Assessing long-term coral reef degradation in Indonesia's Tiworo Strait Marine Conservation Area using remote sensing and rapid appraisal for fisheries approaches

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Abstract

In Indonesia, the coral reef ecosystem in the Tiworo Strait Conservation Area (TSCA) faces various threats of natural and anthropogenic stressors that can damage the coral reef ecosystem's role and services. We analyzed changes in coral reef habitat at TSCA over the 25 years from 1994 to 2019 using multi-temporal and multi-sensor satellite imagery data combined with in-situ measurement data and social surveys. Our results show a decrease in live coral cover from 78.30 ha in 1994 to 8.01 ha in 2019, with a 2.81 ha/year degradation rate. Our analysis of 37 threat attributes shows that the TSCA coral reef ecosystem faces a "high threat" to very high threat levels. Threat scores for coral reefs assessed as facing severe conditions according to threat indices included contributions from the ecological dimension (16.87 = very high threat), economic dimension (31.00 = high threat), social dimension (34.83 = high threat), technological dimension (41.10 = high threat), and law and institutional dimension (26.83 = high threat). Coral reefs will undoubtedly go extinct if local threats continue without preventative measures. Therefore, the sustainability of coral reefs in the TSCA-one of the most important marine conservation sites in the

Coral Triangle Marine Eco-region should be the primary priority for all stakeholders. Appropriate policies and supervision in the field must be carried out rigorously and measurably, implementing the analyzed set of strategies.

Keywords: *coral cover change; rapid appraisal for fisheries (RAPFISH); remote sensing; threats; Tiworo Strait Conservation Area (TSCA), Coral Triangle Eco-region of Indonesia*

1. Introduction

Over the past four decades, numerous studies have identified the trend of continuous coral reef degradation due to natural and anthropogenic pressures. These pressures include enhanced local pollution of coastal areas (Burke *et al.*, 2011; Häder *et al.*, 2020; Randazzo-Eisemann *et al.*, 2021), overfishing (Moussa et al., 2019; Nichols et al., 2019), destructive fishing practices (Yasir Haya and Fujii 2020; Hampton-Smith et al. 2021), sea surface temperature (Hughes et al. 2018; Ngoc 2019), climate change and subsequent ocean warming (Pendleton et al. 2016; Hughes et al. 2017; Zhang et al. 2021), ocean acidification (Allemand and Osborn 2019; Zunino et al. 2021), coral diseases (Lapointe et al. 2019; Hazraty-Kari et al. 2021), nutrient enrichment (Lapointe et al. 2019; Adam et al. 2021), and other anthropogenic threats (Burke et al. 2011; Mellin et al. 2016; Hoegh-Guldberg et al. 2019; Hein et al. 2021). Degradation of coral reefs leads to a loss of their ecological and economic value, particularly the goods and services to coastal and other communities (Cesar and Chong 2004; Mehvar et al. 2018; Yasir Haya and Fujii 2019; Santavy et al. 2021). Given these conditions, coral reef ecosystems require urgent management, such as a marine protected area (MPA) approach (Mellin et al. 2016; Vaughan and Agardy 2020; Hampton-Smith et al. 2021).

MPAs have become one of the most frequently employed marine management tools worldwide for conserving species and habitats, maintaining ecosystem functionality, and ensuring the sustainable use of marine resources (Pagiola et al. 2004; Vaughan and Agardy 2020). In Indonesia, the types and sizes of MPAs differ according to their conservation goals and targets. The Tiworo Strait is a medium-sized marine conservation area that located at the Southeast of the Sulawesi mainland in the center of the Coral Triangle Area, Indonesia (**Fig. 1**). The Tiworo Strait exhibits tremendous marine biodiversity potential with its combination of coral reefs, mangroves, seagrass, and fish, with a total area of around 27,936 ha (KKJI-KP3K, 2019). Because of this potential, the Tiworo Strait was designated as a conservation area by the local government of the Muna Regency and has become one of the most critical marine conservation sites in the Coral Triangle of Southeast Sulawesi, Indonesia. Nevertheless, the coral reefs in the Tiworo Strait Conservation Area (TSCA) are thought to have experienced massive degradation due to pressure from various environmentally unfriendly activities.

The primary sources of coral reef degradation are local anthropogenic factors i.e., blast fishing, trap fishing (locally known as "Bubu"), and bottom-trawling net practices (locally known as "Dogol"). These three fishing practices are considered environmentally unfriendly because they overly exploit fishery resources and violate conservation rules (Gorris 2016; Chan and Hodgson 2017; Kularatne 2020) thus allegedly reducing coral cover in this area. Information on coral reef changes in the TSCA, which is desperately needed for habitat management, is not yet available. However, the combination of remote-sensing technology, in-situ data, and social surveys can provide alternative approaches for monitoring changes in reef composition at high spatial and temporal resolution (Andréfouët et al. 2003; Foo and Asner 2019; Chen et al. 2022). These approaches can facilitate monitoring in remote areas that are not directly accessible including coral reef ecosystems (Purkis 2018; De et al. 2021; Molder et al. 2022).

Remote-sensing technology has been used in a variety of coral reef studies, including the classification of benthic habitats (Zhang 2015; Roelfsema et al. 2018; Zhang et al. 2018; Molder et al. 2022), detection of changes in coral composition (Andréfouët et al. 2007; Hedley et al, 2016; Parsons et al. 2018; Purkis 2018; Nimalan et al. 2021) and benthic reflectance at the bottom (Lee et al. 2013; Barnes et al. 2014; Thompson et al. 2017; Roelfsema et al. 2021) and estimation of coastal water bathymetry (Lyzenga et al. 2006; Mishra et al. 2006; Pacheco et al. 2015; Minghelli et al. 2021). Frequently, these studies only analyze changes in benthic habitat cover without identifying habitat status and types of threats.

To provide adequate coral data, this comprehensive study explores the ability of Landsat Satellites to detect coral reef cover, using four multi-temporal Landsat that have not yet been applied to this region. Our study illustrates the ability of Landsat satellite multi-sensor technology, combined with field data, to monitor changes in coral cover over the past 25 years (from 1994 to 2019) and identify the threat status of coral reef ecosystems.

2. Materials and Methods

2.1. Study Site

The study site was located in the TSCA, Muna Barat Regency, in the Southeast Sulawesi Province of Indonesia, geographically located between 04º16'40"S – 04º32'20"S and 122º13'35"E – 122º32'40"E (**Fig. 1**). The Tiworo Strait was declared a MPA through a Decree of the Muna Regent (No.157/2004) and has a total area of 27,936 ha. For the last several decades, fishermen, fishing boat workers, seaweed and fish cage farmers, small-scale crab entrepreneurs, traders, and grocers living near the TSCA have depended on the marine resources in the Tiworo Strait.

2.2. Data Sources

2.2.1. Satellite Imagery Data

Landsat TM data consist of seven spectral bands with a spatial resolution of 30 m for bands 1–5 and 7. Landsat ETM+ data consist of eight spectral bands with a spatial resolution of 30 m for bands 1–7. Landsat 8 data have nine spectral bands with a spatial resolution of 30 m for bands 1–7 and 9. Landsat TM, ETM, ETM+, and OLI image classifications with a spatial resolution of 30 m can be used to examine the cover of five seabed substrates: live coral, rubble, sand, dead coral, and seagrass. Satellite imagery data used in this study were obtained from multi-temporal and multi-sensor Landsat imagery from 1994, 2002, 2013, and 2019. Landsat imagery data is freely downloadable from US Geological Survey-USGS (2019). The types and characteristics of Landsat imagery are summarized in Table 1.

2.2.2. Field Data

(i) Ground Control Points and Ground Truthing Data

Aside from coral observations, coordinate points as ground control points (GCPs) and for ground truthing (GT) were determined using global positioning system (GPS). GCPs at the location were typically road intersections, docks, or landmarks identifiable in the satellite images. GT data were focused on Pulau Tiga because it has a large surrounding reef flat compared to other islands within the TSCA, making it easy for Landsat satellite sensors to capture spectral responses reflecting seabed cover. Coral reefs off Pulau Tiga can represent the condition of reefs in the TSCA at large because all of its islands can be accessed directly by local and non-local fishermen. GT data were obtained using GPS for each type of seabed cover, which included live corals, dead corals, rubble, seagrass, and sand (Nurdin et al. 2015). *In-situ* data on bottom cover types were obtained using a GPS unit (latitude-longitude data) and snorkeling or SCUBA equipment (data on bottom cover types). GT data were applied to check the accuracy of the image classification results.

(ii) Social Surveys

Socio-economic data were obtained through interviews and questionnaires as supporting information for image interpretation and Rapid Appraisal for Fisheries (RAPFISH) analysis. We used purposive sampling by selecting respondents according to types of fishery activities, occupations, academic positions, and stakeholder roles (Kothari 2004). To ensure the validity and currency of the data, we consulted with marine and fisheries scientists at the Faculty of Fisheries and Marine Science at Halu Oleo University. To strengthen the methodological assessment, we incorporated the opinions and perspectives of resource users (fishers), resource managers, and subject experts (Susilo 2003).

2.3. Data Analysis

2.3.1. Image Processing

Image processing was carried out in several phases, and refers to Nurdin et al. (2015) as follows:

a. Atmospheric Correction

Scattering and absorption of molecules by the atmosphere can decrease the quality of information in an image by up to 10%, depending on the spectral channels (Che and Price 1992). Atmospheric correction is therefore essential to minimize the effect of the atmosphere in multi-temporal images before comparing and analyzing the data (Hadjimitsis et al. 2010). Atmospheric correction was done for five series of Landsat imagery data using Dark Object Subtraction (DOS). In DOS, an absolute correction to the image is performed, such that any reflection value (e.g., from shadows, deep clear water, or dense forest) is reduced to near zero percent. Then, signals recorded for each object by the sensor are a result of atmospheric scattering (Chavez 1996).

b. Geometric Correction

Geometric correction for three series of Landsat imagery data was conducted using the same coordinate points (GCPs). Geometric correction aims to improve the accuracy of and minimize the geometric error in Landsat imagery data. Eight GCP points were chosen for geometric correction using order polynomial transformation and a nearest-neighbor interpolation algorithm (Afwani and Danoedoro 2019). The corrected image was considered acceptable if the root mean square error was less than 0.5 (Baboo and Devi 2011).

c. Image Composites

True color in Landsat 5 TM and Landsat 7 ETM images is displayed with a RGB (red:green:blue) band composition of 3:2:1, whereas that in Landsat 8 OLI/TIRS images is displayed as RGB = 4:3:2 [38,40]. This band combination is often used to detect feature types on the bottom in shallow water at a preliminary stage. Three channels (bands) were selected because the band composites were considered the most appropriate for deducing the appearance of land cover. Red composites using band 3 (Landsat 5 TM/7 ETM) and band 4 (Landsat 8 OLI/TIRS) are suitable for detecting dry land or soil. Green composites were used to detect chlorophyll in vegetation from band 2 (Landsat 5 TM/7 ETM) and band 3 (Landsat 8 OLI/TIRS). High chlorophyll concentrations on the mainland provided high reflection digital values and were shown as dark green colors. Water was detected using band 1 (Landsat 5 TM/7 ETM) and band 2 (Landsat 8 OLI/TIRS) in blue composites so that it could be depicted in blue.

d. Image Subsetting (Cropping)

In image subsetting, or cropping, the aims are to delimit the area of interest, reinforce the geospatial phenomenon, and focus on the study area. In a subset image, objects appear larger such that existing information, such as color, can be seen more clearly.

e. Application of the Depth Invariant Index

The objective of the depth invariant index (DII) algorithm is to improve the accuracy of object information (color) at the sea bottom in an image (Lyzenga 1981, 1985). We created at least 30 polygons in a training area assumed to comprise coral reefs in the study area. The data obtained were analyzed in terms of variance and covariance for blue and green bands. The variance and covariance were then used to determine the attenuation coefficient to clarify the results of coral reef image classification using the following equations:

$$a = \frac{(\sigma ii - \sigma jj)}{2\sigma ij}, \quad (1)$$

$$\frac{ki}{kj} = a + \sqrt{(a^2 + 1)}, \quad (2)$$

$$(DII)ij = \ln(Li) - \left[\left(\frac{ki}{kj}\right) \times \ln(Lj)\right], \quad (3)$$

where i is the blue band, j is the green band, σ_{ii} is the variance of the blue band, σ_{jj} is the variance of the green band, σ_{ij} is the covariance between blue and green bands, $\frac{ki}{kj}$ is the attenuation coefficient index ratio between blue and green bands, and Li and Lj are the radiance pixels of blue and green bands, respectively.

f. Classification, Ground Truth, and Reclassification

Images produced by the DII algorithm were classified based on ISOCLASS unsupervised classification (Call et al. 2003), resulting in 30 unlabeled classes with 100 iterations. These classification results were then grouped according to their spectral and digital values. Each bottom type had a different spectral value identifiable in the image. Reclassification was applied to the unsupervised-classification image based on visual interpretation (spectral class color) and GT data with 75 sampling points in the field survey. Visual and field interpretations were based on the interpretation guides by Suwargana (2014) and Nurdin et al. (2015), as seen in Table 2.

g. Post-Classification Process

At this stage, we produced maps of coral reef distribution and condition based on the extracted Landsat multi-temporal imagery data. Four maps were produced for 1994, 2002, 2013, and 2019, according to the time the images used were acquired. We also generated maps of changes in coral reef condition for the 25-year period using map overlay; coral reef changes from 1994 to 2002, 2002 to 2013, and 2013 to 2019 were mapped.

h. Accuracy Assessment

Overall accuracy is closely related to positional and thematic accuracy (Congalton and Green 2019), which is assessed using a confusion matrix. This method compares the image obtained from classification results (as the basis for the actual class) with field data, which are assumed to represent seabed cover. Data in rows were obtained from remote-sensing data classification, with the accuracy depending on the data producer, whereas data in columns were calculation results of field observations by researchers and were used in calculations of user accuracy. Greater consistency between classification and observation results would generate higher overall accuracy, which was calculated using the following equations:

$$Overall\ accuracy = \frac{\sum_{i=1}^{k} n_{ij}}{n} \times 100\%, \tag{4}$$

$$Producer\ accuracy\ j = \frac{n_{jj}}{n_{+j}} \times 100\%, \tag{5}$$

$$User\ accuracy\ i = \frac{n_{ii}}{n_{i+}} \times 100\%. \tag{6}$$

where n_{ij} is the number of observations at column j and row i, n_{ii} and n_{jj} are the number of observations categorized in the thematic class of i and j, respectively, n_{i+} and n_{+j} are the number of observations classified in the thematic class i from satellite data and j from *in-situ* data, respectively, and n is the total number of observations.

2.3.2. Rapid Appraisal for Fisheries Analysis

The Rapid Appraisal for Fisheries (RAPFISH) was developed at the University of British Columbia, Canada, and is used to evaluate fisheries sustainability with the application of a new multidisciplinary rapid assessment technique. The RAPFISH relies on the ordinance of assessed attributes that are grouped in several evaluation fields using multidimensional scaling (MDS). The fields or dimensions are ecology, economy, technology, social, ethics/law, and institutions (Pitcher and Preikshot 2001; Alder et al. 2002; Fletcher 2006). Each dimension is assigned a specific attribute, or indicator, associated with the threat to coral reefs, as determined by Kennedy et al. (2013). Attributes are then parsed with reference to Pitcher and Preikshot (2001), Susilo (2003), and RAPFISH (2019).

Technically, the stages of data collection and processing in RAPFISH are as follows: (i) identification and determination of threat attributes, as defined according to the principles of the ecosystem approach to fisheries management, (ii) definition and scoring of attributes, (iii) field verification and consultation with fisheries scientists/experts, (iv) data processing, (v) scientific justification, and (vi) RAPFISH analysis (Pitcher 1999). The RAPFISH procedure included data tabulation, data entry into the RAPFISH program, running the RAPFISH program, analysis of multi-dimensional scaling (MDS), sensitivity analysis, Monte Carlo analysis, and interpretation of results based on the threat index and sustainability status.

a. Identification and Determination of Attributes

Thirty-seven threat attributes were identified from a thorough review of all available data. The collected attributes were classified into five dimensions: six attributes in the ecological dimension, eight attributes in the economic dimension, seven attributes in the social dimension, nine attributes in the technological dimension, and seven attributes in legal and institutional dimension (Table 3; (Pitcher and Preikshot 2001)). These attributes represent the variation in threats to the sustainability of coral reefs in the TSCA.

b. Defining and Scoring Attributes

The second step in the analysis was defining and scoring attributes in RAPFISH (Pitcher and Preikshot 2001; Kothari 2004). A "bad" score designates the worst possible condition of a coral reef ecosystem, and a "good" score signifies the most favorable condition. Scoring was performed based on the method formulated by Good et al. (1999) and Hershman et al. (1999).

c. Feasibility of Threat Analysis

Threat analysis feasibility is assessed by measuring stress values (particular measures of goodness-of-fit in MDS), which are calculated using the ALSCAL algorithm (Preikshot et al. 1998). This algorithm is used to optimize the distance of squared data to the original point (O_{ijk}) (d_{ijk}) in three-dimensional space (i, j, k), which is symbolized as stress (S), as described in the following equation:

$$S = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left[\frac{\sum_i \sum_j (d^2{}_{ijk} - d^2{}_{ijk})^2}{\sum_i \sum_j O^4{}_{ijk}}\right]}, \qquad (7)$$

where m is the number of analysts or experts from various scientific backgrounds. In the RAPFISH method, MDS analysis is terminated when the S value lies within a tolerable range, with an acceptable maximum value of 0.25 (25%) (Fauzi and Anna 2002).

d. Rotation Process

The projection of points onto the horizontal axis was done using a rotation process in which “bad” extreme positions were assigned to 0 and “good” extreme positions were assigned to 1. This process was carried out using RAPFISH scores. In addition, RAPFISH includes two "half-way" scores that are mirror images of each other for scaling in the vertical dimension and a set of pre-defined anchor points to avoid vertical "flipping" of the MDS ordinates. A more detailed description is provided in Kavanagh and Pitcher (2004).

e. Index Scale of Threats

We used a modified index scale to assess threats to the sustainability of coral reef ecosystems based on Pitcher and Preikshot (2001). Modifications included the following changes to descriptions of index levels: from unsustainable to very high threats, from less sustainable to high threats, from somewhat sustainable to fewer threats, and from sustainable to no threats. The threat index ranged from 0 to 100 and was divided into four categories (Table 4).

f. Sensitivity Analysis

Sensitivity analysis was done to determine which attribute was most sensitive to the sustainability of coral reef ecosystems. The effect level of each attribute on the sustainability index was analyzed using leverage analysis in RAPFISH to determine the degree to which the ordination result changed when particular attributes were omitted from the dataset. The effect of each attribute was determined by observing the change in root squared correlation (RSQ) of the ordination, especially at the x-axis or accountability scale. Transformation of the RSQ at higher levels due to omission of a particular attribute causes a greater effect on the threat index. In other words, such an attribute is more sensitive to how a coral reef ecosystem is managed. Attributes with higher levels of sensitivity were subsequently used to formulate recommendations for saving coral reef ecosystems (Adiga et al. 2016).

g. Monte Carlo Analysis

Monte Carlo analysis was used to analyze errors in the assessment of attributes caused by several factors, such as 1) inconsistency in assessment, 2) differences in the assessment, 3) level of iterative stability, 4) data errors, and 5) high stress values (Kavanagh and Pitcher 2004). This method was also used to calculate the effect of random errors on the process of estimating/calculating ordination values. The acceptable stress value was set to <25% (Kavanagh and Pitcher 2004).

3. Results and Discussion

3.1. Change in Coral Reefs

The digital number obtained by Landsat multi-sensors is relatively small for the categories of live coral, dead coral, and seagrass, implying higher absorption of visible spectrum radiation (i.e., blue, green, and red channels) by the seabed compared to rubble and sand (**Fig. 2**). Therefore, the three categories appear darker in an image than does rubble or sand. Regression analysis results showed that the ratio of the blue channel vs. the green channel was the highest (RSQ > 94%) compared to other ratios in the visible spectrum. This is coincident with the results in numerous previous studies stating that the ratio of blue to green channels has a better ability to detect seabed cover, including coral reefs (El-Askary et al. 2014; Lillesand et al. 2015; Nurdin et al. 2015). Therefore, blue and green channels in the Landsat imagery data were used to detect seabed cover (**Fig. 3**).

Based on the results of an accuracy test using a confusion matrix, an accuracy test on the classification results of Landsat 8 OLI/TIRS images from 2019 was carried out with field data obtained in 2019 for five classes of seabed cover: live corals, dead corals, rubble, seagrass, and sand. The test yielded a producer accuracy of 83%, user accuracy of 82%, and overall accuracy of 82%. This indicates that the interpretation results are considered acceptable because the accuracies are greater than 80% (Lillesand et al. 2015).

The Landsat multi-temporal images from 1994, 2002, 2013 and 2019 showed that coral reefs have changed over the 25-year period from 1994 to 2019, with a decline in live coral and increased dead coral and rubble (**Fig. 4**). In 1994, the area for each category was 78.30 ha for live coral, 15.43 ha for dead coral, 20.07 ha for rubble, 53.06 ha for seagrass, and 49.41 ha for sand, implying relatively small proportions of damaged coral reefs (7.13%) and rubble (9.28%) compared to live coral (36.20%) (**Fig.4(a)**). The dominance of live coral is considered to benefit the marine ecosystem and local people. Live coral was widely distributed (in cyan) around the island, although some dead coral (in red) and rubble (in dark green) were also found in a small area.

There were significant changes in seabed cover from 1994 to 2003, particularly for live and dead coral and rubble (**Fig. 4(b)**; Table 5). The live coral area decreased significantly by 41.95%, from 78.30 ha in 1994 to 45.45 ha in 2003. Dead coral doubled from 15.43 ha to 30.33 ha during the same period. The rubble area slowly increased by 48.43%, from 20.07 ha in 1994 to 29.79 ha in 2003. Seagrass decreased slightly by 3.10 ha, whereas sandy areas substantially increased from 49.41 ha in 1994 to 54.54 ha in 2003.

By 2013, live coral area had decreased, whereas dead corals had become dominant, especially off the western and southern parts of the island (**Fig.4(c)**). The remaining live coral area was estimated to be 22.32 ha, whereas dead coral cover doubled from 30.33 ha in 2003 to 61.35 ha in 2013 (Table 5). The rubble area increased from 29.79 ha in 2003 to 32.13 ha in 2003, whereas the cover of seagrass and sand decreased slightly.

By 2019, live coral cover had declined to 8.01 ha (Table 5). Dead coral and rubble had slowly increased to 66.42 and 33.66 ha, respectively. The areas of seagrass and sand fell slightly in the same period. Dead coral and rubble occupied 30.71% and 15.56%, respectively, of the total area of the intertidal island (**Fig. 4(d)**).

We observed three types of changes in benthic habitat cover over the 25-year period from 1994 to 2019: an increase, decrease, and fluctuative increase (Table 6). Visually, the greatest decrease in live coral cover occurred between 1994 and 2003, with a reduction of 41.95%, followed by 2003–2013 (29.54%) and 2013–2019 (18.28%). Conversely, the greatest increase in dead coral cover occurred between 2003 and 2013 (201.04%), followed by 1994–2003 (96.57%) and 2013–2019 (32.86%). Rubble cover increased throughout the study period, although the rate gradually decreased. Seagrass exhibited fluctuations in cover: a decrease of 5.84% from 1994 to 2003, a slight increase of 3.79% from 2003 to 2013, and a decrease of 2.60% from 2013 to 2019. Similar to seagrass, sand cover fluctuated with a 10.38% increase from 1994 to 2003, a 16.64% decrease from 2003 to 2013, and a 12.81% increase from 2013 to 2019.

Live coral decreased dramatically by 89.77% from 78.30 ha in 1994 to 8.01 ha in 2019. By contrast, dead coral and rubble increased at an average rate of 2.19 ha/year for dead coral and 0.54 ha/year for rubble. This means that the loss in coral reefs during the period was 70.29 ha, or 2.81 ha/year.

Changes in habitat cover were be classified as follows: 1) live to dead coral, 2) dead coral to rubble, 3) rubble to sand, and 4) unidentified (**Fig. 5**). The largest percentage of change was from live to dead coral (72.54%), followed by dead coral to rubble (19.33%), rubble to sand (4.61%), and unidentified (3.15%). The large amount of change from live to dead coral implies that anthropogenic activities led to high coral reef mortality.

3.2. MDS Analysis

Results of MDS analysis for the 37 threat attributes using the RAPFISH approach showed that the cumulative stress values for the five dimensions were all in the range of 0.11–0.12 (Table 8). As this range was below 0.25, the threat values were statistically valid and fulfilled statistical procedures with a significant interval (RSQ) of 97%. Overall, threats to the TSCA and its coral reefs come from human activities surrounding the area.

3.3. Threat Index of Coral Reefs and Sensitivity

The RAPFISH ordination results indicated that the coral reef threat level varied according to the threat dimension (**Fig. 6**). Threats to coral reefs from the ecological dimension contributed the most (16.87), followed by legal and institutional (26.83), economic (31.00), social (34.83), and technological (41.10) dimensions. Overall, the average threat index was 30.13, indicating a high threat to coral reef ecosystems.

The leverage analysis indicated that the sensitivities of the threat attributes in the five dimensions varied greatly (**Fig. 7**). In this study, attributes that were ranked first to third in terms of contribution to index value in each dimension were selected as the most sensitive attributes. For the ecological dimension, the top three most sensitive attributes were “state of fishing exploitation” with a sensitivity score of 7.59, followed by “state of coral destruction” (7.50) and “predators on corals” (i.e., crown-of-thorns seastar) (6.73). For the economic dimension, the top three most sensitive attributes were “profitability” (5.83), “price of fish caught by destructive fishing” (5.78), and “fishermen’s income level” (5.30). For the social dimension, “level of public awareness” had the highest sensitivity score (6.33). The second and third highest scores were for “habits of dumping waste into the sea” (6.04) and “education level” (5.59). For the technological dimension, the three most sensitive attributes of nine attributes were “intensity of blast fishing for the last 10 years” (5.36), followed by “intensity of trawl net fishing for the last 10 years” (5.17) and “ratio of fishing ground to coral reef area” (5.12). Of the seven attributes analyzed in the legal and institutional dimension, those with the highest index scores were “involvement of law officers” (6.27), “lack of law enforcement” (6.21), and “lack of monitoring and supervision” (5.50).

The 15 attributes were classified according to their high sensitivity values within each dimension for consideration among the TSCA’s stakeholders regarding coral reef management. These 15 attributes were also the basis for developing technical programs and activities for conservation.

3.4. Multi-dimensional Sustainability Index

The results of the threat analysis for shallow water habitats in the TSCA showed that index values for each dimension varied between very high threat (0.00–25.00) and high threat (25.01–50.00) levels. The indices for MDS are visually depicted in **Fig. 8**. Threat scores for coral reefs assessed as facing severe conditions according to threat indices included contributions from the ecological dimension (16.87 = very high threat), economic dimension (31.00 = high threat), social dimension (34.83 = high threat), technological dimension (41.10 = high threat), and law and institutional dimension (26.83 = high threat).

3.5. Causal-loops Diagrams (CLDs) Model

In general, these 15 threat attributes are presented in the causal-loops diagram model of coral reef ecosystem sustainability in the TSCA (**Fig. 9**). Causal-loops diagrams (CLDs) are used to qualitatively model causal relationships among a set of variables in a system; these diagrams capture our dynamic hypotheses and communicate essential feedback loops. An arrow with a "+" indicates that the effect increases when the cause goes up. On the other hand, an arrow with "**-**" indicates that when the cause increases, the effect decreases or harms the affected variable.

As shown in **Fig. 9**, there are three main CLDs variables: threats to coral reef ecosystems, sustainability of coral reef ecosystems, and changes in coral cover. In general, massive threats to coral reefs (i.e., ecological, economic, social, technological, and legal and institutional attributes) can affect the sustainability of coral reef ecosystems. Therefore, an appropriate strategy is needed to reduce pressure on coral reef ecosystems at the study site, ultimately increasing the percentage of coral cover as an indicator of healthy coral reefs.

3.6. Strategies to reduce threats to coral reef ecosystems

Long-term changes in the TSCA's coral reefs during the 25-year period from 1994 to 2019 have influenced the ecological, economic, and social sustainability of the surrounding communities. Coral reefs off Pulau Tiga and its surrounding areas are under "high threat," which means that the reefs and fisheries in the region are in danger. Overall, the TSCA is classified in the "high threat" category, with an average index value of 30.16 (**Fig. 8**). The most highly sensitive and influential threat index was the ecological dimension, with an index value of 16.87. Attributes of the ecological dimension must be seriously considered by all stakeholders if restoration of the TSCA's coral reefs were to occur. Critical attributes of the other dimensions i.e., law and institutional, economic, social, and technological must be addressed with appropriate policies and programs to prevent further degradation of the TSCA's coral reef ecosystems. We offer the following suggestions based on our results to reduce the threat status from highly threatened to threatened, and even to low threat levels.

Better Law Enforcement

Fair and firm law enforcement of illegal and destructive fishing activities is necessary. This is based on our observations at the study site of fishermen who still use bombs and trawl nets. The intensive use of bombs and trawling nets not only damages coral reefs but also depletes and damages aquatic biota (Kularatne 2020). These destructive fishing activities are enabled by a ready supply of materials and a lack of monitoring facilities and personnel.

Improvement of Primary Education Facilities and Infrastructure

Lack of education and awareness within the local communities is a distinct, persistent problem. In some cases, destructive fishing behaviors are taken up by those with little education or awareness and no alternative livelihoods (Destructive Fishing Watch 2003). There is a shortage of teachers and there are no high schools in the TSCA area. More than 80% of the local fishers possess only a junior high school education level (Statistics of Muna Barat Regency 2019). Low levels of education significantly affect the understanding of coral reef resources and result in misconduct. Higher levels of education may promote a better understanding of the principles of sustainable coral reef management.

Enhancement of Community Income and Fishermen's Welfare

In addition to market and supply factors, low wages earned by fishermen are a strong contributing factor to destructive fishing practices. The imbalance of profits received by fishermen and intermediary buyers/traders is problematic and must be examined. Raising community incomes through collaborative management arrangements between the community (fishermen) and local government should be pursued. In some countries, such as Fiji, Chile, St. Lucia, Brazil, the Philippines, and other Pacific countries, collaborative management has been considered a success, especially in small-scale fisheries (d'Armengol et al. 2018). Success depends primarily on i) conducive social and institutional conditions, ii) market access and user dependence on resources, iii) local institutional characteristics, and iv) equitable distribution of benefits in the use of resources.

Regulation of Ocean Pollution from the Land

Agricultural land use and mangrove forest conversion in the Tondasi coastal area contributes to its increasing turbidity and sedimentation. Besides muddiness, increased turbidity in the Tondasi coastal area affects shallow water habitats, particularly coral reefs, off the surrounding islands. Most coral reefs off the surrounding islands (near the mainland) were found to be mostly dead, disrupting their ability to function as habitat for fish and other marine organisms. Implementation of coral reef rehabilitation programs for habitat recovery in this area will be difficult because one of the limiting factors for healthy coral growth is an excessive concentration of suspended sediments (>10 mg/L; (Erftemeijer et al. 2012)).

Strengthening Local Institutions and Role Models

Strong interactions between local fishers and their leaders (role models) can influence positive community behavior in terms of the use of natural resources. The conditions of coral reef ecosystems in the TSCA indicate destructive practices that are difficult to avoid. Leaders and role models in the local communities who are aware of the issues facing local fishers and the coral reef ecosystems should be given roles and responsibilities (Ho et al. 2016). Thus far, the roles of local community leaders have been taken over by village heads appointed by the local government, but most village heads do not have good environmental awareness. Strong local institutions are needed to gather people who are concerned about the future of their marine resources.

Conflict Resolution

Managing and defining zones in the TSCA is necessary to accommodate various economic, social, and environmental interests (Day et al. 2019). The Tiworo Strait as a marine conservation area has not yet implemented a zoning system, such as core zones and sustainable fishing zones. The implementation of zones needs to be accompanied by socialization within the local communities so that all parties support and follow the guidelines.

4. Conclusion

There were significant changes in live coral, dead coral, and rubble cover in the TSCA during the 1994–2019 period. By analyzing satellite images, our results showed that the area of live coral decreased dramatically by 89.77%, from 78.30 ha in 1994 to 8.01 ha in 2019, with a degradation rate of 2.81 ha/yr. Our RAPFISH analysis shows that a multidimensional threat has affected coral reefs during this period with an average threat index value of 30.13, which means that the threat status of coral reefs is categorized as high. This can be seen in the ecological dimension was the most sensitive dimension and was strongly influenced by threat level, with a threat index of 16.87 (very high threat status). If local threats continue without preventative measures, coral reefs will undoubtedly go extinct. In the future, sustainable management of coral reefs should be the primary goal for all stakeholders concerned with implementing the analyzed set of strategies. A multi-stakeholder collaboration model in the area can be the best option to improve coordination and cooperation in minimizing damage to coral reefs.

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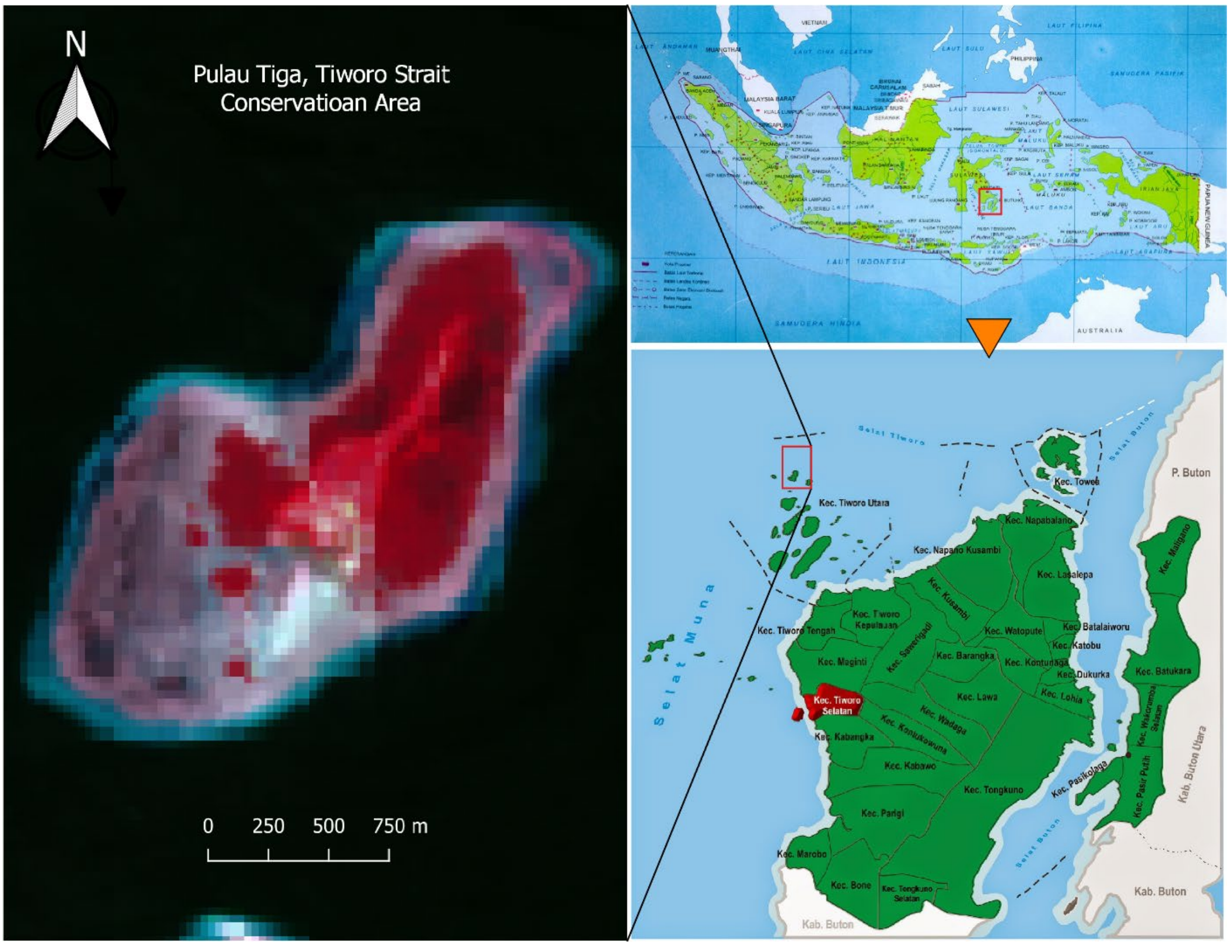

Fig. 1 Study area located in the Tiworo Strait Conservation Area (TSCA) in the Muna Barat Regency of Southeast Sulawesi in Indonesia.

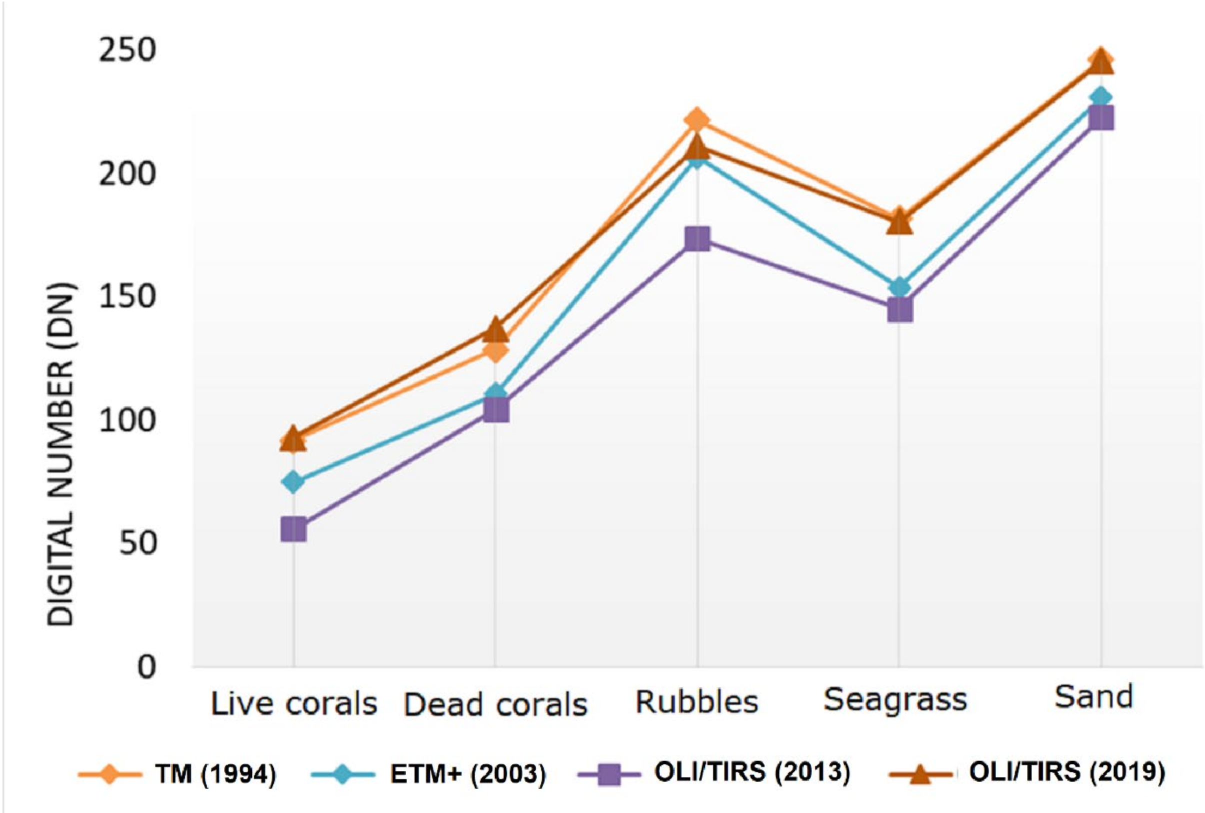

Fig. 2 Spectral responses representing five types of seabed cover obtained by Landsat multi-sensor satellites in 1994 (Landsat 5 TM), 2003 (Landsat 7 ETM+), 2013 (Landsat 8 OLI/TIRS), and 2019 (Landsat 8 OLI/TIRS). Of the five types of seabed cover, it can be seen that the three classes with the lowest response values—live coral, dead coral, and seagrass—have object characteristics in which higher levels of electromagnetic radiation are absorbed compared to rubble and sand. This causes the digital number (DN) values of the three types to be lower than those of rubble and sand.

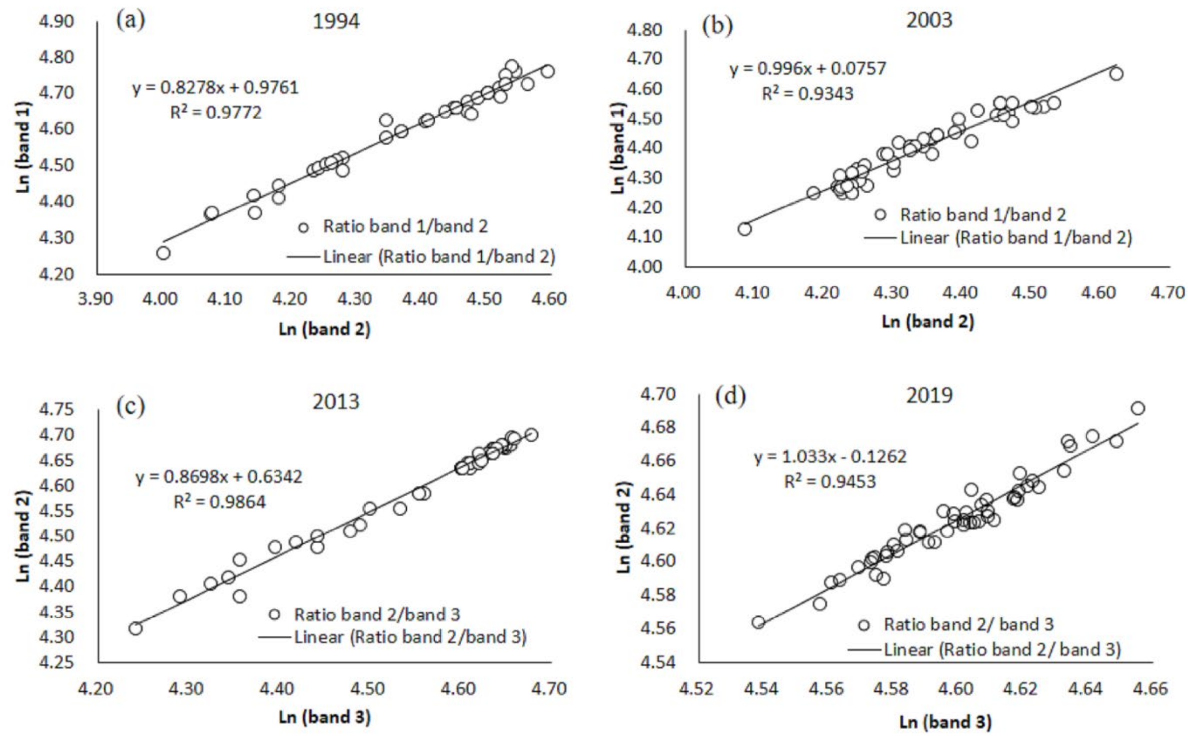

Fig. 3 Ratio of blue to green channels for multi-temporal Landsat imagery obtained in (a) 1994 (Landsat 5 TM), (b) 2003 (Landsat 7 ETM+), (c) 2013 (Landsat 8 OLI/TIRS), and (d) 2019 (Landsat 8 OLI/TIRS). In the visible light spectrum, because blue and green light can penetrate seawater further, the ratio between the blue and green band is more informative for the sea-bottom compared to the red or other bands. In Landsat 5 TM and 7 ETM+, band 1 is the blue band (0.45–0.52 µm) and band 2 is the green band (0.53–0.61µm), whereas in Landsat 8 OLI/TIR, band 2 is blue (0.450–0.515 µm) and band 3 is green (0.525–0.600 µm).

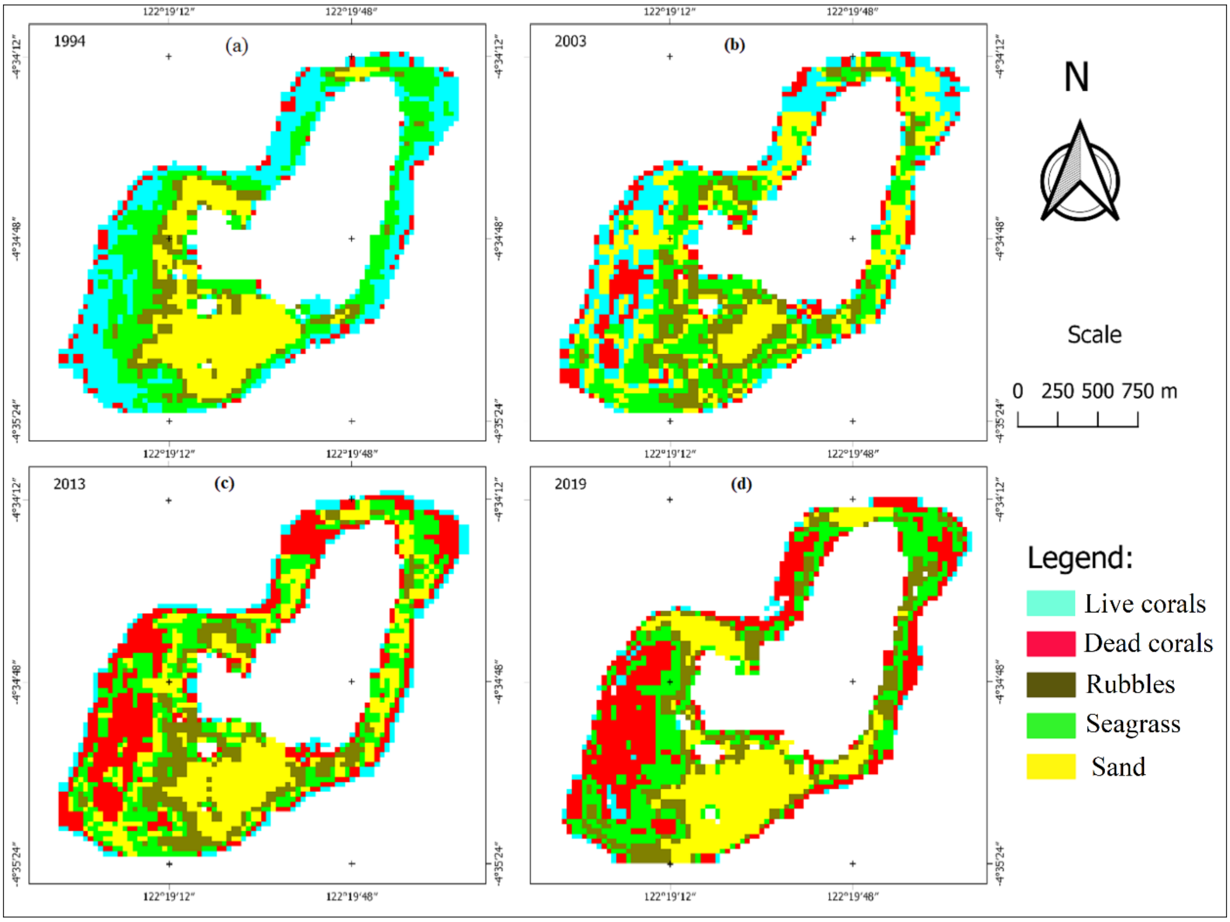

Fig. 4 Distribution of changes in coral cover off Pulau Tiga within the TSCA according to Landsat multi-temporal image data obtained over a 25-year period from 1994 to 2019.

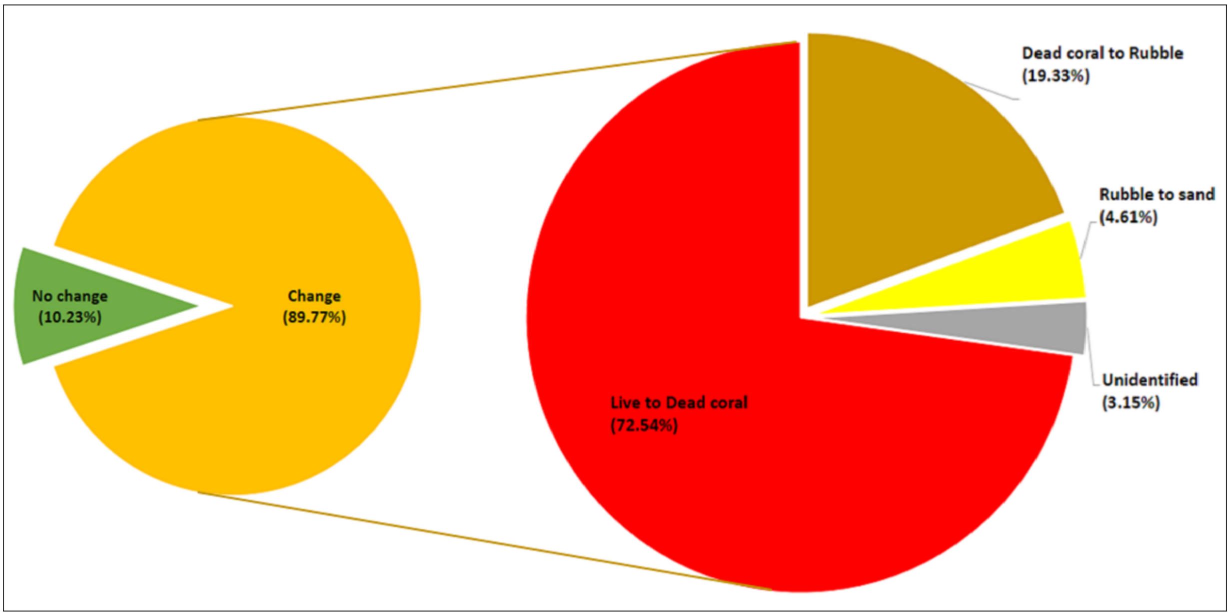

Fig. 5 Composite of live coral change from 1994 to 2019 with four categories of change. In total, 89.77% of the coral reef area was transformed (left pie chart): 72.54% from live to dead coral, 19.33% from dead coral to rubble, 4.61% from rubble to sand, and unidentified changes (3.15%) (right pie chart).

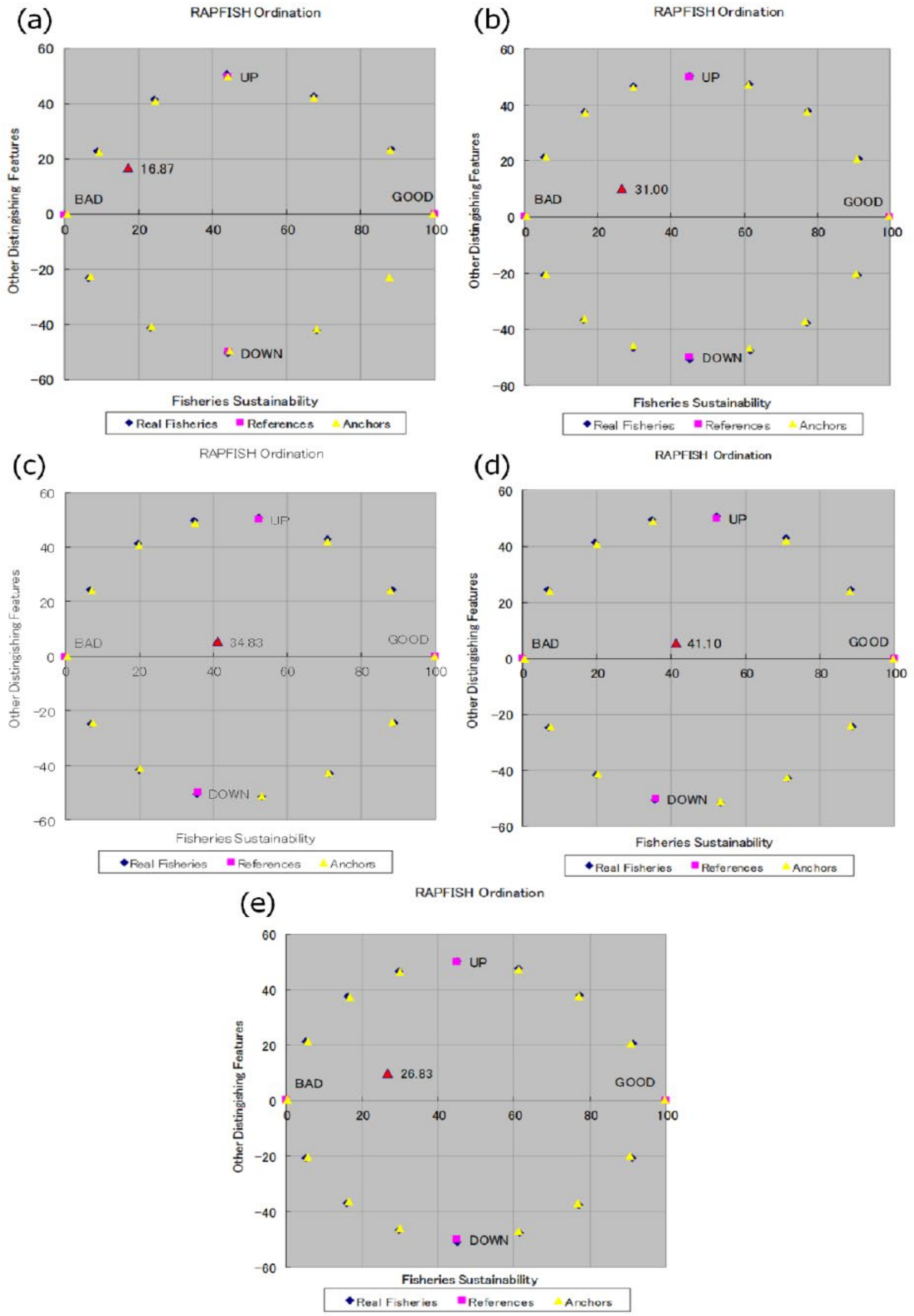

Fig. 6 Two-dimensional Rapid Appraisal for Fisheries (RAPFISH) ordinations of the threats to coral reefs in the TSCA, based on (a) ecological, (b) economic, (c) social, (d) technological, and (e) legal and institutional dimensions. The horizontal axis represents sustainability [0% ("bad") to 100% ("good")] and the vertical axis represents changes in coral reef status (%).

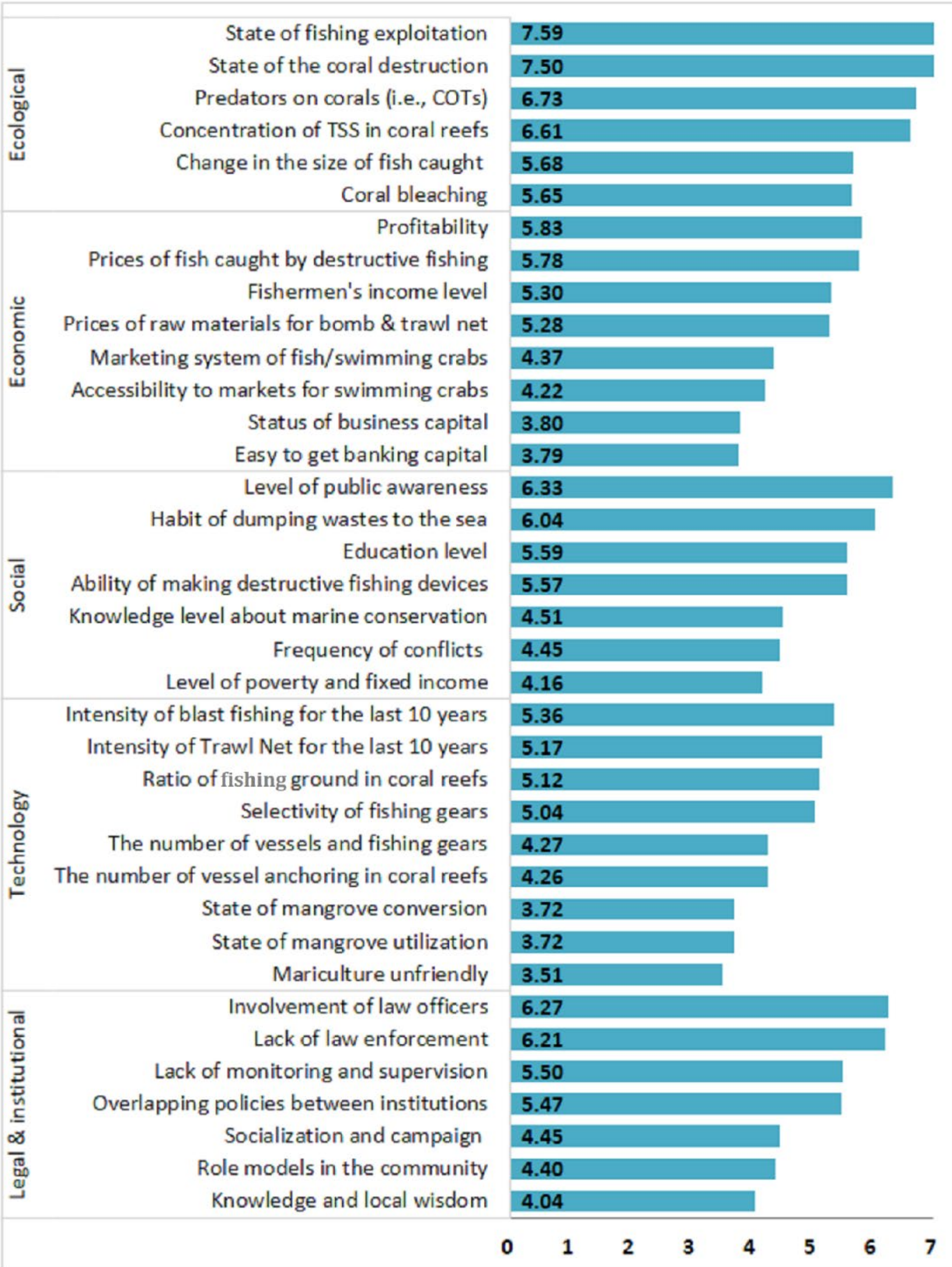

Fig. 7 Attribute leverage analysis of the RAPFISH ordinations for threats to coral reefs in the TSCA. From the five dimensions analyzed (i.e., ecological, economic, social, technological, and legal and institutional), we obtained a root squared correlation (RSQ) value of 0.97, indicating that the analysis was acceptable.

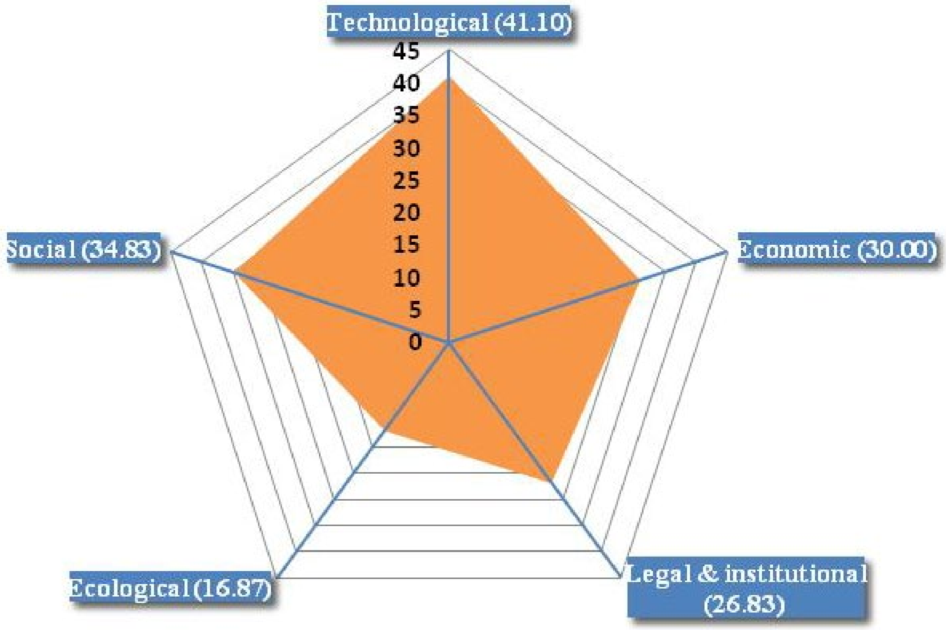

Fig. 8 Kite diagram of the five threat dimensions to coral reef ecosystems in the TSCA. Based on the threshold values listed in Table 4, the ecological dimension was regarded as under "very high threat" and the economic, social, technological, and legal and institutional dimensions contributed to a "high threat" level. The overall value for all threats was 30.13, indicating a "high threat" status of the coral reef ecosystems at the study site.

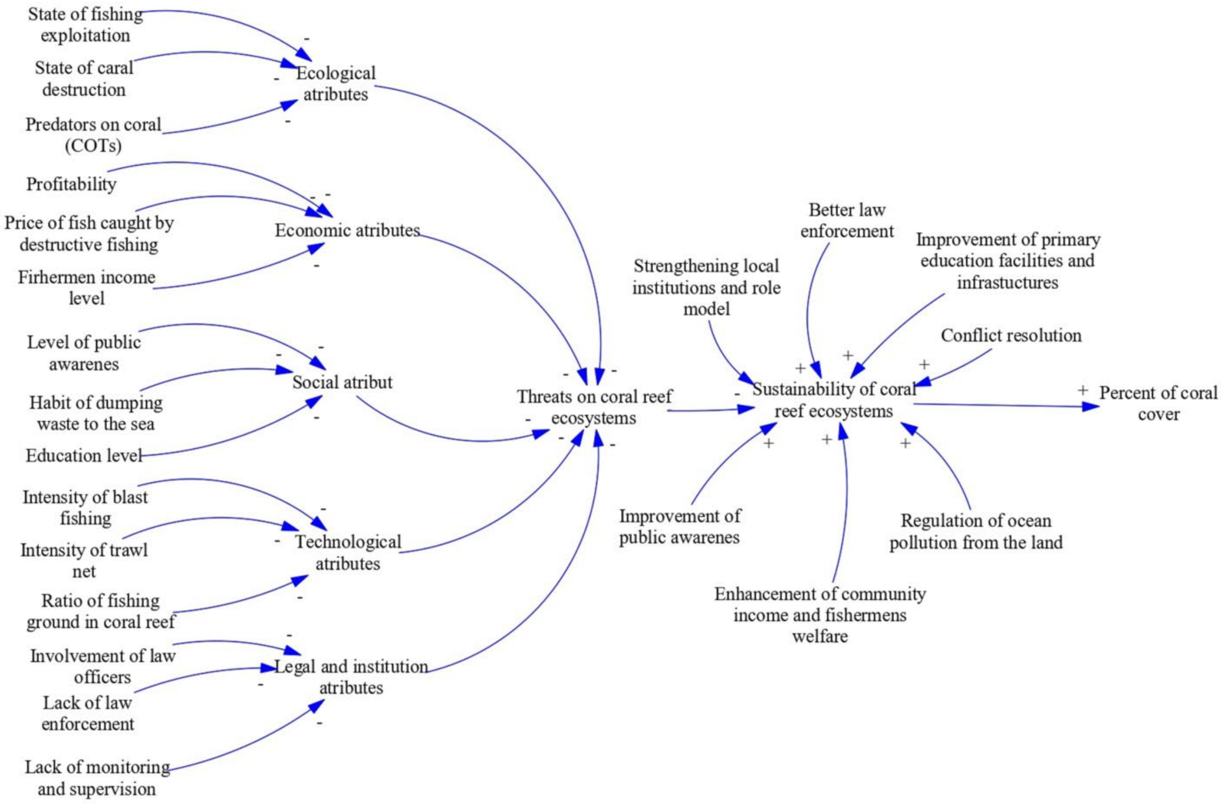

Fig. 9 Causal loop diagram model in terms of threats to coral reef ecosystems and their sustainability strategies in the Tiworo Strait Conservation Areas (TSCAs)

Table 1. Types and characteristics of Landsat image data

No.	Satellite	Sensor	Resolution (m)	Acquisition	Path/Row
1.	Landsat 5	TM	30	July 14, 1994	112/63
2.	Landsat 7	ETM	30	August 28, 2003	112/63
3.	Landsat 8	OLI/TIRS	30	April 29, 2013	112/63
4.	Landsat 8	OLI/TIRS	30	Sept. 21, 2019	112/63

Table 2. Descriptions and definitions of the bottom types surveyed (Suwargana, 2014; US Geological Survey-USGS, 2019).

Classes	Visual description	Field defenitions
Live coral	Cyan to light green cloudy	Habitat dominated by a mix live scleratinian corals
Dead coral	Green with clear boundary	Substrate predominantly made of dead coral
Rubble	Dark orange with clear boundary	Pieces of broken corals, generally found in reef flats
Seagrass	Yellow to light orange with unclear boundary	Flowering plants, generally found intertidal areas and reef flats
Sand	Yellow and red	Sediment from carbonate origin (dead corals and skeleton for calcifying organisms)

Table 3. Attributes of threats to coral reef ecosystems and criteria for Rapid Appraisal for Fisheries (RAPFISH) scoring. The scores ranged from bad (very high threat level; 0) to good (no threats), with the highest scores varying among attributes.

Attribute	Score scale	Remarks	Source/ references
Ecological Dimension			
1. State of fishing exploitation	0,1,2,3,4	Collapsed (0); high (1); moderate (2); low (3); balanced or equal (4)	Pitcher (1999); Pitcher and Preikshot (2001)
2. Coral bleaching	0,1,2,3	% coral bleaching: ≥75-100% (0); 50-74.9% (1); 25-49.9% (2); <25% (3)	Modified from RAPFISH (2019)
3. State of coral reef destruction	0,1,2,3	% coral rubble: ≥75-100% (0); 50-74.9% (1); 25-49.9% (2); <25% (3)	Modified from Hill and Wilkinson (2004)
4. Change in the size of reef fish caught (for the last 10 years)	0,1,2	Declined substantially (0); decreased slightly (1); unchanged (2)	RAPFISH (2019)
5. Concentration of total suspended solid (TSS) in coral reefs	0,1	Threshold for coral growth: >10 mg/L (0); ≤10 mg/L (1)	Erftemeijer et al. (2012)
6. Predators on corals (i.e., crown-of-thorns starfish (COTs), starry puffer fish etc.)	0,1	COTs in coral reefs: >14 individuals/1000 m^2 (0); ≤14 individuals/ 1000 m^2 (1)	Endean and Stablum (1973); Hoeksema (2012)
Economic Dimension			
1. Profitability	0,1,2,3	High profit (0); marginal profit (1); without gain or loss (2); little loss (3); large loss (4)	RAPFISH (2019)
2. Fishermen's income level	0,1,2,3	Average relative income to the regional minimum wage (UMR): Far below (0); below (1); equal (2); higher (3); considerably higher (4)	Modified from RAPFISH (2019)
3. Accessibility to markets for swimming crabs	0,1,2	International market (0); national market (1); local market (2)	RAPFISH (2019)
4. Status of business capital	0,1,2,3	Loan capital (0); joint capital (1); grant capital (2); own capital (3)	Modified from RAPFISH (2019)
5. Marketing system of fish/swimming crabs	0,1,2,3	Monopoly or government buyer (0); semi-closed (1); partially open market (2); fully open market (3)	RAPFISH (2019)
6. Prices of raw materials for bombs &Trawl Net	0,1,2,3	Very affordable (0); affordable (1); expensive (2); very expensive (3)	Modified from RAPFISH (2019)
7. Prices of fish caught by destructive fishing	0,1,2,3,4	Prices compared to fish caught by non-destructive fishing: Very expensive (0); expensive (1); equal (2); cheap (3); Very cheap (4)	Modified from RAPFISH (2019)
8. Easy to get banking capital	0,1,2	Difficult (0); moderate (1); eazy (2)	Yasir Haya and Fujii (2019)
Social Dimension			
1. Knowledge level about marine conservation	0,1,2,3	None (0); low (1); moderate (2); high (3)	Modified from RAPFISH (2019)
2. Education level	0,1,2,3	The number of students who do not proceed to the university: 75-100% (0); 50-74.9% (1); 25-49.9% (2); <25% (3)	Statistics of Muna Barat Regency (2019)
3. Level of poverty and fixed income	0,1,2	High (0); moderate (1); low (2)	RAPFISH (2019)
4. Level of public	0,1,2	Low (0); moderate (1); high (2)	Modified from

awareness			RAPFISH (2019)
5. Habit of dumping wastes to the sea	0,1,2,3,4	Very high (0); high (1); moderate (2); low (3); very low (4)	Modified from RAPFISH (2019)
6. Frequency of conflicts (destructive versus non-destructive)	0,1,2	Frequent (0); seldom (1); none (2)	Modified from Susilo (2003)
7. Ability of making destructive fishing devices	0,1,2,3	High (0); moderate (1); low (2); none (3)	Modified from RAPFISH (2019)
Technological Dimension			
1. The number of vessels and fishing gears (for the last 10 years)	0,1,2	Increasing (0); unchanged (1); decreasing (2)	Statistics of Muna Barat Regency (2019)
2. Intensity of blast fishing for the last 10 years	0,1,2,3	High (0); medium (1); low (2); none (3)	RAPFISH (2019)
3. State of mangrove utilization (fire woods, construction, etc.)	0,1,2,3	High (0); medium (1); low (2); none (3)	RAPFISH (2019)
4. Selectivity of fishing gears	0,1,2,3	None (0); few (1); fair (2); many (3)	RAPFISH (2019)
5. Ratio of fishing grounds in coral reefs	0,1,2,3	75-100% (0); 50-74.9% (1); 25-49.9% (2); <25% (3)	Modified from RAPFISH (2019)
6. The number of vessels anchoring in coral reefs	0,1,2	Many (0); few (1); none (2)	Modified from RAPFISH (2019)
7. State of mangrove conversion (fishpond, settelement, buildings)	0,1,2,3	High (0); medium (1); low (2); none (3)	Modified from RAPFISH (2019)
8. Intensity of Trawl Net for the last 10 years	0,1,2,3	High (0); medium (1); low (2); none (3)	RAPFISH (2019)
9. Mariculture unfriendly	0,1,2,3	Very bad (0); bad (1); fair (2); good (3)	Modified from RAPFISH (2019)
Legal and Institutional Dimensions			
1. Lack of law enforcement	0,1,2,3	The level of legal violation: high (0); medium (1); low (2); none (3)	Modified from FAO (1995)
2. Overlapping policies between institutions	0,1,2,3	Numerous (1); fair (1); few (2); none (3)	Modified from FAO (1995)
3. Socialization and campaign of the public awareness	0,1,2	Never (0); fair (1); frequent (2)	Modified from RAPFISH (2019)
4. Involvement of law officers	0,1,2	Frequent (0); fair (1); never (2)	Modified from FAO (1995)
5. Lack of monitoring and supervision by community	0,1,2,3	Never (0); seldom (1); fair (2); frequent (3)	Modified from RAPFISH (2019)
6. Role models in the community	0,1,2	A public figure who understands the environmental issues: Few (0); fair (1); many (2)	Modified from RAPFISH (2019)
7. Knowledge and local wisdom	0,1,2	Little (0); fair (1); a lot (2)	Modified from Susilo (2003)

Table 4. Threshold index values for assessing the threats to coral reefs (modified from Pitcher and Preikshot 2001).

Threshold value of index	Status
0.00 - 25.00	Very high threats
25.01 - 50.00	High threats
50.01 - 75.00	Less threats
75.01 - 100.00	No threats

Table 5. Aerial estimates of major bottom types in 1994, 2003, 2013, and 2019 off Pulau Tiga within the Tiworo Strait Conservation Area (TSCA).

Type of classes	Area of seabed cover (ha)			
	1994	2003	2013	2019
Live corals	78.30 (36.20%)	45.45 (21.02%)	22.32 (10.32%)	8.01 (3.70%)
Dead corals	15.43 (7.13%)	30.33 (14.02%)	61.35 (28.37%)	66.42 (30.71 %)
Rubbles	20.07 (9.28%)	29.79 (13.77%)	32.13 (14.86%)	33.66 (15.56 %)
Seagrass	53.06 (24.53%)	56.16 (25.97%)	54.15 (25.04%)	55.53 (25.68 %)
Sand	49.91 (22.85%)	54.54 (25.22%)	46.32 (21.42%)	52.65 (24.34 %)

Table 6. Changes in seabed cover from 1994 to 2003, 2003 to 2013, and 2013 to 2019.

Type of classes	Change of bottom types						Type of change
	1994 to 2003 (ha)	Ratio (%)	2003 to 2013 (ha)	Ratio (%)	2013 to 2019 (ha)	Ratio (%)	
Live corals	-32.85	-41.95	-23.13	-29.54	-14.31	-18.28	(-)
Dead corals	14.90	96.57	31.02	201.04	5.07	32.86	(+)
Rubbles	9.72	48.43	2.34	11.66	1.53	7.62	(+)
Seagrass	-3.10	-5.84	2.01	3.79	1.38	2.60	(-/+)
Sand	5.13	10.38	-8.22	-16.64	6.33	12.81	(-/+)

Table 7. Cumulative stress values and analysis of all dimensions. Values indicate the acceptability of the coral reef status analysis [Stress (S) < 0.25, root squared correlation (RSQ) ≈ 1].

Dimension	Stress value	RSQ
Ecological	0.12	0.97
Economic	0.12	0.97
Social	0.11	0.97
Technological	0.12	0.97
Legal and institutional	0.12	0.97