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Percentage cover, biomass, distribution, and potential habitat mapping of natural macroalgae, based on high-resolution satellite data and in situ monitoring, at Libukang Island, Malasoro Bay, Indonesia

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Abstract In this study, we combined remote sensing data and in situ observations to explore the potential habitats of macroalgae at Libukang Island, Indonesia. High-resolution satellite images from the GeoEye-1 were used to estimate and to map the geomorphological structures together with macroalgal species in the study area. Seasonal variations of percentage cover and biomass of macroalgae associated with substrates were investigated in May and November 2014, and June 2015, using quadrats as sampling unit. A total of nine common genera were found in the study area with three dominant genera: *Sargassum*, *Padina*, and *Turbinaria*. Most of macroalgae was observed in the eastern part of the Island, on several substrate types and particular oceanographic conditions (wave and current). Mean biomasses of *Sargassum* and *Padina* were high in May (1189.6 ± 455 and 166.7 ± 15.4 g DW.m^{-2}, respectively), while the biomass of *Turbinaria* was high in November (3245 ± 599.8 g DW.m^{-2}). The map accuracy of image classification for all typology substrates was 74.19%. Overall, approximately 62.3% of the total study area can be considered as potential for natural macroalgae habitats. Spectral response characteristic of shallow water substrates at study area based on GeoEye-1 is also presented. The results of this study exhibit a potential utilization of natural macroalgae in the study area, and provide information for a possible diversification of the use of macroalgae in Indonesia. The method could be useful for habitat management and future biomonitoring in the study area or other similar areas in Indonesia.

Keywords Remote sensing · Brown algae · Biomass · Habitat structure · Seaweed monitoring

Introduction

Indonesia is located in the Southeast Asia, in a meeting point of two shelves: Sunda Shelf in the west connecting to Asia, and Sahul Shelf in the east to Australia. The country is a vast archipelago state consisting of 13,446 islands, hosting a center of a high biodiversity in marine organisms and important habitat for diverse and abundant macroalgal species (Veron et al. 2009). However, data and information related to the abundance and distribution of natural populations of macroalgae in Indonesia are very scarce.

Macroalgae, as primary producers, are not only a food source for herbivores but also provide a refuge for many marine species, and represent then a possible indicator of ecosystem health in coastal areas and around offshore islands (Lobban and Harrison 1997; Hay 1997; Gattuso et al. 1997; Diaz-Pulido and McCook 2003; Golléty et al. 2008; Iken 2012; Migné et al. 2015). Their chemical compounds also have commercial values as dry raw materials often used for food, and particularly their phycocolloids product which

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represent important bioactive materials usually used for pharmaceutical and cosmeceutical products (Stengel et al. 2011; Bourgougnon and Stiger-Pouvreau 2011; Chopin and Neish 2014; Stiger-Pouvreau et al. 2015).

As Indonesia represents a hot-spot of biodiversity, it is important to consider the ecological and economical values of the macroalgae. Therefore, mapping and monitoring the habitats of natural populations is crucial to evaluate their distributions and density and to establish strategies related to conservation and a sustainable use together with possible restoration within a spatial management framework. Previous studies have shown that seasonal variations in the physicochemical environment parameters strongly influence changes in the structure of macroalgae affecting distribution and density, especially for natural populations of tropical macroalgae (Stiger and Payri 1999a; Ateweberhan et al. 2009; Le Lann et al. 2012; Noiraksar et al. 2014).

Direct sampling methods to describe shallow and intertidal water marine habitats like in situ quadrats or line transects are considered time-consuming, data lagged, expensive, and labor intensive. Accurate and effective techniques for mapping and monitoring benthic habitats including macroalgae beds are already established (Hau et al. 2009; Casal et al. 2011; Sagawa et al. 2012a, b). Satellite imagery, aerial imagery, and other remote sensing methods and geographic information system (GIS) offer the most powerful analytical tools for ecological assessment (Kerr and Ostrovsky 2003). Several studies have shown that these techniques are effective for mapping, assessing, and evaluating biodiversity and biomass of macroalgae associated with habitat and biophysical properties (Mumby et al. 1997; Andréfouët et al. 2004; Mattio et al. 2008a; Wouthuyzen et al. 2009). However, remote sensing identification of marine vegetation at the species level is difficult because the low spatial resolution limits the use of certain sensors (Kutser et al. 2006; Casal et al. 2011). Mumby et al. (1998) also suggested that the influence of variable depth on the reflectance of sea beds features is the main difficulty of mapping of benthic communities. The accuracy of such analysis greatly depends on the spatial and spectral resolution of satellite data.

In ecological studies such as biodiversity estimation and distribution, high-resolution satellites have generated more precise area estimation and a more accurate representation of field observed data (Siddiqui and Zaidi 2015), while moderate spatial resolution satellites such as Landsat ETM+ and SPOT have achieved only moderate success, and have provided conflicting outcomes (Nagendra 2001). High-resolution satellite imagery data has been combined directly with traditional measurements, i.e., ecological field observation. It was used in order to achieve greater thematic accuracy and detailed information about the substrate cover as the macroalgal habitat (Andréfouët et al. 2003; Vahtmäe and Kutser 2007; Hoang et al. 2016).

In this study, we mapped and characterized the distribution of macroalgal populations and the respective substrates at Libukang Island using a combination of high-resolution satellite imagery data and in situ observations. The spectral reflectance of substrate was identified and indicated the possibility of differentiation of algal genera. Using the same tools, we also estimated their natural stocks at a small island scale. We then identified promising sites (potential areas) for natural macroalgae collection and cultivation for further possible utilization for industry. This approach can be useful for monitoring the distribution of natural macroalgae and estimating their natural stock in the other parts of Indonesia. The result provides information for industry to diversify macroalgal exploitation in Indonesia, which for the moment is turned to red macroalgae. It provides also information for stakeholders to support a sustainable exploitation of macroalgae in the study area, as well as for conservation activities.

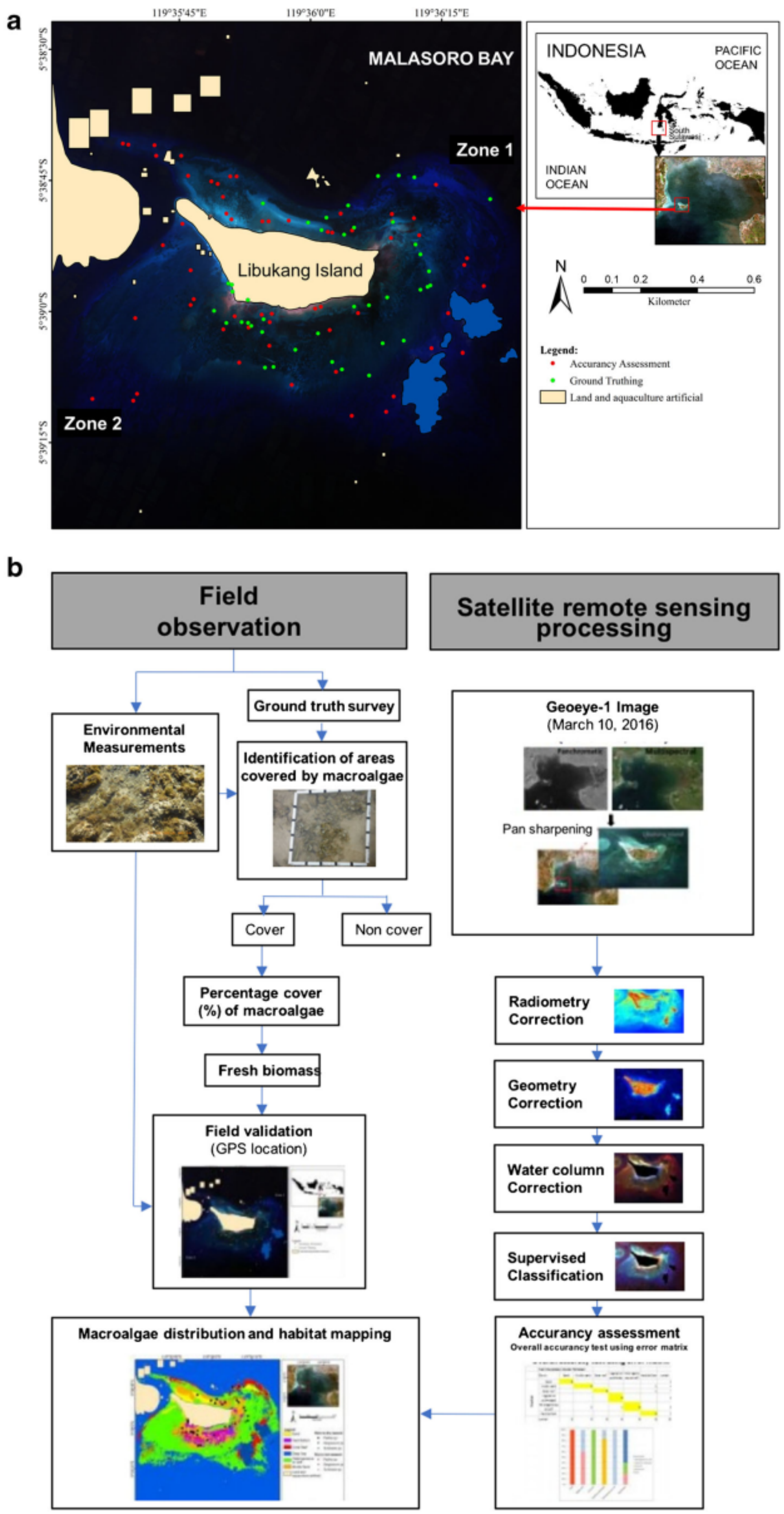
Materials and method

Study site

Malasoro Bay is located in South Sulawesi Province of Indonesia, at 5° 36′ 46.40″–5° 40′ 31.25″ S and 119° 35′ 14.88″–119° 39′ 42.92″ E (inset in Fig. 1a). It is a shallow semi-closed basin bordered with the Flores Sea. We selected Libukang Island located in the south west of the bay (5° 38′ 53.08″ S and 119° 35′ 54.61″ E), see Fig. 1a. The island has a dense population with approximately 75 heads of household, mostly working as macroalgal farmers in Malasoro Bay. The bay itself holds a major commercial area for macroalgae production in Indonesia. Utojo et al. (2007) demonstrated a 1087.7 ha area suitable for seaweed culture development with 70% moderate to high suitability condition.

The surrounding areas of Libukang Island have a sloping beach. Sea surface temperature varied between 24.8 ± 0.04 °C in September and 31.8 ± 0.15 °C in December. Salinity varied between 32.4 ± 0.01 psu in the period of January–February (monsoon season with heavy rainfall) and 35.0 ± 0.09 psu in September–October (season with low rainfall). There are generally two seasons in Indonesia: dry season (May to October) influenced by the Australian continental air masses and rain season (November to April) influenced by the Asia's mainland and Pacific Ocean air masses. Two variations of

Fig. 1 Satellite imagery and processing carried out to map the potential habitat of natural populations of Indonesian macroalgae. **a** Satellite imagery of Libukang Island within the Malasoro Bay (South Sulawesi, Indonesia). *Points with different symbols* represent ground validation and random stratified accuracy assessment from three field sampling periods. **b** Diagram of high spatial resolution of satellite image processing and field survey for the mapping of macroalgal distribution and their habitat in Libukang Island (Indonesia) ▶


a
119°35'45"E
119°36'0"E
119°36'15"E
5°38'30"S
5°38'45"S
5°39'0"S
5°39'15"S
MALASORO BAY
Zone 1
Zone 2
Libukang Island
INDONESIA
PACIFIC OCEAN
INDIAN OCEAN
South Sulawesi
N
0 0.1 0.2 0.4 0.6
Kilometer
Legend:
Accurancy Assessment
Ground Truthing
Land and aquaculture artificial
b
Field observation
Satellite remote sensing processing
Ground truth survey
Environmental Measurements
Identification of areas covered by macroalgae
Cover
Non cover
Percentage cover (%) of macroalgae
Fresh biomass
Field validation (GPS location)
Macroalgae distribution and habitat mapping
Geoeye-1 Image (March 10, 2016)
Pan sharpening
Radiometry Correction
Geometry Correction
Water column Correction
Supervised Classification
Accurancy assessment
Overall accurancy test using error matrix

monsoons, Northwest (NW) and Southeast (SW), prevail in almost all the archipelagos (Morrison and Sudjito 1992). The Northwest monsoon season is indicated by a high Sea Surface Temperature (SST) and significant rainfall. Aldrian and Susanto (2003) identified dominant rainfall in relation to SST. SST is less during the Southeast monsoon than the counterpart season, Northwest monsoon.

This study was concentrated in an intertidal area surrounding Libukang Island. The mixed semi-diurnal tide was measured at 219 cm Highest Astronomical Tides (HAT). Based on degrees of wave exposure and current velocity that measured by water meter mini Air20, we found two different coastal areas of the island: north (zone 1) and south (zone 2). The description is shown in Fig. 1a and Table 1.

Field survey for substrate identification, macroalgal diversity, and coverage

The field observations were carried out in May 2014 and June 2015 with 38 points of observation. May and June represent rain-to-dry season which coincided with the season for the growth of brown algae, while November represents dry-to-rain season (with 15 points of observation), see again Fig. 1a. For getting more comprehensive information about macroalgal and substrate coverages in the area and limiting the water column error in the shallow intertidal area, the study was conducted during low tide when macroalgae were air-exposed. Transects were selected based on the covering range of different habitats colonized by algae. The seasonal habitat attributes, substrate, and percent cover of macroalgae were recorded during observations. Other information related to biogeographical zonation, geomorphological structure, and biological type cover for benthic habitats (macroalgae coverage) were also collected including additional information in the area where identification using photographs was difficult.

The depth of the site was recorded using a hand-held depth sounder. Handwritten field notes survey and underwater pictures were taken as a support to the digital data collected on a GPS data logger (Garmin GPSMAP 78s). Water quality for nutrient assessment was measured using spectrometer analysis (Table 1).

In the studied area, three genera were particularly monitored: *Padina*, *Sargassum*, and *Turbinaria*, as they were found abundant throughout the monitored period. Each specimen of brown macroalgae was determined at the species level using morphological criteria, using determination keys and local floras (Rohfritsch et al. 2007; Mattio et al. 2008a, 2009; Mattio and Payri 2011; Atmadja and Prud'homme van Reine 2012; Guiry and Guiry 2016), but also using NMR analysis as already described for the genus *Turbinaria* (Le Lann et al. 2008, 2014). Only one species of *Padina*, *Padina boryana*, was found around Libukang while more species of *Sargassum* and *Turbinaria* were present: *Sargassum ilicifolium* and *Sargassum polycystum* were found more abundant respectively in November and May and *Turbinaria conoides* and *Turbinaria decurrens* were observed more abundant respectively in May and November. As satellite imagery is unable to distinguish algae at species level in algal beds, results are given at the genus level.

The diversity of macroalgal genera and respective percentage covers were visually sampled and assessed using the method of Rogers et al. (1994) and Mumby et al. (1997). The percentage cover of macroalgae was estimated using square quadrats. For each sampling point and each species, three quadrats of 0.25 m^2 were thrown haphazardly, i.e., pseudo-randomly, in different benthic substrates based on two categories of percent cover: I = 0–10% classified as no cover area; II = >10% classified as cover area. We also determined the probability of the presence of genera, using the number of quadrats sampled on a substrate divided by total quadrats of a given genus, and multiplied by 100%.

Satellite data and habitat map creation

Macroalgae are marine benthic species attached to the bottom substrate. Several definitions of substrate types were adopted from the habitat typology of Kendall et al. (2001) and Andréfouët et al. (2003). The term of benthic classification was identified based on the visual observation of substrate during field study. The substrate and geomorphological conditions were correlated with macroalgae found in the area following the field site monitoring.

High-resolution multispectral satellite imagery was used to perform delineation of all boundaries associated with benthic habitats. Cloud and also cloud shadow covering the water surface not excluded in the mask processing were removed manually. It is essential to avoid them covering the water

Table 1 Description of substrate and seaweed sampling zones at Libukang Island (Malasoro Bay, South Sulawesi, Indonesia) during the field survey in 2014/2015

Parameters	Zone 1 (south)		Zone 2 (north)	
Phosphate (mg.L^{-1})	0.057 (NW)	0.058 (SE)	0.0375 (NW)	0.044 (SE)
Nitrate (mg.L^{-1})	0.25 (NW)	0.158 (SE)	0.127 (NW)	0.123 (SE)
Current (ms^{-1})	0.1–2.2		2–10	
Position	Is a sheltered location face to the mainland coast		Is a relatively exposed location	

NW Northwest monsoon and *SE* Southeast monsoon surface. Thus, the satellite image exploited with minimal cloud was the GeoEye-1 image acquired on March 10, 2016.

GeoEye-1 is a commercial satellite which was recently launched by Digital Globe (https://digitalglobe.com) with enhanced spatial and spectral resolution. It generates multispectral images with 1.65 m spatial resolution in red (625–695 nm), green (520–600 nm), blue (450–520 nm), and NIR (780–920 nm) from a 684-km orbital altitude in 15.2 mm swaths and fused imagery with 0.41 m spatial resolution of the panchromatic band (450–900 nm).

The substrate maps were analyzed in a four-step process (Fig. 1b). First, a draft map of natural macroalgal habitat was produced by delineating all features (geomorphologic structure and biological cover types) by visual inspection of the satellite imagery. The process was conducted using ArcGIS software version 10.2. All delineation was conducted based on colors and textures of the features, supported by field observations and the extensive knowledge of the area of the observer. The process consecutively included the following: (1) pan sharpening correction, i.e., combining data source imagery between panchromatic image and multispectral image; (2) enhancement by geometric (registered at WGS 84 datum with the Universal Transverse Mercator (UTM) zone 55S projection, radiometric correction (at this point, we used ERDAS ER Mapper software), and water column. The geometric correction used two methods: (a) a polynomial 2nd order rectification was used to shift pixel locations and remove distortion and (b) resampling using nearest neighbor type for pixels transformation. Radiometric correction was processed by histogram adjustments with original Digital Number (DN). Lyzenga's method (Lyzenga 1978, 1981) is used widely for water column radiative transfer analysis because of its simplicity of application to identification bottom substrate in shallow water with limited information of water properties; (c) cropping area of interest; (d) pseudo-color composite; and (e) supervised classification based on training area that referred to the field observation data. The supervised classification consisted on the selection of several different pixels as sample of specific input classes or training sites. Maximum likelihood classification (MLC) as a well-established supervised classification method was used in this study. The pixels representing particular substrate were selected and grouped based on visual interpretation. These selected substrate or training sites (42 points) were used as references by the software to classify all areas. Secondly, in situ observations and field surveys were conducted and the information collected was used as ground truth for accuracy (51 points) determination and assessment of the classification map resulting in the previous step. Thirdly, the resulting map was validated based on the ground information to generate a second draft habitat map which statistically analyzed the spectral value of shallow water and substrate characteristics.

Finally, the accuracy assessment of map was statistically reviewed and analyzed to determine the overall accuracy. The overall accuracy analysis was based on Hudson and Ramm (1987) and Congalton (1991). The accuracy assessment was a matrix that compared attributes assigned to a polygon generated from the interpretation of the image and the information from field observation and ground truth data (Fig. 1b).

Furthermore, the Kappa analysis (Cohen 1960) indirectly incorporated the off-diagonal elements as a product of the row and column marginal. The result of performing a KAPPA analysis is a KHAT statistic (an estimation of KAPPA), which is another measurement of agreement or accuracy. The map marginal proportions were calculated as the area of each map category divided by the total mapped area of the Libukang Island benthic habitat map. This method has been used in the accuracy assessment of the NOAA Florida Keys benthic habitat map (Walker and Foster 2009) and the NOAA shallow-water St. John habitat map (Zitello et al. 2009).

Distribution of macroalgae and relation with substrate

Logistic regression was used to relate macroalgal presence and substrate type, as described by Hosmer and Lemeshow (2000). A model was fit from this prediction process (the presence of macroalgae on substrate type alone in the sample):

$$p = \frac{1}{1 + e^{-\beta oi}}$$

where p is the probability of macroalgal presence, β is the coefficient estimated by maximum likelihood, and i represents the substrate type.

The result of field observation was overlaid on the map of predicted substrates and each location was detected and coded for the corresponding remotely sensed substrate category.

Biomass estimation

Biomass with spatial and temporal variabilities was estimated using the method adopted by Mattio et al. (2008a). Only biomass of three genera, i.e., *Padina*, *Sargassum*, and *Turbinaria,* representing the dominant genera in the study area, was estimated in this study. These three genera are widely distributed from the Indo-Pacific waters (Phillips 1995; Silberfeld et al. 2013). As species could not be determined at satellite scale, we present the results of abundance or biomasses at the genus level. The total biomass was estimated using the following equation:

$$W_x = S\alpha \times a_x \times R_x$$

where W_x is the biomass of a given abundant species, $S\alpha$ is the total area calculated from the satellite image, a_x is the slope of linear relationship between abundance biomass per unit of surface for a given species x in all the substrate classes and all representative seasons, and R_x is the linear relationships between the surface cover of the abundant species.

Linear relationships between surface cover of an abundant genus (R_x) and its biomass (W_x) were derived from the quadrat. For a same genus, individuals from three random 0.25 m^2 quadrats were gathered, washed, dried (freeze-dried), and then weighed to obtain the mean of W_x per waypoint sampling. The total biomass of the measured species in per km^2 was calculated from the satellite image estimated-substrate of bed class α ($S\alpha$).

Results

Macroalgal diversity and coverage

During field observations, nine common genera of macroalgae were found around Libukang Island: *Sargassum*, *Ulva*, *Padina*, *Halimeda*, *Turbinaria*, *Colpomenia*, *Eucheuma*, *Halymenia*, and *Codium*. The diversity of genera found in the field site varied spatially and seasonally. Among these genera, *Turbinaria, Sargassum*, and *Padina* were found abundantly throughout the studied seasons. Thus, this result section will focus on these three genera for further analysis. The coverage of these three genera throughout the entire sampling period ranged from 20 to 80% (Table 2). Based on personal observations, the percentage cover for *Turbinaria* and *Sargassum* was greater than the other genera due to the length of their thallus.

Habitat mapping and macroalgal distribution

The mapping focused on the area where natural macroalgae were found during the three field observations. The process also focused on the major substrate types divided into five classes: (1) sands (>80% white sand), (2) muddy sands (combination of sand and mud), (3) heterogeneous soft (combination sand, scattered dead coral structures, rubble coral, submerged vegetation); (4) hard bottom (hard substrate composed of exposed bedrock or created through depositional cementation of sediment including flat bedrock); and (5) coral reef (collection of marine fauna, e.g., soft coral, live coral gathered into one form reefs in benthic habitat including dead coral colony). The resulting maps present the distribution of habitats in two seasons as mentioned: May and June for rain-to-dry season and November for dry-to-rain season.

The area of classification was calculated by using the number of pixels on the satellite imagery (Table 3). The result was represented using a thematic map of substrate types present around the Libukang Island (Fig. 2). This study assumes that there is no significant temporal modification in the substrate distribution between seasons confirmed by the field and satellite data observations.

Macroalgae in the study area were mostly found in the eastern part of Libukang Island, in the area covered by diverse substrate types such as coral reef, hard bottom substrate, sand, and muddy sand (Fig. 2). *Turbinaria*, *Sargassum*, and *Padina* were the dominant genera with the percentage cover range from 60 to 100%. *Turbinaria* seemed to prefer the north of the island, which presented sheltered waters with mild current, as it was not found elsewhere. Conversely, *Sargassum* was found only in the south of the island, a relatively exposed water area with stronger currents than that in the north of the island. The fucaleans *Turbinaria* and *Sargassum* were generally attached to rocks or patches and rubble corals. The dictyotalean *Padina* was a genus also growing on rocks, gravel, or dead coral but mostly observed on sand. In the western part of the island, *Padina* is the only macroalgal genus found. This western area was mostly covered by a heterogeneous soft substrate.

The total study area was divided into two categories: (1) no algal cover to covered approximately 37.8% or 0.5578 km^2 and (2) the rest was considered as greatly macroalgae covered. Subsequently, the study area of macroalgal cover was classified as spare/moderate locations and dense locations for natural populations of macroalgae. Table 3 shows the total area of both zones, i.e., 0.6232 km^2 in where the heterogeneous soft substrate dominated this area. Heterogeneous soft substrate was the mix of reef, sand, and submerged vegetation constituted by seagrasses and macroalgal beds. The total area analyzed for all categories

Table 2 Seasonal variation and percentage cover (in quadrats) of brown algae found at Libukang Island (Malasoro Bay, South Sulawesi, Indonesia)

Genera	May 2014		November 2014		June 2015	
	Zone 1 (mean ± SD)	Zone 2 (mean ± SD)	Zone 1 (mean ± SD)	Zone 2 (mean ± SD)	Zone 1 (mean ± SD)	Zone 2 (mean ± SD)
Turbinaria	–	65 ± 4	86 ± 5.7	93 ± 4.4	–	60 ± 8
Sargassum	84 ± 4.8	–	60 ± 6.7	–	68 ± 6.5	–
Padina	60 ± 6.7	60 ± 13	26 ± 6.7	39 ± 1	58 ± 10	40 ± 10

Table 3 Training area of the substrate types divided by two categories of macroalgal coverage: covered area (>10%) and not covered area (<10%) at two zones of Libukang Island (Indonesia)

Substrate	Covered area			Not covered area			Total area (km^2)
	Zone 1 (km^2)	Zone 2 (km^2)	Total zone (km^2)	Zone 1 (km^2)	Zone 2 (km^2)	Total zone (km^2)	
Sand	0.0057	0.0423	0.048	0.0256	0.0052	0.0308	0.0788
Hard bottom	0.0621	0.0126	0.0747	0.0053	0.0058	0.0111	0.0858
Coral reef	0.0415	0.0399	0.0814	0.0284	0.0298	0.0582	0.1396
Heterogeneous on soft	0.3915	0.2317	0.6232	0.1916	0.2598	0.4514	1.0746
Muddy sand	0.0643	0.0582	0.1225	0.0263	0.0054	0.0317	0.1542
Total area (km^2)			0.9498			0.5832	1.533

(covered and non-covered area) were 1.50 km^2, approximately 62.3% (0.9498 km^2) was considered to be a potential area for the observation of natural populations of macroalgae. The most promising sites for natural macroalgae, identified by GIS, were areas characterized as shallow and relatively protected from wave action, in areas with depth ranging from 0 to 3 m from the highest point of tide.

Table 4 presents the error matrices for major substrate in the study area. The adjusted overall accuracy corrected for bias using the true map marginal proportions was 74.19% (α = 0.05). The user's and producer's accuracies were similarly low for coral reef and hard bottom (Table 4). The maximum likelihood classifier (MLC) gained the best results with sufficient accuracy, with Cohan's kappa coefficient equal to 0.87.

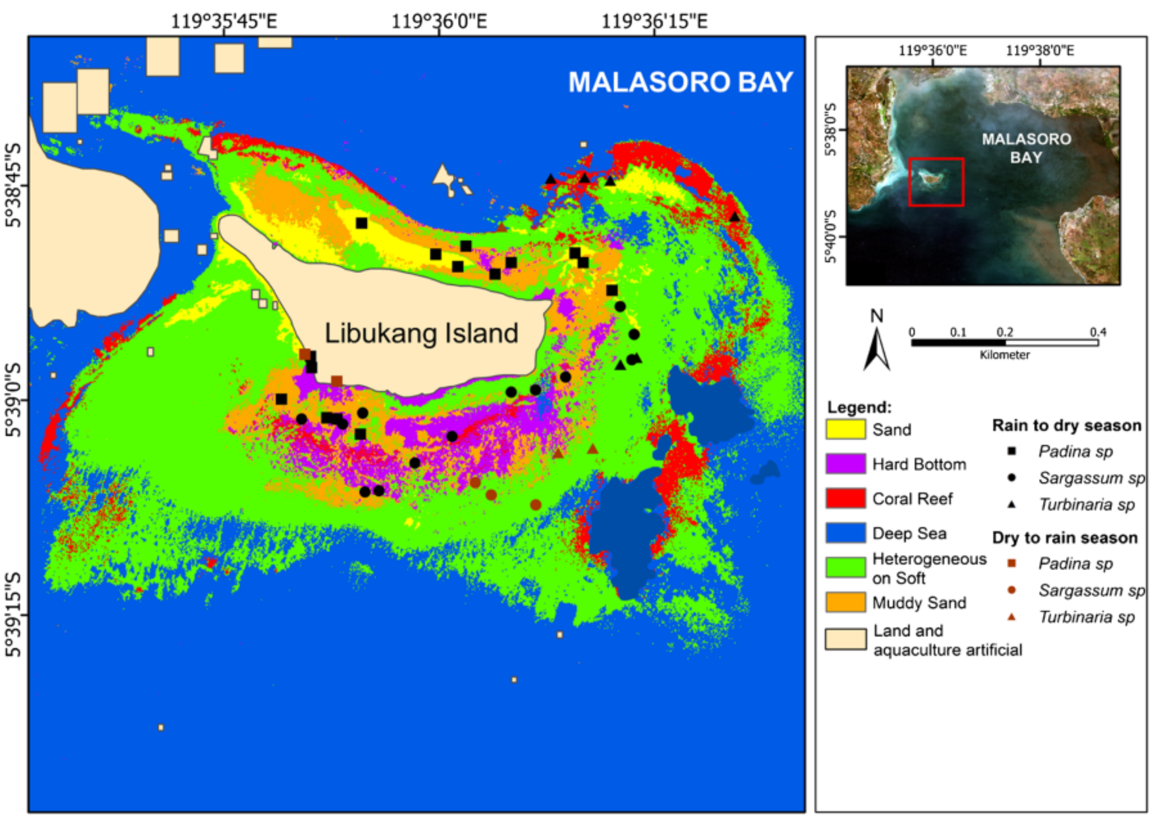


Fig. 2 Map of macroalgae distribution and their habitat from satellite image classifications showing their distribution and five classification substrate habitats (sand, muddy sand, hard bottom, heterogeneous soft, and coral reef) around Libukang Island (South Sulawesi, Indonesia). May and June represent rain-to-dry season, while November represents dry-to-rain season

Table 4 Error matrix for major substrate structure around Libukang (Malasoro Bay, South Sulawesi, Indonesia) using satellite image. The major diagonal (in grey) presents correct classifications from waypoints during sampling

	Ground Truth Data						
Satellite image classification data (Map Data)	**Sand**	**Muddy sand**	**Coral reef**	**Heterogeneous on soft**	**Hard bottom**	**Total**	**User 's Accuracy (%)**
Sand	4					4	100
Muddy sand		3			1	4	75
Coral reef			3		2	5	60
Heterogeneous on soft			2	11	1	14	78.5
Hard bottom		1		1	2	4	50
Total	4	4	5	12	6	31	0
Producer's accuracy (%)	100	75	60	91 .6	33.3		
Overall accuracy (P_o)	74.19%						
Kappa coefficient	0.87						

Based on results of training site selected to the supervised classification process data of substrate, spectral response values for each wavelength of GeoEye-1 image were statistically analyzed for bands 1, 2, and 3. Table 5 shows the statistical data of substrate spectral response values for each wavelength of GeoEye-1 image. Band 1 was associated with the band of blue color; band 2 with green and band 3 with red colors. The spectral response characteristics indicated five substrates classes, e.g., sands, muddy sand, heterogeneous soft hard bottom, coral reef in surrounding Libukang island.

Table 5 Spectral response characteristic of shallow water substrates at study area based on GeoEye-1, min = minimum; max = maximum; mean ± SD = means ± standard deviation

Substrate	Band 1				Band 2				Band 3			
	Min	Max	Med	Mean ± SD	Min	Max	Med	Mean ± SD	Min	Max	Med	Mean ± SD
Coral reef	22	41	25	27 ± 5	19	71	31	33 ± 9	41	201	89	104 ± 45
Sand	75	244	85	87 ± 15	143	291	218	219 ± 38	175	356	270	274 ± 43
Muddy sand	0	198	110	111 ± 29	0	228	82	92 ± 39	0	257	91	106 ± 91
Hard bottom	129	466	367	355 ± 58	117	249	163	164 ± 22	126	247	166	166 ± 22
Heterogeneous on soft	21	45	33	32 ± 4	26	93	40	41 ± 7	36	145	50	54 ± 13
Deep sea	5	34	11	11 ± 4	3	19	7	8 ± 5	3	23	11	11 ± 3

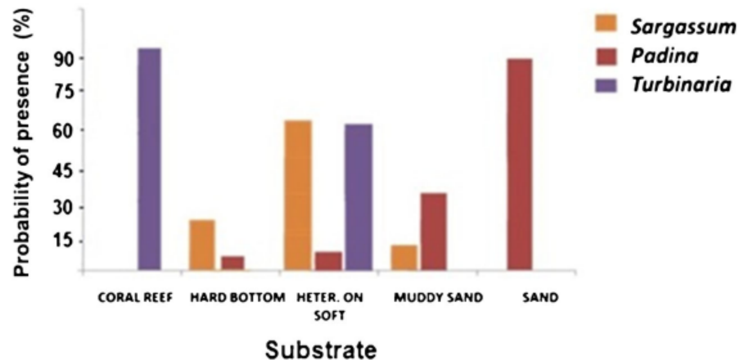


Fig. 3 Distribution of the genera *Sargassum*, *Padina*, and *Turbinaria* on different major substrates (in percentage of probability) around Libukang Island (South Sulawesi, Indonesia)

Relation between macroalgal abundance and substrate

The estimation of the percentage cover and the macroalgal distribution around Libukang Island showed that certain genera tended to have their own preferences to a particulate substrate, as presented on Fig. 3. *Sargassum* was abundant on the heterogeneous and soft substrate, as demonstrated by its probability of presence greater than 60. But this genus also inhabited the hard bottom and muddy sand substrate, but at low probability (Fig. 3). This genus was never found on coral reef and sand substrates. *Turbinaria* was mainly (probability of presence of 90) observed in the area of coral reef but also to a lesser extent on heterogeneous on soft bottom substrate (Fig. 3). *Padina* was able to colonize diversified substrates, but was mostly found on sand substrate. It was also found inhabiting other substrates (heterogeneous on soft and hard bottom) but was never found on coral substrate.

Each genus has a specific preference for the attachment of their holdfast on available substrates. Based on logistic regression between genus and type of substrate, our results indicated that *Sargassum* and *Turbinaria* were significantly related to substrate, but this was not the case for *Padina* (Table 6). Thus, in the aim at determining areas for macroalgae cultivation, substrate selection should be one of the major considerations to include as this component could have a significant effect on the presence and growth of macroalgae.

Abundance and biomass estimation

Based on field data sampling of the three focused genera, *Turbinaria* was the most abundant genus in both areas around Libukang Island, with highest percentage cover in November 2014 (86 ± 5.1), followed by *Sargassum* (84 ± 4.8) and *Padina* (60 ± 9.3) in May 2014 (Fig. 4).

In May 2014, the area in the south was dominated by *Sargassum* whose biomass reached 1189.6 ± 455 $g.m^{-2}$. For this period, *Padina* was not abundant with biomass less than 200 $g.m^{-2}$ for north and south areas around Libukang Island (Fig. 4).

In November 2014, *Turbinaria* was found with highest biomass that reached 3245 ± 599.84 $g.m^{-2}$. For this same period, the biomasses of *Sargassum* and *Padina* decreased drastically (164 ± 38 and 3.6 ± 1.5 g. m^{-2}, respectively), see Fig. 4.

Table 6 Logistic regression between genera of brown macroalgae and substrate ($p < 0.05$) studied around Libukang (Malasoro Bay, South Sulawesi, Indonesia)

Genus	*df*	*t* value	*p* value
Sargassum	2	18.34	<0.05
Padina	3	3.647	0.21
Turbinaria	1	27.05	<0.05

Discussion

Brown algae are particularly common in the temperate zones of the world and only a few genera like *Sargassum*, *Turbinaria*, and *Padina* grow abundantly in warmer tropical waters (Phillips 1995). In our present study, *Sargassum*, *Turbinaria*, and *Padina* were determined as the three major and most conspicuous genera around Libukang Island (Indonesia). Hadi et al. (2016) in their study on the macroalgal diversity in Kasiak Gadang Island, Indonesia, found similar results. Otherwise, Phaeophyta showed the lowest species diversity in Drini Beach, Southern Java Island, Indonesia. However, authors showed a greater percentage cover than other seaweeds, although only a few individual fronds were observed. In fact, the dominance of brown fleshy macroalgae is also observable in many worldwide regions, as along the Great Barrier Reef (Bellwood et al. 2006; Hughes et al. 2007; Wismer et al. 2009) and in the Atlantic Ocean at Belize (McClanahan et al. 2003). Three genera in this study were also found abundant, as demonstrated by Stiger and Payri (1999a, b, 2005) in their study on South Pacific Islands from French Polynesia. *Turbinaria ornata* and *Sargassum pacificum* (known previously as *Sargassum mangarevense*, Mattio et al. 2008b) were the dominant species that grew on dead coral colonies, while *Padina* was common but sometimes dominant in both intertidal and shallow sub-tidal regions associated with coral reefs. Thongroy et al. (2007) found

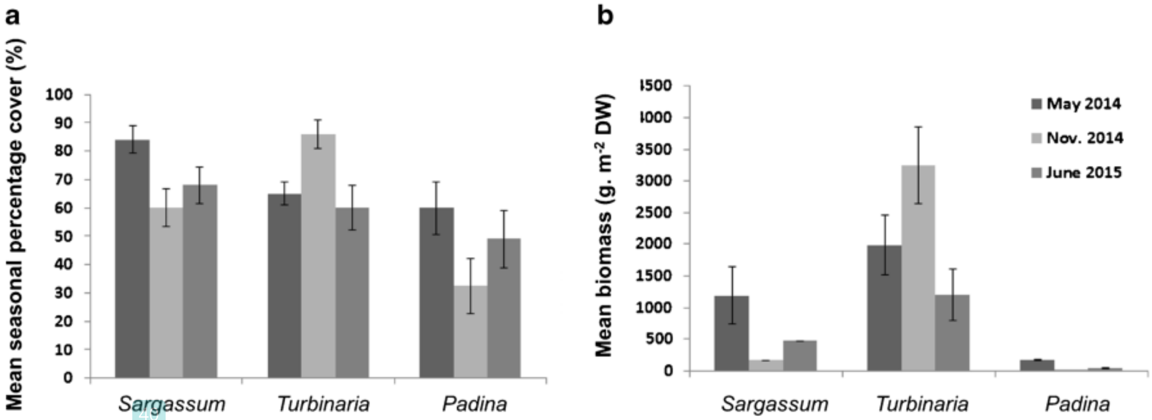


Fig. 4 Seasonal percentage cover (%) and biomass (g.m^{-2} DW) per genus of brown macroalgae with data representing mean ± SD (standard deviation) for all considered zones at Libukang Island (South Sulawesi, Indonesia)

that *Padina* spp. was the most common at all sites on the tropical coast of Sirinart Marine National Park, Thailand.

Seasonal variability of macroalgal diversity and coverage

Seasonality in the biomasses and the percentage covers of the three genera were also demonstrated in this study based on seasonal field survey data. *Sargassum* was abundant on May and June, *Turbinaria* on November, while *Padina* was present all around the year in all zones of sampling. Ateweberhan et al. (2009) reported that the density and biomass of three Sargassacean species, i.e., *S. ilicifolium*, *Sargassum subrepandum*, and *Turbinaria triquetra*, monitored in the southern Red Sea varied strongly according to season, with highest values occurred during cooler months. In a similar manner, Stiger and Payri (1999a, b) showed also that the abundance of *T. ornata* and *S. mangarevense* varied seasonally with an abundance of both species more important during the austral cool season (in May/June).

The biomass and density of the genus *Turbinaria* studied in the present study around Libukang was higher in November when temperature is high. Prathep et al. (2007) in their study about *T. ornata* from Thailand found similar results: this species was denser on the semi-exposed shore and reached its peak of development during high temperature of seawater.

Habitat mapping and macroalgae distribution

Shifts in environmental conditions are likely to result in altered species composition of macroalgae including potential changes in propagule dispersal and consequently changes in distribution patterns, range expansions, and thus, potential source for species introductions in marine benthic communities (Schiel et al. 2004). In our study, water motion, current, and substrate bottom were likely to play an important role in determining species distribution and composition of macroalgae. Prathep (2005) in his study on macroalgae from Thailand demonstrated that the highest diversity was found on the semi-exposed shore during the dry season, when the seawater hydrodynamism was rather calm. However, McCook (1999) stated that under low ambient nutrient conditions, high water motion can stimulate an increase in growth rates of macroalgae.

Macroalgae in the study area were mostly found in the eastern part of the Libukang Island. Three genera of brown algae spread from north, over east to the south and none were observed in the west of the island. The current velocity in the west southern part of Libukang Island was stronger (2–10 m s^{-1}) than in the northwestern one (0.1–2.2 m s^{-1}).

Among the various factors that contribute to an increase in the algal population are the nutrients supplies along the adjacent land. Community activities in Libukang Island could affect the coral-algal shift through an increase in the water nutrient of the area. Organic pollution in the area is not yet a major problem. High nutrient inputs into ambient seawater may have both direct and indirect biological effects.

Remote sensing is an alternative and complementary approach to monitor change of natural resources such as macroalgae and their habitat, especially in remote areas or areas with poor data (Hossain et al. 2016), such as Indonesia and more particularly Indonesian Islands. The high spatial resolution satellite imagery was exceedingly helpful in discriminating seafloor habitats especially in the study areas with clear and shallow waters, as demonstrated also by Heege et al. (2016). Although, high-resolution imagery can be difficult to obtain and consecutive to its high cost compared to low and medium resolution images (Xie et al. 2008), we found that such imagery is critical for detecting accurately small objects in narrow areas such as in our study.

Fyfe (2003) studied the possibility of a hyperspectral sensor with narrow bands centered on pigment-related spectral features in the visible wavelengths for a discrimination of benthic aquatic vegetation until the species level. It seems an appropriate method to be applied in the study area due to the high diversity and richness in term of species indicated with the high range of percent coverage (20–80%). Moreover, high-resolution image is expensive compared with low and medium resolution. However, it was more reliable to generate the substrate benthic classification in shallow water in this case.

Macroalgae and benthic substrate

Brown algae fixed commonly on the hard substrates in the intertidal area. However during field survey, brown algae seem attached on several different substrates considering the five classes made in this study. For a better understanding, the relation between algal presence and their preference substrates were statistically analyzed using logistic regression. It was inferred that heterogeneous soft is the substrate preference for the three brown genera studied.

The combination of benthic substrate map from image satellite processing and from field observations provides the baseline data and information for further statistical analysis. The statistical data of spectral response characteristics provides baseline data for the recognition of similar substrate types, i.e., sands, muddy sand, heterogeneous soft hard bottom, and coral reef in other shallow waters. Based on the understanding of the spectral response characteristics, it can be applied for producing more accurate maps of substrate types without much field survey work.

A single image of multispectral sensors with high spatial resolution can provide more detailed information about the benthic cover. The reflectance spectra shape from different bottom types and spectral resolution of the sensor created in this study can be used as a spectral library. The spectral library data are used as a reference for image processing on analysis and similar monitoring at different times in other locations. In situ data are merely needed for ground checking together with the analysis of the macroalgal population structure. Thus, combination between in situ and remote sensing could be applied to monitor and to identify seaweeds potential habitats.

Maps elaborated in this study demonstrated the potential use of high-resolution satellite data to characterize the substrate type associated to macroalgae, and to identify potential areas for the settlement of macroalgae in the intertidal zone. In Indonesia, habitat mapping was concerned with coral reef issues. Laws and regulations are often directly related to the conservation of coral reef ecosystem. Different reef structures reflect different biomass and abundance of macroalgae as Andréfouët et al. (2004) highlighted in their study on Sargassacean species from French Polynesia.

Perspectives

The spectral response characteristics of macroalgal substrate took into account the range of spectral variability expected for the macroalgal habitat under natural conditions. It will be serviceable for future ecological studies in more extent areas and for a long-term monitoring of macroalgal communities in Indonesia.

Our study provided a rapid way for a biomass estimation of major genera occurring around the Island of Libukang (Indonesia). Our results indicated that a small island could provide a good study site for understanding a small-scale seaweed distribution, within a bay or along intertidal zones. The approach used in this study can be applied in other shallow water areas. Moreover, it will be projected to a wider area. Further studies might be conducted in a large macroalgal beds area, over an extended period by taking into account more environmental parameters.

The presence of several macroalgae and their high biomass could become an interesting area for macroalgal production. It could support local economy by macroalgae cultivation activities. The exploitation of brown macroalgae such as *Sargassum* and *Turbinaria* is promising, since in the Pacific Ocean they are known to produce interesting molecules such as alginates, mannitol, polysaccharides (Deslandes et al. 2000; Zubia et al. 2008, Zubia and Andrefouet 2015), fucoxanthin and fatty acids (Le Lann et al. 2012, 2014), and phenolic compounds (Stiger et al. 2004; Zubia et al. 2008; Le Lann et al. 2012). Thus, they represent a valuable and significant renewable resource for Indonesian people.

This study is the first seasonal study and habitat mapping of brown macroalgal ecology in a small island-scale in Indonesia using high multispectral resolution satellite data. However, taxonomic resolution in this study is highly limited as we only gave data on genera, instead of species. Satellite data are not capable to distinguish algal species. Nevertheless, the results obtained in this study can be used as basic information for further studies of macroalgal communities in tropical intertidal and reef areas. Long-term monitoring program is needed to provide data set that allows identification of long-term trends of the percentage cover of macroalgae, which are extremely diversified in Indonesia.

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