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Land Cover Change and Carbon Potential in Mangrove Ecosystems at The Social Forestry Area (Study Case: Indramayu Regency, Indonesia)

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ABSTRACT

This study investigates land cover change and carbon potential in mangrove ecosystems within the social forestry area of Indramayu Regency. The research aims to assess land cover changes from 2014 to 2020 and estimate the carbon potential stored in mangrove ecosystems. Field surveys and satellite images analyze land cover change patterns and quantify mangrove carbon storage potential. The research findings reveal that aquaculture land cover dominates the study area (reaching 90%). The study did not find significant changes in land cover within the social forestry area. Only minor changes were noted, with mangroves converting to aquaculture and vice versa. The carbon potential is obtained from biomass calculated based on tree diameter within the research area. According to the calculations, it was found that the three research areas have different potentials due to varying tree diameters and densities. The carbon potential from the permitted areas of Karya Wana Tiris, Babadan Lestari, and Hijau Mandiri are 24.54 tons, 18.33 tons, and 24.87 tons. The highest carbon potential occurred in 2020 (2,419.69 tons), while the lowest was in 2017 (1,414.06 tons).

Introduction

Climate change has become an increasingly urgent issue in Indonesia in recent years. One contributing factor is global warming, caused by the increased emission of greenhouse gases into the atmosphere due to human activities, such as burning fossil fuels, deforestation, and industrial pollution. These human activities lead to an increase in atmospheric CO_2 (increasing temperatures by up to 0.30 °C), which is known as the greenhouse effect [1–3] . Forests play a crucial role in absorbing and storing carbon, which helps reduce the concentration of greenhouse gases in the atmosphere and address global issues [4]. Forest photosynthesis allows plants to absorb carbon dioxide (CO_2) from the air and store it in biomass and soil [5].

Mangrove ecosystems and forests in coastal areas, dominated by mangrove trees, also have significant carbon absorption capabilities [6]. Research by Donato et al. [7] has shown that mangrove forests can sequester much more carbon than terrestrial and tropical rainforests because of the high biomass density and low decomposition rate within the mangrove ecosystem [8]. Therefore, preserving and restoring mangrove forests is essential for reducing carbon emissions and maintaining the coastal ecosystem balance. Indonesia is the world's largest archipelagic country, with approximately ± 17,508 islands and a coastline extending up to 81,000 km [9–10]. Mangrove ecosystems are among the primary and most extensive coastal ecosystems [11].

Although the global extent of mangrove ecosystems is only approximately 2% of the total surface area, Indonesia has the largest mangrove ecosystem with the highest biodiversity in the world [12]. The extent of mangrove ecosystems in Indonesia is 3,189,359 hectares, or more than 22% of the total mangrove area worldwide, with 43 species of mangroves [13]. Indramayu, a regency in West Java, has a mangrove forest area of 2,228.79 hectares within the forest area and 1,007.21 hectares outside the forest area. Over ten years

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(2008 to 2018), this regency experienced mangrove forest degradation, reaching around 82%, the highest among other regencies in West Java [14]. Most mangrove forest areas are granted access to the community as managers (social forestry).

The community manages social forestry in mangrove forest areas under the Recognition of Protection and Forestry Partnership scheme through a decree from the Minister of Environment and Forestry. The three research areas representing the mangrove ecosystem in Indramayu Regency are Karya Wana Tiris, Babadan Lestari, and Hijau Mandiri Permit Area. The research objective was to observe land cover changes at the research locations in 2014, 2017, and 2020. Carbon estimation is then conducted at these three points in time. This carbon estimation can serve as basic information for determining the amount of carbon stored and its dynamics at those points in time.

Materials and Methods

Research Area

The research was conducted in three different locations in Indramayu Regency: the permitted area of Karya Wana Tiris, Pabean Ilir Village, Pasekan Subdistrict, with an approximate area of 340.29 hectares; the permitted area of Babadan Lestari, Babadan Village, Sindang Subdistrict, with an area of 313.23 hectares; and the permitted area of Hijau Mandiri, Karang Anyar Village, Pasekan Subdistrict, with an area of 759.03 hectares. The research locations are shown in Figure 1.

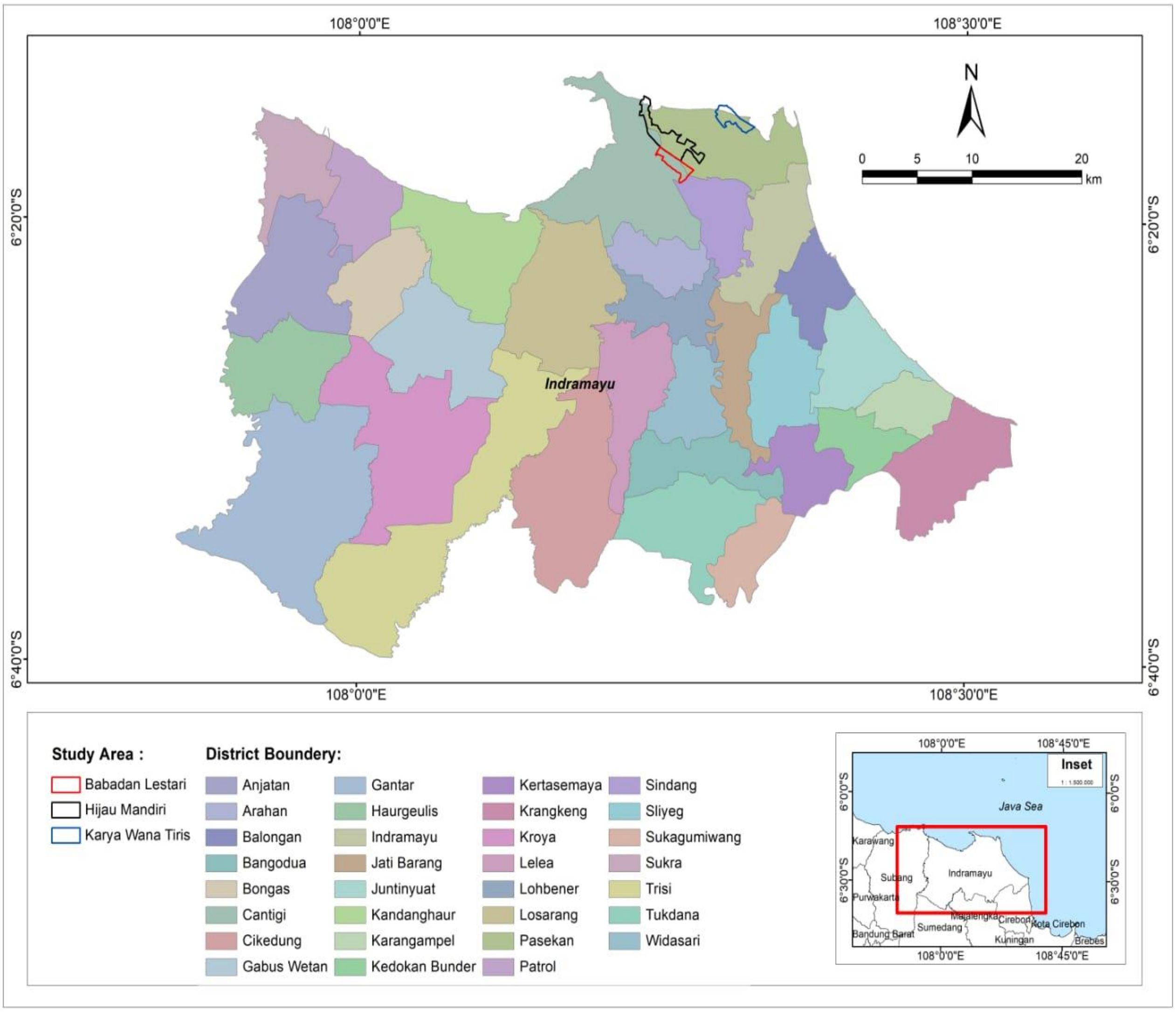


Figure 1. Research area map.

Research Materials and Tools

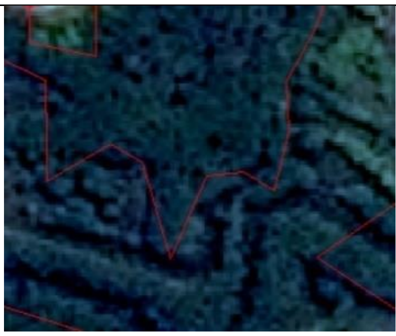
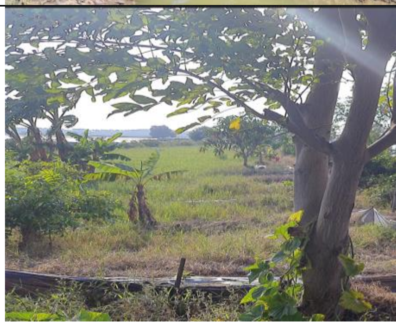
The data used in the research consisted of primary data, which included field measurements, and secondary data, which included spatial data. Field measurements were conducted by creating plots of 10 × 10 m for tree measurements and 5 × 5 m for stake measurements. A total of 26 plots were established for tree and stake measurements at each research location. The spatial data required for the research included SPOT 6/7 satellite imagery for 2014, 2017, and 2020 and forest area maps in the Indramayu Regency. The Avenza application and GPS were used to determine the sample locations. Data processing was carried out using ArcGIS 10.8 and Microsoft Excel.

Data Analyst Method

Interpretation of Land Cover Using SPOT Imagery

Land Cover analysis was conducted through the visual interpretation of SPOT imagery corrected for 2014, 2017, and 2020. These years were chosen as the points of analysis for land cover to demonstrate changes before and after the Forest Recognition, Protection, and Partnership Agreement issuance through the Minister of Environment and Forestry decree. Land cover types include ponds, mangroves, bodies of water, and dryland agriculture. The land cover types were classified based on the visible physical properties in the imagery. The classification process considers several factors, such as color, shape, size, texture, pattern, shade, and association [15]. The following table describes the land cover at the research location, as depicted on the map (Table 1).

Table 1. Land cover feature in map and the reality in the field.

Land cover	Feature	Reality
Pond		
Mangrove		
Dryland agriculture		

Land cover	Feature	Reality
Waterbody		

The visual interpretation was conducted based on color, texture, pattern, size, shape, shadow, and site as guidelines for delineating land use classes. Differences in object appearance in the images can be identified by arranging the appropriate band compositions in RGB (red, green, blue) channels. Accuracy testing of the classification results was performed by creating an error matrix, where the classification results were compared with additional field check information or available reference data. The required accuracy for land cover interpretation with a high confidence level is at least 80% [16]. Accuracy is generally calculated as the ratio of correctly identified pixels on the diagonal to the total number of test points. Kappa Accuracy, on the other hand, is a measure of agreement between the classification results and the actual conditions. The error matrix can be used to assess the accuracy of the classification results by calculating the Overall Accuracy and Kappa Accuracy values (Table 2). A Kappa value of 1 indicates perfect agreement, while a Kappa value of 0 suggests no agreement.

Table 1. Error matrix interpretation.

Land cover	Reference land use (Validation)					
as a result of interpretation	P_{i+}	P_{i+}	………	……….	P_{i+}	Total
P_{+i}	X_{ii}					X_{+i}
P_{+i}		X_{ii}				X_{+i}
……….			Xii			X_{+i}
……….				Xii		X_{+i}
P_{+i}					Xii	X_{+i}
Total	X1+	X1+	X1+	X1+	X1+	N

Notes: P+I = land cover type i, based on the result of interpretation; Pi+= land cover type i, based on validation data.

The overall accuracy was calculated using the equation (1) Where x is the number of interpreted LC points that align with the field check results, and N represents the total number of field checkpoints. As stated by Rwanga and Ndambuk [17], a kappa coefficient of 1 signifies absolute accuracy. Furthermore, they state that a kappa coefficient between 0.61 and 0.80 is considered substantial, while a coefficient ranging from 0.81 to 1.00 falls within the almost perfect category. In addition, Lillesand et al. [18] define the Kappa Accuracy equation (2).

$$Overall\ Accuracy\ (OA) = \frac{x}{N} \times 100\% \quad (1)$$

$$Kappa\ Accuracy\ (K) = \frac{N \sum_i^r Xii - \sum_i^r (X_{i+}\, X_{+i})}{N^2 - \sum_i^n (X_{i+}\, X_{+i})} \quad (2)$$

Where:

X+i : The number of interpretation points for land use type i.

X+i : Number of points interpreted for land use type i.

Xi+ : Number of validation points for land use type i.

Xii : Number of points correctly classified for land use type i (diagonal elements).

i : Row or column index.

R : Number of land use types.

N : Total number of validated land use points.

K : Kappa value.

The method used to determine the checkpoints was Stratified Random Sampling, which involves selecting samples based on the proportion of the area for each land use class. This method resulted in larger sample points for classes with larger areas. The three study areas have different sizes, and the number of test points was calculated using the Slovin formula (3):

$$n = \frac{N}{1+Ne^2} \quad (3)$$

where N is the population size and e is the margin of error (15%). Using this formula, the minimum numbers used in the study were determined. The minimum number of samples calculated based on the Slovin's formula can be shown in Table 3.

Table 3. Minimal number sample size.

Permit area	Mangrove		Pond		Agricultural land		Waterbody	
	Population	Minimal sample size	Population	Minimal sample size	Population	Minimal sample size	Population	Minimal sample size
Karya Wana Tiris	25	20	30	23	5	5	5	5
Babadan Lestari	35	26	25	20	-	-	-	-
Hijau Mandiri	40	29	102	55	-	-	-	-

Checkpoints were selected using a purposive sampling method, which involved the researcher's judgment to choose the most relevant samples for the study. Mweshi and Sakyi [17] noted that considerations included the representativeness of samples from various land cover types and the accessibility of sample locations in forested areas. The locations of these field checkpoints are illustrated in Figure 2.

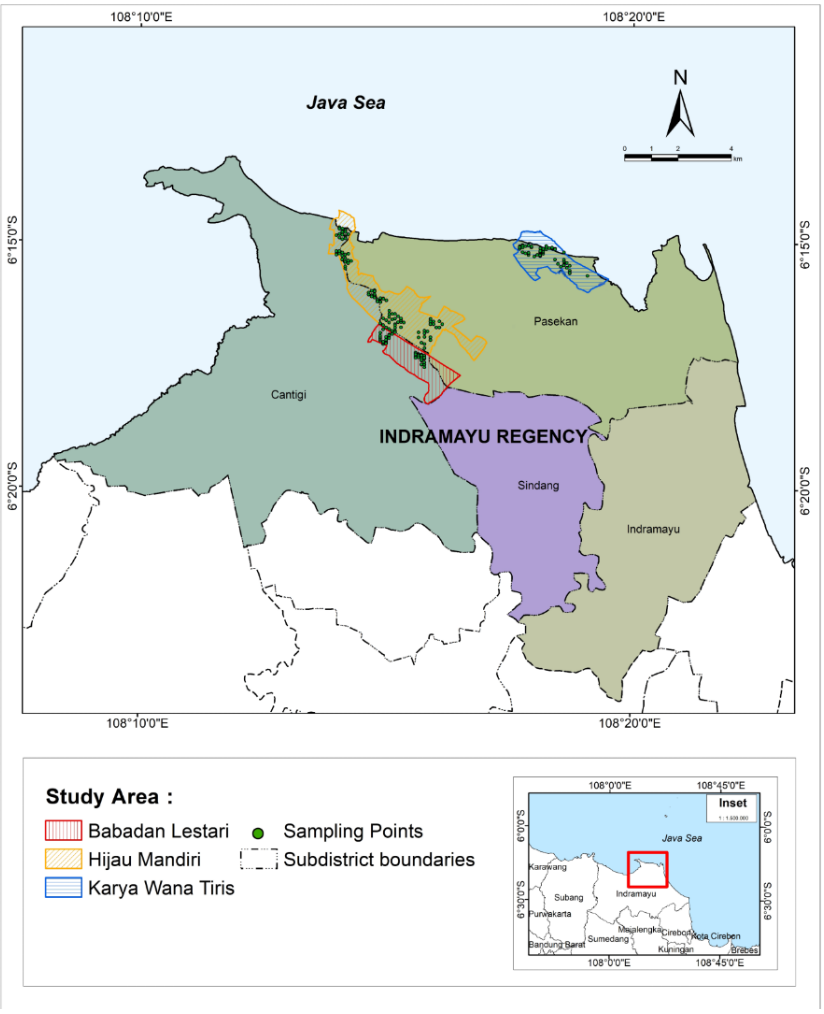


Figure 2. Ground check points.

Forest Biomass and Carbon Potential Based Allometric Approach

Calculations were based on the diameter at breast height (DBH) of stakes (plot size 5 x 5 m) and trees (plot size 10 x 10 m) to estimate carbon in mangrove ecosystems in the research area. Carbon estimation began by determining the biomass of the measured trees and stakes. The trees measured included both trees, stems, and stakes. Trees have stem diameters (DBH) equal to or greater than 10 cm, whereas stakes have a DBH below 10 cm. The allometric formula used to determine the biomass content of these stands was as follows (equation 4 and 5).

Trees (DBH ≥ 10 cm): B = 0.1466 × (DBH) 2.3136 (B= forest biomass) [18] (4)

For stakes (DBH < 10 cm): B = 0.128 x (DBH)2.60 [19] (5)

This study focused on measuring aboveground tree biomass only, disregarding litter beneath the trees because litter tends to decompose and contributes little to carbon. Based on previous research by Windarni [20], trees have a greater carbon storage capacity (99.37%) than litter (0.63%). Therefore, litter was not a significant component for measuring carbon levels in the research area. This study obtained a carbon potential of 50% of the total estimated biomass value [21]. Thus, after calculating the biomass of trees and stakes according to the previously mentioned formulas, the carbon potential value can be calculated by taking 50% of the total biomass value. This estimates the carbon content of the mangrove stands in the study area.

Results and Discussion

The Land Cover Changes in Mangrove Ecosystems at Social Forestry Area

The land cover in the permit areas of Karya Wana Tiris, Babadan Lestari, and Hijau Mandiri were classified based on SPOT 6 and 7 satellite imagery from 2014, 2017, and 2020 at a scale of 1: 500. The interpretation results indicated the presence of land cover in the form of ponds and mangroves. Water bodies and dryland agriculture are also found in the Karya Wana Tiris area. Accuracy classification testing was conducted using a stratified random sampling method with 210 test points from three research areas. The number of different test points applied was based on the area of research, namely, 60 test points for Karya Wana Tiris, 50 test points for Babadan Lestari, and 100 test points for Hijau Mandiri. The accuracy test results (Table 4) showed an overall accuracy of 98.3% and kappa accuracy of 97.3% for the Karya Wana Tiris Permit Area. The overall accuracy of Babadan Lestari Permit Area was 94%, and the kappa accuracy was 87.6%. Meanwhile, for KTH Hijau Mandiri, the overall and kappa accuracies were 97.00% and 92.8%, respectively.

Table 4. Ground check confusion matrix.

Permit area	Ground check	Classification result				Number	Producer's accuracy (%)
		Mangrove	Pond	Waterbody	Agricultural land		
Karya Wana Tiris	Mangrove	20				20	100
	Pond		30	1		31	96.8
	Waterbody			7		7	100
	Dryland agriculture				2	2	100
Total		20	30	8	2	60	
User's accuracy		100%	100%	87.5%	100%		
Overall accuracy						98.3%	
Kappa accuracy							97.3
Babadan Lestari	Mangrove	19	2	-	-	21	88.3
	Pond	1	28	-	-	29	87
Total		20	30	-	-	50	
User's accuracy		95%	93.3%	-	-		
Overall accuracy						94%	
Kappa accuracy							87.6
Hijau Mandiri	Mangrove	28	1	-	-	29	91.9
	Pond	2	69	-	-	71	93.7
Total		30	70	-	-	100	
User's accuracy		93.3%	98.6%	-	-		
Overall accuracy						97%	
Kappa accuracy							92.8

Based on Anderson [22], the minimum interpretation accuracy level should be at least 85%. The land cover classification results can be used for further analysis. The land cover areas in the 2014, 2017, and 2020 research areas were based on the digitization results of the land cover classification. Table 5 analyzes the land cover area changes in the Karya Wana Tiris, Babadan Lestari, and Hijau Mandiri permit areas over six years. These findings indicate that in Karya Wana Tiris, there were no significant changes in the land cover area during this period. Although the mangrove area increased by approximately 2.74 hectares from 2014 to 2017, it decreased by approximately 0.89 hectares in 2020. Tiny fluctuations were also observed in the pond area during the same period, whereas the dryland agricultural areas remained stable. Interestingly, the pond area decreased when the mangrove area increased in 2017. Conversely, the pond area increased when the mangrove area decreased by 2020. This phenomenon indicates a shift between the two land cover types, where ponds are converted into mangroves and vice versa. However, a small portion of mangrove and pond areas has also been converted into water bodies.

Table 5. Land cover area in research area.

Permit area	Land cover	Year					
		2014 (Ha)	2014 (%)	2017 (Ha)	2017 (%)	2020 (Ha)	2020 (%)
Karya Wana Tiris	Mangrove	12.44	3.65	15.18	4.46	14.29	4.20
	Pond	255.02	74.94	251.82	74.00	252.71	74.26
	Dryland agriculture	1.96	0.58	1.96	0.58	1.96	0.58
	Waterbody	70.87	20.83	71.32	20.96	71.32	20.96
Babadan Lestari	Mangrove	1.82	0.58	2.30	0.73	6.22	1.98
	Pond	311.41	99.42	310.93	99.27	307.01	98.02
Hijau Mandiri	Mangrove	47.66	6.28	40.18	5.29	78.60	10.36
	Pond	711.38	93.72	718.86	94.71	680.43	89.64

Similar changes were observed in the land covers of the Babadan Lestari and Hijau Mandiri permit areas. However, the rate of change differs: Babadan Lestari experienced minor changes from 2017 to 2020, while Hijau Mandiri experienced relatively more significant changes in land cover. Unlike Karya Wana Tiris, Babadan Lestari and Hijau Mandiri only have two types of land cover, namely mangroves, and ponds, so an increase in one type of land cover will decrease the area of the other. Further details of these changes can be seen in Table 6, which provides a more detailed overview of the changes in land cover area and the dynamics between mangroves, ponds, and water bodies during the same period.

Table 6. Land cover changes in research area.

Permit area	Land cover			Area (Ha)
	2014	2017	2020	
Karya Wana Tiris	Mangrove	Mangrove	Mangrove	7.49
			Pond	2.08
		Pond	Pond	2.41
		Waterbody	Waterbody	0.45
	Dryland Agriculture	Dryland Agriculture	Dryland Agriculture	1.96
	Pond	Mangrove	Mangrove	5.60
		Pond	Mangrove	1.19
			Pond	248.22
	Waterbody	Waterbody	Waterbody	70.87
Total area (ha)				340.28
Babadan Lestari	Mangrove	Mangrove	Mangrove	1.63
		Pond	Mangrove	0.18
	Tambak	Mangrove	Mangrove	0.66
		Pond	Mangrove	3.74
			Pond	307.01
Total area (Ha)				313.227
Hijau Mandiri	Mangrove	Mangrove	Mangrove	39.87
		Pond	Mangrove	7.61
			Pond	0.18
	Pond	Mangrove	Mangrove	0.31
		Pond	Mangrove	30.82
			Pond	680.25
Total area (Ha)				759.03

The land cover changes in all three research areas, albeit insignificant in magnitude, indicate the presence of human activities or other factors influencing the shift. These factors may include land degradation (reduction in mangrove area), mangrove reforestation (increase in mangrove area), abrasion (increase in mangrove and pond areas), and policy changes [23–26]. Figure 3 shows the trends in land cover change in the three research areas from 2014 to 2020. Figure 3 shows the trend of change in the three studied permit areas. The line formed from the land cover change data is only slightly curved, with the Babadan Lestari permit area showing a tendency to be straight owing to changes occurring only in a small part of the area.

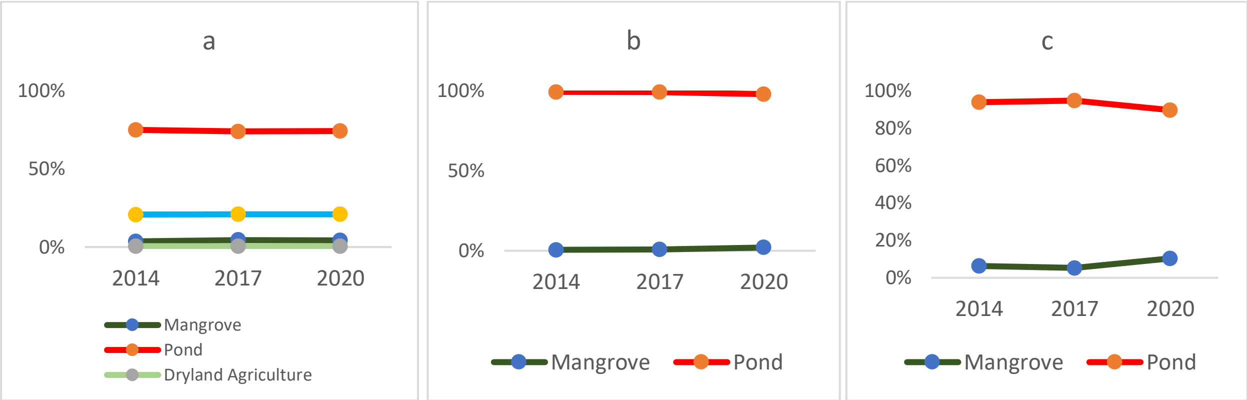


Figure 3. The land cover percentage graph in research area in Karya Wana Tiris (a), Babadan Lestari (b), and Hijau Mandiri Permit Area (c).

Table 7. The percentage of land cover changes in research area.

Permit area	Land cover	Land cover changes (%)	
		2014–2017	2017–2020
Karya Wana Tiris	Mangrove	18.09	–5.88
	Pond	–1.27	0.35
	Dryland agriculture	0.00	0.00
	Waterbody	0.64	0.00
Babadan Lestari	Mangrove	20.89	63.06
	Pond	–0.15	–1.20
Hijau Mandiri	Mangrove	–15.70	48.89
	Pond	1.04	–5.35

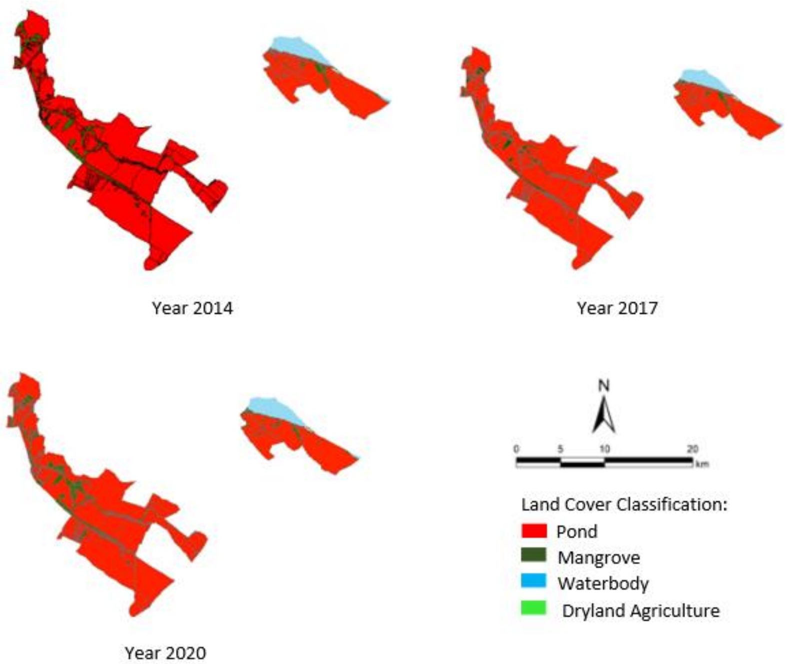


Figure 4. Land cover changes in the research area.

The cause of this is minimal human activities that significantly affect land changes in the research areas. Human activities are limited to several activities, such as converting pond areas into mangrove forests through rehabilitation programs supported by government seedling assistance. Additionally, there are activities of mangrove forest logging for firewood purposes, as well as efforts to expand ponds for milkfish cultivation. Table 7 shows the percentage change in land cover in the three permit areas, and Figure 4 shows the spatial distribution of the change. Figure 4 illustrates that most of the map is red, indicating that ponds were the dominant research area during the six years. The observed changes only occurred in small parts of the study area. These changes generally involve transitions from ponds to mangroves, mangroves to ponds, ponds to water, and mangroves to water bodies. However, the changes were very minor. As an important part of silvofishery management, ponds dominated the land cover in the research location. More than 90% of pond areas occupy forest areas, which are part of the social forestry licensing area.

Carbon Potential in Karya Wana Tiris, Babadan Lestari, and Hijau Mandiri Permit Area

The presence of carbon in the air in the form of CO_2 results from combustion residues that forests do not absorb. The increased CO_2 in the atmosphere leads to the greenhouse effect, which is commonly known as global warming [27]. The role of forests as carbon absorbers and stores is crucial for reducing greenhouse-gas emissions. The mangrove species in the research area are homogeneous and predominantly consist of Rhizophora mucronata. Carbon estimation began by estimating the biomass of the measured poles and trees. The formula used to determine the biomass content of these stands utilized the allometric equation (equation 5).

B (aboveground biomass) = 0.1466(DBH)2.3136 for poles/trees [18] and B = 0.128(DBH)2.60 [19] (5)

This study focused solely on measuring above-ground stand biomass, disregarding litter beneath the stands because litter tends to decompose and has a minor carbon contribution. Windarni et al. [20] Showed that stands had a higher carbon storage capacity (99.37%) than litter (0.63%). Therefore, litter was insignificant in measuring the amount of carbon in the research area. The Karya Wana Tiris permit area has approximately 700 stands per ha, the Babadan Lestari permit area has 633 stands per hectare, and the Hijau Mandiri permit area has approximately 657. The results of biomass measurements from the three regions are presented in Table 8.

Table 8. Biomass and carbon potential in research area.

Permit area	dbh (cm)	Biomass (kg)	Carbon (kg)	Permit area	dbh (cm)	Biomass (kg)	Carbon (kg)
Karya Wana Tiris	3.5	3.32	1.66	Babadan Lestari	3.3	2.85	1.43
	4.4	6.03	3.01		4.1	5.02	2.51
	4.6	6.77	3.38		4.8	7.56	3.78
	5.5	10.77	5.38		7.6	24.96	12.48
	6.2	14.70	7.35		7.8	26.71	13.35
	7.2	21.69	10.85		7.8	26.71	13.35
	8.2	30.42	15.21		8.9	37.64	18.82
	9.2	41.03	20.51		9.3	42.20	21.10
	10.8	36.06	18.03		9.8	48.35	24.18
	11.4	40.87	20.43		11.4	40.87	20.43
	11.5	41.70	20.85		12.3	48.72	24.36
	12.5	50.58	25.29		14.9	75.93	37.97
	13.4	59.40	29.70		15.1	78.31	39.15
	14.2	67.93	33.97		15.2	79.51	39.76
	17.0	103.02	51.51		15.4	81.96	40.98
	18.1	119.10	59.55		16.1	90.83	45.42
	18.6	126.85	63.42		16.3	93.47	46.73
	19.4	139.83	69.91		19.5	141.50	70.75
	19.6	143.19	71.59		19.8	146.59	73.29
	19.9	148.31	74.15				
	25.4	260.83	130.41				
	Total	**1,472.38**	**736.19**		**Total**	**1,099.69**	**589.84**
Hijau Mandiri	2.60	1.54	0.77	Hijau Mandiri	11.90	45.14	22.57
	2.90	2.04	1.02		13.20	57.37	28.69
	2.90	2.04	1.02		13.80	63.59	31.79
	3.00	2.23	1.11		13.80	63.59	31.79

Permit area	dbh (cm)	Biomass (kg)	Carbon (kg)	Permit area	dbh (cm)	Biomass (kg)	Carbon (kg)
	3.00	2.23	1.11		15.20	79.51	39.76
	3.50	3.32	1.66		15.80	86.97	43.48
	3.80	4.12	2.06		16.10	90.83	45.42
	4.50	6.39	3.20		16.30	93.47	46.73
	5.20	9.31	4.65		17.10	104.42	52.21
	5.30	9.78	4.89		17.10	104.42	52.21
	6.40	15.97	7.98		18.10	119.10	59.55
	6.40	15.97	7.98		18.50	125.27	62.64
	6.50	16.63	8.31		18.80	130.02	65.01
	6.50	16.63	8.31		18.90	131.63	65.82
	7.20	21.69	10.85		19.20	136.51	68.26
	7.30	22.48	11.24		19.80	146.59	73.29
	8.70	35.48	17.74		19.80	146.59	73.29
	9.30	42.20	21.10		20.00	150.04	75.02
	9.40	43.39	21.69		20.10	151.78	75.89
	9.70	47.08	23.54		21.60	179.28	89.64
	9.90	49.64	24.82		23.40	215.75	107.88
	11.70	43.40	21.70		25.30	258.46	129.23
	11.90	45.14	22.57		28.60	343.23	171.61
	Sub-total	458.67	229.33		Sub-total	3,023.55	1,511.77
	Total					**3,482.22**	**1,741,11**

This study calculated the total carbon values for the Karya Wana Tiris and Babadan Lestari permit areas, based on an area of 300 m². In comparison, the Hijau Mandiri permit covers an area of 700 m². The area considered for calculating the total carbon was approximately 1/10 of the permit area under investigation. When presenting the data in hectares (Ha), the total carbon values per hectare for each permit are as follows: Karya Wana Tiris permit area is 24.54 tons; Babadan Lestari permit area is 18.33 tons; and Hijau Mandiri permit area is 24.87 tons. Total carbon values were obtained from a 50% biomass estimation [21]. The difference in carbon quantity in this research area is influenced by the diameter and density of the *Rhizophora mucronata* stands. The larger the diameter of the stands and the denser they are, the greater the amount of carbon in the area, and vice versa. The relationship between the mangrove area in the research regions and its carbon potential can be examined in Table 9.

Table 9. The mangrove area and carbon potential in research area.

No	Permit area	Mangrove (Ha)			Carbon productivity (ton/ha)	Carbon potential (ton)		
		2014	2017	2020		2014	2017	2020
1	Karya Wana Tiris	12.44	15.18	14.29	24.54	305.27	372.51	350.67
2	Babadan Lestari	1.82	2.30	6.22	18.33	33.36	42.15	114.00
3	Hijau Mandiri	47.66	40.18	78.60	24.87	1,185.45	999.40	1,955.02
Total		61.92	57.66	99.11		1,524.08	1,414.06	2,419.69

The mangrove area dramatically influences the carbon potential in the research area [28]. As shown in Table 9, the Karya Wana Tiris permit area in 2014 had a carbon potential of 305.27 tons, but the carbon potential increased in 2017 owing to the expansion of the mangrove area. The carbon potential in the Karya Wana Tiris permit area in 2017 reached 372.51 tons, whereas in 2020, it decreased to 350.67 tons due to the reduced mangrove area. The Babadan Lestari permit area has a productivity of 18.33 tons/ha, resulting in a carbon potential of 33.36 tons in 2014. Carbon potential increased to 42.15 tons in 2017 and 114 tons in 2020. This was attributed to the increasing mangrove area in the research permit area from 2014 to 2020. Although there was a consistent increase in the mangrove area, the area was relatively small, resulting in a relatively small carbon potential.

In contrast to the previous two permit areas, the Hijau Mandiri permit area experienced a decrease in mangrove area in 2017 but then increased in 2020. Based on the data in Table 6, the mangrove potential in the Hijau Mandiri permit area was 1,185.45 tons in 2014, 999.40 tons in 2017, and increased to 1,955.02 tons in 2020. The increase in mangrove area from 2017 to 2020 was significant, resulting in a large difference in the carbon potential between the two years. Figure 5 depicts the trend of the changes in carbon potential in the research area. The highest total carbon potential was achieved in 2020, amounting to 2,419.69 tons. This was followed by 2014, with a carbon potential of 1,524.08 tons, and the lowest in 2017, totaling 1,414.06 tons. Reducing the Hijau Mandiri permit area's mangrove area was the dominant factor in decreasing carbon potential in 2017.

As seen in Figure 5, the Karya Wana Tiris permit area experienced an increase in carbon potential in 2017 but decreased in 2020, resulting in a slightly lower potential than in 2014. On the other hand, the carbon potential of the Babadan Lestari permit area continues to increase, although limited productivity and the mangrove area remain below the other two regions. Similarly, the Hijau Mandiri Permit Area stands out for its high mangrove potential. Despite a decrease in the carbon potential in 2017, there was a significant spike in 2020, reaching almost 2,000 tons.

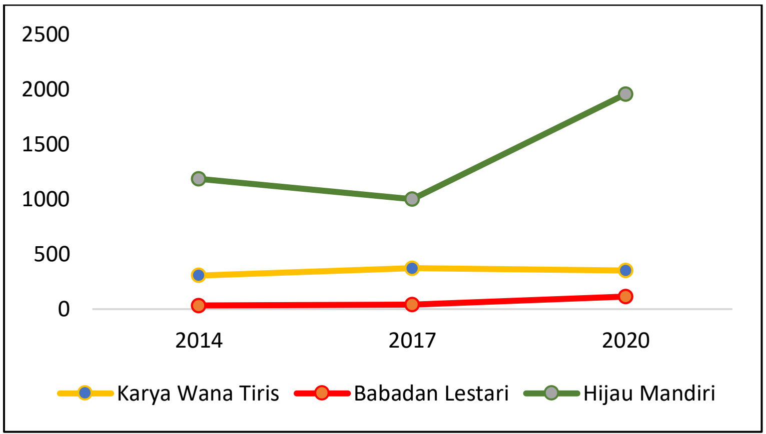


Figure 5. Carbon potential in research area.

Although the Independent Green Permit Area had the most significant carbon potential compared with the other two permit areas, this potential is relatively small compared to the literature on carbon potential in mangrove areas [28–30]. Therefore, mangrove planting is considered a highly effective measure for enhancing an area's capacity to absorb and store carbon from the atmosphere [31]. Increasing the area of mangrove forests by at least 30% of the permitted area [32]. It can significantly enhance the potential for carbon absorption and storage. However, it is imperative to emphasize that mangrove planting must be conducted carefully and sustainably to avoid potential damage to existing ecosystems.

Conclusions

Based on the findings, there were no significant changes in land cover in the three research areas from 2014 to 2020. The mangrove land cover in the Karya Wana Tiris permit area increased in 2017 but decreased again in 2020. The land cover in the Babadan Lestari permit area increased from 2014 to 2020, albeit in small amounts. Meanwhile, the Hijau Mandiri permit area experienced a decrease in 2017 but then increased in 2020. The Karya Wana Tiris, Babadan Lestari, and Hijau Mandiri permit areas had carbon productivity of 24.54 tons/ha, 18.33 tons/ha, and 24.87 tons/ha, respectively. Hijau Mandiri is the permit area with the most extensive mangrove potential. The Hijau Mandiri permit area has significant carbon potential because of its extensive mangrove area and high carbon productivity compared with the other two permit areas. The carbon potential in the Hijau Mandiri permit area reaches 1,955.02 tons. The highest total carbon potential was achieved in 2020, amounting to 2,419.69 tons, followed by 2014, with a carbon potential of 1,524.08 tons, and the lowest was in 2017, with a total of 1,414.06 tons. Based on the data obtained from the research results, the three research areas indicated that the mangrove ecosystem is unsustainable and requires significant intervention in its management to achieve sustainability. However, with appropriate intervention measures, there is potential to restore and maintain the balance of the mangrove ecosystem, offering hope for its optimal functioning.

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Author Contributions

RBP: Conceptualization, Methodology, Software, Investigation, Writing - Review and Editing; **DRP**: Review and Editing, Supervision; **ORU**: Review and Editing, Supervision.

Conflicts of interest

The authors declare no conflicts of interest.

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