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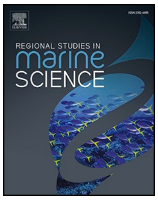

Identifying changes in mangrove landscapes in the Philippines and Indonesia using remote sensing and community perceptions: Towards ecosystem services management

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ABSTRACT

Mangrove ecosystems provide important services in mitigating global climate change while delivering various co-benefits at the local level. However, they are subjected to multiple anthropogenic and natural disturbances, leading to several investigations aimed at addressing these threats and/or restoring them. This study was conducted to develop site-specific scale land cover maps using remote sensing to monitor and quantify mangroves, alongside assessing community perceptions to identify the direct drivers of mangrove cover changes. Results showed that in Balangkayan, (Philippines), the mangrove cover increased by approximately 500 ha between 2014 and 2021, following a decline in 2013 due to Typhoon Haiyan. In Muaragembong (Indonesia), mangrove cover increased by about 176.13 ha between 2000 and 2022 after years of conversion to fish and shrimp ponds. Community perceptions in both sites revealed that natural disturbances, such as strong typhoons and coastal erosion, were the primary drivers of mangrove cover changes. The key findings of this study provide valuable insights into (1) mangrove cover changes over time, (2) proximate and underlying drivers of these changes, and (3) land use and land cover maps highlighting mangroves in less-explored sites. These local-scale observations offer global perspectives on the long-term effects of natural disasters and sustained mangrove restoration efforts on mangrove blue carbon.

1. Introduction

Mangrove forests are among the most productive ecosystems providing an array of ecosystem services that directly and indirectly support local communities and biodiversity. Among these services, mangroves can be a source of food and livelihood (e.g., fishing, gleaning) for coastal communities, provide good protection cover against coastal hazards (e.g., storm surges, strong waves), and serve as recreational site (e.g., bird watching, firefly watching) (e.g., Quevedo et al., 2020; Quevedo and Kohsaka, 2024). Mangroves also play a significant role in biodiversity by providing a unique habitat and supporting a range of species (Carugati et al., 2018). In more recent years, mangrove forests, along with salt marshes and seagrass meadows reached international prominence for their valuable service in climate mitigation (Macreadie et al., 2021). More commonly known as the "blue carbon" concept, these coastal vegetations (collectively referred to as blue carbon ecosystems) can sequester and store atmospheric carbon in their biomass and soil (Nellemann et al., 2009). Among the blue carbon ecosystems, mangroves are of particular interests as they are among the most carbon-rich forests in tropical ecosystems; storing organic carbon up to five times higher than tropical upland forests (Donato et al., 2011). Because of their significant contributions to people's well-being, biodiversity, and climate mitigation, mangroves are well-represented, for instance, in scientific investigations (Barrella and Ferraz, 2021; Sharma, 2017), policy and financial schemes conversations (Herr and Landis, 2016), and sustainable management, conservation, and restoration strategies (Lovelock et al., 2022).

Mangroves, despite their various benefits locally and globally, are

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highly threatened by several anthropogenic threats such as conversion to fishponds, oil palm plantations, economic development, and natural factors, including climate change and disasters (Richards and Friess, 2016; Thomas et al., 2017). On a global scale, Southeast Asia observed the greatest ratio of mangrove loss, approximately 50 % of the region showed evidence of mangrove loss (Thomas et al., 2017). Among the countries in the region, Indonesia faced rapid decline due to land-use conversion particularly converting mangroves to fishponds (Quevedo et al., 2023). Additionally, it has been noted that the cultivation and expansion of oil palm in Indonesia contributed to mangrove loss (Richards and Friess, 2016). Meanwhile in the Philippines, occurrence of strong typhoon is the one of the most frequent major drivers of mangrove degradation in the Philippines (Quevedo et al., 2022).

Anthropogenic and natural disturbances on mangrove forests can cause significant damage over time. For instance, in terms of impact on biodiversity, Carugati et al. (2018) reported that disturbed mangrove area exhibited a loss of 20 % of benthic biodiversity and local extinction of four Phyla. Similarly, roughly 40 % of 69 species considered restricted to mangrove forests are highly vulnerable to extinction due to mangrove habitat loss (Luther and Greenberg, 2009). Meanwhile, in terms of impact on ecosystem services, several studies have reported such as loss and/or reduction of provisioning, regulating, and cultural benefits (Malik et al., 2015; Kumar et al., 2017; Estoque et al., 2018; Polidoro et al., 2010). Thus, there has been a breadth of studies from small- to large-scale estimations of mangrove cover changes at local- to global-level and identifying the drivers (Buitre et al., 2019; Goldberg et al., 2020; Hagger et al., 2022). These investigations are critical information to obtain to rehabilitate and restore degraded mangrove areas, which in turn facilitate the recovery of biodiversity and ecosystem functioning (Goldberg et al., 2020; Hagger et al., 2022). The responses of governmental bodies (from local to national) are also equally important to successfully address these disturbances, yet, responses are tended to be "command and ban" approach and oftentimes failed to understand the underpinning causes, particularly in developing countries (Lukman et al., 2019).

Despite the progress on estimation of mangrove loss and identification of drivers, there remain knowledge gaps since changes in mangrove landscapes vary and depend on geographical and socio-ecological contexts. Geographic background can be influenced by the lifestyles and economic conditions of local people as well as government policies and initiatives. Country-specific environmental settings such as exposure to typhoons and earthquakes could also contribute to varying levels of mangrove degradation. There are remaining areas in certain regions around the world that are not well documented, and how mangrove loss contributes to livelihoods, biodiversity, and ecosystem service loss. Botha and Fouche (2000) suggested a combination of remote sensing and local knowledge to provide a more accurate assessment method, since physical assessment alone has been suggested to often lead to misleading results. Therefore, in this study, we used remote sensing to identify changes in mangrove forests in the Philippines and Indonesia and to verify consistency with perceptions derived from local communities.

Remote sensing is an efficient method of mangrove mapping and monitoring because visible spectral and spatial signatures of mangroves can be easily detected in satellite images. Mangrove forests cover vast areas and there are areas not accessible for field surveys but can be assessed using remote sensing technology. Satellite data analysis and geographic information systems (GIS) are one of the easiest ways to regularly monitor mangrove ecosystems. Several methods for detecting and mapping mangroves have been established (e.g., Maurya et al., 2021). Quantifying variation in mangrove distribution will lead to the promotion of better mangrove management. Thus, several studies have shown time series analysis of mangrove cover changes, aiming to provide more responsive actions in restoring and/or rehabilitating degraded mangrove areas (e.g., Buitre et al., 2019; Zhu et al., 2021). However, despite the advancement in remote-sensing applications, identification of drivers of such changes is often not included or largely overlooked (Quevedo et al., 2022).

Consequently, community perceptions of potential drivers and addressing the underpinning causes are needed to complement the remote sensing data for sustainable management of mangroves (Gnanappazham and Selvam, 2011). To date, there are many studies that examine the role of people's perceptions, for example, to understand the status and causes of coastal problems, as well as the trends of ecosystem changes (Lukman et al., 2021a). There is a growing evidence showing the importance of community perceptions in mangrove management (Nfotabong-Atheull et al., 2011; Owuor and Newton, 2019). The awareness of local communities on mangrove ecosystem services is an essential contributing factor on their participation to various mangrove management activities (Quevedo et al., 2021). However, it should be noted that these connections between ecosystem services and people's lives are frequently multifaceted, and their values and evaluations may differ between local communities and the government (Fedele et al., 2017). Thus, a better understanding of local communities' perceptions of mangrove cover changes is essential for successful mangrove management and decision-making (Sinare et al., 2016).

This study applied a mixed-method approach, employing remote sensing (quantitative) and focus group discussion and participatory mapping with local communities (qualitative). By doing so, we aim to (1) estimate mangrove losses and gains (effects) and (2) identify the main drivers (causes). After quantifying mangrove cover changes and determining the drivers, we also aim (3) to develop land cover maps highlighting mangrove forest areas, which are not yet available in the surveyed sites. Collectively, these objectives will provide (1) critical information on the present conditions of mangroves in local settings of the Philippines and Indonesia, (2) persistent drivers that can be addressed and those that can't be directly addressed but can be mitigated, and (3) readily available and accessible mangrove maps which are vital information for the protection, conservation, and sustainable management of mangroves.

2. Materials and methods

An overview of the research flow of this study is presented in Fig. 1. Based on the three objectives mentioned above, three analyses (triangulation method approach) were conducted. Firstly, we performed satellite data analyses covering the data processing, land use or cover change detection, and mangrove extraction. Next, community perceptions were collected using focus group discussion and participatory mapping to elucidate the proximate and underlying drivers as well as to identify areas with mangroves. Lastly, to achieve our third objective, we complemented the remote sensing data with community perception data to develop more detailed land use/land cover maps.

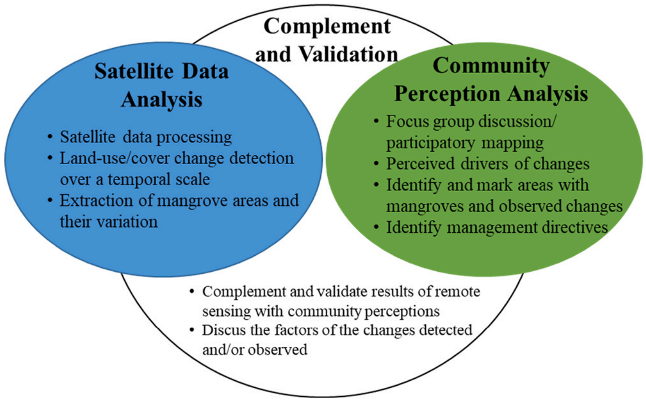

Fig. 1. Schematic diagram of the research flow employed in this study.

2.1. Study sites

The study sites are located in the municipality of Balangkayan in Eastern Samar province, Philippines and in Muara Gembong, Bekasi Regency, in West Java province, Indonesia (Fig. 2). Both countries are two of the most mangrove-rich areas in Southeast Asia. For example, at least 50 % of the world's approximately 65 mangrove species are in the Philippines (Garcia et al., 2013). Mangroves along these coastlines provide a variety of coastal resources that provide food and livelihood for many communities in the Philippines, but losses of mangroves due to natural disasters and other impacts have been noted (Hagger et al., 2022). For instance, the extent of damage to mangroves in Balangkayan caused by Typhoon Haiyan was around 86 % in terms of tree density and 68 % in terms of basal area (Alura et al., 2015). Community perceptions collected in Balangkayan have also revealed the massive change in their mangrove areas caused by Typhoon Haiyan (Quevedo et al., 2022). Meanwhile, large land use conversions occurred in Indonesia (Richards and Friess, 2016). In West Java province, conversion of mangrove areas to aquaculture ponds, residential areas and agricultural lands were documented (Quevedo et al., 2023). From the case of Muara Gembong, Bekasi Regency, mangrove degradation was largely attributed to land clearing by locals to produce new shrimp ponds and fishponds (Nugraha et al., 2019). Both study sites have reported changes in mangrove areas, with different drivers. Thus, this study could provide insights on the diversity of management schemes in response to various threats. However, before developing threat-specific management and conservation strategies, it is instrumental to clarify first the types of changes observed in these mangrove sites. To avoid confusion in presenting and discussing the results, we simply referred our sites as "Balangkayan" and "Muara Gembong."

2.2. Satellite data preprocessing and analysis

The satellite data (Landsat-8 OLI, Landsat-7 ETM+ and Landsat-5 TM (Level −2 surface reflection products)) used for creating land use land cover maps of Balangkayan and Muara Gembong were acquired from the USGS Earth Explorer (earthexplorer.usgs.gov). The Landsat-5 TM imagery data contains spectral wavelength 0.45–0.52 (Blue), 0.52–0.60 (Green), 0.63–0.69 (Red), 0.77–0.90 (NIR), 1.55–1.75 (SWIR), 10.40–12.50 (TIR) and 2.09–2.35 (SWIR). Meanwhile, the Landsat-8 OLI imagery data have spectral wavelength 0.435–0.451 (Coastal Aerosol), 0.452–0.512 (Blue), 0.533–0.590 (Green), 0.636–0.673 (Red), 0.851–0.879 (NIR), 1.566–1.651 (SWIR1) and 2.107–2.294 (SWIR2). Both data have a 30-meter resolution. The satellite image dates used for each study site included 2000/2/12, 2005/1/24, 2010/2/23, 2013/7/9, 2014/2/18 and 2021/8/16 for Balangkayan and 2000/10/8, 2013/8/25 and 2022/9/3 for Muara Gembong.

Both the Philippines and Indonesia are tropical countries, so clouds often cover the entire area of the study sites. Therefore, for our remote sensing analyses, we have retrieved satellite images that have the least amount of clouds. In images where a large amount of cloud cover is observed, we visually confirmed the location, and if cloud cover is over the ocean, we still utilized them since it would not affect the analysis. For these reasons, the year and date of satellite images used for analysis at each site differed. For Balangkayan, the 2014 image was selected for the comparison with 2013 image to indicate the changes before and after the typhoon made landfall, even though it had slightly more cloud cover than the other images. For images that contain clouds, we used the Cloud Masking tool, a QGIS plug-in, to divide the clouds into one class. Geometric correction was done for these images and clipped as two target areas.

Several attempts have been made to propose effective methods to capture the wide distribution of mangroves (For example, Baloloy et al.,

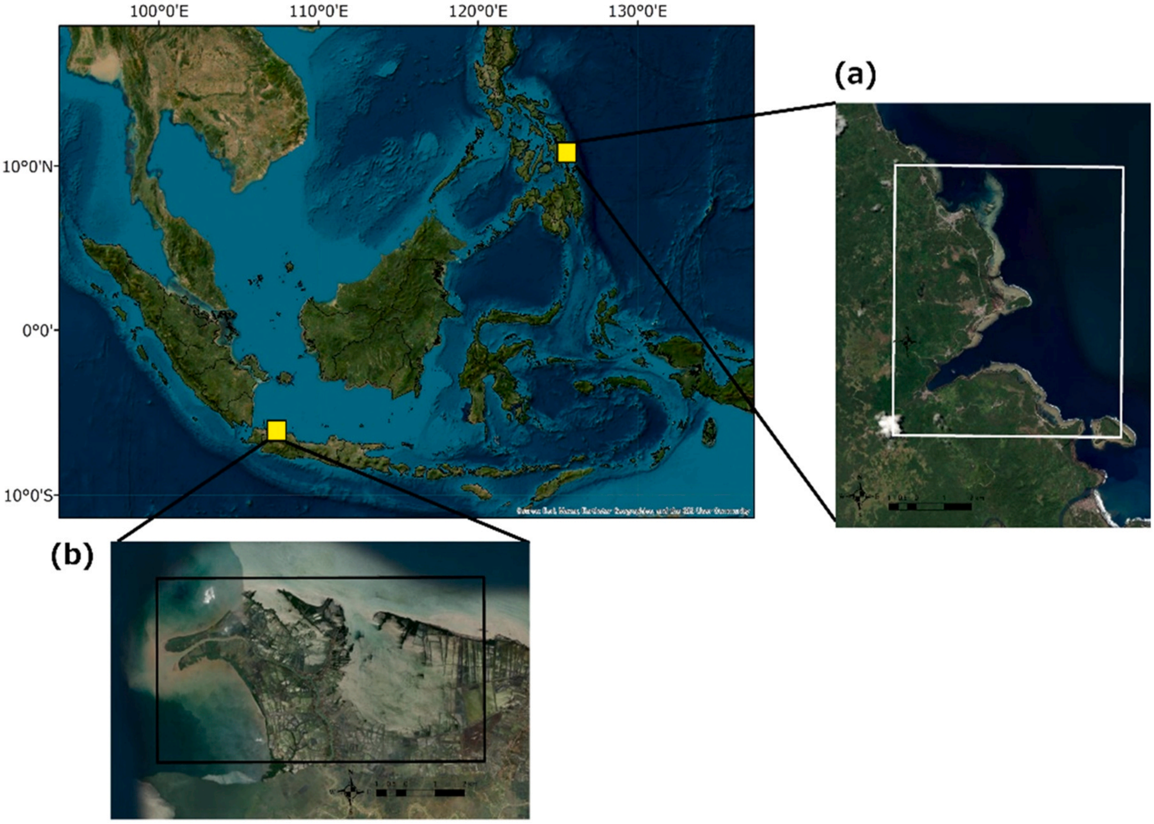

Fig. 2. Location map of the study sites: (a) Balangkayan, Eastern Samar province, Philippines and (b) Muara Gembong, Bekasi, West Java province, Indonesia. [Map source: Satellite images; USGS].

2020). Among them, Alsaaideh et al. (2013) devised a method to detect mangrove forests by using reflective properties. In this study, we obtained the Normalized Differential Water Index (NDWI) and Normalized Differential Vegetation Index (NDVI), SWIR/NIR band ratio, and band SWIR difference from Landsat TM and OLI using the method devised by Alsaaideh et al. (2013) and generated composite images. NDWI (Gao, 1996) is sensitive to changes in the water content of vegetation. It is an independent vegetation index that was developed to delineate vegetation water content features in remotely-sensed imagery. NDWI is expressed using the following:

$$NDWI = (NIR - SWIR)/(NIR + SWIR)$$

NDVI was used widely to monitor the quality and distribution of vegetation. The formula for this index is the following equation (Rouse et al., 1973).

$$NDVI = (NIR - Red)/(NIR + Red)$$

Two methods were used for image classification. In supervised classification, reference samples with known land cover were used in the first step to "train" the classification procedure, and then samples with unknown land cover were classified in the second step. In unsupervised classification, there was no reference sample. Classes were defined according to different criteria. In unsupervised classification, the k-means algorithm is widely used in various contexts (Hastie et al., 2009). It requires the specification of the number of groups (or clusters) represented as K, and the algorithm proceeds by assigning observations to groups according to their distance to the group mean (Lloyd, 1982). If these averages are unknown (which is the most common case), several initial values are randomly selected, observations are assigned as described above, the center of the group is recalculated, and the entire procedure is repeated until the group assignment is stable. This method works with multivariate data using multivariate distances such as Euclidean distance. For this analysis, we performed unsupervised clustering on the images. The K-means clustering method was used for the algorithm. The Python programming language was used to implement the algorithm. Based on these results, land use and land cover maps were prepared and integrated with topographic information to extract land cover areas such as mangrove forests. Cloud classes that could not be removed by cloud masking were also created as a result of classification. The six final classification classes include water areas, bare land, mangroves, other vegetation, urban areas, and clouds. The flow of this method is shown in Fig. 3.

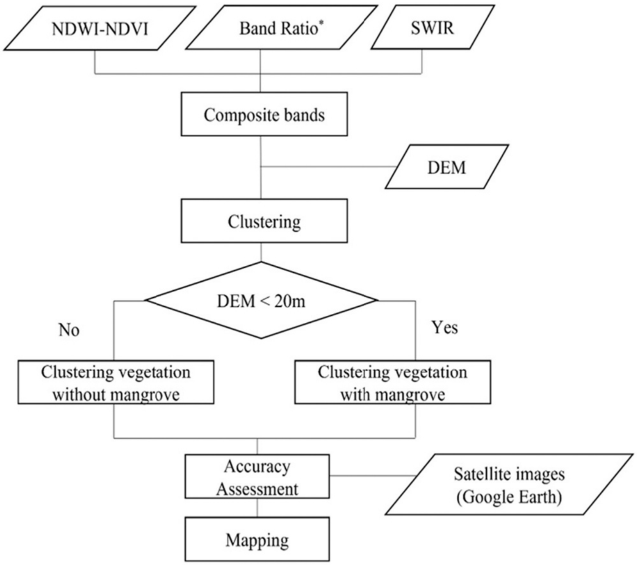

Fig. 3. Flowchart of the land-use/land-cover mapping procedures. Band Ratio shows SWIR – NIR.

Over 300 random points were created for each clustered image. As a sampling method, stratified random sampling was performed in the analysis. This method is recommended from the perspective of statistical rigor and practicality (Thomlinson et al., 1999). Overall accuracy and kappa coefficient were calculated using Google Earth and Sentinel −2 images. Additionally to the RGB images, near-infrared false color images, NDVI images, and NDWI images were created from Sentinel-2 images and used in conjunction with Google Earth images for validation. For mangroves, we also used the Global Mangrove Map provided by JAXA as a reference. The Global Mangrove Watch (GMW) was launched in 2011 under the Kyoto Carbon Observation Project by JAXA. The Global Mangrove Watch (GMW) dataset (version 3.0) is a map of the distribution of mangrove forests worldwide for 11 years, intermittently, from 1996, 2007–2010, and 2015–2020. The analysis utilizes the years 2010, 2015, and 2020 that are closest to the target year. These images have a resolution of 25 m. Validation of mangroves from other years referred to high-resolution images from Google Earth.

2.3. *Community perceptions - focus group discussion and participatory mapping*

Drivers of changes in mangrove landscapes were identified through focus group discussion and participatory mapping. The former was utilized to gather information on the potential proximate and underlying drivers of mangrove cover changes while the latter was used to identify areas with mangroves to supplement the land cover maps generated using remote sensing. The two activities were conducted in Muara Gembong from 6th to 7th of December 2022 with seven participants. The participants included the leaders and members of two civil society organizations, namely POKDARWIS Alipbata group (4 individuals) and Kebaya group (3 individuals). These community organizations promote the protection, restoration, and conservation of mangroves in Muara Gembong through ecotourism and alternative livelihood programs. Limiting the number of participants in focus group discussion could encourage active participation and equal opportunity in sharing opinions and foster a more meaningful and in-depth analysis of varying perceptions (Cortini et al., 2019; Quevedo et al., 2024). The discussions were conducted in Bahasa and were simultaneously translated into English by the third author. Participants' responses were recorded accordingly by the first and second authors. For the participatory mapping, the participants identified and marked the areas with mangroves (Fig. 4).

For Balangkayan, we have utilized secondary sources to supplement the land cover maps produced using remote sensing. Insights from focus group discussion and participatory mapping were retrieved from studies conducted by Quevedo et al. (2022); (2024). The discussion was conducted on the 21st of October 2022 with 19 participants, representing civil society organizations (2 individuals), local government members (13), and village-level officials (4). These sectors are in charge in the protection and restoration of mangroves, encompassing ordinance formulation, policy enforcement, and restoration activity implementation. Meanwhile, participatory mapping was conducted done in 2019.

Although the focus group discussion and participatory mapping were conducted once in each site, nevertheless, this allowed us to have sufficient time (approximately 3 hours) to let the participants mark the mangrove areas accurately as possible and express their views on the drivers genuinely.

3. Results

3.1. *Mangrove cover changes*

The results of the accuracy evaluation for Balangkayan are shown in Tables 1 to 6. The overall accuracy assessment obtained from the stratified random sampling process ranges from 95 % to 99 %. It

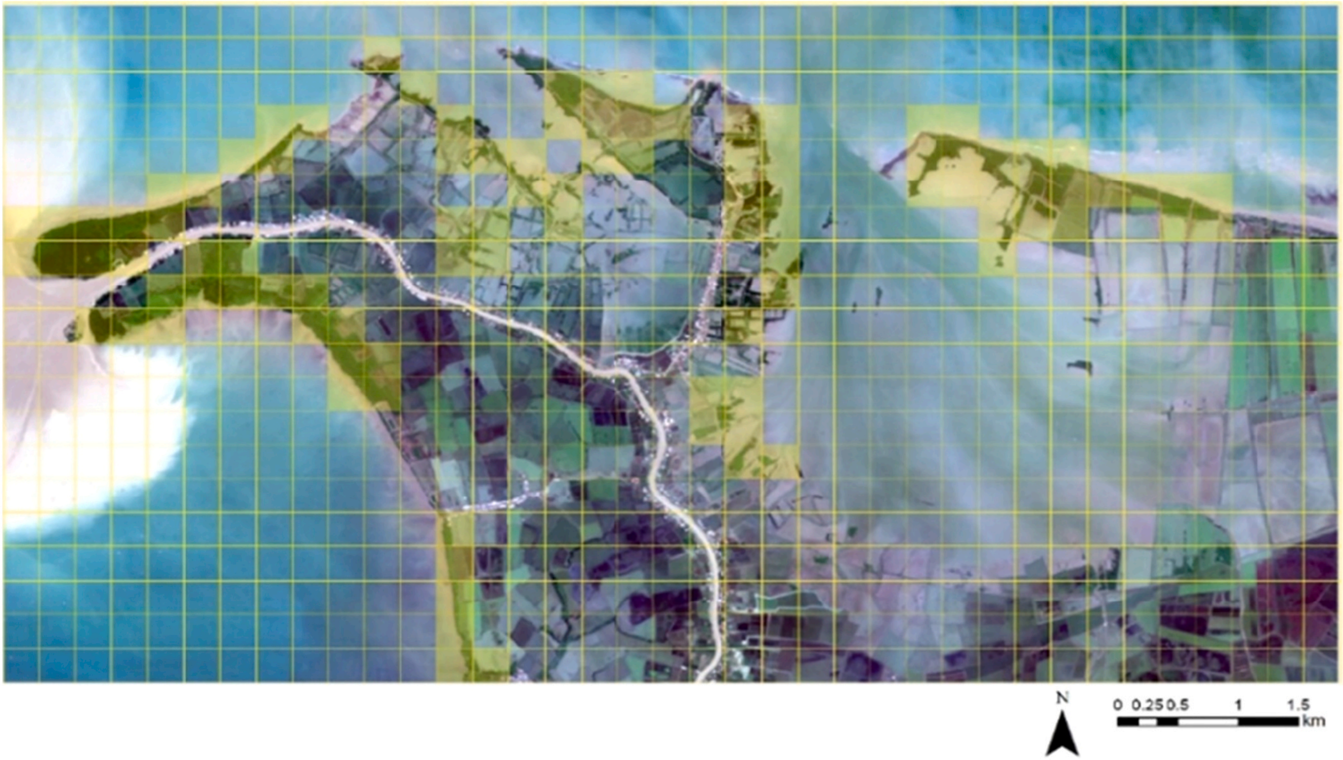

Fig. 4. Location of mangrove areas in Muara Gembong based on participants' perceptions (yellow parts). [Map source: Sentinel-2 image, 2022].

Table 1
Results of accuracy assessment of the clustered maps for Balangkayan in 2000.

	Water	Soil	Vegetation	Mangrove	City	Cloud	Total	User accuracy
Water	204	0	0	0	0	0	204	1.00
Soil	0	22	10	0	0	2	34	0.65
Vegetation	0	1	102	1	0	1	105	0.97
Mangrove	0	0	1	17	0	0	18	0.94
City	0	5	1	0	13	1	20	0.65
Cloud	0	0	0	0	0	14	14	1.00
total	204	0	0	0	0	0	204	
Producer accuracy	1	0.92	0.90	0.95	1.00	0.82		
Overall Accuracy	0.95							
kappa	0.91							

Table 2
Results of accuracy assessment of the clustered maps for Balangkayan in 2005.

	Water	Soil	Vegetation	Mangrove	City	Cloud	Total	User accuracy
Water	167	0	0	0	0	0	167	1.00
Soil	0	36	1	0	0	1	38	0.95
Vegetation	0	0	115	1	1	0	117	0.98
Mangrove	0	0	7	16	0	0	23	0.70
City	0	6	0	0	14	5	25	0.56
Cloud	0	1	0	0	0	25	26	0.96
total	167	43	123	17	15	31	396	
Producer accuracy	1	0.94	0.93	0.94	0.73	0.93		
Overall Accuracy	0.96							
kappa	0.92							

satisfied the overall accuracy standard of 85 % or more by Thomlinson et al. (1999). The user's accuracy ranges from 560 % to 100 % while producer's accuracy ranges from 58 % to 100 %. The broad range of accuracy in our study was attributed to city classification, which has high reflectance in most wavelength bands and is often confused with cloud and soil classes. Nevertheless, it did not affect our analysis since our main focus is on mangroves. Fig. 5 shows the calculated area of difference (amount of change in mangroves) in Balangkayan between 2013 and 2014 and 2014–2021. The area showed a decrease in mangroves in 2014. The decrease is consistent with the results of previous studies (e.g., Cabello et al., 2021) and are probably due to Typhoon Haiyan, which made landfall in November 2013. In the target area, about 192 ha was shown to have declined. However, from 2014–2021, the mangrove forest areas increased by about 500 ha. This could be

Table 3
Results of accuracy assessment of the clustered maps for Balangkayan in 2010.

	Water	Soil	Vegetation	Mangrove	City	Cloud	Total	User accuracy
Water	192	0	0	0	0	0	192	1.00
Soil	1	28	1	0	2	0	32	0.88
Vegetation	0	0	115	2	0	0	117	0.98
Mangrove	0	0	0	18	0	0	18	1.00
City	0	7	0	0	13	0	20	0.65
Cloud	0	0	0	0	0	18	18	1.00
total	193	35	116	20	15	18	397	
Producer accuracy	0.99	0.95	0.99	0.90	0.58	1.00		
Overall Accuracy	0.98							
kappa	0.96							

Table 4
Results of accuracy assessment of the clustered maps for Balangkayan in 2013.

	Water	Soil	Vegetation	Mangrove	City	Cloud	Total	User accuracy
Water	194	0	0	0	0	1	195	0.99
Soil	0	34	2	0	0	2	38	0.89
Vegetation	0	0	111	0	0	0	111	1.00
Mangrove	0	0	0	22	0	0	22	1.00
City	0	3	1	0	14	2	20	0.70
Cloud	1	1	0	0	0	8	10	0.80
total	195	38	114	22	14	13	396	
Producer accuracy	1.00	0.95	0.98	1.00	1.00	0.66		
Overall Accuracy	0.98							
kappa	0.95							

Table 5
Results of accuracy assessment of the clustered maps for Balangkayan in 2014.

	Water	Soil	Vegetation	Mangrove	City	Cloud	Total	User accuracy
Water	149	0	0	0	0	1	150	0.99
Soil	0	44	0	0	0	3	47	0.94
Vegetation	0	0	114	0	0	0	114	1.00
Mangrove	0	0	0	15	0	0	15	1.00
City	0	7	1	0	17	0	25	0.68
Cloud	1	0	0	0	0	44	45	0.98
total	150	51	115	15	17	48	396	
Producer accuracy	0.99	0.99	1.00	1.00	1.00	0.92		
Overall Accuracy	0.98							
kappa	0.96							

Table 6
Results of accuracy assessment of the clustered maps for Balangkayan in 2021.

	Water	Soil	Vegetation	Mangrove	City	Cloud	Total	User accuracy
Water	193	0	0	0	0	0	193	1.00
Soil	0	40	0	0	0	0	40	1.00
Vegetation	0	0	99	2	0	0	101	0.98
Mangrove	0	0	4	28	0	0	32	0.88
City	0	5	1	0	14	0	20	0.70
Cloud	0	2	0	0	0	10	12	0.83
total	193	47	104	30	14	10	398	
Producer accuracy	1.00	0.93	0.96	0.93	1.00	1.00		
Overall Accuracy	0.98							
kappa	0.96							

attributed to several mangrove planting programs in the municipality (Quevedo et al., 2022; 2024). Overall, mangroves in this area have increased by about 312 ha in the last 20 years

The results of the accuracy assessment for Muara Gembong are shown in Tables 7 to 9. Results from the stratified random sampling process showed an overall accuracy ranging from 95 % to 98 %. User's accuracy ranged from 70 % to 100 % while producer's accuracy ranged from 78 % to 100 %. The producer's accuracy satisfies a threshold of 70 %, and is considered acceptable (Thomlinson et al., 1999). The land cover of mangroves in Muaragembong Sub-district, Bekasi Regency between 2000 and 2022 showed variations (Fig. 6). For instance, based on the calculations, mangrove areas decreased by about 76.86 ha and increased by 220.86 ha from 2000 to 2013, whereas a loss of 155.97 ha and gain of 188 ha was observed from 2013 to 2022. Overall, an increase of approximately 176.13 ha was recorded between 2000 and 2022, indicating the recovery of mangrove forests in Muara Gembong due to rehabilitation efforts. Our results agree with the findings of Ditian Meganatha et al. (2021), where they reported that mangrove areas increased by 20.05 % from 2000 to 2010 and by 181.39 % from 2010 to 2020 across Muara Gembong district. The decline of mangroves between

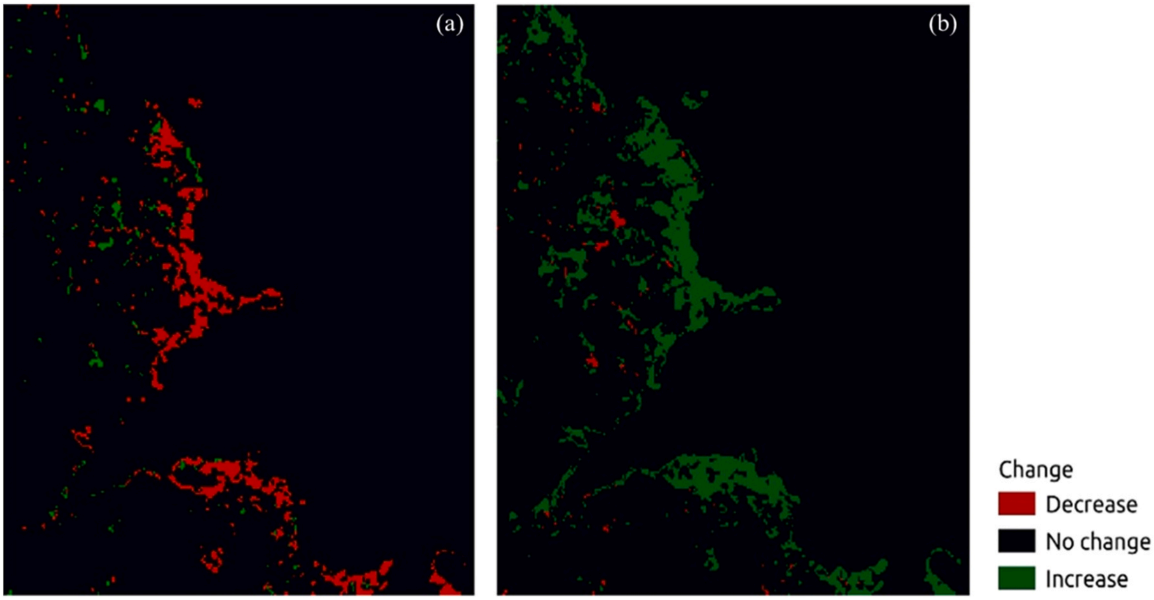

Fig. 5. Mangrove Cover Change in (a) 2013–2014 and (b) 2014–2021 in Balangkayan.

Table 7
Results of accuracy assessment of the clustered maps for Muara Gembong in 2000.

	Water	Soil	Vegetation	Mangrove	City	Total	User accuracy
Water	227	4	5	0	0	236	0.96
Soil	3	105	2	0	0	110	0.95
Vegetation	2	3	31	0	0	36	0.86
Mangrove	0	0	0	6	0	6	1.00
City	0	0	1	0	6	7	0.86
total	232	112	39	6	6	395	
Producer accuracy	0.98	0.94	0.79	1.00	1.00		
Overall Accuracy	0.95						
kappa	0.92						

Table 8
Results of accuracy assessment of the clustered maps for Muara Gembong in 2013.

	Water	Soil	Mangrove	City	Total	User accuracy
Water	350	0	0	0	350	1.00
Soil	2	18	0	0	20	0.90
Mangrove	0	2	13	0	15	0.87
City	0	3	0	8	11	0.73
total	352	23	13	8	396	
Producer accuracy	0.99	0.78	1.00	1.00		
Overall Accuracy	0.98					
kappa	0.95					

2013 and 2022 was attributed to coastal erosion.

3.2. Land use and land cover changes

In Balangkayan, mangrove forests have declined due to urbanization and tropical cyclones. From 2000 to 2013, urban areas have increased which could have driven the decrease in mangrove areas (Figs. 7, 8). Results from previous studies have also attributed the reduction of mangroves due to urbanization, where mangrove forests were cut for residential spaces from 2001 to 2012 (Quevedo et al., 2022). Additionally, the occurrence of a major typhoon (Typhoon Haiyan) that made landfall in Eastern Samar in 2013 have significantly contributed to the decrease in mangroves during the target period. The estimated results of this analysis showed that approximately 192 ha of mangroves were lost from 2013 to 2014 (Figs. 7, 8). However, current data shows

Table 9
Results of accuracy assessment of the clustered maps for Muara Gembong in 2022.

	Water	Soil	Vegetation	Mangrove	City	Total	User accuracy
Water	297	0	0	0	0	297	1.00
Soil	5	45	0	1	0	51	0.88
Vegetation	4	3	16	0	0	23	0.70
Mangrove	0	0	0	17	0	17	1.00
City	0	2	0	0	7	9	0.78
total	306	50	16	18	7	397	
Producer accuracy	0.97	0.90	1.00	0.94	1.00		
Overall Accuracy	0.96						
kappa	0.93						

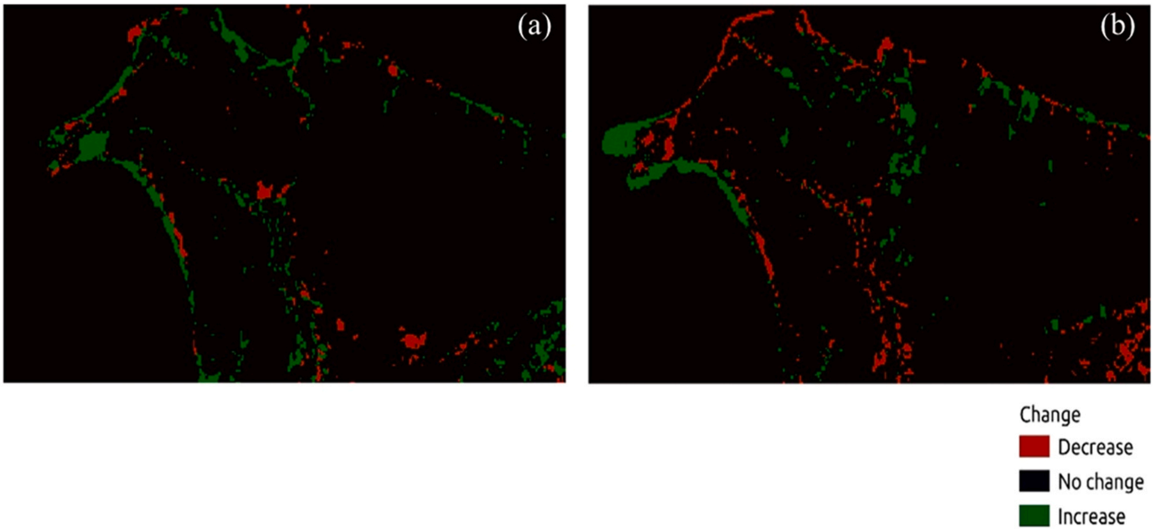

Fig. 6. Mangrove Cover Change in (a) 2000–2013 and (b) 2013–2022 in Muara Gembong.

mangroves are recovering in Balangkayan, with an increase of about 504 ha from 2014 to 2021. Similar findings were reported by Long et al. (2016); they documented that mangroves have recovered within 18 months after the destruction of Typhoon Haiyan.

Meanwhile, in Muara Gembong, significant changes were observed along the shorelines due to coastal erosion and subsequent land use conversions. Indonesia has lost nearly 1 million ha of mangroves since 1800, about 800,000 ha of which were converted to fishponds between 1970 and 2003 (Ilman et al., 2016). It has been pointed out that large-scale coastal erosion is caused by mangrove loss due to conversion to fishponds in the study area (Nugraha et al., 2019). Despite this, our results indicated that from 2000 to 2013, mangroves have increased from 106 to 250 ha, and continued to expand to 283 ha in 2022 (Figs. 9, 10).

Fishponds account for a large proportion of the area in this district, however, the number of fishponds has decreased significantly due to flooding caused by erosion. Land use and land cover maps obtained from our analysis showed similar trends, with some areas being inundated inland by erosion due to shoreline changes from 2000 to 2013 (Fig. 10). However, with the 30 m resolution of Landsat satellite images, it is difficult to extract the areas with fishponds in detail. To address this limitation, fishponds, which is one of land use classes, were digitized using Google Earth high-resolution satellite imagery and Sentinel-2 satellite imagery. Google Earth satellite imagery was first available for the region in 2001, so we used images from 2001 and 2022. The results showed that an extensive coastal erosion have occurred from 2000 to 2022, flooding many fishponds. It was estimated that the number of fishponds in Muara Gembong have decreased from 3251.32 ha in 2001–1870.75 ha in 2022 (Fig. 11).

3.3. *Community perceptions of mangrove cover changes and their drivers*

Overall, participants in Muara Gembong are generally aware of mangroves and their benefits. They were able to identify and mark the areas with mangroves (Fig. 4). Their perceptions provided insights on various drivers that influence mangrove cover changes. Firstly, they have shared that coastal erosion is the main culprit of mangrove degradation in the area and has been persistent since the 1980s. They also perceived that climate change is affecting the mangrove landscape in the area. For instance, one of the participants observed that sea level rise as an impact of climate change is already happening and affecting the growth of mangrove seedlings. Due to mangrove degradation, they experienced sea water flooding during high tides. The participants acknowledged the impacts caused by mangrove degradation, so they have initiated various mangrove management activities which began in 2016. Specifically, they aim to strengthen the protection of remaining mangroves since it is important for migratory birds and endemic species.

For Balangkayan, participants were able to recall the destruction of their mangroves in 2013 caused by Typhoon Haiyan (Quevedo et al., 2024). Participatory mapping also captured the areas where massive changes occurred (Quevedo et al., 2022). Communities living near the affected areas discussed the protection benefits of mangroves to their properties. Despite this, they shared that there are still persistent prohibited activities being done such as harvesting mangrove trees as raw materials in building houses. Nevertheless, local ordinances are being implemented which the participants thought could stop these illegal activities.

4. Discussion

4.1. *Changes in mangrove areas and its drivers*

Mangrove areas in Balangkayan in Eastern Samar, Philippines and Muara Gembong in West Java, Indonesia have fluctuated over the last 20 years. The decreasing trend of mangrove forests has been identified as a major phenomenon in many previous studies. These declines were mainly due to anthropogenic activities (e.g., agriculture and tourism) and natural disasters (e.g., tropical cyclones, coastal erosion) (Curnick et al., 2019). Nevertheless, expansion of mangrove forests has also been reported in several areas (e.g., Liu et al., 2022). To produce accurate land cove maps with emphasis on mangrove cover, it is important to monitor these changes (gains and losses).

Mangroves are generally described as being more resilient to disturbance by nature than by human activity. However, the downward trend observed in Balangkayan in 2014 was mainly due to Typhoon Haiyan that made landfall in several areas in the Philippines in November 2013. The classification results in Figs. 5 and 7 showed that mangroves along the Eastern Samar coastline varied through time. For instance, previous policies being implemented were aimed to stimulate the fishing sector by promoting the development of large fish ponds rather than the protection of mangrove forests. Although these policies progressed the economic development, it resulted to negative consequences such as vulnerability of coastal areas to tsunamis and storm surges.

From 2014 onwards, subsequent conservation activities in Balangkayan were conducted such as mangrove planting (Quevedo et al., 2022). There is also an increase of participation of communities to mangrove-related management (Quevedo et al., 2020). Consequently,

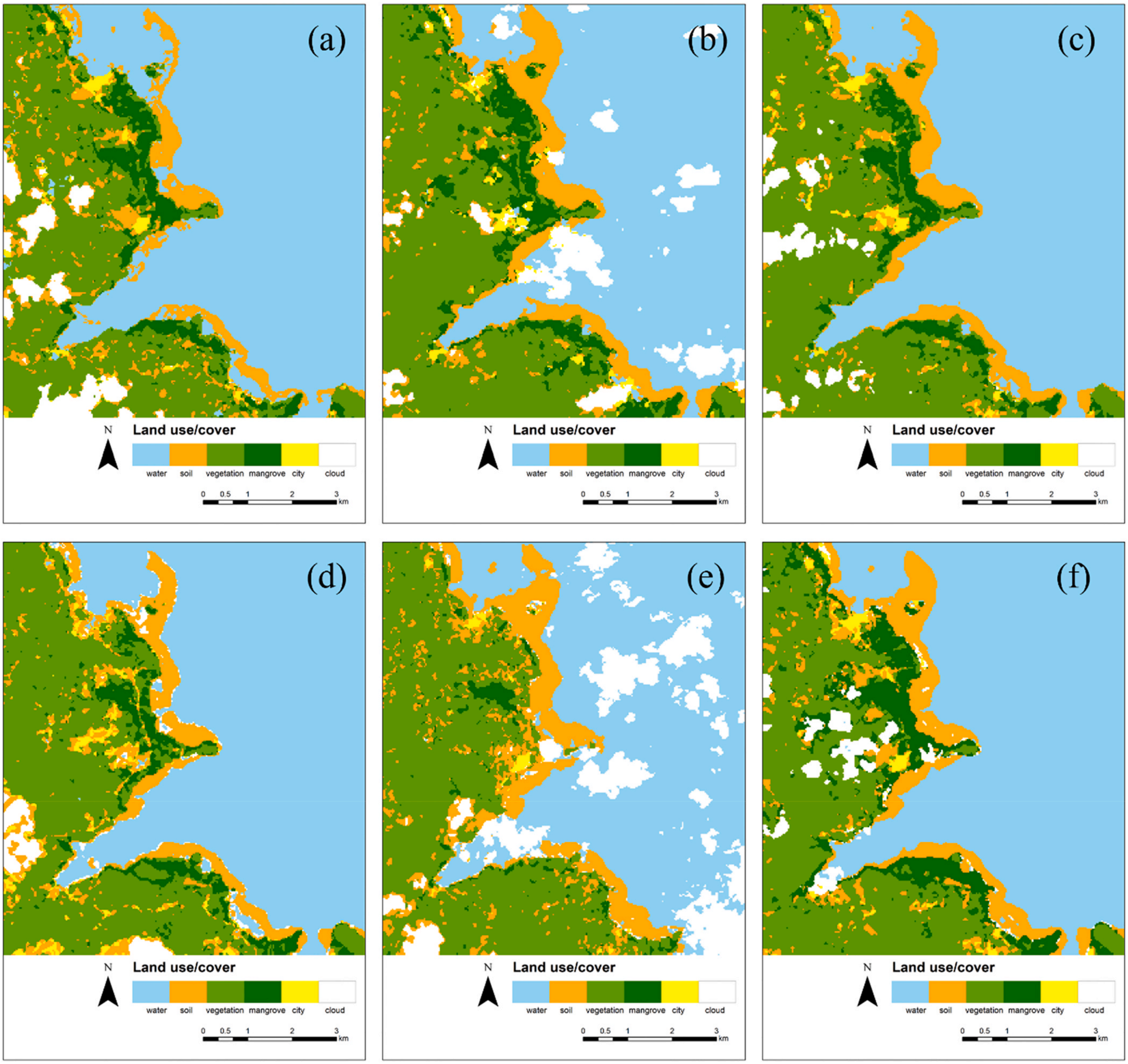

Fig. 7. Land use/cover clustering of (a) 2000, (b) 2005, (c) 2010, (d) 2013, (e) 2014, (f) 2021 Landsat images of Balangkayan.

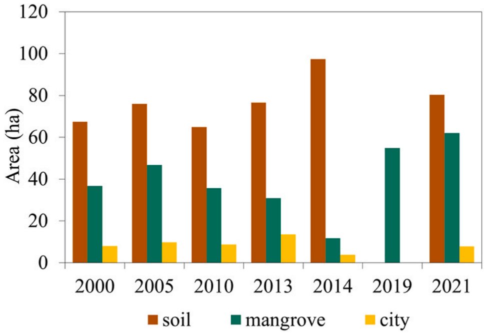

Fig. 8. Land use/cover change detection and estimation in Balangkayan from 2000 to 2021. For 2019, only mangrove ground truth data is reflected.

these actions led to recovery of mangroves after the 2013 typhoon, and have continued to increase.

Meanwhile, the development and expansion of aquaculture industry in Muara Gembong over the years have been considered as the main driver of mangrove degradation (Nugraha et al., 2019). In general, the loss of mangrove forests in coastal areas of Bekasi district poses a threat, namely coastal erosion. Nugraha et al. (2019) reported that three villages in Muara Gembong had been displaced and consequently disappeared due to coastal erosion. Coastal erosion in Muara Gembong is a negative by-product of mangrove degradation since land-use changes affect erosion and sedimentation rates (Sanjoto and Nugraha, 2019).

The most significant shoreline change on the north coast of West Java is in the area encompassing Muara Gembong, which recorded a maximum shoreline retreat speed of 200 m/year over the past 20 years (2000–2022), with a total inundation area of 10.2 km2 (Solihuddin et al., 2021). Having experienced these losses, active mangrove conservation efforts have been undertaken by the community in this area.

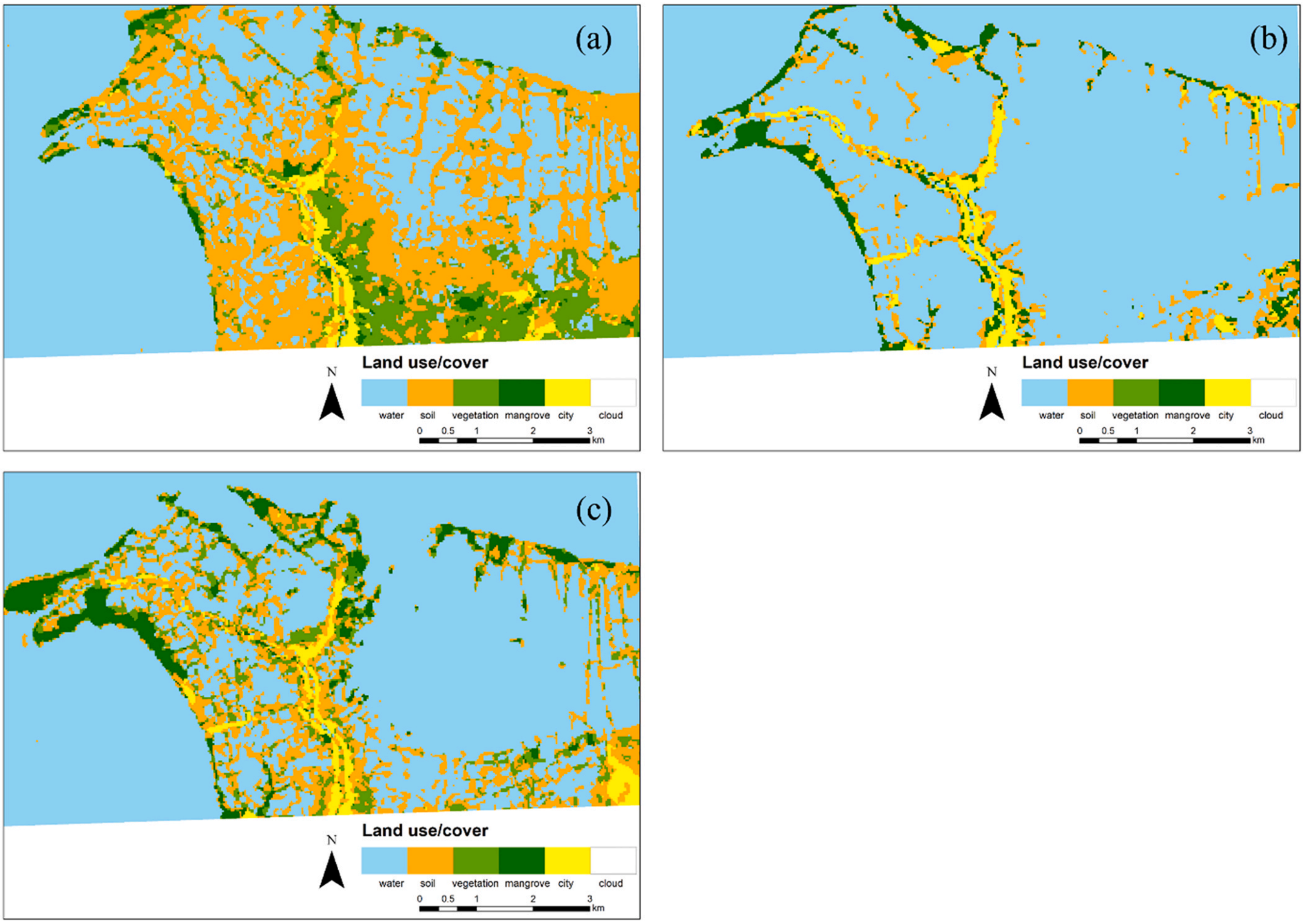

Fig. 9. Land use/cover clustering of (a) 2000, (b) 2013, and (c) 2022 Landsat images of Muara Gembong.

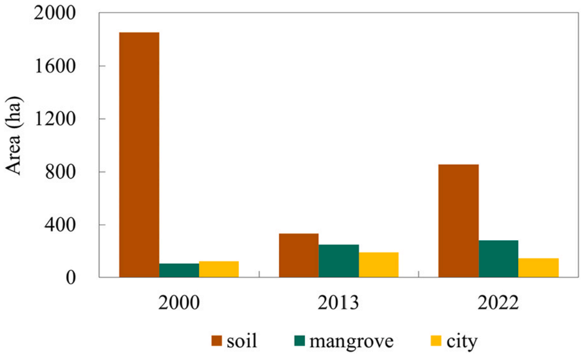

Fig. 10. Land use/cover change detection and estimation in Muara Gembong in 2000, 2013, and 2022.

Our analysis shows an increase in mangrove area of approximately 180 ha over the roughly 20 years from 2000–2022, consistent with the upward trend shown by Ditian et al. (2021).

4.2. Community perceptions of mangrove cover changes

In the Philippines, local people perceived that natural disasters are the number one threat that damages mangroves, which in turn result to the loss and/or reduction of their valuable benefits (Delfino et al., 2015). Findings from focus group discussion and participatory mapping captured the same observation, with huge mangrove cover loss in Balangkayan caused by Typhoon Haiyan in 2013 (Quevedo et al., 2022; 2024). Evidently, local communities are highly aware of the impact of natural disturbances. Balangkayan, which is located in Eastern Visayas region, is highly vulnerable to tropical cyclones. The region is often frequented by typhoons, with an average frequency of 2.2 typhoons making landfall per year (Takagi and Esteban, 2015). The Philippines, being a country prone to typhoons has a long history of large-scale implementation of mangrove planting activities to address mangrove losses caused by natural disasters and human activities (Primavera et al., 2016). Thus, in Balangkayan, efforts to rehabilitate and restore degraded mangrove areas are being implemented after catastrophic events. To date, there are guidelines available for assessment of mangrove damage to help establish the need for additional tree planting and manage funds wisely (PTFCF and ZSL, 2015). These established practices are considered to support the awareness and activities of local residents toward mangroves.

Meanwhile, Indonesia's political, social and economic situation has promoted the exploration and exploitation of natural resources, transforming the face of land ownership and resulting in the massive destruction of the mangrove forests of Muara Gembong (Nihayah, 2017). The destruction has led to increased coastal erosion in the area since 1970, threatening the livelihoods of local residents. Particularly notable was the coastal erosion that occurred between 2000 and 2022, flooding large swaths of the interior. Focus group discussion revealed that they were acutely aware of the role of mangroves in such disasters. Moreover, they were cognizant of the benefits of mangroves in controlling coastal erosion, preventing saltwater intrusion, protecting various organisms, and providing food. From political perspectives, they

Fig. 11. Location map of fishponds in Muara Gembong in (a) 2001 and (b) 2022. The yellow lines indicate fishponds. The locations of these ponds were confirmed based on SENTINEL-2 images provided by ESA.

recognized the benefits of receiving funding from industry, universities and other educational institutions and how such funding can actively promote mangrove conservation efforts.

Community members in Muara Gembong have been doing conservation works since 2013. Around 2016, the planting of mangroves began, contributing to the increase in mangroves. Moving forward, the concept such as bundled ecosystem services and Indonesia's policy of aquaculture practice can be promoted to complement the mangrove ecosystem conservation (Lukman et al., 2021b). Particularly for Muara Gembong, aquaculture is still a part of the local livelihoods, while creative and unique ways of mangrove usages such as creation of foods and beverages as part of the community activities are increasingly recognized.

Overall, community perceptions can complement the data derived from remote sensing. For instance, remote sensing can effectively quantify mangrove cover changes but it lacks the capacity to identify the factors driving these changes. The findings of this study show that community perceptions (through focus group discussion and participatory mapping) can identify these drivers. Our results also showed that perceptions can capture the similarities and differences of these drivers in local settings. For instance, we documented that natural disturbances are perceived to be the number one threat in both study sites. Yet, the type of natural disaster is different – typhoons in Balangkayan and coastal erosion in Muara Gembong. In terms of management, both sites acknowledged the role of local stakeholders, yet, communities in Muara Gembong are more invested that Balangkayan. This information is critical when developing and implementing site-specific management activities. It is imperative to identify the motivations of local stakeholders to successfully operationalize such activities.

5. Conclusion

This study applied a triangulation method and demonstrated the validity in two contexts of developing countries, Balangkayan in the Philippines and Muara Gembong in Indonesia. Specifically, we conducted satellite data and community perception analyses. In doing so, we obtained unique insights into the interrelationship of extent of changes and corresponding drivers.

The authors extracted changes in land cover and land use using satellite imagery and discussed the quantification of changes in mangrove cover. Furthermore, we also conducted focus group discussion and participatory mapping to identify the areas where changes occurred and the potential drivers. A strong typhoon in 2013 resulted to a significant decrease in mangroves in Balangkayan. However, in the following years (2014 onwards), mangrove cover increased, indicating that assisted regeneration (mangrove planting) can facilitate further rehabilitation of the degraded areas. The increase can also be attributed to the increase of conservation and afforestation activities by the government and local stakeholders. Similar findings were documented in Muara Gembong, were participants recognized the remaining areas with mangroves. They are also highly aware of the vital role of mangroves in providing protection against natural disasters such as cyclones, tsunamis and coastal erosion, and ecological value as habitat for birds and other species, including endemic species. Because of these benefits, they are active in mangrove conservation efforts such as mangrove planting activities, which in turn contributed to the increasing trend in mangrove cover.

In promoting mangrove conservation, quantification using remote sensing data and validation using community perceptions can effectively provide site-specific information across temporal and spatial scales. In more concrete terms, the site-specific findings presented in this study provide useful information in terms of (1) mangrove cover changes over a temporal scale, (2) proximate and underlying drivers of these changes over a spatial scale, and (3) land use and land cover maps highlighting mangroves in less explored sites. These points, despite being drawn from a local scale, offer global insights in the context of long-term effects of natural disasters and sustained mangrove planting efforts to mangrove blue carbon. Thus, in future investigations, it is important to develop strategies for sustainable mangrove management by understanding local community's perceptions and factors of long-term land-use and land-cover changes in conjunction with quantitative analysis.

CRediT authorship contribution statement

Yuki Sofues: Writing - original draft, Visualization, Validation, Software, Methodology, Data curation, Conceptualization. **Jay Mar D. Quevedo:** Writing - review & editing, Investigation, Data curation, Conceptualization. **Kevin Muhamad Lukman:** Writing - review & editing, Investigation, Conceptualization. **Ryo Kohsaka:** Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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