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STUDY OF CHANGES IN MANGROVE FOREST COVER IN THREE AREAS LOCATED ON THE EAST COAST OF NORTH SUMATRA PROVINCE BETWEEN 1990 AND 2020

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Monitoring mangrove distribution is essential to ensure appropriate and efficient management of mangrove forests, as an effort to minimise the damage that potentially occurs in the ecosystem, including preventing human-induced activities that could lower the quantity and quality of mangroves. On the other hand, monitoring activities are also important for mangrove forest rehabilitation programmes. The use of high- and medium-resolution satellite imageries, especially free Landsat images, is very popular for mapping mangrove forests. As a unique wetland ecosystem, mangroves are mapped by applying unsupervised and supervised classification techniques. The specific objective of this study was to examine the rate of change in mangrove forest cover in two regencies and one city located on the east coast of North Sumatra province over a period of three decades. It was found that mangrove forests have lost 34,063.12 ha over three decades between 1990 and 2020, with the main drivers of mangrove deforestation being conversion to agricultural lands (~20,961.27 ha) and ponds (~8,584.39 ha). The normalised difference vegetation index showed that the current extent of mangroves in North Sumatra Province in 2020 were: very poor (344.91 ha), poor (244,78 ha), moderate (844.98 ha), healthy (5,692.58 ha) and very healthy (12,989.71 ha).

Keywords: Deforestation, Landsat, mangrove, North Sumatra, restoration

INTRODUCTION

Indonesia houses 23% of the world's mangroves, with 43 true mangrove species, the highest biodiversity in the world (FAO 2007, Giri et al. 2011). Mangroves play a crucial role in providing numerous ecosystem services, including coastal protection from natural phenomena, coping with rising sea levels, enhancing climate change mitigation, increasing fisheries production and contributing to the livelihoods and well-being of coastal communities through the delivery of ecosystem goods and services (Mazda et al. 2007, Alongi 2008, Bell et al. 2013, Duke et al. 2014, Murdiyarso et al. 2015, Hanggara et al. 2021).

Despite the ecological and economic importance of intact mangrove systems, forest degradation and deforestation continue apace, driven by the need for clear land to promote particular economic activities along the coast (Richards & Friess 2016). These economic activities, such as aquaculture, agricultural expansion such as oil palm plantations, paddy rice, forest extraction, logging and urban development are the main drivers of mangrove loss in Indonesia (FAO 2007, Long et al. 2014, Richards & Friess 2016). In addition to human interventions, natural phenomena such as tsunamis, tropical storm surges, high winds and waves may contribute to mangroves' degradation (Alongi 2008).

The current state of Indonesian mangroves and mangrove loss is perhaps best illustrated in the North Sumatra Province. There, mangroves are widely distributed along the east coast bordering the Malacca Strait. At the same time, three areas of Meladang (Medan, Langkat and Deli Serdang) have been experiencing population growth and high development pressures. Medan, Deli Serdang and Langkat occupy the top three regencies/cities and the largest population in North Sumatra Province with a population growth rate of 0.8–1.4% per year over the past decade (BPS North Sumatra 2010, 2020). These pressures contribute to ongoing trends in land use and land cover change as mangroves

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are removed to make way for agriculture and settlements.

The Indonesian government has shown a serious commitment to achieving the 2016 Paris Agreement emission reduction targets. Indonesia has a nationally determined contribution (NDC) target of 29% reduction by 2030 under a 'business-as-usual' (BAU) scheme, and 41% under the BAU scheme with adequate international support. Incorporation of peatland and mangrove ecosystems into the Peatland and Mangrove Restoration Agency (BRGM) in 2020, a non-structural government institution that is under and responsible to the President, represents the most visible effort by the Indonesian government in fulfilling the NDC target. Starting from 2021, the rehabilitation of mangroves will be focusing in nine provinces including North Sumatra with a total budget of Rp 1.5 trillion (≈ US$ 1.053 million) for restoring 83,000 ha. Hence, understanding the dynamics of mangrove change, and what land cover is involved as a factor causing mangrove deforestation, is essential in determining mangrove rehabilitation strategies, especially in North Sumatra.

Mapping and monitoring the past and current distribution of mangrove forests are important for management and restoration efforts. Spatial data and trends can reveal the extent of damage to mangrove systems from both natural disturbances and anthropogenic activities. Further, monitoring is crucial for establishing a baseline status of mangrove ecosystems and evaluating the success rate of mangrove conservation and restoration efforts (Schmitt & Duke 2015). This in turn can be used to support management and conservation policy (Ruslisan et al. 2018). Remotely sensed data have been widely used to identify and monitor land cover change, revealing landscape dynamic responses to management practices over time (Rawat & Kumar 2015). Several remote sensing indices can be used to detect the health quality of vegetation, including the normalised difference vegetation index (NDVI) and normalised difference water index (NDWI) which can demarcate the boundary between forest and open water in sharp relief (McFeeters 1996, Xiao & McPherson 2005, Chellamani et al. 2014). The NDWI in particular can be applied to report on flooding and flood-related damages, a capability with clear benefits for mangrove monitoring (Memon et al. 2015). Several remote sensing images can be used as data sources for monitoring mangrove forests, including purchased high-resolution satellite imagery (e.g., GeoEye-1, World-4 and Ikonos-2) and free-of-charge satellite data such as moderate resolution imaging spectroradiometer (MODIS) and medium spatial resolution Landsat images. Of these, Landsat imagery tends to be popular and widely used for land cover classification for a few reasons, such as, (1) Landsat imagery is easily downloadable directly from the United States Geological Survey (USGS) EarthExplorer website, (2) the 30-m spatial resolution of Landsat imagery is adequate for observing and monitoring land-use and land-cover change, (3) spectral and thermal bands can be combined in a variety of ways to target specific land-cover features and (4) the wide availability of Landsat has, in turn, encouraged a host of novel methods for image pre-processing, vegetation identification and land-cover change (Muttitanon & Tripathi 2005, Masek et al. 2006, Giri et al. 2011, Peña-Barragán et al. 2011, Barsi et al. 2014, Long et al. 2014, Zanter 2016, Song & Deng 2017).

In this study, it was sought to answer the following questions:

(i) What are the spatial and temporal land cover/use changes in three areas of Medan, Langkat and Deli Serdang which are adjacent to the east coast of North Sumatra?

(ii) What conservation efforts are needed for North Sumatran mangroves in the future?

MATERIALS AND METHODS

Study area

This study monitored the distribution of mangroves on the east coast of North Sumatra from 1990–2020, with specific attention paid to the mangrove dynamics in areas around Medan, Langkat and Deli Serdang (Figure 1). Coastal North Sumatra is classified as having a tropical rainforest climate. In Medan, the mean annual temperature is 25.4 °C with humidity around 78–91%. The average annual rainfall recorded is 3220 mm, with a relatively rainy period from September through November (Saputra & Lee 2021). Hanggara et al. (2021) showed that most mangroves forests on the east coast of Sumatra were dominated by four families of Rhizophoraceae (i.e. *Rhizophora*

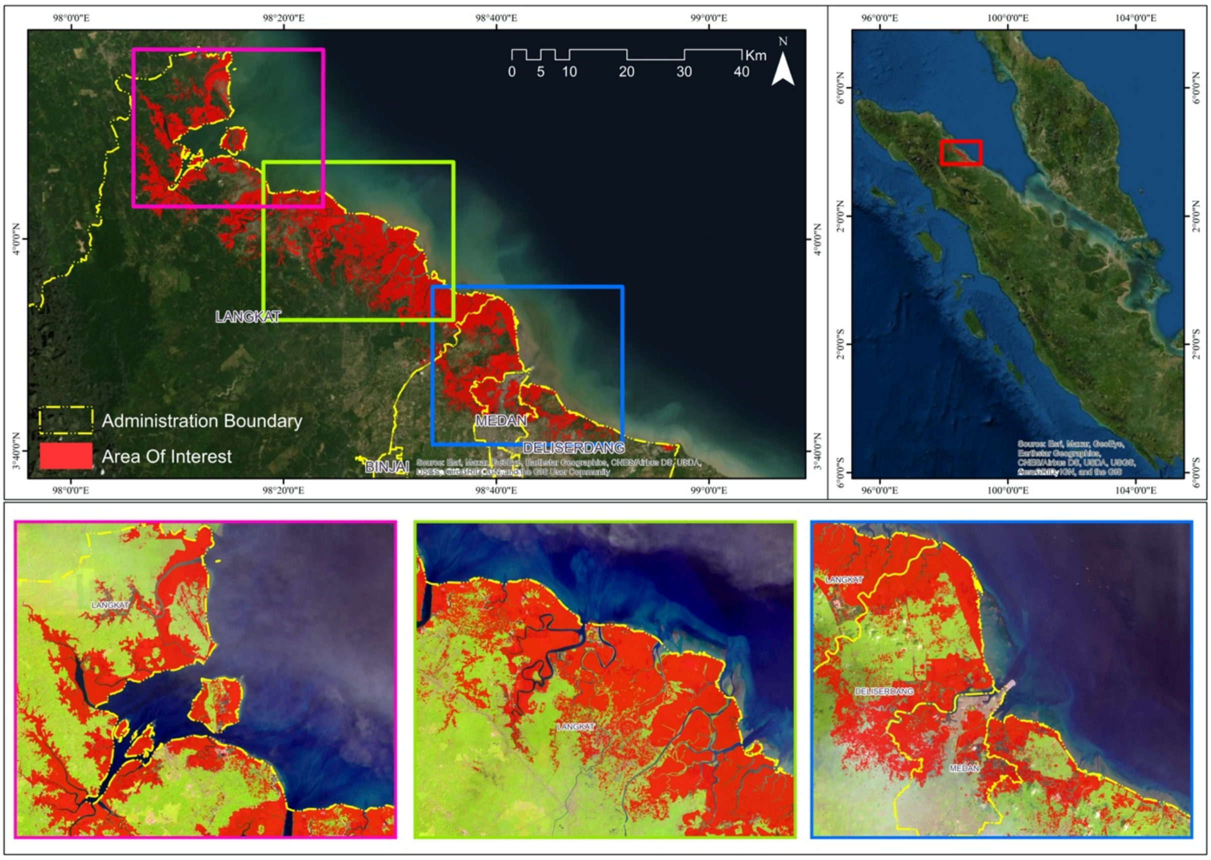

Figure 1 Map of the study sites on the east coast of North Sumatra, mangrove cover (areas in red) is clearly visible, the boundaries of this research location are Medan City, Langkat Regency and Deli Serdang Regency which are directly adjacent to the east coast of North Sumatra province, subsequently the image of the mangrove forest cover on the east coast of North Sumatra province was cut based on the administrative boundaries of Medan, Langkat and Deli Serdang

mucronata, Rhizophora apiculata, Bruguiera cylindrica, Bruguiera sexangula and *Ceriops tagal*), Meliaceae (i.e. *Xylocarpus granatum*), Avicenniaceae (i.e. *Avicennia alba, Avicennia officinalis,* and *Avicennia marina*) and Euphorbiaceae (i.e. *Excoecaria agallocha*), whose aerial root types are pneumatophore, stilt or prop, and knee.

The North Sumatra Province population is the fourth largest in Indonesia, with a total of 14,799,361 people or 5.5% of the total national population (BPS Indonesia 2020). Medan, Deli Serdang and Langkat, are the three largest population centers in North Sumatra, contributing 16.46, 13.05 and 6.96%, respectively, of the total population across 33 regencies/cities in North Sumatra (BPS North Sumatra 2020). Further, the population growth rates in the last decade (2010–2020) were 1.4, 0.8 and 0.6%. As the provincial capital as well as the center of North Sumatra's government and economy, Medan has the highest population density (9,186 people per km^2). The population densities in Deli Serdang and Langkat are 773 people per km^2 and 389 people per km^2, respectively. The contribution of the agricultural, forestry and fishery business sectors to the gross regional domestic product (GRDP) of Medan, Langkat and Deli Serdang in 2020 were 1.11, 39.57 and 10.46%, respectively (BPS Medan 2020, BPS Langkat 2020, BPS Deli Serdang 2020).

Analysis of land use/cover trend

The Landsat 5 thematic mapper (TM) and Landsat 8 operational land imager (OLI)/thermal infrared sensor (TIRS) satellite images were collected for the years 1990, 2000, 2011 and 2020. Images included mangroves and other land coverage within the area captured by path (129) and row (57). Image subsetting was applied to only cover three areas in this study. Efforts were made to improve mangrove forest classification by limiting cloud cover across the respective acquisition dates.

Interactions between radiation from the Earth's surface and the atmosphere can influence the quality of the information from remote sensing analysis, including NDVI and NDWI (Hadjimitsis et al. 2010). The problem was solved by using Landsat data level–2 or surface reflectance where atmospheric corrections have been applied. Light from the atmosphere is reflected diffusely from the earth's surface, traveling back through the earth's atmosphere, resisting further scattering effects. Some of these factors can be corrected by using the top of atmosphere (TOA) reflectance value instead of digital numbers (DNs). The DNs of Landsat images were converted to TOA planetary reflectance that corrected the results for the sun angle (Zanter 2016).

An unsupervised classification technique was applied to determine which pixels were related and grouped them into classes. Further, supervised classification of iterative self organising data analysis technique (ISODATA), was introduced by creating a specific class representative, and then directing the image processing software to use this training site as a reference for the classification of all other pixels in the image. The training sites (also known as test sets or input classes) were selected based on the user's knowledge as well as the land cover data classification system developed by the Director-General of Forestry Planning of Indonesia (MoEF 2020) (Table 1). The kappa accuracy assessment was tested to describe the accuracy of the map with real conditions in the field (Figure 2).

Table 1 Land cover data classification system: regulation of the Director-General of Forestry Planning of Indonesia, number P.1/VII-IPSDH/2015, concerning guidelines for land cover monitoring

Land cover classes	Descriptions	Interpretation keys
Waterbody	All aquatic features, including seas, rivers, lakes, reservoirs, coral reefs, seagrass beds, etc.	Dark hue, dusky blue color, smooth texture, irregular pattern
Mangrove	Mangrove forests (both primary and secondary) are located in brackish waters that have not experienced or experienced human disturbance (such as logging and fire scars), including those that grow/plants on sedimentary soil	Dark hue, dark green or brownish-green, smooth texture, irregular pattern, located in coastal areas or around rivers that are still experiencing tides, secondary mangroves usually have land openings (can be in the form of ponds or open fields)
Settlement	Settlements, whether urban, rural, industrial, transmigration areas, etc.	Light hue, pink color (sometimes with green spots), slightly rough to coarse texture, uniform and regular pattern, there is a network of roads
Agricultural land	1) Dryland farming: the whole appearance of the cultivation of seasonal crops on dry land such as fields, 2) Mixed dryland farming: all features which are a mixture of agricultural areas, plantations, shrubs, 3) Paddy rice: all the features of seasonal crop cultivation in wetlands characterized by a bund pattern, 4) Plantation: all appearances of cultivation of perennials included in the plantation group, including oil palm, rubber, coconut, cocoa, coffee, tea, etc.	1) Dryland farming: light hue, pink color with green spots, slightly rough to coarse texture, irregular shape, irregular pattern, close to settlements, close to the road network, 2) Mixed dryland farming: light hue, pink with green spots, slightly rough to coarse texture, irregular in shape and pattern, associated with settlement, 3) Paddy rice: light to dark hue, blue color with light green spots, fine texture, uniform pattern, close to settlements and water sources (river, reservoir, etc.), 4) Plantation: light hue, light green to dark green or yellowish-brown, texture from smooth to slightly rough and usually rectangular (according to the topography of the area), regular pattern, there is a network of roads
Shrub	The entire appearance of the area is dominated by low vegetation on dry land	Light hue, light yellowish-green color, slightly rough texture, irregular pattern, associated with natural forest, sloping and steep topography
Pond	All characteristics of inland fisheries (fish/shrimp) or salting that appear with a bund pattern, usually located around the coast	Dark hue, blue-black color, smooth texture, uniform pattern, associated with tides and mangroves
No data (cloud)	The appearance of clouds and their shadows that cover the land of an area	Light hue, smoky white color, smooth texture, irregular pattern

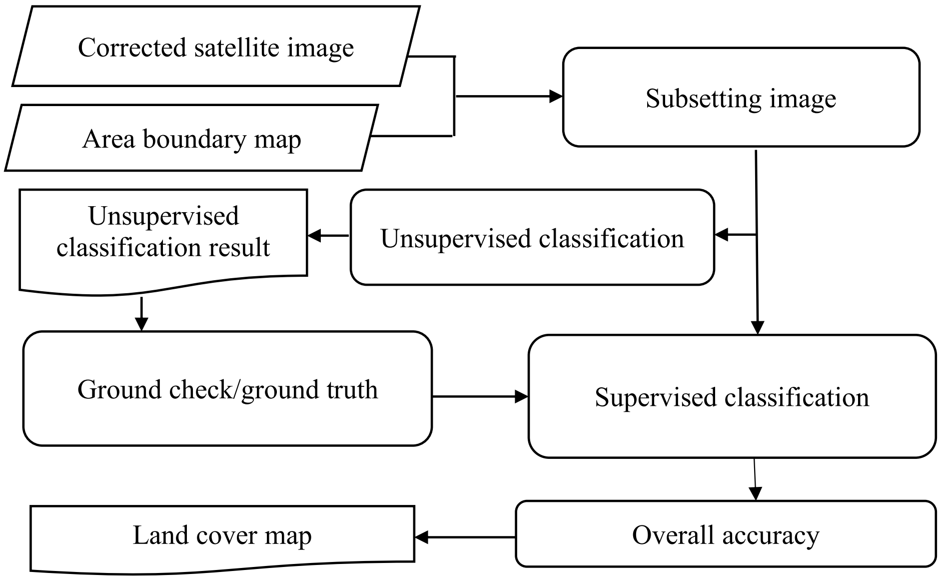

Figure 2 Landsat satellite image analysis process in generating land cover

Normalised difference vegetation index (NDVI) analysis

The health condition of mangrove forests was estimated by applying the NDVI. The NDVI is a normalised ratio of visible red and NIR spectral reflectance, and has become one of the most popular and widely used indices. The NDVI values are determined by the degree of absorption by plant chlorophyll in the red wavelengths, which is proportional to leaf chlorophyll density, and by the reflectance of near-infrared (NIR) radiation, which is proportional to green leaf density (Chellamani et al. 2014, Razali et al. 2019, Samanta et al. 2021). The NDVI is sensitive to the green leaf area or green leaf biomass (Tucker 1979). A study conducted by Santin-Janin et al. (2009) showed that NDVI time-series data could be linked to vegetation productivity. Healthy vegetation absorbs visible red light emitted by the sun and reflects a large portion of NIR. Meanwhile, unhealthy vegetation reflects more visible red light than healthy vegetation. The NDVI is calculated as a proportion between the red (R) and near infrared (NIR) values: (NIR - R)/(NIR + R), where on Landsat 5, the R and NIR are on band 4 and band 3, respectively, while on Landsat 8, they are on band 5 and band 4, respectively. The NDVI values range from -1.0 to 1.0 (Jensen 2009). For the division of mangrove forest health classes based on the NDVI value, it was refered to the research conducted by Chellamani et al (2014) in the Sundarbans mangrove forest. There are five classes, including very healthy mangrove (0.6 > NDVI ≤ 1.0), healthy mangrove (0.4 > NDVI ≤ 0.6), moderate mangrove (0.2 > NDVI ≤ 0.4), poor mangrove (0.0 > NDVI ≤ 0.2) and very poor mangrove (-0.1 > NDVI ≤ 0.0).

RESULTS

Accuracy assessments

The data provided in Table 2 show accuracy assessment results for the four years considered. A kappa value greater than 0.80 for the ISODATA classifier indicates good classification performance. The overall accuracy results at four years of observation meet the minimum accuracy benchmark of at least 85% (Jensen 2009, Lillesand et al. 2004).

Land use/cover change and rate in Medan, Langkat and Deli Serdang between 1990–2020

From the analysed area of 65,354 ha, the mangrove ecosystem in 1990 covered 82.86% of the total area, with shrub (8.94%), agricultural land (4.12%), pond (3.02%), water body (0.73%) and settlement (0.13%), representing

Table 2 Accuracy assessment results of 1990, 2000, 2011, and 2020 imagery

Year	Overall accuracy	Kappa coefficient	Type	MG	WB	ST	AL	SH	PN	ND
1990	92	0.88	PA (%)	90	100	100	83	96	100	–
			UA (%)	96	100	100	90	100	80	–
2000	90	0.85	PA (%)	94	100	100	92	69	91	–
			UA (%)	89	67	100	100	90	95	–
2011	91	0.86	PA (%)	96	–	100	92	100	72	–
			UA (%)	87	–	100	92	95	100	–
2020	98	0.95	PA (%)	98	100	100	93	100	100	100
			UA (%)	100	50	100	96	83	100	100

Note: PA is producer's accuracy, UA is user's accuracy, land cover types are mangrove (MG), water body (WB), settlement (ST), agricultural land (AL), shrub (SH), pond (PN), and no data/cloud (ND)

the remaining coverage (Table 3). By 2000, mangrove coverage experienced a loss of 9,633.80 ha, a 17.84% decline compared to the expanse of mangrove in 1990 (Table 4). Further mangrove deforestation was recorded between the period 2000–2011 (-13,266.96 ha) and 2011–2020 (-11,132.36 ha). At the same time, an increasing trend in other land covers was observed (Table 4). Of particular interest to this study, over the same period of time (1990–2020), agricultural land increased from 2,691.26 ha to 23,652.54 ha, a 778.86% increase. Similarly, the area of ponds increased by 424.64%, while water bodies (340.12%) and settlements (368.98%) also increased. The current mangrove area in 2020 was 20,115.97 ha, followed by agricultural land (23,652.54 ha), ponds (10,605.96 ha), shrubs (5,665.29 ha), water bodies (2,097.37 ha) and settlements (393.68 ha), while 2,853.29 ha are covered with clouds. This represents a 63% loss in mangrove coverage over the study period. Land cover maps between 1990–2020 are shown in Figure 3.

DISCUSSION

What land use/cover is responsible for the deforestation of mangrove forests?

In the first decade of observation (1990–2000), the expansion of agricultural areas and ponds were the two main drivers that contributed to mangrove deforestation (Table 5). In the first decade, 4,067.65 ha of mangrove were converted into agricultural land. This trend continued from 2000 through 2020, where mangroves were deforested and converted to agricultural land by 4,327.54 ha (2000–2011)

Table 3 Land use/cover classification on the east coast of North Sumatra concerning mangrove forests from 1990 to 2020

Land use classes	Area (ha)			
	1990	2000	2011	2020
Mangrove	54,179.09	44,515.29	31,248.33	20,115.97
Water Body	476.54	782.89	913.05	2,097.37
Settlement	83.94	155.53	228.26	393.68
Agricultural land	2,691.26	4,428.23	8,487.18	23,652.54
Shrub	5,849.06	5,643.18	13,569.80	5,665.29
Pond	2,021.57	9,828.11	10,851.64	10,605.96
No data (cloud)	82.63	30.87	85.85	2,853.29
Total	65,384.10	65,384.10	65,384.10	65,384.10

Table 4 Land use/cover change on the east coast of North Sumatra between 1990–2020

Land use classes	Change in ha (1990–2000)	Change (%)	Change in ha (2000–2011)	Change (%)	Change in ha (2011–2020)	Change (%)	Change in ha (1990–2020)	Change (%)
Mangrove	-9,663.80	-17.84	-13,266.96	-29.80	-11,132.35	-35.63	-34,063.11	-62.87
Water Body	306.34	64.28	130.16	16.63	1,184.32	129.71	1620.83	340.12
Settlement	71.59	85.28	72.73	46.76	165.42	72.47	309.73	368.98
Agricultural land	1,736.97	64.54	4,058.95	91.66	15,165.35	178.69	20,961.27	778.86
Shrub	-205.88	-3.52	7,926.61	140.46	-7,904.50	-58.25	-183.77	-3.14
Pond	7,806.54	386.16	1,023.53	10.41	-245.68	-2.26	8,584.39	424.64
No data (cloud)	-51.76	-62.64	54.98	178.13	2,767.44	3,223.67	2,770.66	3,353.25

Note: The minus symbol (-) indicates a decrease in land cover area in a certain class

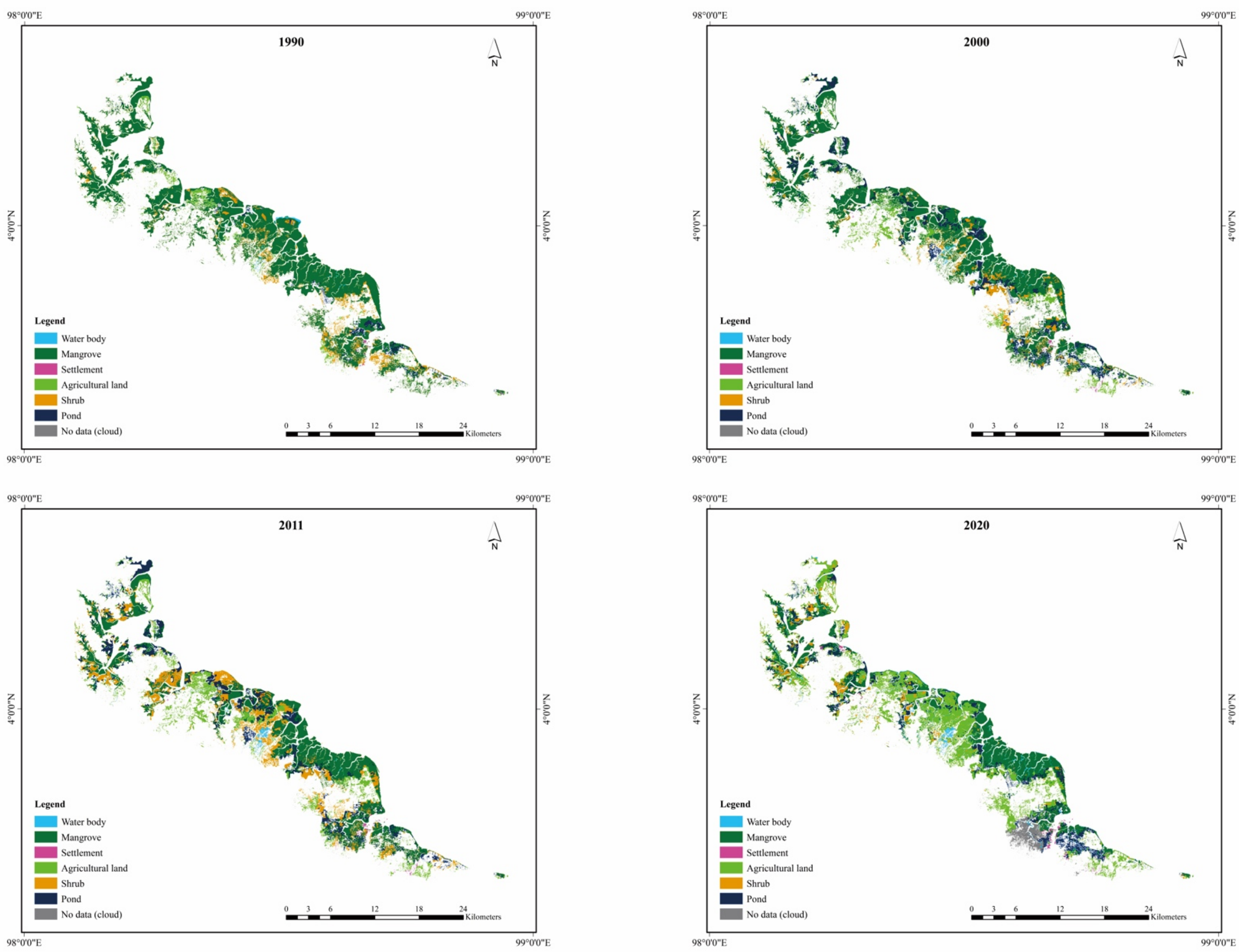

Figure 3 Land cover maps in 1990, 2000, 2011 and 2020

Table 5 Land use/cover change detection

From 1990 to 2000 (ha)

	Land cover	2000 (ha)							Area (ha)
		Waterbody	Mangrove	Settlement	Agricultural land	Shrub	Pond	No data (cloud)	
1990 (ha)	Water body	170.6	305.94	0	0	0	0	0	476.54
	Mangrove	612.38	36,665.04	116.36	4,067.65	4,755.39	7,939.2	23.08	54,179.10
	Settlement	0	44.77	39.18	0	0	0	0	83.95
	Agricultural land	0	2,461.2	0	226.62	0	3.45	0	2,691.27
	Shrub	0	4,166.59	0	130.98	887.29	664.2	0	5,849.06
	Pond	0	806.57	0	2.99	0	1,212.02	0	2,021.58
	No data (cloud)	0	65.18	0	0	0	9.66	7.79	82.63
	Total	782.98	44,515.29	155.54	4,428.24	5,642.68	9,828.53	30.87	65,384.13

From 1990 to 2000 (ha)

	Land cover	2011 (ha)							Area (ha)
		Waterbody	Mangrove	Settlement	Agricultural land	Shrub	Pond	No data (cloud)	
2000 (ha)	Water body	494.57	288.23	0	0	0	0	0	782.8
	Mangrove	418.42	25,817.85	80.54	4,327.54	9,556.81	4,245.18	68.95	44,515.29
	Settlement	0	7.81	147.72	0	0	0	0	155.53
	Agricultural land	0	345.25	0	4,078.29	2.4	2.3	0	4,428.24
	Shrub	0	1,569.55	0	68.12	3,948.66	56.85	0	5,643.18
	Pond	0	3,205.66	0	13.24	61.93	6,547.22	0	9,828.05
	No data (cloud)	0	13.97	0	0	0	0	16.9	30.87
	Total	912.99	31,248.32	228.26	8,487.19	13,569.80	10,851.55	85.85	65,383.96

continued

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Table 5 Continued

From 2011 to 2020 (ha)

	Land cover	2000 (ha)							Area (ha)
		Waterbody	Mangrove	Settlement	Agricultural land	Shrub	Pond	No data (cloud)	
1990 (ha)	Water body	832.68	23.21	0	23.19	6.73	25.84	1.27	912.92
	Mangrove	946.5	16,213.86	122.86	5,365.77	2,205.57	4,999.63	1,394.13	31,248.32
	Settlement	1.36	54.77	83.62	42.69	10.78	11.7	23.34	228.26
	Agricultural land	37.67	292.15	58.19	6,706.11	636.27	462.89	293.9	8,487.18
	Shrub	151.64	1,760.42	70.37	7,597.26	1,742.81	1,738.40	508.9	13,569.80
	Pond	125.61	1,756.93	58.5	3,880.07	1,042.32	3,356.45	631.75	10,851.63
	No data (cloud)	1.91	14.63	0	37.45	20.81	11.06	0.00	85.86
	Total	2,097.37	20,115.97	393.54	23,652.54	5,665.29	10,605.97	2,853.29	65,383.97

and 5,365.77 ha (2011–2020). The expansion of agricultural land, including paddy rice, can be caused by an increase in the human population which contributes to an increase in food consumption. This is also directly proportional to the productivity of agricultural land. As an illustration, the population in North Sumatra Province has continued to grow for three decades, from 10,256,027 people in 1990, to 14,703,532 people in 2020, a population growth rate of 148,250 people per year (BPS North Sumatra 2020). The increase in population is followed by an increase in food production, such as rice. Rice production in North Sumatra Province in 2006 was 3,007,636 tons and increased to 3,423,578 tons by 2010, while rice consumption was 1,921,811 tons and 2,163,015 tons in 2006 and 2010, respectively (Herdianty 2017).

Fishery activities by making ponds are the second biggest trigger of mangrove forest deforestation in three areas in North Sumatra, with 7,939.2 ha of mangrove converted between 1990 and 2000. The same trend still emerges in the next two decades, where the mangrove ecosystem lost 4,245.18 ha between 2000–2011 and 4,999.63 ha between 2011–2020. In Indonesia, the amount of brackish water ponds tend to increase every year, helping to support an important, diverse aquaculture sector, with the main commodities being milkfish, snapper, tiger prawns, king prawns, crabs and seaweed. As an example, production from the aquaculture sector was 1.76 million tons in 2012, increasing to 3.01 million tons by 2016. In North Sumatra Province, the number of brackish water pond cultivation households was 2,583 households in 2012, increasing to 2,969 households in 2016 (MoMAF 2018). In addition to meeting the demand of the local and regional markets, the growth in aquaculture production was triggered by high export transactions, especially to the United States, Japan and China.

The dynamics of changes in the area of the shrub are also closely related to the creation of ponds. Before the pond is built, usually mangrove forest clearing and land preparation will be carried out, and before the pond is completed, shrubs will grow. In addition, if the pond is no longer productive and becomes abandoned, shrubs will quickly grow around it.

Conservation efforts for mangrove restoration and rehabilitation

Mangrove forests in North Sumatra have been deforested by 63% (34,063.12 ha) over three decades (1990–2020), with anthropogenic activities involving land use and land cover changes being the main drivers. In addition, of the current 20,115.97 ha of mangrove ecosystems in North Sumatra, it should be noted that 7% (1,408 ha) are considered to be in damaged condition (Figure 4). Restoration and rehabilitation efforts will be vital for restoring the function of the mangrove ecosystem and continued delivery of various ecosystem goods and services. To this end, accelerating the recovery of mangroves is a BRGM priority, although development pressures are likely to continue the deforestation trends observed over the past 30 years without additional engagement.

Monitoring efforts may help in slowing the rate of deforestation of mangrove forests. For monitoring efforts to be successful, local governments, relevant agencies (e.g., Ministry of Environment and Forestry, Ministry of Maritime Affairs and Fisheries), non-governmental organisations (NGOs) and the private sectors need to work together if mangrove restoration is to be realised alongside other economic ends.

CONCLUSIONS

This study provides a significant contribution to the dynamics of forest cover loss in mangroves along the east coast of North Sumatra, bordering Medan, Langkat and Deli Serdang between 1990–2020. In three decades, mangrove forests lost 34,063.12 ha, with the primary cause of deforestation being conversion to agricultural lands (+20,961.27 ha) and ponds (+8,584.39 ha). Ongoing trends presented by the data reinforce the importance of restoration and rehabilitation efforts, particularly given the current condition of mangrove forests. This study has shown that Landsat imagery is capable of describing changes in land cover at regional scales, and how the dynamics of land cover change is closely related to human activities involving changes in land use. Apart from the enormous costs that must be incurred to protect the mangrove ecosystem, restoration and rehabilitation of mangroves must also be seen as a form of Indonesia's real

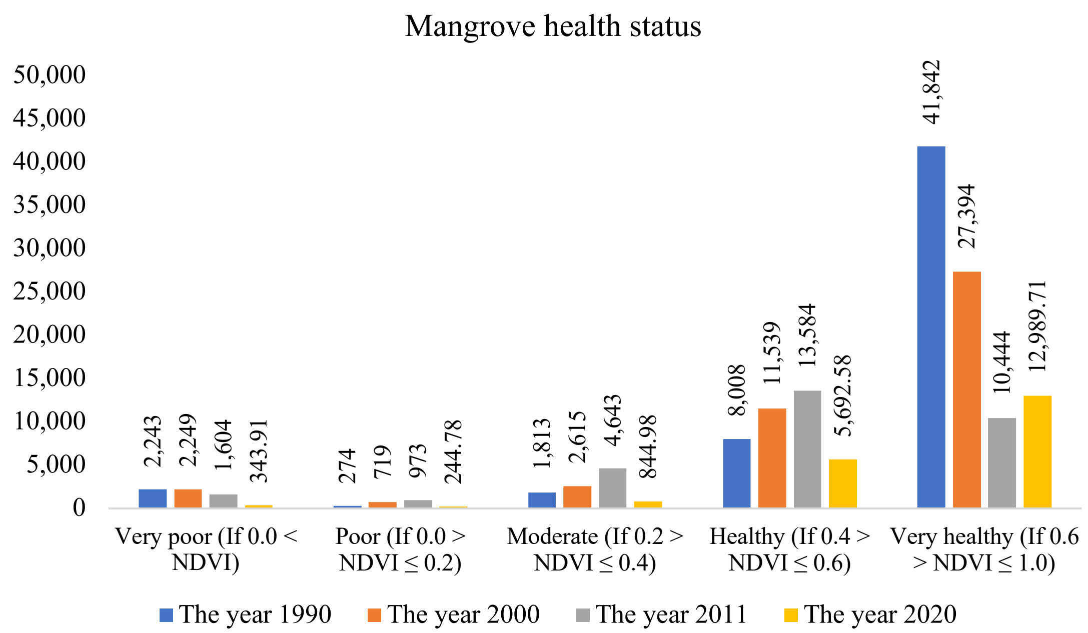

Figure 4 Mangrove health status (1990–2020) on the east coast of North Sumatra Province

commitment to combating climate change. The Indonesian government still has to work hard to achieve the GHG emission reduction target agreed in the Paris Agreement, which is 26% of greenhouse gases in 2020 and 29% of greenhouse gases under the BAU scheme. Although the achievement of NDC from the energy sector until 2020 is already above the target, which is 64.4 million tons of CO_2e from the target of 58 million tons of CO_2e. Even so, the emission reduction rate is still relatively small, reaching 314 million tons of CO_2e, in other words, achieving the 29% target in 2030, which is still very far away. In the future, the expansion and restoration of mangrove ecosystems and the involvement of mangrove ecosystems, as ecosystems that are very important in the absorption of GHG emissions, will become important issues in the effort to achieve emission reduction targets from the land sector or commonly referred to as agriculture, forestry and other land uses (AFOLU).

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REFERENCES

Alongi DM. 2008. Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science* 76: 1–13. doi: 10.1016/j.ecss.2007.08.024.

Barsi JA, Schott JR, Hook SJ, Raqueno NG, Markham BL & Radocinski RG. 2014. Landsat-8 thermal infrared sensor (TIRS) vicarious radiometric calibration. *Remote Sensing* 6: 11607–11626. doi: 10.3390/rs61111607.

Bell JD, Ganachaud A, Gehrke PC et al. 2013. Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nature Climate Change* 3: 591–599. doi: 10.1038/nclimate1838.

BPS (Badan Pusat Statistik) Deli Serdang. 2020. *Distribusi PDRB Atas Dasar Harga Berlaku Menurut Lapangan Usaha, 2018–2020 (Distribution of GRDB Based on Current Prices by Business Field, 2018–2020).* Badan Pusat Statistik (BPS), Deli Serdang.

BPS (Badan Pusat Statistik) Indonesia. 2020. *Hasil Sensus Penduduk 2020 (Results of the 2020 Population Census).* Badan Pusat Statistik (BPS), Jakarta.

BPS (Badan Pusat Statistik) Langkat. 2020. *Distribusi PDRB Atas Dasar Harga Berlaku Menurut Lapangan Usaha, 2018–2020 (Distribution of GRDB Based on Current Prices by Business Field, 2018–2020).* Badan Pusat Statistik, (BPS), Langkat.

BPS (Badan Pusat Statistik) Medan. 2020. *Distribusi PDRB Atas Dasar Harga Berlaku Menurut Lapangan Usaha, 2018–2020 (Distribution of GRDB Based on Current Prices by Business Field, 2018–2020).* Badan Pusat Statistik, (BPS), Medan.

BPS (Badan Pusat Statistik) North Sumatra. 2010. *Hasil Sensus Penduduk 2010 Provinsi Sumatera Utara (Results of the 2010 Population Census of North Sumatra Province)*. Badan Pusat Statistik (BPS), Medan.

BPS (Badan Pusat Statistik) North Sumatra. 2020. *Hasil Sensus Penduduk 2020 Provinsi Sumatera Utara (Results of the 2010 Population Census of North Sumatra Province).* Badan Pusat Statistik (BPS), Medan.

Chellamani P, Singh CP & Panigrahy S. 2014. Assessment of the health status of Indian mangrove ecosystems using multi temporal remote sensing data. *Tropical Ecology* 55: 245–253.

Duke N, Nagelkerken I, Agardy T, Wells S & Van Lavieren H. 2014. *The Importance of Mangroves to People: A Call to Action.* United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), Cambridge.

Fao (Food and Agriculture Organisation). 2007. *The World's Mangroves 1980–2005.* FAO Forestry Paper, Rome.

Giri C, Ochieng E, Tieszen LL et al. 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography* 20: 154–159. doi: 10.1111/j.1466-8238.2010.00584.x.

Hadjimitsis DG, Papadavid G, Agapiou A et al. 2010. Atmospheric correction for satellite remotely sensed data intended for agricultural applications: impact on vegetation indices. *Natural Hazards and Earth System Sciences* 10: 89–95. doi: 10.5194/nhess-10-89-2010.

Hanggara BB, Murdiyarso D, Ginting YRS, Widha YL, Panjaitan GY & Lubis AA. 2021. Effects of diverse mangrove management practices on forest structure, carbon dynamics and sedimentation in North Sumatra, Indonesia. *Estuarine, Coastal and Shelf Science* 107467. doi: 10.1016/j.ecss.2021.107467.

Herdianty AP. 2017. *Analisis Kebijakan Ketahanan Pangan di Provinsi Sumatera Utara (Policy Analysis of Food Security in North Sumatra Province).* Universitas Muhammadiyah Sumatera Utara, Medan.

Jensen JR. 2009. *Remote Sensing of The Environment: An Earth Resource Perspective 2/E.* Pearson Education, India.

Lillesand TM, Kiefer RW & Chipman JW. 2004. Concepts and foundations of remote sensing. *Remote Sensing and Image Interpretation* 7: 1–57.

Long JB & Giri C. 2011. Mapping the Philippines' mangrove forests using Landsat imagery. *Sensors* 11: 2972–2981. doi: 10.3390/s110302972.

Long J, Napton D, Giri C & Graesser J. 2014. A mapping and monitoring assessment of the Philippines' mangrove forests from 1990 to 2010. *Journal of Coastal Research* 30: 260–271. doi: 10.2112/JCOASTRES-D-13-00057.1.

Masek JG, Vermote EF, Saleous NE et al. 2006. A Landsat surface reflectance dataset for North America, 1990-2000. *IEEE Geoscience and Remote Sensing Letters* 3: 68–72. doi: 10.1109/LGRS.2005.857030.

Mazda Y, Wolanski E & Ridd P. 2007. *The Role of Physical Processes in Mangrove Environments: Manual for the Preservation and Utilization of Mangrove Ecosystems.* Terrapub, Tokyo.

Mcfeeters SK. 1996. The use of the normalized difference water index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing* 17: 1425–1432. doi: 10.1080/01431169608948714.

Memon AA, Muhammad S, Rahman S & Haq M. 2015. Flood monitoring and damage assessment using water indices: a case study of Pakistan flood-2012. *The Egyptian Journal of Remote Sensing and Space Science* 18: 99–106. doi: 10.1016/j.ejrs.2015.03.003.

MOEF (Ministry of Environment and Forestry). 2020. *Petunjuk Teknis: Penafsiran Citra Satelit Resolusi Sedang untuk Update Data Penutupan Lahan Nasional (Technical Guidance: Interpretation of Medium Resolution Satellite Imagery for National Land Cover Data Update).* Ministry of Environment and Forestry of Indonesia, Jakarta.

MOMAF (Ministry of Marine Affairs and Fisheries). 2018. *Kelautan dan Perikanan dalam Angka Tahun 2018 (Marine and Fisheries in Figures 2018).* Ministry of Marine Affairs and Fisheries of Indonesia, Jakarta.

Murdiyarso D, Purbopuspito J, Kauffman JB et al. 2015. The potential of Indonesian mangrove forests for global climate change mitigation. *Nature Climate Change* 5: 1089–1092. doi: 10.1038/nclimate2734.

Muttitanon W & Tripathi NK. 2005. Land use/land cover changes in the coastal zone of Ban Don Bay, Thailand using Landsat 5 TM data. *International Journal of Remote Sensing* 26: 2311–2323. doi: 10.1080/0143116051233132666.

peña-barragán JM, Ngugi MK, Plant RE & Six J. 2011. Object-based crop identification using multiple vegetation indices, textural features and crop phenology. *Remote Sensing of Environment* 115: 1301–1316. doi: 10.1016/j.rse.2011.01.009.

Rawat JS & Kumar M. 2015. Monitoring land use/cover change using remote sensing and GIS techniques: a case study of Hawalbagh block, district Almora, Uttarakhand, India. *The Egyptian Journal of Remote Sensing and Space Science* 18: 77–84. doi: 10.1016/j.ejrs.2015.02.002.

Razali SM, Nuruddin AA & Lion M. 2019. Mangrove vegetation health assessment based on remote sensing indices for Tanjung Piai, Malay Peninsular. *Journal of Landscape Ecology* 12: 26–40. doi: 10.2478/jlecol-2019-0008.

Richards DR & Friess DA. 2016. Rates and drivers of mangrove deforestation in Southeast Asia, 2000–2012. *Proceedings of the National Academy of Sciences* 113: 344–349. doi: 10.1073/pnas.1510272113.

Ruslisan R, Kamal M & Sidik F. 2018. Monitoring the restored mangrove condition at Perancak estuary, Jembrana, Bali, Indonesia from 2001 to 2015. *IOP Conference Series: Earth and Environmental Science* 123: 012022.

Samanta S, Hazra S, Mondal PP, Chanda A, Giri S, French JR & Nicholls RJ. 2021. Assessment and attribution of mangrove forest changes in the Indian Sundarbans from 2000 to 2020. *Remote Sensing* 13: 4957. doi: 10.3390/rs13244957.

Santin-Janin H, Garel M, Chapuis JL & Pontier D. 2009. Assessing the performance of NDVI as a proxy for plant biomass using non-linear models: a case study on the Kerguelen archipelago. *Polar Biology* 32: 861–871. doi: 10.1007/s00300-009-0586-5.

Saputra MH & Lee HS. 2021. Evaluation of climate change impacts on the potential distribution of *Styrax sumatrana* in North Sumatra, Indonesia. *Sustainability* 13: 462. doi: 10.3390/su13020462.

Schmitt K & Duke NC. 2015. Mangrove management, assessment and monitoring. Pp 1–29 in: Köhl M. & Pancel L (eds) *Tropical Forestry Handbook*. Springer, Berlin, Heidelberg. doi: 10.1007/978-3-642-41554-8_126-1.

Song W & Deng X. 2017. Land-use/land-cover change and ecosystem service provision in China. *Science of the Total Environment* 576: 705–719. doi: 10.1016/j.scitotenv.2016.07.078.

Tucker CJ. 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment* 8: 127–150. doi: 10.1016/0034-4257(79)90013-0.

Xiao Q & Mcpherson EG. 2005. Tree health mapping with multispectral remote sensing data at UC Davis, California. *Urban Ecosystems* 8: 349–361. doi: 10.1007/s11252-005-4867-7.

Zanter K. 2016. *Landsat 8 (L8) Data Users Handbook*. Department of the Interior United States Geological Survey, Virginia.

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