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Analysis of forest damage using geographic information systems: Case study of Pidie district, Aceh, Indonesia

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ABSTRACT

This study aims to quantify land cover changes, carbon emissions, and carbon sequestration in Pidie Regency, Aceh Province, Indonesia, over a decade (2010–2020), addressing the gap in localized analyses of deforestation and its impacts on carbon dynamics. Utilizing high-resolution GIS and remote sensing data, the study integrated spatial analysis with carbon stock calculations to assess the implications of forest cover transitions across different forest functions. The findings reveal that production forests experienced the highest deforestation (1,008 ha), contributing to peak carbon emissions of 2,218,017 tons of CO_2 during 2018–2020. Concurrently, carbon sequestration peaked at 1,174,395 tons of CO_2, primarily due to reforestation and natural regeneration in secondary forests and shrubs. Protected forests retained the most extensive carbon stocks, reaching 22,649,615 tons of CO_2 in 2017, underscoring their critical role in carbon storage. This research highlights the balance between carbon loss from deforestation and gains from recovery, offering actionable insights for targeted reforestation, agroforestry systems, and community-based forest management. A limitation is its reliance on satellite data, which may affect the precision of land cover classifications in complex forest ecosystems. The findings provide practical value for policymakers and conservationists by identifying key areas for intervention and reinforcing the need for sustainable forest management practices. Information regarding the condition of the forest in Pidie Regency is limited and has yet to receive attention; however, the potential for more significant forest damage is likely to occur, and scientific data from this research can be an initial step in forest conservation efforts.

Keywords: carbon emissions, land cover changes, deforestation, environmental damage.

INTRODUCTION

Forests are vital ecosystems that integrate biotic and abiotic elements and address global challenges like climate change, food security, and energy crises. As a key resource, forests contribute to carbon sequestration, biodiversity preservation, and ecological balance (Gakaev, 2023). However, forest degradation and deforestation remain significant global issues, particularly in tropical regions such as Indonesia. Despite national regulations such as Law No. 41 of 1999 and Government Regulation No. 10 of 2010 aimed at sustainable forest management, Indonesia continues to experience extensive forest loss due to illegal logging, encroachment, mining, and infrastructure development without adequate ecological planning (Purnomo *et al.*, 2023). These pressures are evident in

Aceh Province, where, over the past 27 years, approximately 675,864 hectares of forest have been lost, averaging 25,032 hectares annually (FREL, 2018). This deforestation not only threatens biodiversity but also contributes significantly to carbon emissions, reducing the ability of the region to mitigate climate change (Wang *et al.*, 2024).

Pidie Regency, one of the administrative regions in Aceh Province, exemplifies these challenges. It is a region with significant forest resources comprising conservation, protection, and production forests (Gayo *et al.*, 2024). Despite these designations, Pidie has experienced substantial forest degradation, particularly in production forests, leading to increased carbon emissions and reduced carbon sequestration (Achmad *et al.*, 2023). These effects necessitate detailed investigations as information to promote sustainable forest management practices. Although considerable research has been conducted on Indonesia's forest carbon stocks and deforestation patterns, studies focusing specifically on the Pidie Regency remain limited. Existing research often lacks localized, high-resolution analyses that capture decade-long land-cover dynamics and their implications for emissions and sequestration. Moreover, applying advanced remote sensing technologies, such as Landsat 7 and Landsat 8 OLI, has not been thoroughly explored to quantify these changes at the regency level (Zidane *et al.*, 2021).

This study aims to fill this research gap by analyzing land cover changes, carbon emissions, and sequestration, specifically in the Pidie Regency over 10 years (2010–2020). By employing advanced geographic information systems (GIS) and high-resolution remote sensing data, this study mapped the spatial and temporal changes in forest cover and quantified carbon dynamics across different forest area functions. The objectives were to identify key drivers of deforestation, analyze emissions and sequestration trends, and provide scientific information to encourage implementing sustainable forest management practices to mitigate deforestation impacts and enhance carbon storage.

MATERIALS AND METHOD

Study area

This research was conducted in Pidie Regency, which is located at 04.30°–04.60° North latitude and 95.75°–96.20° East longitude. Administratively, it is bordered to the north by the Malacca Strait, to the south by West Aceh and Aceh Jaya districts, to the east by Pidie Jaya district, and to the west by Aceh Besar district.

Materials

The tools and materials used in the research are Landsat-7 and Landsat-8 OLI (operational land imagery) image path 131 Row 56 which covers the observation period from 2010 to 2020 obtained from the United State Geological Survey (USGS) Global Visualization Viewer (GloVis) through the page http://earthexplorer.usgs.gov, the data will provide information on changes in forest cover and land use. Other additional data include forest area maps based on the decree, administrative boundary maps, and Tahura land cover maps. Data processing for mapping and spatial data processing using ArcGis 10.1.

Spatial analysis of land cover change (deforestation)

Analysis of land cover change using the classification method which is the extraction of from-to information changes in the form of thematic information or categories obtained from overlaying land cover data from year to year (period per 3 years) using Arc.Gis 10.4 software (Jensen, 1996). Interpretation of Landsat-7 and Landsat-8 OLI (Operator Land Imager) Path 131 Row 56 image maps from 2010 to 2020 for a period of 10 years was carried out to determine the existing land cover by classifying according to SNI 76452010 (BSN, 2010) with a total of 23 classes, 7 classes are forest cover and 16 classes are non-forest cover. While in the research location there are 8 classes, 2 classes of forest cover and 6 classes of non-forest cover. The flow of land cover change analysis can be seen in Figure 1.

Emissions and carbon stock calculation analysis

Emission calculation

He calculation of carbon stocks was carried out by calculating the area of each land cover type in the Pidie District Forest area for a period of 10 years from 2010–2020 (period per 3 years) which is referred to as annual activity data. Deforestation emissions in a period (Et, tons CO_2e) are calculated based on the multiplication between the area (A, ha) and the emission or sequestration factor (EF, tons CO_2e/ha), with the following Equation 1.

$$Et = A \times E \times F \quad (1)$$

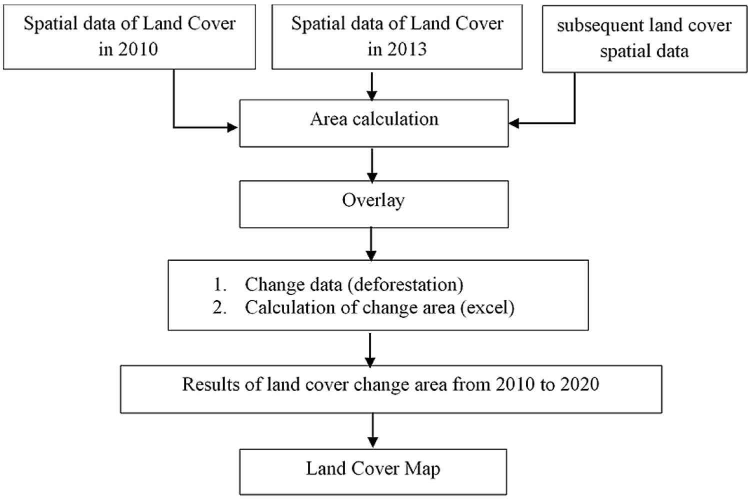

Figure 1. Land cover change analysis procedure

where: *Et* – deforestation emissions, *A* – area, *EF* – emission factor (IPCC, 2006)

The calculation of past emissions is based on land cover change and emission factor data for each land cover type. Carbon density data can be used to determine carbon stocks, carbon content data (C tons/ha) for each land cover type sourced from the Directorate of IPSDH and the Forestry Research and Development Agency of the Ministry of Forestry in Table 1 can be used.

Calculation of carbon stock by land cover class

The area of vegetated land cover was calculated through image classification, to estimate the carbon sequestration capability. Carbon sequestration is calculated with Equation 2.

$$CO\ SC = A\ (\text{tons/ha/year}) \times B\ (\text{ha}) \qquad (2)$$

where: *SC* – sequestration capability *A* – carbon sequestration capacity, *B* – land cover area (Habib, 2014).

Then, calculate the difference between carbon stock at time 1 and time 2 to get the value of carbon stock change. This calculation is the result of calculating the change in carbon stocks for each land cover class, namely from high carbon values to low carbon values calculated at the beginning of the calculation time and the end of the calculation time using Equation 3.

Table 1. Carbon stock per hectare for each land cover type

Land cover class	Carbon content (c·ton/ha)	Data source
Primary dryland forest	132.99	World Agroforestry Centre (2011); Rahayu et al. (2005); IPCC (2006); Saatchi et al. (2011); World Agroforestry Centre (2011), Harja et al. (2011) at Bappenas (2014)
Secondary dryland forest	98.84	NFI (1996-2013),2014
Forest plantation	98.38	Balitbanghut, 2014
Scrub	30.00	JuknisPEPRADGRK,2013
Residential	4.00	JuknisPEPRADGRK,2013
Plantation	63	JuknisPEPRADGRK,2013
Grass/savanna	4.00	JuknisPEPRADGRK,2013
Dryland agriculture	10.00	JuknisPEPRADGRK,2013
Dryland agriculture mixed with Shrubs	30.00	JuknisPEPRADGRK,2013
Open/empty land	2.50	JuknisPEPRADGRK,2013

Note: Directorate of IPSDH (NFI Measurement Results 1996–2013), 2014; Forestry R&D Agency, 2014; Technical Guidelines for GHG PEPRAD in 2013; Tosiani, A (2017) in the Carbon Sequestration and Emission Activity Book of the Ministry of Environment and Forestry.

$$\Delta C = \frac{Ct2 - Ct1}{t2 - t1} \quad (3)$$

where: ΔC – change in carbon stocks per year in each carbon storage (tons C/year), $Ct1$ – carbon stock in carbon storage in year t1 (tons C), $Ct2$ – carbon stock in carbon storage in year t2 (tons C).

Melati (2019) stated that if land change occurs from land cover that has low carbon value to land cover that has high carbon value, for example from shrubs/shrubs to secondary dryland forest, carbon sequestration occurs. Land cover that does not change, it is assumed that there is no emission or sequestration in this land cover.

RESULTS AND DISCUSSION

Land use in Pidie Regency based on the interpretation of spot 5 imagery in 2009 and field observations, is generally dominated by protected forests covering 180,658.97 ha (56.73%), production forests covering 35,130.81 ha (11.03%), plantations covering 47,290.93 (14.85%), wetland agriculture covering 26,648.63 ha (8.36%). Pidie Regency has a wet tropical climate with an average temperature of 22–34 °C with rainfall of 146–232 mm. The topography of the area varies in altitude between 5–1,500 meters above sea level, where the dominant high class is 100–500 m above sea level around 23.86% and the lowest is 0–25 meters above sea level by 3.68% of the district area, with slopes that also vary from flat to mountainous.

Forest cover and damage (deforestation) in the Regency

The results of spatial analysis using Landsat ETM+8 imagery, obtained the area of each category based on the function of forest areas that have undergone changes. Image interpretation is based on stand estimation, not distinguishing between natural stands and stands that have undergone changes from planting. The results of the interpretation of satellite imagery coverage for the period 2010 to 2020 obtained the results of forest cover in each function of the Forest Area in Pidie Regency, in detail can be seen in Table 2.

Meanwhile, based on sub-districts, there are 10 sub-districts that have forest cover. The extent of forest cover by sub-district can be seen in Table 3. There are three sub-districts that have forest cover, namely Geumpang, Mane and Tangse sub-districts, which amount to 29–30% of the total area of forest cover in Pidie District. Meanwhile, the sub-districts with the least forest cover are Mila, Keumala, and Muara Tiga, with 0.01% to 0.05% of the total forest cover area.

Deforestation based on forest area

The results of the analysis using ArcGIS obtained the area of forest area that experienced damage from 2010 to 2020. The calculation of the percentage of forest damage is calculated based on the function of the SK.580/2018 area as a baseline, in detail presented in Table 4. The highest deforestation occurred in the 2014–2016 period covering an area of 791 ha, which came from 697 ha of production forest or 1.9% of the total production forest area and 95 ha or 0.1% of the total protected forest area. The cause of the high deforestation in that period was due to the Aceh earthquake and tsunami, in line with post-earthquake rehabilitation needs (ILEDSA, 2020). Within the forest area function, in the 10-year period (2010–2020) the highest deforestation occurred in the production forest area of 1,008 ha or 54% of the total deforestation that occurred.

Land cover change trends

The results of the analysis show the trend of land cover change over a certain period of time (2010–2020). In 2010–2012, land cover change occurred in the secondary dryland closure class of 292 ha to shrubs of 105 ha and mixed dryland agriculture of 186 ha. In 2013–2015, there was no trend of land cover change. In 2016–2017,

Table 2. Forest cover data from 2010-2020 based on forest area function SK.580/2018

Area function forest	Forest cover/year (ha)					
	2010	2012	2014	2016	2018	2020
Protection forest	173.228	172.937	172.891	172.796	172.645	172.169
Production forest	11.895	11.513	12.087	11.390	11.478	11.548
PMI forest park	2	2	2	3	3	3
Total	185.125	184.453	184.980	184.189	184.027	183.720

Table 3, Forest cover area by sub-district

Sub-district	Forest cover/Year (ha)					
	2010	2012	2014	2016	2018	2020
Geulumpang Tiga	415	361	343	354	369	369
Geumpang	59,333	59,282	59,282	59,027	59,082	58,955
Keumala	95	83	83	83	83	83
Mane	55,327	55,169	55,165	54,957	54,960	54,938
Mila	29	25	25	24	25	23
Muara Tiga	131	131	87	109	112	70
Padang Tiji	4,652	4,579	5,292	4,827	4,581	4,559
Tangse	55,959	55,764	55,720	55,830	55,840	55,772
Tiro/Trusep	9,112	8,985	8,910	8,907	8,903	8,878
Titeu	72	72	72	72	72	72
Total	185,125	184,453	184,980	184,189	184,027	183,720

Table 4. Percentage rate of forest deforestation

Forest area function	Luas Kawasan SK.150/2018	Deforestation (ha)					
		2010–2012	%	2014–2016	%	2018–2020	%
Protection forest	179,766	291	0.2	95	0.1	476	0.3
Production forest	35,797	381	1.1	697	1.9	+70	+0.2
PMI forest park	72	0	0.0	+1	+1.4	–	0
Total	215,635	672	1.3	791	0.6	406	0.1

Note: (+) increase in forest cover, (-) permanent forest cover/no deforestation

changes occurred in the primary dryland forest closure class of 736 ha and secondary dryland forest of 1,739 ha, changing to shrubs of 1,279 ha and mixed dryland agriculture of 1,194 ha. Meanwhile, in the 2018–2020 period, there was a change in the primary dryland forest closure class of 4,541 ha and also in the open/empty land closure class of 176 ha. The largest change became secondary dryland forest 2,665 ha, and shrubs 1,886 ha. The graph in Figure 2 shows the land cover class in the protected forest area.

Land cover trends in production forest areas also occur in certain classes and regions. In the 2010–2020 period, there were significant changes in land cover. In 2010–2012, 383 ha of secondary dryland forest turned into shrubs.

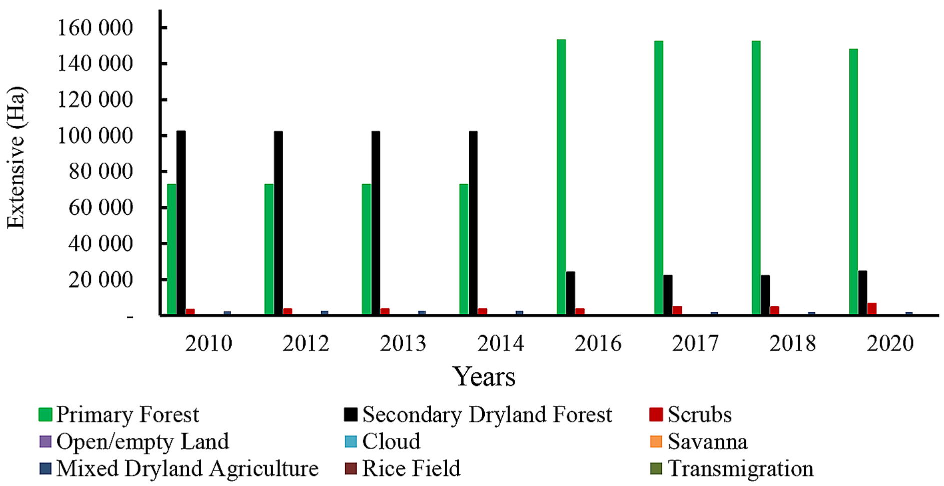

Figure 2. Land cover classes in protected forest areas

Furthermore, in 2013–2015, 2 ha of shrubs turned into open land. The 2016–2017 period recorded changes in primary forest (388 ha), secondary dryland forest (3,530 ha) and plantation forest (168 ha) to shrubs (3,633 ha), savanna (275 ha) and mixed dryland agriculture (178 ha). Finally, in 2018–2020, 2,657 ha of shrubs and 81 ha of primary dryland forest turned into mixed dryland agriculture (1,569 ha), open land (820 ha), savanna (283 ha), plantation (60 ha), and secondary dryland forest (5 ha). These changes indicate a decrease in forest cover and an increase in open land and agriculture (Figure 3).

The results of the analysis of land cover change trends in the TAHURA area show changes since 2010 as a baseline. In 2010–2012, there was a change of 0.03 ha from forest to shrubs. There was no significant change in the 2013–2017 period. In 2018–2020, there was a change in land cover from shrubs of 10.40 ha and open land of 0.47 ha to mixed dryland agriculture (Figure 4).

Calculation of emissions and carbon capture

Calculating carbon emissions and capture is an important part of understanding climate change impacts and helping to plan mitigation strategies to reduce greenhouse gas emissions. The calculation of carbon sequestration and emissions uses land cover data overlaid on a 2-year period, namely 2010–2012, 2013–2015, 2016–2018, and 2018–2020. Data on carbon emissions and sequestration in Pidie District based on the function of forest areas for a period of 10 years (period every 2 years) from 2010 to 2020 is obtained based on the calculation of the difference in carbon stocks based on land cover classes at 2 (two) observation times (initial observation year and final observation year), can be seen in Table 5.

The 2018–2020 period showed the highest carbon emissions and removals in Pidie District due to deforestation, where primary forests turned into secondary forests, open land, and transmigration areas. High carbon uptake also occurs due to reforestation

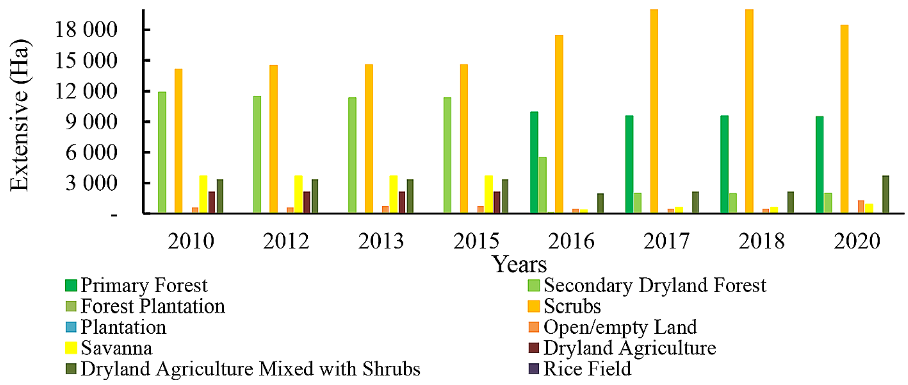

Figure 3. Land cover class in production forest area

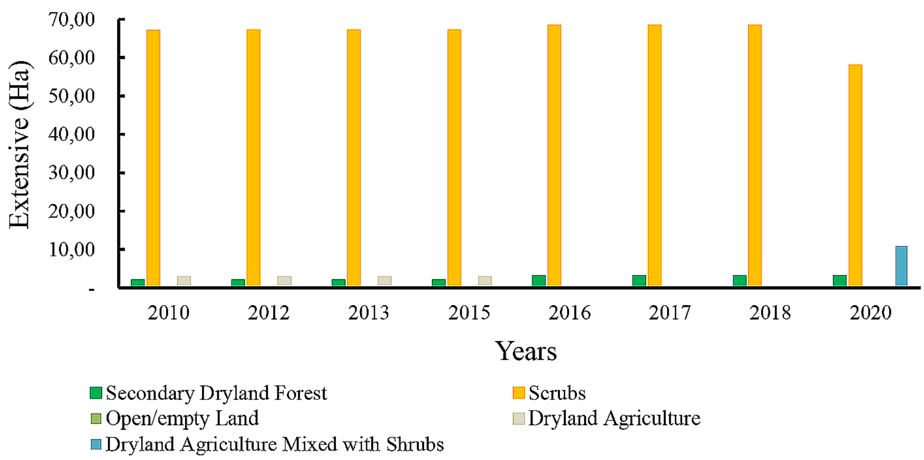

Figure 4. Land cover class in production forest area

Table 5. Carbon emissions and removals within protected forest areas by land cover 2010–2020

No	Land cover	Carbon emission & capture (tons CO_2)			
		Th. 2010–2012	Th. 2013–2015	Th. 2016–2018	Th. 2018–2020
1	Primary forest	–	–	-359,289	-2,216,449
2	Secondary dryland forest	-105,741	–	-630,711	966,550
3	Shrubs	3,164	–	140,835	207,608
4	Open/empty land	–	–	–	-1,617
6	Savanna	–	–	–	53
7	Mixed dryland agriculture	20,484	–	131,467	167
8	Rice field	–	-	–	17
9	Transmigration	–	–	–	-41
Total emissions (tons of CO_2)		-105,741	–	-990,000	-2,218,107
Total capture (tons of CO_2)		23,648	–	272,317	1,174,395

that converts primary drylands into secondary forests and shrubs. Emissions were calculated from the change in carbon stocks from high-carbon land to low-carbon land, while removals were calculated from the change of low-carbon land to high-carbon land. Unchanged land cover classes are assumed to neither sequester nor emit carbon. The highest emissions occurred in the 2018–2020 period at 2,218,017 tons of CO_2, with the largest contribution from primary dryland forests. The largest carbon sink in the same period reached 1,174,395 tons of CO_2, with secondary dryland forests as the main contributor. Increased sequestration can be achieved by increasing forest biomass through reforestation, tree planting, and better forest management.

The results of the analysis show that emissions in the production forest area were the largest in the 2016-2018 period at 1,530,818 tons of CO_2, and the smallest in the 2013–2015 period at 15 tons of CO_2. Meanwhile, the highest absorption occurred in the 2016-2018 period of 423,627 tons of CO_2 followed by the 2018-2020 period of 200,214 tons of CO_2. Table 6 shows the highest emissions in secondary dryland forests at 1,280,499 tons of CO_2, followed by shrubs in the 2018–2020 period with 292,552 tons of CO_2. The lowest emissions occurred in open land in the 2013–2015 period with 15 tons of CO_2, and primary dry forest in 2018-2020 with 39,424 tons of CO_2. The highest uptake over 10 years occurred in shrubs with 400,002 tons of CO_2 in 2016-2018, and mixed dryland agriculture with 172,727 tons of CO_2 in 2018-2020. The lowest uptake occurred in dry farmland, with 23 tons of CO_2 in 2016–2018 and 40 tons of CO_2 in 2018–2020.

In the Pocut Meurah Intan botanical forest park (TAHURA) area, the highest emissions occurred in the 2018–2020 period of 1,145.22 tons of CO_2

Table 6. Carbon emissions and removals within production forest areas by land cover 2010–2020

No	Land cover	Carbon emission & capture (ton CO_2)			
		Th. 2010–2012	Th. 2013–2015	Th. 2016–2018	Th. 2018–2020
1	Primary dry forest	–	–	-189,487	-39,424
2	Secondary dryland forest	-138,959	–	-1,280,499	1,995
3	Plantation forest	–	–	-60,832	–
4	Shrubs	42,173	182	400,002	- 292,552
5	Plantation	–	–	–	13,773
6	Open/empty land	–	-15	–	7,519
7	Savanna	–	–	4,043	4,161
8	Dryland agriculture	–	–	23	40
9	Dryland mixed farming	–	–	19,560	172,727
10	Rice paddy	–	–	–	–
Total emissions (tons of CO_2)		-138,959	-15	- 1,530,818	- 331,977
Total capture (tons of CO_2)		42,173	182	423,627	200,214

from shrubs, while the 2013–2018 period had no emissions because there was no land cover change. In 2010–2012, emissions reached 12,643 tons of CO_2 from secondary dryland forests. The highest carbon uptake occurred in the 2018–2020 period of 1,197.28 tons of CO_2 from mixed dryland agriculture, while in 2010–2012 the uptake from shrubs was 3,848 tons of CO_2. In the 2013–2015 period, there was no uptake because the land remained. For 10 years, total emissions reached 1,149.561 tons of CO_2 and total uptake of 1,197.452 tons of CO_2. Table 7 shows carbon emissions and capture within the botanical forest park (TAHURA) area.

Carbon stock by forest area function

The calculation of carbon stocks in the forest area for each land cover class used carbon stock references sourced from Tosiani (2015), the Directorate of IPSDH and the Forestry Research and Development Agency of the Ministry of Forestry (2014) based on measurement results (NFI 1996–2013) and the 2013 RAD GRK PEP Technical Guidelines. The carbon stock potential used is above ground carbon. Average carbon stocks in forest areas can vary depending on site type, forest or crop type, stand development stage, and management practices.

Carbon reserves in forest areas in Pidie Regency are highest in the function of protected forest areas with varying reserves for each study year period. Carbon reserves in protected forest functions were highest in 2017 at 22,649.615 tons of CO_2, and lowest in 2015 at 19,930.006 tons of CO_2. The high forest carbon stock in protected function is due to the forest area with protected function of 83.37% of the total forest area in Pidie Regency. In addition, it is also influenced by the land cover class in each forest area function, where the protected forest area primary and secondary dryland forest cover classes are greater than the function

Table 7. Carbon emission and sequestration in botanical forest park (TAHURA) based on land cover 2010–2020

No	Land cover	Carbon emission & capture (ton CO_2)			
		Th. 2010–2012	Th. 2013–2015	Th. 2016–2018	Th. 2018–2020
1	Secondary dryland forest	-12,643	–	–	0,17
2	Shrubs	3,848	–	–	-1.145,22
3	Open/empty land	–	–	–	-4,34
4	Dryland agriculture	–	–	–	–
5	Mixed dryland agriculture	–	–	–	1.197,28
Total emissions (tons of CO_2)		-12,643	0	0	-1.149,561
Total capture (tons of CO_2)		3,838	0	0	1.197,452

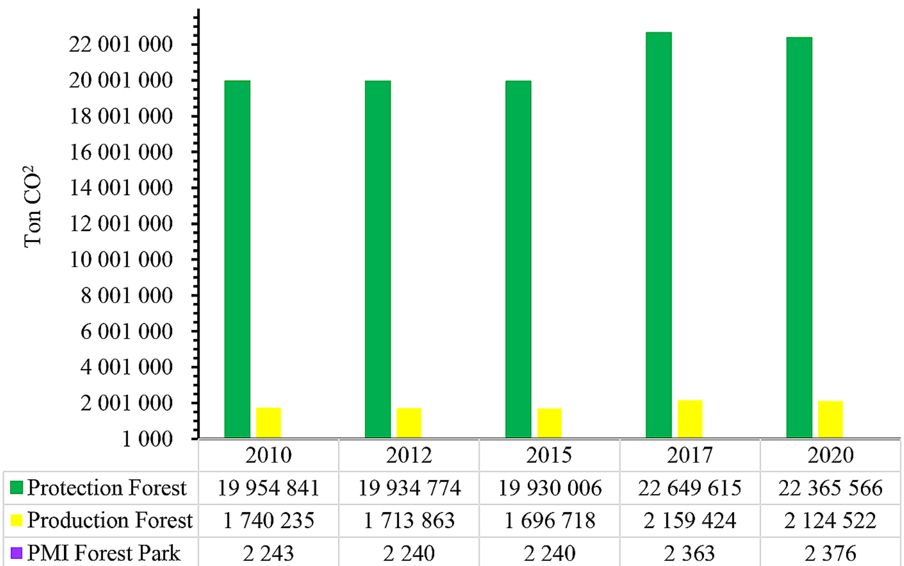

Figure 5. Total carbon stocks based on forest area functions for the 2010–2020 period in Pidie Regency

of production areas and TAHURA. Figure 5 shows a graph of forest carbon stocks based on the function of the forest area.

Several interventions can be implemented to enhance carbon stocks in the forest area of Pidie Regency. Precise quantification of carbon stocks utilizing destructive sampling methodologies ensures accurate data for effective monitoring. Reforestation and afforestation initiatives directly augment carbon sequestration by expanding arboreal cover. Sustainable forest management practices, including responsible timber extraction and ecosystem conservation, contribute to the maintenance and enhancement of carbon stocks. Mitigating illegal and unsustainable logging is crucial for preventing ecosystem degradation and carbon loss. Averting forest conversion to agricultural land or plantations precludes significant carbon stock reductions while rehabilitating degraded lands through agroforestry systems, which restores ecosystems and increases carbon storage capacity. Lastly, engaging local communities in forest management through education, capacity building, and incentive mechanisms promotes sustainable practices and long-term forest conservation.

CONCLUSIONS

This study provides a detailed analysis of land cover changes, carbon emissions, and sequestration trends in Pidie Regency from 2010 to 2020, addressing critical knowledge gaps at the regency level. The highest deforestation occurred in production forests (1,008 ha), contributing to peak carbon emissions of 2,218,017 tons of CO_2 during 2018–2020, while reforestation and natural regeneration in secondary forests and shrubs led to significant carbon sequestration of 1,174,395 tons of CO_2. Protected forests retained the most extensive carbon stocks, reaching 22,649,615 tons of CO_2 in 2017. The findings highlight the dynamic balance between carbon loss and recovery, agroforestry systems, and community-based forest management to mitigate deforestation impacts and enhance carbon storage while integrating scientific data for forest conditions of Pidie Regency.

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