30 cm, 30– 50 cm, 50–100 cm, and 100–200 cm using a Russian peat corer [29]. Soil samples were carefully dried at 70 °C until constant weight and grounded before being sent to the laboratory for organic carbon concentration analysis. Soil carbon stock (MgC ha^{-1}) was the product of bulk density (g cm^{-3}), soil thickness (cm), and carbon content (%).

2.6. Biomass Assessment

Measurement of 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 with ≥5 cm DBH for total biomass estimation (Table 1, [30–38]). Biomass carbon stock (MgC ha^{-1}) was the product of biomass (Mg), carbon content of biomass of 50%, and divided by the the area of the sampling plot [30].

Table 1. Allometric equations for calculating mangrove tree biomass used in this study [30].

Above-Ground Tree Weight (Wtop in kg)	Below-Ground Tree Weight (WR in kg)
Avicennia marina $Wtop = 0.308\ DBH^{2.11}$ $r^2 = 0.97$, n = 22, Dmax = 35 cm, [31] *Rhizophora apiculata* $Wtop = 0.235\ DBH^{2.42}$ $r^2 = 0.98$, n = 57, Dmax = 28 cm, [32] *Rhizophora* spp. $Wtop = 0.128\ DBH^{2.60}$ $r^2 = 0.92$, n = 9, Dmax = 32 cm, [33] $Wtop = 0.105\ DBH^{2.68}$ $r^2 = 0.99$, n = 23, Dmax = 25 cm, [34] *Xylocarpus granatum* $Wtop = 0.0823\ DBH^{2.59}$ $r^2 = 0.99$, n = 15, Dmax = 25 cm, [34] Common equation $Wtop = 0.251\ p\ D^{2.46}$ $r^2 = 0.98$, n = 104, Dmax = 49 cm, [35] $Wtop = 0.168\ pDBH^{2.47}$ $r^2 = 0.99$, n = 84, Dmax = 50 cm, [36]	*Avicennia marina* $WR = 1.28\ DBH^{1.17}$ $r^2 = 0.80$, n = 14, Dmax =35 cm, [31] *Bruguiera* spp. $WR = 0.261\ DBH^{1.86}$; $r^2 = 0.92$, n = 5, Dmax = 15 cm, [31] $WR = 0.0188\ (D2H)^{0.909}$ r^2: unknown, n = 11, Dmax = 33 cm, [37] *Rhizophora* spp. $WR = 0.00974\ (D2H)^{1.05}$ r^2: unknown, n = 16, Dmax = 40 cm, [37] Common equation $WR = 0.199\ p\ 0.899\ D^{2.22}$ $r^2 = 0.95$, n = 26, Dmax = 45 cm, [35] *Xylocarpus granatum* $WR = 0.145\ DBH^{2.55}$ $r^2 = 0.99$, n = 6, Dmax = 8 cm, [38]

2.7. Data Analysis

Data were expressed in mean ± standard deviation (SD). Regression analysis was used to assess the relationship between height, diameter, above-ground biomass, below-ground biomass, number of leaves, and leaf thickness. The statistical significance of carbon stocks between planting treatments was evaluated by performing Tukey test comparison. The p-value < 0.05 was selected as a limit of statistical significance.

Statistical analysis was performed by using Microsoft Excel and the R statistical software [39].

3. Results

3.1. Vegetation Structure

A total of 14 mangrove species were found in the restored forest; the dominant species were *Rizophora apiculata*, *Sonneratia alba*, and *Rhizophora stylosa*. Three minor species were also found, namely *Acrostichum aureum*, *Finlaysonia maritimea*, and *Sesuvium portulacastrum* (Tables 2 and 3).

Table 2. Species found in the Lubuk Kertang restored area in 2016–2022 planted with propagules.

Year	Observation Method	Species
2016–2019	Sampling	*Rhizophora apiculata*
2019	Census (13 species)	*Acrostichum aureum*, *Avicennia marina*, *Bruguiera gymnorrhiza*, *Excoecaria agallocha*, *Finlaysonia maritima*, *Nypa frutican*, *Rhizophora apiculata*, *Rhizophora mukronata*, *Rhizophora stylosa*, *Scyphiphora hydrophylacea*, *Sesuvium portulacastrum*, *Sonneratia alba*, and *Sonneratia caseolaris*
2020	Census (14 species)	*Acrostichum aureum*, *Avicennia marina*, *Aegiceras corniculatum*, *Bruguiera gymnorrhiza*, *Excoecaria agallocha*, *Finlaysonia maritima*, *Nypa frutican*, *Rhizophora apiculata*, *Rhizophora mukronata*, *Rhizophora stylosa*, *Scyphiphora hydrophylacea*, *Sesuvium portulacastrum*, *Sonneratia alba*, and *Sonneratia caseolaris*
2022	Census (14 species)	*Acrostichum aureum*, *Avicennia marina*, *Aegiceras corniculatum*, *Bruguiera gymnorrhiza*, *Ceriops tagal*, *Excoecaria agallocha*, *Finlaysonia maritima*, *Nypa frutican*, *Rhizophora apiculata*, *Rhizophora mukronata*, *Rhizophora stylosa*, *Scyphiphora hydrophylacea*, *Sesuvium portulacastrum*, and *Sonneratia alba*

Tree diameter, height, and number of leaves were increased at both propagules and seedlings planting method along the age gradient of the plantation from 6 to 48 months old (Table 4). After 6 and 12 months of planting, the average height of propagule planting trees was taller than the height of the seedling planting trees. However, when the plants were 30–48 months old, the average seedling height at seedling planting was taller than the propagule planting's height. However, this pattern was not much observed for diameter, number and thickness of leaves (Table 4).

Table 3. Types of species found in the Lubuk Kertang restored area 2016–2022 planted with seedlings.

Year	Observation Method	Species
2016–2019	Sampling	*Rhizophora apiculata*
2019	Census (12 species)	*Acrostichum aureum*, *Avicennia marina*, *Bruguiera gymnorrhiza*, *Excoecaria agallocha*, *Finlaysonia maritima*, *Nypa frutican*, *Rhizophora apiculata*, *Rhizophora mukronata*, *Rhizophora stylosa*, *Scyphiphora hydrophylacea*, *Sesuvium portulacastrum*, and *Sonneratia alba*
2020	Census (12 species)	*Acrostichum aureum*, *Avicennia marina*, *Bruguiera gymnorrhiza*, *Excoecaria agallocha*, *Finlaysonia maritima*, *Nypa frutican*, *Rhizophora apiculata*, *Rhizophora mukronata*, *Rhizophora stylosa*, *Scyphiphora hydrophylacea*, *Sesuvium portulacastrum*, and *Sonneratia alba*
2022	Census (12 species)	*Acrostichum aureum*, *Avicennia marina*, *Bruguiera gymnorrhiza*, *Excoecaria agallocha*, *Finlaysonia maritima*, *Nypa frutican*, *Rhizophora apiculata*, *Rhizophora mukronata*, *Rhizophora stylosa*, *Scyphiphora hydrophylacea*, *Sesuvium portulacastrum*, and *Sonneratia alba*

Table 4. Comparison of height, diameter, number of leaves, and leaf thickness between the propagules and seedlings planting methods from 6 to 48 months after planting.

Month	Height (cm)	Diameter (cm)	Number of Leaves	Leaf Thickness (mm)
Propagules planting				
6	50.65 ± 13.28	0.62 ± 0.12	19.93 ± 9.50	0.54 ± 0.11
12	69.86 ± 14.99	0.86 ± 0.19	37.66 ± 16.34	0.71 ± 0.09
18	92.09 ± 20.74	1.62 ± 0.39	107.80 ± 58.55	0.64 ± 0.10
24	105.72 ± 20.96	1.89 ± 0.42	125.27 ±57.93	0.84 ± 0.41
30	123.53 ± 24.62	2.12 ± 0.46	144.48 ± 65.60	1.02 ± 0.42
36	141.14 ± 24.91	2.42 ± 0.52	165.74 ± 66.01	1.25 ± 0.44
42	157.36 ± 26.06	2.82 ± 0.46	188.77 ± 65.61	1.41 ± 0.56
48	171.44 ± 23.78	2.98 ± 0.48	205.81 ± 64.10	1.64 ± 0.19
Seedlings planting				
6	38.19 ± 6.76	0.48 ± 0.07	19.93 ± 9.40	0.60 ± 0.13
12	45.17 ± 7.74	0.60 ± 0.08	26.25 ± 10.57	0.80 ± 0.09
18	58.10 ± 13.60	1.33 ± 0.36	104.55 ± 55.27	0.50 ± 0.07
24	67.03 ± 14.85	1.50 ± 0.37	120.67 ± 53.64	0.72 ± 0.13
30	158.40 ± 51.91	1.81 ± 0.37	139.63 ± 52.82	1.15 ± 0.27
36	170.36 ± 51.68	2.02 ± 0.37	158.61 ± 52.30	1.41 ±0.31
42	184.40 ± 50.73	2.48 ± 0.34	228.70 ± 59.43	0.55 ± 0.05
48	190.03 ± 50.95	2.87 ± 0.42	288.59 ± 52.43	1.05 ± 0.05

After monitoring for 3 consecutive years, in 2020, 15 species of mangrove plants were found across sampling plots, and in 2022, 14 species were found as a result of *Sonneratia caseolaris* logging. In our 2022 observations, there were 5506 individuals at the restoration site that was planted with propagules; these were divided into 117 seedlings, 1714 saplings, and 3675 individual trees (Table 5).

Meanwhile, at the planting location using seedlings, 13 species of mangrove plants were found, and there were 4482 individuals divided into 147 individual seeds, 1141 individual saplings, and 3194 individual trees (Table 6).

The H′ value at the location that was restored by planting using propagules was in the low-medium category (Table 7). At the seedling level, it was included in the medium category with an H′ value of 1–2. Meanwhile, the sapling level was in the low category with a value of H′ > 1, and the tree level in 2019 was also in the low category. In 2020 and 2022, it was in the medium category with an H′ value of 1–2.

Table 5. Number of individuals observed in the restored areas planted with propagules using the census method from 2019–2022.

No	Species	Seedling			Sapling			Tree		
		2019	**2020**	**2022**	**2019**	**2020**	**2022**	**2019**	**2020**	**2022**
1	*Acrostichum aureum*	101	180	187	-	-	-	-	-	-
2	*Aegiceras corniculatum*	-	1	-	-	-	1	-		
3	*Avicennia marina*	4	1	6	5	17	6	-	5	21
4	*Bruguiera gymnorrhiza*	11	12	50	2	13	8	-	2	18
5	*Ceriops tagal*	-	-	5	-	-	-	-	-	-
6	*Excoecaria agallocha*	7	5	4	9	2	-	-	8	12
7	*Finlaysonia maritima*	77	90	160	-	-	-	-	-	-
8	*Nypa frutican*	-	-	4	3	3	3	-	3	3
9	*Rhizophora apiculata*	891	227	322	2334	2945	2293	71	960	1871
10	*Rhizophora mucronata*	8	1	15	8	21	15	-	3	21
11	*Rhizophora stylosa*	241	237	98	316	252	206	1	266	252
12	*Scyphiphora hydrophyllacea*	6	7	70	17	20	12	-	-	11
13	*Sesuvium portulacastrum*	78	139	120	-	-	-	-	-	-
14	*Sonneratia alba*	858	160	998	802	1433	969	43	465	1433
15	*Sonneratia caseolaris*	-	-	-	2	-	-	2	2	
	Total	2282	1060	2039	3495	4814	3527	117	1714	3675

Table 6. Number of individuals observed in restored areas planted with seedlings using the census method from 2019–2022.

No	Species	Seedling			Sapling			Tree		
		2019	**2020**	**2022**	**2019**	**2020**	**2022**	**2019**	**2020**	**2022**
1	*Acrostichum aureum*	21	26	41	-	-	-	-	-	-
2	*Avicennia marina*	10	2	8	9	16	14	1	2	2
3	*Bruguiera gymnorrhiza*	15	18	61	2	24	18	-	1	-
4	*Ceriops tagal*	-	-	2	-	-	-	-	-	-
5	*Excoecaria agallocha*	-	-	-	13	13	11	-	-	2
6	*Finlaysonia maritima*	9	25	39	-	-	-	-	-	-
7	*Nypa frutican*	-	-	3	-	-	-	11	11	11
8	*Rhizophora apiculata*	621	714	339	3259	3040	2061	10	449	1996
9	*Rhizophora mucronata*	10	1	-	25	19	19	-	4	4
10	*Rhizophora stylosa*	62	66	115	271	387	262	1	79	118
11	*Scyphiphora hydrophyllacea*	13	11	27	77	65	31	1	1	34
12	*Sesuvium portulacastrum*	10	28	40	-	-	-	-	-	-
13	*Sonneratia alba*	745	133	234	880	1252	769	121	592	1026
	Total	1516	1024	909	4541	4816	3185	147	1141	3194

Table 7. Diversity (H′) observed in the restored areas planted with propagules surveyed between 2019–2022.

No	Species	Seedling			Sapling			Tree		
		2019	**2020**	**2022**	**2019**	**2020**	**2022**	**2019**	**2020**	**2022**
1	*Acrostichum aureum*	0.14	0.30	0.22	-	-	-	-	-	-
2	*Aegiceras corniculatum*	-	0.01	-	-	-	0.01	-		
3	*Avicennia marina*	0.01	0.01	0.02	0.01	0.02	0.00	-	0.02	0.03
4	*Bruguiera gymnorrhiza*	0.03	-	0.09	0.00	0.02	0.01	-	0.01	0.03
5	*Ceriops tagal*	-	0.05	0.01	-	-	-	-	-	-
6	*Excoecaria agallocha*	0.02	0.03	0.01	0.02	0.01	-	-	0.03	0.02
7	*Finlaysonia maritima*	0.11	-	0.20	-	-	-	-	-	-
8	*Nypa frutican*	-	0.21	0.01	0.00	0.00	0.00	-	0.01	0.01
9	*Rhizophora apiculata*	0.37	0.33	0.29	0.27	0.29	0.28	0.30	0.32	0.34
10	*Rhizophora mucronata*	0.02	0.1	0.04	0.01	0.02	0.02	-	0.01	0.02
11	*Rhizophora stylosa*	0.24	0.33	0.15	0.22	0.15	0.17	0.04	0.29	0.29
12	*Scyphiphora hydrophyllacea*	0.02	0.03	0.12	0.03	0.03	0.04	-	-	0.03
13	*Sesuvium portulacastrum*	0.12	0.27	0.17	-	-	0.35	-	-	-
14	*Sonneratia alba*	0.37	0.29	0.35	0.34	0.36	0.35	0.37	0.35	0.36
15	*Sonneratia caseolaris*	-	-	-	0.00	-	-	0.07	0.01	-
	Total	1.43	1.86	1.67	0.90	0.90	0.89	0.78	1.05	1.13

The H′ value at the location that was restored by planting using seedlings was in the low-medium category (Table 8). At the seedling level, it was included in the medium category with an H′ value of 1.1–1.7. Further, sapling and tree classes had H′ value < 1 or categorized as low diversity.

Table 8. Diversity (H′) observed in the restored areas planted with seedling surveyed between 2019–2022.

No	Species	Seedling			Sapling			Tree		
		2019	2020	2022	2019	2020	2022	2019	2020	2022
1	*Acrostichum aureum*	0.06	0.09	0.14	-	-	-	-	-	-
2	*Avicennia marina*	0.03	0.01	0.04	0.00	0.02	0.02	0.02	0.01	0.00
3	*Bruguiera gymnorrhiza*	0.05	0.07	0.18	0.02	0.03	0.03	-	0.01	-
4	*Ceriops tagal*	-	-	0.01	-	-	-	-	-	-
5	*Excoecaria agallocha*	-	-	-	0.02	0.02	0.02	-	-	0.00
6	*Finlaysonia maritima*	0.03	0.09	0.14	-	-	-	-	-	-
7	*Nypa frutican*	-	-	0.02	-	-	-	0.14	0.04	0.02
8	*Rhizophora apiculata*	0.37	0.25	0.37	0.24	0.29	0.28	0.13	0.37	0.29
9	*Rhizophora mucronata*	0.03	0.01	-	0.03	0.02	0.03	-	0.02	0.1
10	*Rhizophora stylosa*	0.13	0.18	0.26	0.17	0.20	0.21	0.02	0.19	0.12
11	*Scyphiphora hydrophyllacea*	0.04	0.05	0.10	0.07	0.06	0.05	0.02	0.01	0.05
12	*Sesuvium portulacastrum*	0.03	0.01	0.14	-	-	-	-	-	-
13	*Sonneratia alba*	0.35	0.27	0.35	0.32	0.35	0.34	0.09	0.34	0.36
	Total	1.12	1.11	1.75	0.86	0.98	0.99	0.43	0.98	0.86

The Evenness index value (E) of propagules planting was classified between low-high (Table 9). For seedling class, E value was >0.6 (high), and subsequently sapling class was low to medium (0.39–0.43), and tree class had medium Evenness index with E value between 0.4–0.6. In addition, the Dominance index value for planting using propagules is the absence of dominant species in the rehabilitation area (Table 10).

Table 9. Index of evenness and dominance of vegetation planting with propagules.

Indexes	Seedling			Sapling			Tree		
	2019	2020	2022	2019	2020	2022	2019	2020	2022
Evenness (E)	0.60	0.75	0.67	0.41	0.39	0.43	0.56	0.48	0.51
Dominance (D)	0.31	0.17	0.29	0.51	0.49	0.50	0.50	0.41	0.38

Table 10. Index of evenness and dominance of vegetation planting with seedlings.

Indexes	Seedling			Sapling			Tree		
	2019	2020	2022	2019	2020	2022	2019	2020	2022
Evenness (E)	0.48	0.48	0.76	0.41	0.47	0.47	0.24	0.47	0.48
Dominance (D)	0.41	0.50	0.23	0.55	0.47	0.48	0.81	0.43	0.50

The Evenness index value (E) of Seedlings planting was classified between low-high (Table 10). For seedling class, E value was >0.6 (high), and subsequently sapling class was low to medium (0.39–0.56), and tree class had medium Evenness index with E value between 0.4–0.6. In addition, the Dominance index value for planting using propagules is the absence of dominant species in the rehabilitation area (Table 10).

3.2. Survival and Mortality Plants

Table 11 shows that the percentage of planting survival in the rehabilitation area surveyed every six months over 2016 to 2022. Our monitoring showed that after 48 months old, plant survival rates were 87.75% and 92% for respectively planting using propagules and seedlings. However, in 2022 plant survival rates were decreased for both treatments to only 69.42% and 86.38% for planting using propagules and seedlings, respectively. Higher plant survival rates at 48 months old (2019 monitoring) compared to 2022 monitoring were due to low pest attack intensity, with only 7.54% in propagules planting plot and 4.43% in seedlings planting plot (Table 12). We observed that weaver ants (*Oecophylla smaragdina*) were the main pest in the study site (Supplementary Figure S1).

Table 11. Percentage of plant survival and mortality between 6–48 months (2016–2019) of individual observation and followed by plant census for the remaining period up to 2022 or 7 years old.

Years	Month	% Survival	% of Mortality
Planting with Propagules			
2016	6	92.50	7.50
2016	12	91.00	9.00
2017	18	89.75	10.25
2017	24	88.75	11.25
2018	30	88.50	11.50
2018	36	88.25	11.75
2019	42	88.25	11.75
2019	48	87.75	12.25
2019	48 (census)	71.60	28.40
2020	60 (census)	71.83	28.17
2022	72 (census)	69.42	30.58
Planting with seedlings			
2016	6	93.25	6.75
2016	12	92.50	7.50
2017	18	92.25	7.75
2017	24	92.00	8.00
2018	30	92.00	8.00
2018	36	92.00	8.00
2019	42	92.00	8.00
2019	48	92.00	8.00
2019	48 (census)	79.80	20.20
2020	60 (census)	84.88	15.12
2022	72 (census)	86.38	13.62

Note: Observations when the plants are 6–48 months old; a sample of 800 seeds is used.

Table 12. Intensity of pest attacks on mangrove stands.

Planting with	Plot	Number of Plants	Pest Attack Intensity (%)	Category
Propagules	1	92	6.52	mild
	2	83	7.23	mild
	3	94	11.70	mild
	4	85	4.70	mild
Seedlings	1	93	2.15	mild
	2	90	5.55	mild
	3	88	6.81	mild
	4	94	3.19	mild

3.3. Physical and Chemical Properties of Soil

When the plants were 48 months old, soil condition in the study site was dominated by clay (>80%), and followed by silt and sand fractions (Supplementary Table S1). dominated by clay (>80%), and followed by silt and sand fractions (Supplementary Table S1). The pH level at the two planting treatments was similar, ranged between 4.8–5 and classified as acidic. The total N content was low at 0.1%, while the Na content was high (8.5–10.7 me/100 g), above >8 me/100 g, the Ca content was also very low at <2 me/100 g. for the K content at planting using medium propagules, whereas with very high seedlings. The salinity level at both planting locations was very high namely >20 Ppm (Tables 13 and 14).

Table 13. Analysis of soil chemical properties for planting rehabilitation using propagules.

Parameters	Unit	Standard Value	Rehabilitation Land	Description
pH		4.5–5.5	4.850	Acidic
N-total	%	0.10–0.20	0.107	Low
Na	me/100 g	>1.0	8.540	Very high
K	me/100 g	0.3–0.5	0.540	Medium
Mg	me/100 g	2.1–8.0	3.310	High
Ca	me/100 g	<2	1.140	Very low
KTK	me/100 g	5–16	8.200	Low
Salinity	Ppm	20–45	21.260	Very high

Table 14. Analysis of soil chemical properties for planting rehabilitation using seedlings.

Parameters	Unit	Standard Value	Rehabilitation Land	Description
Ph		4.5–5.5	5.000	Acidic
N-total	%	0.10–0.20	0.110	Low
Na	me/100 g	>1.0	10.700	Very high
K	me/100 g	0.6–1	0.690	Very high
Mg	me/100 g	2.1–8.0	3.790	High
Ca	me/100 g	<2	1.580	Very low
KTK	me/100 g	17–24	11.060	Medium
Salinity	Ppm	20–45	28.670	Very high

3.4. Carbon Stored in Restored Forests

The aboveground biomass carbon stocks at the four years planting age were 2.13 Mg ha^{-1} and belowground root biomass carbon stocks were 1.00 Mg ha^{-1} (Figure 4). Both above- and below-ground biomass were increased significantly after five years old, specifically in the seedling planting plots, to 15.81 Mg ha^{-1} (for AGC) and 3.98 Mg ha^{-1} (for BGC). After seven years old, the above-ground carbon stocks at planting using propagules plots were 41.00 Mg ha^{-1}, while at planting using seedling were 46.53 Mg ha^{-1}. The below-ground carbon stocks at planting using propagules plots were 10.18 Mg ha^{-1}, while at planting using seedling plots were 10.26 Mg ha^{-1}. The mean annual increment (MAI) carbon in this restoration area was 6.15 Mg ha^{-1} for planting using propagules and 3.35 Mg ha^{-1} for planting using seedlings (Figure 4). Overall, we observed a significant increase in carbon stocks from 2019 to 2022 at both planting using propagules and using seedlings (Figure 4, Supplementary Figures S2 and S3).

Soil carbon stocks at the planted site with propagules were 506.89 ± 250.74 MgC ha^{-1}, and planted site with seedlings were 461.85 ± 102.23 MgC ha^{-1} (Figure 5). The total ecosystem carbon stocks (including biomass carbon pool) in the planted site using propagules were 558.07 MgC ha^{-1}, while that in the planted site using seedlings were 518.64 MgC ha^{-1}.

3.5. Growth Correlation

The planting growth relationship between measured parameters at two planting approach sites are summarized in Figure 6. For example, at propagules planting plots (Figure 6A), the correlation between height and diameter was 0.85, and the correlation between height and aboveground biomass was 0.79. At the seedlings planting, we observed tree height and diameter correlation of 0.84, and tree height and above-ground biomass of 0.80 (Figure 6B).

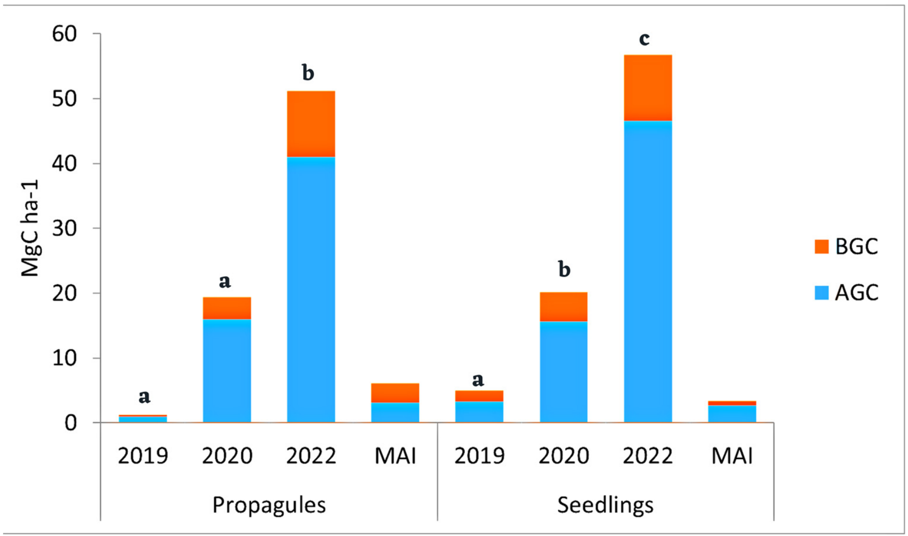

Figure 4. Above-ground (AGC) and below-ground biomass carbon (BGC) stocks stored and mean annual increment (MAI) in rehabilitated land planted with propagules and seedlings. The different letter notation shows significant differences in the Tukey at $p < 0.05$.

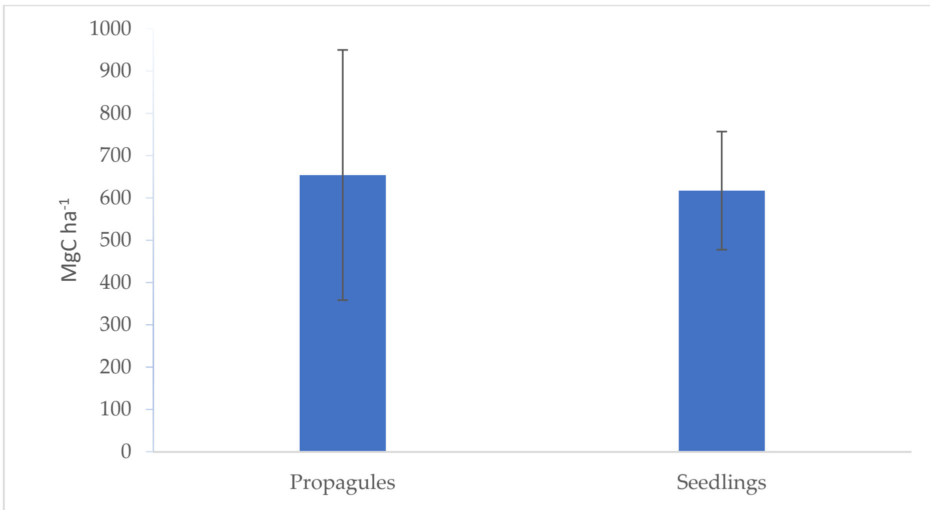

Figure 5. Soil carbon stocks in two planted approaches in rehabilitated aquaculture ponds of Lubuk Kertang.

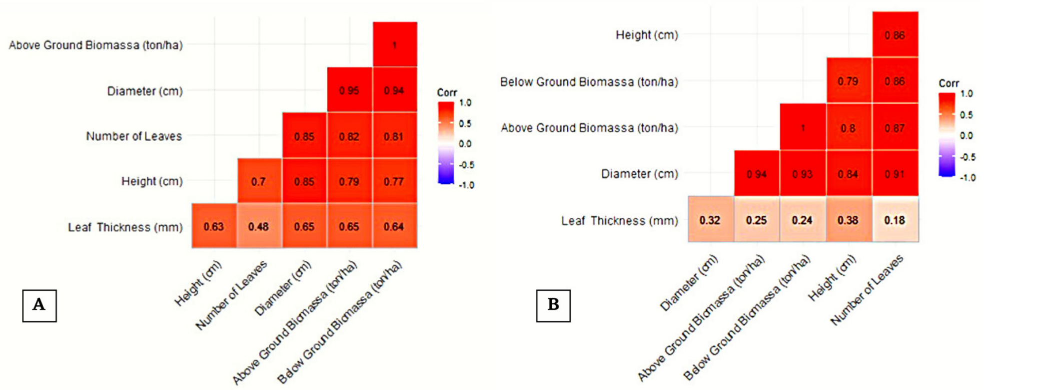

Figure 6. Relationships between height, diameter, above-ground biomass, underground biomass, number of leaves, and leaf thickness. (**A**) Planting with propagules; (**B**) planting with seedlings (the increasing intensity of the red color in the diagram indicates that the correlation was higher).

4. Discussion

4.1. Vegetation Structure

At the initial stage of planting in 2016, there was only one species introduced at the study site of abandoned aquaculture pond, namely *Rhizophora apiculata*. After 7 years, 14 species of mangrove plants were encountered at the restoration site, where the results were not much different from previous research conducted by [40] located near our study site in Lubuk Kertang Village and they recorded 15 mangrove species in secondary mangrove forests. The presence of other species in the restored area was most likely due to propagules movement and being carried by water through the river at high tide, as the rehabilitated aquaculture ponds in this study was located near the river channel and surrounded by secondary forest (Figure 1). According to Balke et al. [41], tidal and river systems within the same catchment are closely connected and have the same WoO (Windows of Opportunity), which is essential for the restoration of coastal vegetation. Seedlings planting plots in general have higher adaptability to cumulative disturbances, such as sediment erosion that causes the uprooting of plant roots, water movement, and inundation stress. Lowering the frequency of disturbances allows more time for plants to acclimate to local condition and is therefore expected to increase growth [42].

The plants that grew from seedlings had higher shoots and larger shoot diameters compared with plants from propagules (Supplementary Figure S2). Therefore, it is suggested that the use of *Rhizophora apiculata* through seedlings introduction may enhance the success rates of a restoration program rather than propagules. This findings are consistent with previous study by Miyakawa et al. [24] who recommends similar approach for rehabilitation programs on ex-pond land. Furthermore, the mortality percentage of planting using propagules was higher than using seedlings. Therefore, the seedling selection during first planting must also be considered for an improved survival rates can be seen in Supplementary Figures S3–S5.

The high number of *S. alba* found in the restored areas may be due to similar required environmental condition and suitability of this species with introduced *R. apiculata* [43]. The increase and decrease in the number of plants at the restoration site over monitoring period was caused by various factors. For example, there was a few number of logging activities in the site with quite significant number of individuals were removed (Supplementary Figure S6A). We also observed that some mature trees have produced new propagules and facilitated new plant establishement after seven years since first planting (Supplementary Figure S6B).

4.2. Survival and Mortality Plants

Overall it is observed that seven years mangrove rehabilitation in aquaculture ponds in this study has high plant survival rates, low mortality rates and pest attacks. Biotic, abiotic, and anthropogenic disturbances affect forest diversity index values, some species may tolerate and adapt with disturbance, while others may fail to survive. The increase in the number of individuals found in our study site was quite high, and due to various factors including the suitability of the habitat for mangrove growth. Although it was formerly an aquaculture pond, the the water exchange of the site was maintained due to its location near the main river and surrounded by a secondary forest that serves as a natural source of seeds for new seedling establishment.

Based on the results of field observations and identification of pests, several types of pests found that attack plants in large numbers, belong to the order of *Lepidoptera* such as bagworms (*Pteroma* sp.), green hornworms (*Polyura schreiber*), and white cocoons (Supplementary Figure S1). *Lepidoptera* is one of pests that can caused high number of plant mortality especially for young plant establishement [44].

According to Kalshoven [45], other damage observed on the leaves is also caused by the gastropod family, namely the herbivore snail. Root damage is caused by a type of Grapsid crabs that eat roots and stems when they are still propagules, seedlings, and tillers [46] in this mangrove species. Generally, young stems and roots in mangroves attract several types of crabs because they are still quite soft and quite sweet. The worst result of crab attacks is that the stems and roots become hollow and porous [47]. Weaver ants influence the behavior of flower visitors and the reproductive success of their host plants; they have the potential to influence the structure of the pollination network [48].

4.3. Physical and Chemical Properties of Soil

The soil condition of mangrove rehabilitation site in this study has mostly low pH, which may associate with a decrease in the availability of nutrients for plants and the development of microorganisms [49,50]. Soil organic matter including C-organic content plays a very important role in the ability of the soil to maintain soil fertility and productivity through the activity of soil microorganisms [51,52]. Compared to mud or clay dominated sediments, sand sediments contain less organic matter because they have a larger grain structure, low density, and high permeability and are easily washed away, making it difficult to store dissolved organic matter.

Nitrogen is one of the main macronutrients that is very important for plant growth. However, although rehabilitated mangrove land in our study has low nitrogen content, the planting still has high survival rates. However, the the potassium content obtained in the study site was high. According to Tisdale [53], the availability of potassium for plants depends on soil aspects and climatic parameters and is essential to support vegetation growth.

The cation exchange capacity in the rehabilitated land using propagules is lower than the rehabilitated land using seedlings, which indicates that this land has a higher nutrient binding capacity than the land planted with propagules. The Na content in the rehabilitated mangrove area was considered high concentration because it may be influenced by the higher salinity of sea water during high tide water exchange.

4.4. Carbon Stored in Restored Forests

The increase of mangrove biomass carbon stocks can be seen following the increase number of individuals, diameter, height and density of wood, stand type and age, history of vegetation development, composition and structure of the stand [29,54,55]. If this restored forest is left undisturbed and allowed to self-regenerate for more than 25 years, it may achieve the same level of biomass carbon as undisturbed forests [56]. Regeneration efforts (restoration, rehabilitation, and reforestation) can lead to biomass recovery after 40 years [57]. Regeneration can help restore aboveground carbon stocks back to their previous levels in just a few decades, with a faster rate of biomass recovery than in soil carbon stocks [58]. Therefore, the management of mangrove ecosystems can be improved by preventing further land use and cover changes. Promoting rehabilitation is therefore very important and effective for climate change mitigation policies [57].

Mangroves can store carbon per hectare more than three times the average terrestrial tropical forest, indicating that the optimal function of carbon absorption by mangroves reaches 77.9%, where the carbon absorbed is stored in mangrove biomass in tree trunks [6]. The increase in organic matter in trees is positively correlated with tree diameter and height; in this regard, the carbon content of trees especially in the trunk, is high because carbon is the organic material that makes up the trunk cell wall [59–61].

Mangrove ecosystems store more carbon in the belowground carbon pool. Mangrove organic carbon is mainly stored in the soil, which contains more than two-thirds of the total carbon stock of mangrove ecosystems [57]. According to Aminudin [54], the rate of increase in tree biomass such as stand age, history of vegetation development, stand composition, and vegetation structure affects forest stand biomass. These results are in line with research conducted by Sasmito et al (2020) [59] in the mangrove forest of Bintuni that the top 100 cm soil carbon stock was not significantly different between post-harvest stands, only varying between 354 $\pm$ 71 Mg C ha^{-1} in 10 year old stands and 442 $\pm$ 57 Mg C ha^{-1} in 15 year old stands.

Mangroves store large stocks of organic carbon (C) in their soil which are important in the global C cycle, the belowground mangrove tree biomass is the main contributor to this organic C stock. Another factor affecting C-organic reserves is the density of soil contents (BD), where the BD of planting using propagules ranges from 0.29–0.76 g/cm^3 with an average of 0.63 g/cm^3, the BD value of planting using seedlings ranges from 0.44–0.73 g/cm^3 with an average of 0.58 g/cm^3. Soil BD affects mangrove root growth with dense patches tending to have increased root growth and organic C uptake potential compared to less dense soil patches [62]. Soil C concentration with forest age showed consistent and positive changes, even in the youngest forests (<5 years), this is in line with our observation that soil C content increased over time after 7 years of mangrove reforestation [63]. Based on this finding, this study has limitation to present carbon vegetation and soil for the whole restoration site and not based on species.

5. Conclusions

Overall, it can be concluded that the restoration in this area is classified as successful with a high survival rate of plants, low death rates and pest attacks, large enough carbon stores up to 600–700 Mg h^{-1}. Selection of the right location and type of vegetation is a key factor in carrying out restoration activities. This study also provides important data that is expected to be used by decision makers regarding the promotion of climate change mitigation strategies in Indonesia.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f14010158/s1, Figure S1. Pests in 2015 and 2016 plots: (A) green hornworm, (B) bagworm, (C) weaver ant, (D) cocoons of Family Lepidoptera, (E) Family of gastropods, (F) Crab; Figure S2. Condition of the land for rehabilitation after 7 years. (A) Planting with seedlings; (B) Planting with propagules; Figure S3. Plant development in the rehabilitation area where planting with propagules was carried out. (A) When planting was carried out in 2015, (B) monitoring in 2016, (C) monitoring in 2017, (D) monitoring in 2018, (E) monitoring in 2019, (F) monitoring in 2020; Figure S4. Plant development in the rehabilitation area where planting using seedlings was carried out. (A) When planting was carried out in 2016, (B) monitoring in 2016, (C) monitoring in 2017, (D) monitoring in 2018, (E) monitoring in 2019, (F) monitoring in 2020; Figure S5. Condition of restored land from initial planting to 2022. (A) planting with propagules in 2015, (B) team members participating in planting propagules, (C) planting using seeds, (D) team members participating in planting with seedlings, (E) monitoring in 2017, (F) monitoring in 2018, (G) monitoring in 2019, (H) monitoring in 2020 using drones, (I) monitoring in 2022 using drones; Figure S6. The current condition of the restoration site. (A) *Sonneratia alba* was logged, (B) *Rhizophora apiculata* was logged, (C) *R. apiculata* planted had produced propagules, (D) *S. alba* had new seedlings; Table S1. Soil texture of mangrove rehabilitation land in Lubuk Kertang Village.

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