

Decadal Remote Sensing Analysis of Seagrass Changes in Palu Bay, Central Sulawesi

Musayyadah Tis'in¹, Rohani Ambo-Rappe^{2*}, Supriadi Mashoreng², Ahmad Faizal²

¹Faculty of Animal Husbandry and Fisheries, Tadulako University, Indonesia.

²Faculty of Marine Science and Fisheries, Hasanuddin University, Indonesia.

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Correspondent email:
musayyadahtisin@gmail.com

Abstract. Seagrass meadows provide a variety of material, non-material and regulatory coastal ecosystem service; however, as the distribution of seagrass beds changes over time due to both anthropogenic activities and natural factors, it is important to monitor changes in seagrass condition. Seagrass meadows in Palu Bay are threatened by activities such as coastal development and land reclamation. Additionally, the bay was hit by a significant tsunami in 2018, which could have impacted ecosystems in the bay, including seagrass meadows. The aim of this study was to detect changes in seagrass extent and distribution over a 10-year period from 2012 to 2022 and changes in land use over approximately a decade (2010 and 2021) through the use of remote sensing technology. Changes in seagrass meadow areal extent were analyzed using data from a 2012 Landsat 7 Satellite Data Acquisition and a 2022 Landsat 8 Satellite Data Acquisition. Water column correction was implemented using the Lyzenga Algorithm. The results showed a significant decrease in the area of seagrass meadows around the coastal area of Palu Bay. Seagrass meadows in 2012 and 2022 covered 127.08 Ha and 87.79 Ha, respectively, indicating a decrease in extent of 43.29 Ha. As the accuracy of the satellite data classification results was 80%, the results are considered acceptable. Anthropogenic activities (mainly mining and construction related) are strongly suspected as the main drivers of this decline, while earthquake and tsunami events likely aggravated the degradation of coastal ecosystems in Palu Bay, including seagrass meadows.

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1. Introduction

Seagrass meadows are coastal ecosystems that provide important ecosystem services (Mazarrasa et al., 2018; Wahyudi et al., 2020). These ecosystem services include fishing grounds that are important for the welfare of the global community (Nordlund et al., 2018), mariculture and recreational areas, research sites, sources of inspiration in the fields of art, architecture and advertisement, serving as a source of food for humans (McKenzie et al., 2021) and associated organisms (Nordlund et al., 2016). Some seagrasses are also important in the pharmaceutical field, including medicines used to treat diarrhea (UNEP, 2004). Regulatory services of seagrass meadows include their roles in reducing ocean acidification, stabilizing sediments and coastal protection (McKenzie et al., 2021), and as carbon sinks (Marba et al., 2015; Gullstrom et al., 2018; Serrano et al., 2018; McKenzie et al., 2021; Potouroglou et al., 2021).

Seagrass ecosystem services are very complex; however, these ecosystems are positioned relatively close to land and most are therefore threatened by anthropogenic activities, so that changes in seagrass ecosystem condition and extent can occur over time, due to anthropogenic activities (Waycott et al., 2009; Grech et al., 2012). Across the Indonesian Archipelago, human utilization of coastal areas has tended to increase in line with the rising human population, leading to ongoing coastal development, which is has been reported as one of the

main causes of seagrass decline in Indonesia (Unsworth et al., 2018). The site chosen for this research was Palu Bay in the Indonesian province of Central Sulawesi. Palu Bay has a coast that is vulnerable to changes in ecosystem condition. The bay and its coast span two administrative regions, namely Palu City and Donggala Regency. In both of these jurisdictions, some of the steep hills surrounding the Bay are mined, mainly open-cast mining of aggregate materials (*galian C* in the Indonesian mining classification), while several coastal areas are used for crushing and/or stockpiling the aggregate as well as the construction of ports or jetties for loading ships and barges with the mined material. While mining activities and associated development are one potential threat to the seagrass ecosystems around Palu Bay, natural phenomena in this tectonically active region such as the 2018 earthquake and tsunami also have the potential to cause change and affect the seagrass meadows in Palu Bay (Omira et al., 2019; Patria & Putra, 2020). Based on these conditions, there is a need for monitoring of the seagrass beds in Palu Bay.

Seagrass destruction has been occurred in various coastal areas in Indonesia makes it important to conduct seagrass monitoring (Setiawan et al., 2012; Supriyadi et al., 2018). Traganos et al. (2018) emphasize that seagrass mapping and monitoring are crucial for coastal area management planning, assisting coastal conservation and eventually climate change mitigation. Seagrass monitoring has been carried out in

several areas across Indonesia such as the Thousand Islands (Kawaroe *et al.*, 2010), Banten Bay (Setiawan *et al.*, 2012), the eastern waters of Bintan Island, Riau Islands (Supriyadi *et al.*, 2018) and around Bonebatang Island, Spermonde Archipelago (Mashoreng *et al.*, 2020). These studies have shown changes in seagrass meadow extent, with a general trend of decreasing seagrass area over time. Additionally, an assessment of Indonesian seagrass condition was conducted in 2018 using national seagrass monitoring data and showed that Indonesian seagrass meadows were mostly in moderate condition (Hernawan *et al.*, 2021).

Monitoring seagrass condition, especially areal extent changes, can often be done more efficiently via mapping. Several methods have been used for seagrass mapping, including lightweight drone and consumer grade cameras (Duffy *et al.*, 2018), side scan and underwater video (Vandermeulen, 2014), remote sensing (Wicaksono & Hafizt, 2013; Fauzan *et al.*, 2017; Thalib *et al.*, 2018; Topouzeli *et al.*, 2018; Traganos *et al.*, 2018; Wicaksono *et al.*, 2019; Nguyen *et al.*, 2021; Wicaksono *et al.*, 2022) and field survey (Short *et al.*, 2006). The use of remote sensing technology is one approach that has become widely used for monitoring changes of shallow marine habitats because it is effective and efficient, including for detecting changes in seagrass condition and extent (Mumby *et al.*, 1999; BIG, 2014; Giofandi *et al.*, 2020). In addition, remote sensing has the ability to cover a wide area (Topouzeli *et al.*, 2018).

With respect to managing Indonesia's valuable but threatened seagrass beds (Unsworth *et al.*, 2018), collaboration between stakeholders is needed to maintain the seagrass ecosystems and their functions, including monitoring to inform management. However, time series data are missing for many seagrass meadows, including those in Palu Bay. Therefore, the purpose of this research was to fulfill the need for data on the changes in seagrass condition in Palu Bay, Central

Sulawesi, over the past ten years (2012–2022) as well as changes in land-use over a decade (2010 and 2021), and to analyze whether the changes in seagrass extent could be attributed to the land use changes. This research applied remote sensing technology, analyzing Landsat 7 and Landsat 8 satellite data to detect changes in seagrass meadow extent over the study period, and is the first study of its kind in Palu Bay, Central Sulawesi, Indonesia. The information obtained from this research is expected to provide a scientific basis for integrated management of Palu Bay coastal ecosystems, considering that up to the present time the seagrass beds around Palu Bay have not been included in the list for coastal management priorities in Palu Bay. Furthermore, the information obtained is expected to contribute to the calculation of seagrass extent in Indonesia because until now the validated seagrass extent only cover around 16%-35% of the potential seagrass areas in Indonesia, as reported by Sjafrie *et al.* (2018). Therefore, information on the distribution and extent of seagrass beds in various parts of the country is still very much needed. The results of this study will also contribute to global information on seagrasses, including public perceptions regarding the roles of seagrass beds.

2. Methods

Study site and materials

This research comprised three main stages: preliminary analysis of the satellite data, field survey/ground-truthing, and data analysis. The flowchart of the research procedure is shown in Figure 1. The study site was the coastal waters of Palu Bay in Central Sulawesi Province, Indonesia (Figure 2). The field work was conducted in August 2022. The satellite data used comprised a Landsat 7 acquisition from 2012 and a Landsat 8 acquisition from 2022 with the description is shown in Table 1.

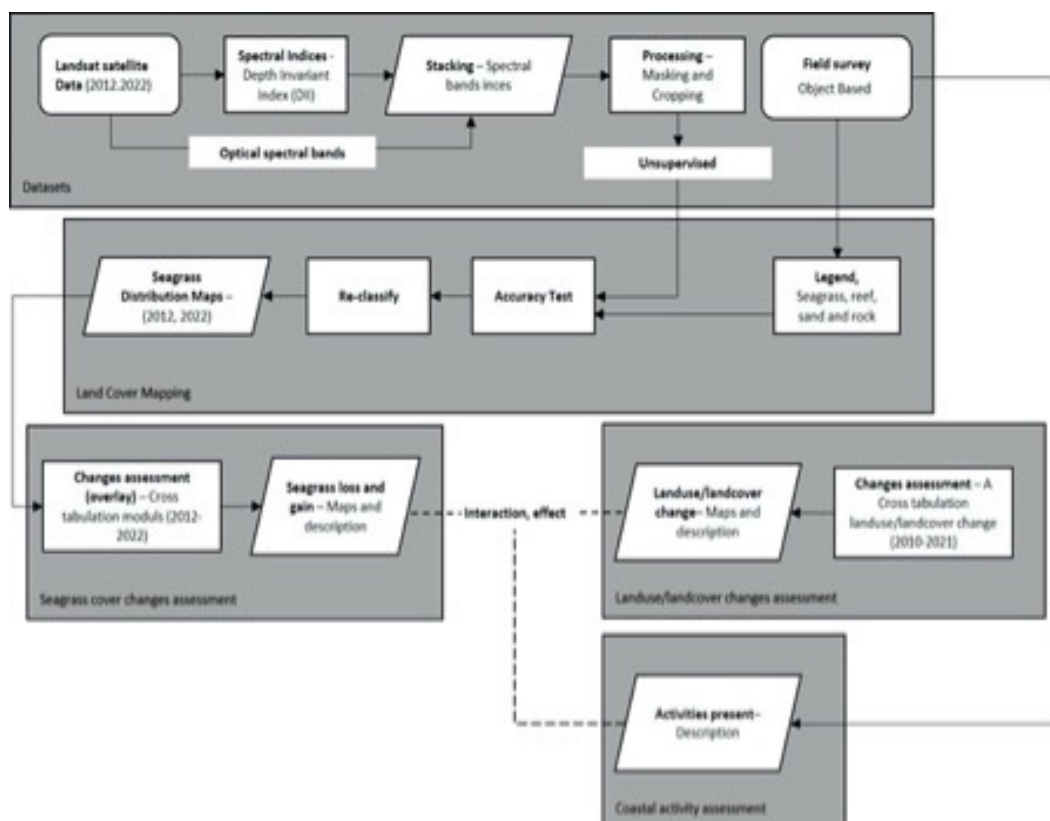


Figure 1. The flowchart of the research procedures

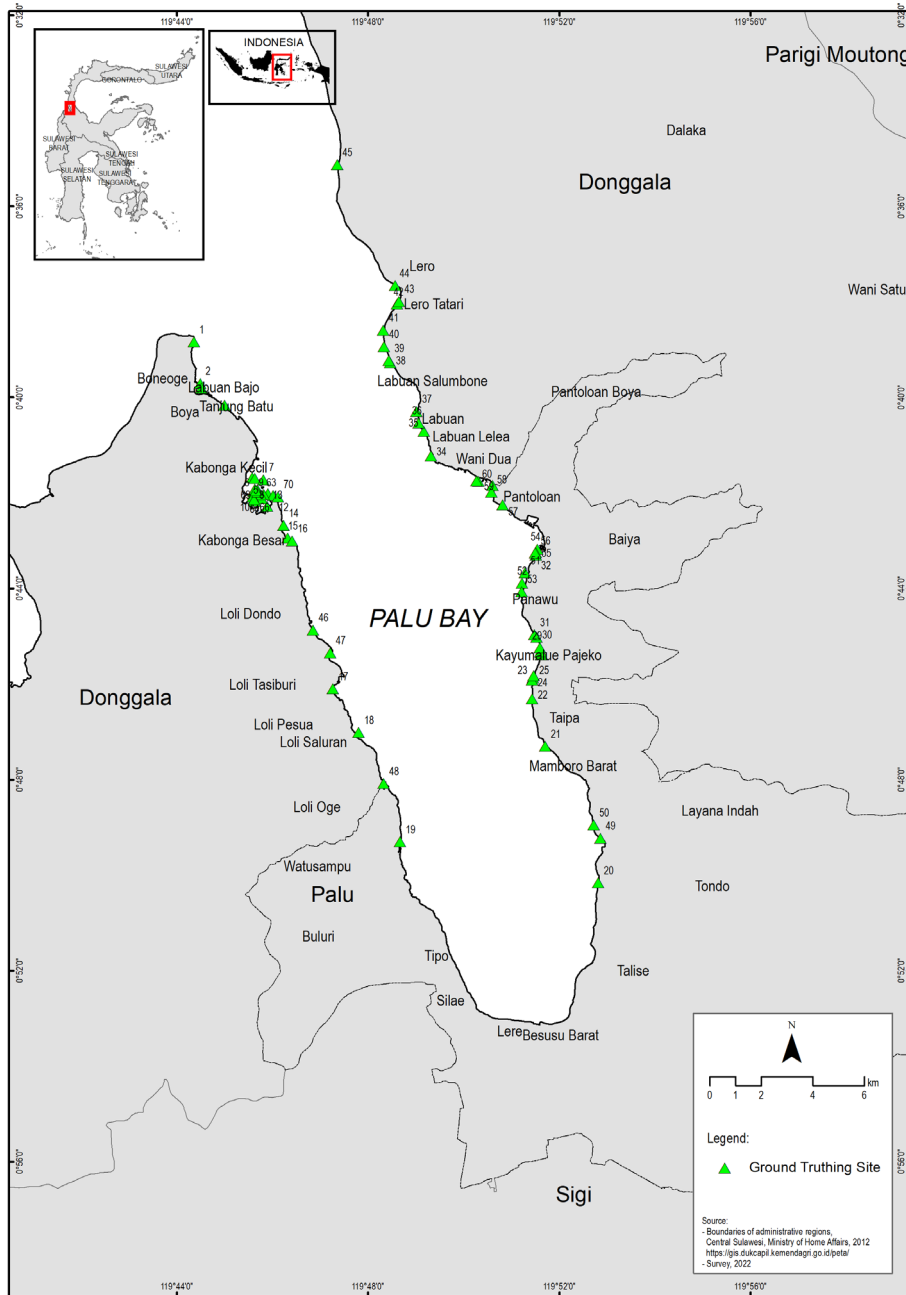


Figure 2. Map of Palu Bay showing the field sites

Table 1. Satellite image description

Satellite image type	Acquisition	Path/row	Band
Landsat 7 ETM	5 March 2012	115/60	1 and 2
Landsat 8 OLI	4 January 2022	115/60	2 and 3

The digital value of band 1 and band 2 of Landsat 7 imagery as well as band 2 and band 3 of Landsat 8 imagery were used to calculate the attenuation coefficient ratio.

Image processing

Preliminary processing of the satellite data comprised several stages following the manual produced by the Indonesian Geospatial Agency (BIG, 2014). The first stage was pre-processing to improve image quality. The second stage was correction for the depth of the water column using the Lyzenga method. The equation used in applying the Lyzenga method refers to Green et al. (2000) as shown below:

$$depth\ invariant\ index\ (DII) = \ln (band\ i) - \left[\left(\frac{k_i}{k_j} \right) \cdot \ln (band\ j) \right] \quad (1)$$

$$k_i/k_j = a + \sqrt{a^2 + 1} \quad (2)$$

$$a = \frac{\sigma_{ii} - \sigma_{jj}}{2\sigma_{ij}} \quad (3)$$

- Where: k_i/k_j = Attenuation coefficient ratio
- σ_{ii} = Variance of band i
- σ_{jj} = Variance of band j
- $2\sigma_{ij}$ = Covariance between band i and band j
- band i, band j = Digital value of the blue channel, digital value of the green channel

An offset can be used to make all data positive if some depth-invariant bottom-index values are negative (Green et al., 2000). After the water column-correction, a more enhanced image was generated that enabled visually identifying seagrass patches and made it possible to discriminate seagrass from the waterbody. Thus, seagrass extent information was extracted, and region of interests (ROIs) were created for each meadow of each image. There were 30 ROIs used for this study that were considered sufficient to obtain the digital value of blue (*band i*) and green (*band j*) channels, and were then used to calculate the attenuation coefficient ratio (ki/kj). The third stage was classification using unsupervised classification. The fourth stage was reclassification. After the classification results were obtained, all classes other than seagrass were eliminated through the reclassification process into seagrass and non-seagrass. The last stage was overlay using QGIS 3.22 LTR software. Changes in seagrass area were then detected by overlaying the classified images (Landsat 7 2012 imagery and Landsat 8 OLI 2022 imagery).

Ground-truthing

The ground-truthing survey was conducted to collect information on basic aquatic habitat types as a reference for satellite image interpretation and to be used as a sample for testing the accuracy of the classification (Rahmawati et al., 2017). Sampling was determined using purposive and proportional random sampling methods following Prayuda (2014). Purposive sampling considered the diversity of shallow sea bottom habitat classes, while proportional random sampling was used to determine sample points at locations, and the number of sample points was determined in a representative and proportional manner based on the size of the area being mapped. Tentative maps were used as a guide in the field.

The coordinates of 70 selected ground-truthing points were determined based on the results of the unsupervised classification of the satellite imagery. A GPS (Global Positioning System) was used to find these coordinates in the field in order to collect data on the underwater objects present at these points in the coastal waters of Palu Bay. The ground truthing sites can be seen in Figure 2.

Participatory Rural Appraisal (PRA)

One of the approaches used in this research was Participatory Rural Appraisal (PRA). Conceptually, Participatory Rural Appraisal (PRA) describes a set of approaches and methods that encourage the local community to share, enhance and analyze their knowledge of life and their condition, to plan and make action (Chambers, 1994). Literally, PRA is defined as a participatory rural and/or coastal assessment. This method is also not only for rural communities, but also for urban and coastal communities (COREMAP, 2006). In the context of this research, the aims of the Participatory Rural Appraisal (PRA) were to obtain information related to the changes that had occurred in the coastal areas of Palu Bay. The PRA was conducted by involving the local communities living around Palu Bay. The local community included people who live around the coastal area, both those working as fishermen and those with other professions, including environmental activists.

There are several techniques for implementing the PRA method, but in this study the techniques applied were

participatory mapping and semi-structured interviews. Participatory mapping is a method for collecting and mapping information on what is happening in the community as well as the surrounding conditions. The information obtained helps to understand past and current conditions, and to predict potential future conditions, especially those relevant for coastal management. In addition, this participatory mapping also aims to identify opportunities for and limitations on the use of natural resources for coastal development.

Semi-structured interviews are interviews conducted with individuals or groups for a purpose, usually using a list of guide questions (COREMAP, 2006). In this study, the PRA target was to obtain information from local communities on several aspects, including the types of changes that had occurred, when and where changes had occurred, and the impact of these changes on people as well as on coastal ecosystems (seagrass meadows, mangroves and coral reefs). This is in line with the statement of Muhsin et al. (2018) that PRA will produce information on resource condition, problems, opportunities and strengths by involving the community.

In this research, the PRA method was applied by visiting community groups in several villages that were considered representative of the coastal communities of Palu Bay, especially villages where significant changes in coastal land use were suspected. The data from the PRA was used to validate the classification of the 2012 satellite data as well as to provide complementary information to support the interpretation of the results of the satellite data analysis.

Satellite data analysis

The analysis of seagrass ecosystem change based on the satellite imagery were included estimating seagrass area in 2012 and in 2022, and then calculating the change in the extent of seagrass beds by overlaying the two classified images. To test the accuracy of the data obtained from this process, the satellite data classification results for 2022 were compared with actual conditions in the field. The level of accuracy "K" was calculated using the following equation (BIG, 2014):

$$K = (\text{Number of correctly interpreted sample pixels} / \text{number of tested sample pixels}) \times 100 \quad (4)$$

Land-use change

This research also analyzed descriptively on changes in land use over a period of approximately one decade (2010 and 2020) to identify patterns of land use change and to further estimate the likely impact of the changes in land use on the deterioration of the seagrasses during a similar period (2012-2022). Data on land-use/land cover in 2010 with a resolution of 300 m were sourced from the European Space Agency (ESA) GlobCover Land Cover Map repository (http://due.esrin.esa.int/page_globcover.php). Data on land-use/land cover in 2021 with a resolution of 10 m were sourced from the Copernicus Sentinel-2 mission via the ESRI ArcGIS portal (<https://www.arcgis.com/apps/instant/media/index.html?appid=fc92d38533d440078f17678ebc20e8e2>). The area boundary used was the Palu Bay watershed area shapefile, sourced from the geoportal of the Indonesian Ministry of the Environment and Forestry (<https://sigap.menlhk.go.id/sigap/peta-interaktif>). The data were analyzed in ArcGIS 10.8.

3. Results and Discussion

Accuracy test

The Accuracy test is performed to assess the quality of the map produced (Prayuda, 2014). The accuracy test compared the 2022 satellite image classification with the results of the ground-truth survey using a confusion matrix (Table 2). The number of sample points used was 70 samples. The accuracy level K obtained was 80%, which meets the standard established by the Indonesia Geospatial Agency (BIG, 2014), which is a K value of 60% or greater.

Distribution of seagrass meadows in Palu Bay

The satellite image classifications for 2012 and 2022 (Figure 3) show changes in the distribution and extent of the seagrass meadows in Palu Bay. In 2012 (Figure 3a), seagrass meadows were scattered along the coasts of Palu Bay, extending seawards at several sites such as Kabonga Kecil, Kabonga Besar, Panau and Baiya (see the sites in Figure 2), with most other seagrass meadows forming a narrow fringe along the

shore. The distributions shown for 2012 are consonant with the information obtained from the PRA (Participatory Rural Appraisal) (see supplementary material).

Comparison of the seagrass distribution maps for 2012 and 2022 (Figure 3a and 3b) shows that there have been some changes in distribution, including the loss of seagrass ecosystems in some areas, but distribution patterns of other areas remained similar or did not change significantly. In both 2012 and 2022, the classification maps show distribution of seagrass within the western zone, in particular the relatively extensive seagrass meadows in front of Kabonga Kecil and Kabonga Besar villages did not change significantly. During the field survey, anthropogenic activities that could potentially threaten the existence of seagrass beds were not found at these sites. Moreover, Kabonga Besar Village has mangrove ecosystems around the coast and around several small islands close to the shore as well as fringing coral reefs around Levuto Kabonga Island. The presence of these two coastal ecosystems (mangrove and coral reef) most likely helps to support the



Figure 3. Distribution of seagrass meadows in Palu Bay based on classification of satellite data from 2012 (Landsat 7) and 2022 (Landsat 8).

Table 2. The accuracy test of the classification result of satellite imagery in 2022

	Live coral	Dead coral	Seagrass	Sand	Number of rows	User Accuracy
Live coral	5	0	2	0	7	71.43
Dead coral	1	5	0	3	9	55.56
Seagrass	1	2	18	0	21	85.71
Sand	0	0	3	28	31	90.32
<i>Number of rows</i>	7	7	23	31	70	
<i>Producer accuracy</i>	71.43	71.43	78.26	90.32		
<i>Overall accuracy K</i>	80%					

continued presence of the seagrass ecosystems in this area. In the eastern zone of Palu Bay, the seagrass ecosystems in front of the villages from Panau to Baiya also show little change. The presence of mangroves and coral reef ecosystems was also observed in this area. Mangroves protect seagrass beds from landward discharges and sedimentations, while coral reefs protect seagrass beds from high storm seaward by reducing the size of waves entering the bays (Guannel *et al.*, 2016).

On the other hand, changes in seagrass distribution were visible along the coast at several sites in both the western and eastern zones of Palu Bay. In the western zone, one area where seagrass extent had been reduced and some seagrass meadows had been lost in 2022 was the coast between Kabonga Kecil Village and Boya Village (see the sites in Figure 2). Reclamation had occurred along 1.5 km of the coastline for the construction of a ring road as well as tourism facilities including a platform and recreational park area called an *anjungan*. At several other sites along the western coast of Palu Bay seagrass meadows had been lost due to the use of the coastal strip for stockpiling mined aggregate (sand, stones and gravel) prior to use or shipment to other areas on cargo ships or barges. This was especially prevalent from Buluri Village in Palu City to Kabonga besar Village in Donggala Regency (see the sites in Figure 2). Another possible cause of the loss of seagrass meadows is reclamation for various purposes, such as housing development, hotels, tourism and economic area in the coast of Silae, Lere, Talise and Tondo villages (see the sites in Figure 2) which have been implemented since 2014. According to Muliati (2015), large-scale reclamation in some parts of Palu Bay has the concept of equatorial commerce point. Information related to the reclamation of Palu Bay can be accessed through online news media such as Antara Sulteng (Maruto, 2014) and Mongabay (Dhika, 2016; Doaly, 2016a, 2016b). Fishing communities informed that before the reclamation was carried out they often used seagrass meadows in the area as a fishing ground. These statements are also supported by the 2012 and 2022 seagrass distribution maps which show that seagrass meadows were still found in this area in 2012 but had disappeared in 2022. Unsworth *et al.* (2018) reported that coastal development and land reclamation are the significant causes of the loss of seagrass beds in Indonesia. Other information obtained from the community included reports that before the 2018 tsunami people often saw several dugongs on the coast between Mamboro and Taipa Village (see the sites in Figure 2), but since the tsunami dugongs have rarely been seen and only in lower numbers. Dugongs have also been reported slightly further north along the east coast of Palu Bay (Moore *et al.*, 2017). Dugongs eat seagrass as their main source of food, especially small seagrass species such as *Halodule* sp. and *Halophila* sp. (Sheppard *et al.*, 2007). This is in accordance with information from the community during the PRA that in the past *Halophila* and *Halodule* was common along the coast of Mamboro Village.

It is also interesting to note that the people of Mamboro Village expressed an interest in the ornamental Banggai cardinalfish (BCF) *Pterapogon kauderni* (local name *capungan layar*), which was introduced to the site by an ornamental fish trader in 1998. This introduced fish became established and bred successfully, providing an additional source of income for the community. Seagrasses is one of the important habitats for the BCF (Moore *et al.*, 2019, 2020). The tsunami almost wiped out the BCF population along with its habitats (the seagrass,

corals and other benthic organisms), leaving barren substrate strewn with debris.

The PRA produced other information related to the distribution of seagrass and other aspects of coastal ecosystems in the eastern zone of Palu Bay. In particular, several years before the tsunami event, seagrass ecosystems along the coast of Mamboro Village were quite extensive and comprised several types (species). According to Nordlund *et al.*, (2016), the loss of seagrass ecosystems can have an impact on people's livelihood who use these ecosystems directly or indirectly. The respondents mentioned organisms associated with the seagrass beds including fish such as rabbitfishes (Siganidae), seahorses (*Hippocampus* sp.), dugongs, macroalgae (e.g., *Padina* sp.) and many other organisms. There are also data on other invertebrate taxa including mollusks and echinoderms (Ndobe *et al.*, 2021). The seagrass meadows observed were quite narrow, only extending around 15-25 m seawards, because of the coastal topography which is not gently sloping but drops steeply beyond the narrow coastal shelf. Similar narrow seagrass meadows were found along the coast to the north of Mamboro, in Taipa, Kayumalue and Pantoloan villages (see the sites in Figure 2), although in some areas the seagrass belt was more sparse or narrower. The tsunami caused severe damage to many of the seagrass beds along the east coast of Palu Bay. However, by the time of the survey in 2022 the seagrass in Mamboro Village and several other locations was showing signs of recovery.

Meanwhile, along the coasts of Talise and Tondo Villages (see the sites in Figure 2), the extent of seagrass meadows had already begun to decrease before the tsunami due to the direct and indirect impacts of reclamation activities, and more were lost during the tsunami. The field observations indicated that several other areas along the east coast of Palu Bay, such as in Talise Village, are no longer suitable for the post-tsunami growth and recovery of seagrass ecosystems, due to reclamation projects, the construction of seawalls and embankments, and the high turbidity of the waters close to the Palu River estuary. Seagrass recovery is also likely to be difficult or even impossible in some areas of Tondo Village due to reclamation for housing construction along approximately 700 m of the coastline.

In the western zone, the community also reported that several years ago seagrass meadows with associated organisms such as shellfish, gastropods, rabbitfishes and dugongs were also found along the coastal from Silae Village in the south to Watusampu Village in the north (see the sites in Figure 2). Seaweed farming was also common along the coast from Buluri Village to Watusampu Village (see the sites in Figure 2) before the rock mining became prevalent. As rock mining extended along the western coast of Palu Bay from Buluri Village in Palu City to Loli Dondo Village, in Donggala Regency (see the sites in Figure 2), along with stockpiling aggregate and the construction of docks for the ships and barges, this seaweed farming had to stop. Rock mining activities also have an impact on seaweed cultivation in the western zone of the bay. The impact of mining on seaweed cultivation is reflected in the report, published in the online news media on 23 October 2015 (Hajiji, 2015), that the government of Palu City stopped the seaweed development program in 2015 due to these anthropogenic activities. Seaweed farming on the east coast of Palu Bay had failed a few years earlier due to thermal pollution from cooling water discharged by a coal-fired power station at Panawu Village (see the sites in Figure 2).

As pointed out by Nordlund et al. (2018), nearshore seagrass fisheries are important for the livelihoods and well-being of coastal communities in developing countries. According to the fishing community, the income of fishermen and shellfish/gastropods gleaners in Palu Bay has decreased drastically due to the impact of mining and the 2018 earthquake and tsunami. For example, previously shellfish/gastropods gleaners could collect an average of 50 kg of shellfish/gastropods per day during the lowest ebb period (the most effective time for gleaning fisheries), but in 2022 they could only collect less than 10 kg per day during the lowest ebb period. The catch of finfish such as snapper, grouper and rabbitfishes had also declined sharply, and these fishes were now very difficult to obtain.

Based on information from the community (PRA) and direct observations made in the field, most of the changes in or loss of seagrass meadows along much of the western coast of Palu Bay were caused by mining and construction related activities, including stockpiling for hotel construction, aggregate storage, docks/jetties and seawall construction. The tsunami caused some direct damage, and moreover exacerbated these processes, so that the rate of seagrass ecosystem loss has accelerated since the 2018 earthquake and tsunami. Meanwhile along the eastern coast of Palu Bay, the tsunami and earthquake events played a greater role in seagrass change, although seagrass ecosystems in this zone are also affected by anthropogenic activities such as coastal reclamation and aggregate mining in the Labuan River, both of which raise the level of turbidity and sedimentation.

Generally, based on the PRA, most people around the coast of Palu Bay are not aware of the direct benefits or ecosystem service provided by seagrass ecosystems. However, some people did understand the function of seagrass as a habitat for marine organisms such as rabbitfishes, shellfish and gastropods. One habit of Palu Bay fishermen which can be seen as positive with respect to seagrass conservation is that they do not generally anchor their boats in the seagrass ecosystem but keep them at the top of the beach, so the potential for damage due to boat anchors is relatively low.

Based on the 2012 and 2022 seagrass distribution maps, it can be said that there have been changes in coastal conditions that have occurred several years ago until now. The cause is strongly suspected by the existence of anthropogenic activities such as rock mining in conjunction with coastal stockpiling activities, and natural factors such as earthquakes and tsunamis that are aggravating the condition of coastal ecosystems including seagrasses. Based on observations during the survey that some parts of the coast of Palu Bay such as in some parts of Buluri Village experienced subsided beach to a depth of about 4 m (see supplementary material). Patria & Putra (2020) also reported that part of the coast of the Silae Village had experienced the similar condition with subsided beach into a depth of about 1.5 m (see supplementary material). The part of the coast that experiences subsided beach is the Palu-Koro fault line.

Rock mining activities in western zone of Palu Bay are accompanied by beach stockpiling activities for the construction of a barge dock for transporting mining products (sand, gravel and rocks) and the activity of barges going back and forth in Palu Bay. Based on the information gathered from the community and the map of the distribution of seagrass in 2012 and 2022, it can be concluded that in addition to natural factors, this anthropogenic activity is strongly suspected of

causing ecosystem damage on the coast of Palu Bay, including seagrass ecosystems, especially in the coastal area of western zone of Palu Bay.

Issues related to rock mining (*galian* C) and reclamation along the coast of Palu Bay and their impact on the environment including coastal ecosystems have been hotly discussed in recent years by various elements of society through various discussion forums and reported through local and national media. Rock mining in the hills occurs from Buluri Village, Palu City to Kabonga Besar, Donggala Regency (west bay zone), in addition, rock mining activities occur in Labuan River (east bay zone). Meanwhile, the reclamation of the Palu Bay coast is carried out with various purposes, such as docks for ships transporting rock mining products, housing, hotels, and others.

Changes in seagrass ecosystem extent

The area of seagrass based on image analysis of classification results in 2012 and 2022 was 127.08 Ha and 83.79 Ha, respectively, meaning that the seagrass area decreased by 43.29 Ha for a decade. The images from the 2012 and 2022 classifications can then be compared by overlaying to see areas that have changed (Figure 4).

In Indonesia, the main causes for the loss of seagrass beds are coastal development, land reclamation, sedimentation, coral and sand mining, seaweed cultivation, overuse of associated organisms, and ship activities (Unsworth et al., 2018), while natural factors include such as earthquakes, strong currents, large waves, storms and tsunamis (Rahmawati et al., 2017). Changes in seagrass area in the Palu Bay Coast are most likely caused by rock mining activities, coastal reclamation, barge activities going back and forth in the waters, sedimentation, and the 2018 earthquake and tsunami. The shrinkage of seagrass area in Palu Bay was smaller than what happened in Van Phong Bay, Vietnam (Vo et al., 2020), which also reported that natural disasters, coastal reclamation and various other human activities such as aquaculture activities have a negative impact on the distribution change of seagrass beds in Vietnam. Moreover, Telesca et al. (2015) reported the massive changes in the distribution of *Posidonia oceanica* meadows in the Mediterranean Seas due to multiple local stressor including increasing human activities (e.g. trawling, anchoring, dredging and pipeline refilling) that have been threatened the seagrass due to increase sediment, organic matter, and freshwater inputs into the sea.

The analysis of secondary data on land-use/land cover (ESA 2010 GlobCover Land Cover Maps Repository; Copernicus Sentinel-2 2021 Mission; watershed data from the Ministry of Environment and Forestry) shows significant change over the period 2010 to 2021 (Figure 5). In particular, the built-up area increased from around 1,564 Ha in 2010 to 20,546 Ha in 2021, an increase of an order of magnitude. This increase is likely an overestimate, as the low resolution of the 2010 data undoubtedly missed many smaller developments, especially ribbon development along the coastal and inland roads, and even the town of Donggala. Nonetheless, many of the newer built-up areas visible to the east and south of the Bay in 2021 (Figure 5b) clearly cover more than one 300 m squared pixel, and should therefore have appeared on the 2010 map (Figure 5a) had they been present then.

Figure 5 shows that by 2021 the built-up area had expanded and spread around the coast of Palu Bay, decreasing available land for agriculture and plantations. In particular,

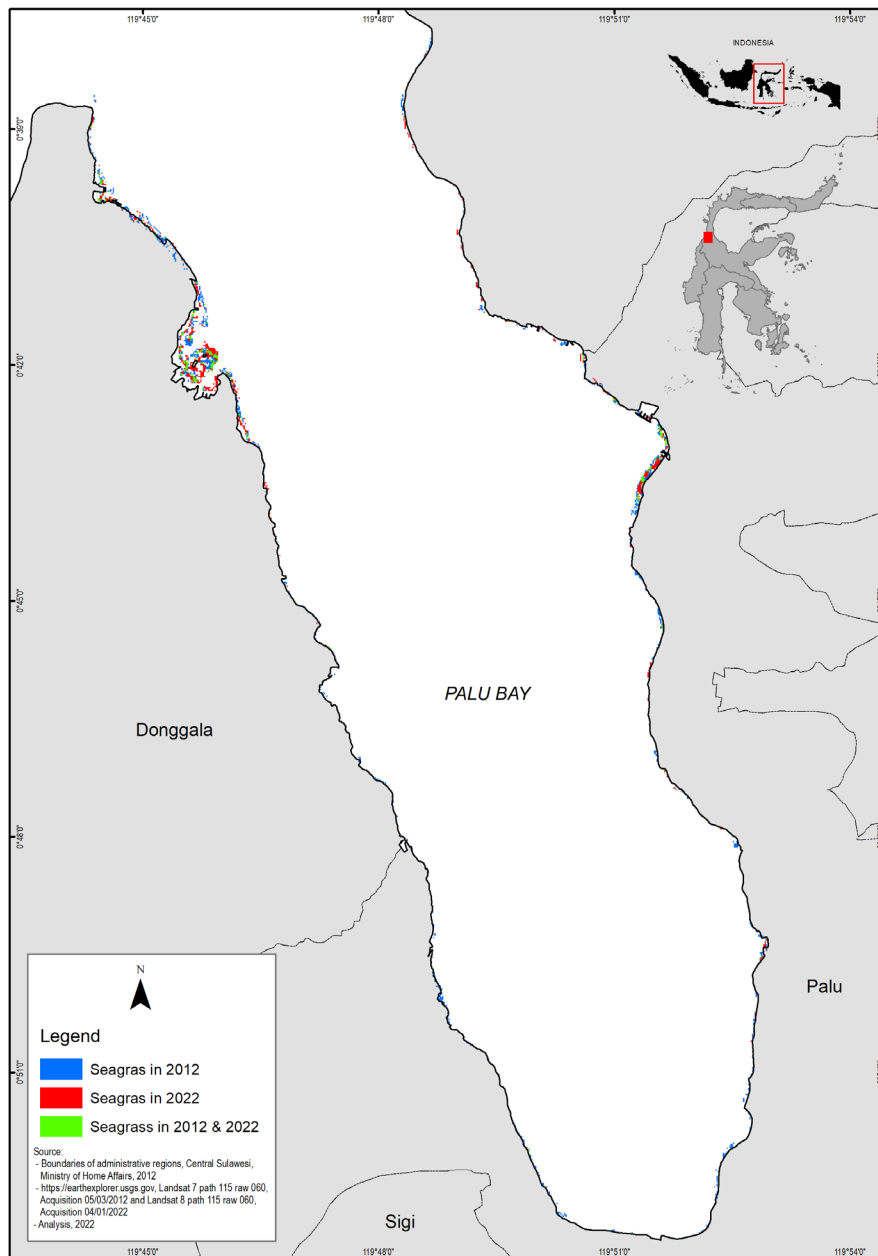


Figure 4. Overlay of seagrass ecosystems in Palu Bay in 2012 and 2022

the expansion of the already growing built-up area in Tondo Village, Mantikulore District (see the sites in Figure 2), was accelerated by the construction of housing for victims of the 2018 earthquake and tsunami. Conversely, some areas previously cultivated or used for housing and other facilities have reverted to vegetated (forest or scrub) areas. This is thought to be due to the effects of the triple disaster in 2018 (Syamsidik et al., 2019), as some of the land affected by the earthquake and liquefaction has been abandoned and allowed to revert to nature (Nurdin et al., 2022).

Open land identified in 2021 covered an area of 11,273 Ha, and appears to include the aggregate rock mining areas along the escarpment of the mountains lining the western coast of Palu Bay as well as the Poboya gold mining area. Some of the rock mining areas to the west of Palu Bay used to be plantations, with commodities including coconut and sugar apple or srikaya (*Annona squamosa*). Meanwhile, the highly degraded Poboya gold mine area used to be the Palu Forest Park, a protected area (Muhammad et al., 2012; Ambo-Rappe & Moore, 2018). These and other land-use changes may have

had negative impacts on the seagrass meadows around Palu Bay.

According to Baja et al. (2018) lack of integration in land use planning can lead directly to problems in coastal areas. As previously mentioned, the expansion of open areas in the form of rock mining quarries accompanied by anthropogenic activities in the form of reclamation has the potential to disrupt coastal ecosystems through increasing water turbidity and sedimentation loads in Palu Bay. Supriyadi et al. (2018) stated that land-use changes from vegetated to open land accelerate surface sediment transport rates and increase water turbidity levels. Furthermore, the impacts of land clearance that resulted in an increased extent of open land also caused seagrass condition to decline in eastern Bintan, Indonesia. Based on the results of this land-use change analysis, it can be said that the changes from vegetated to open land and various accompanying activities have had negative impacts on the coastal ecosystems of Palu Bay, including the presence and extent of seagrasses.

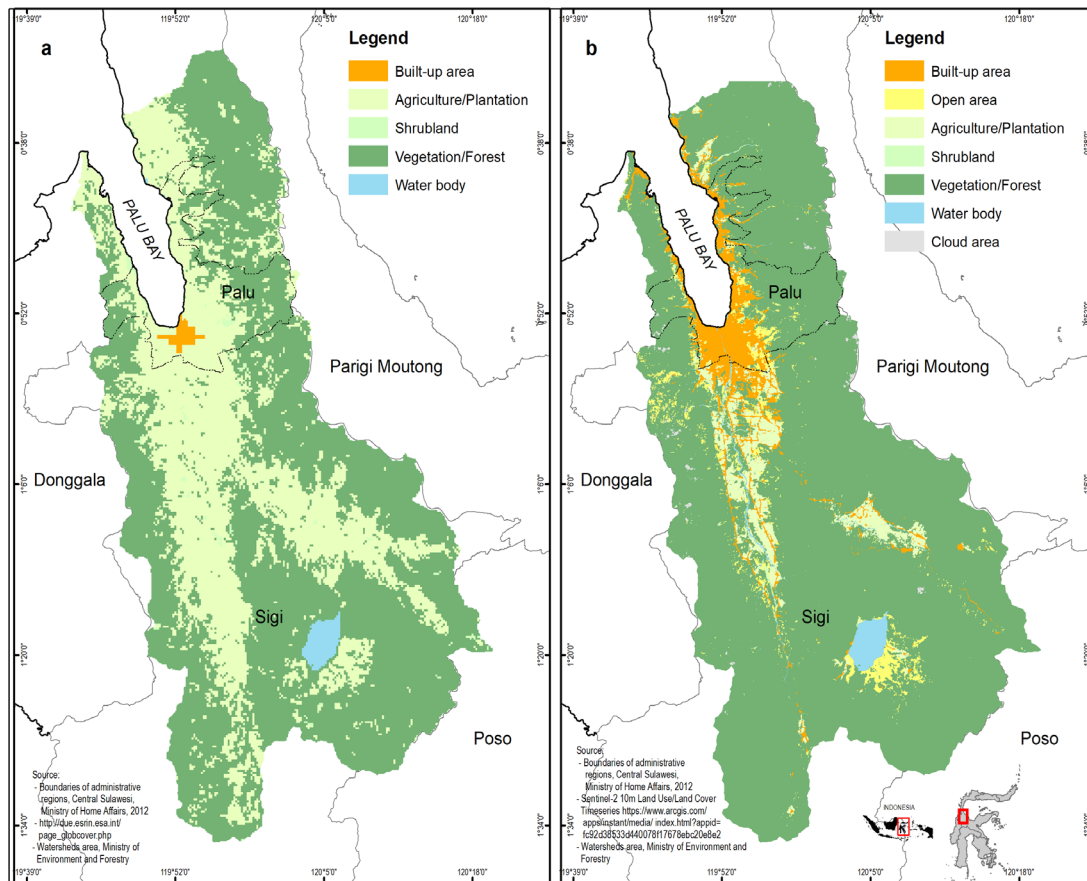


Figure 5. Land-use around Palu Bay (Palu City and Donggala Regency): a. 2010 (Source: European Space Agency (ESA) GlobCover Land Cover Map repository (http://due.esrin.esa.int/page_globcover.php), b. 2021 (Source: Copernicus Sentinel-2 2021 Mission via The ESRI ARCGIS portal (<https://www.arcgis.com/apps/instant/media/index.html?appid=fc92d38533d440078f17678ebc20e8e2>)).

4. Conclusion

Analysis of the seagrass meadows in Palu Bay based on satellite data was validated by ground-truthing with a classification accuracy of 80%. The results show a significant decrease in seagrass ecosystem extent over the decade from 2012 to 2022. Direct observation and participatory methods indicate that the main drivers of the decline in seagrass extent of Palu Bay are anthropogenic activities such as aggregate mining, activities associated with the shipping of mining products, and coastal reclamation. Moreover, the conversion of vegetated land into open land has the potential to increase water turbidity and sedimentation that reduced seagrass habitat, resulting in losses of the seagrass bed in some of the area in Palu Bay. The natural disaster in 2018 also appears to have been worsened the condition of the seagrass beds in Palu Bay.

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