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1	Assessing long-term coral reef degradation in Indonesia's Tiworo Strait Marine
2	Conservation Area using remote sensing and rapid appraisal for fisheries approaches
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16	Abstract
17	In Indonesia, the coral reef ecosystem in the Tiworo Strait Conservation Area (TSCA) faces various threats of
18	natural and anthronogenic stressors that can damage the coral reef ecosystem's role and services. We analyzed
10	natural and antihopogenic successors that can damage the coral feet ecosystem's fole and services. We analyzed
19	changes in coral reef habitat at TSCA over the 25 years from 1994 to 2019 using multi-temporal and multi-sensor
20	satellite imagery data combined with in-situ measurement data and social surveys. Our results show a decrease in
21	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
22	threat attributes shows that the TSCA coral reef ecosystem faces a "high threat" to very high threat levels. Threat
22	
23	scores for coral reefs assessed as facing severe conditions according to threat indices included contributions from
24	the ecological dimension ($16.87 =$ very high threat), economic dimension ($31.00 =$ high threat), social dimension
25	$(34.83 = \text{high threat})$, technological dimension $(41.10 = \text{high threat})$, and law and institutional dimension $(26.83 = 10^{-10})$
_0	
26	high threat). Coral reefs will undoubtedly go extinct if local threats continue without preventative measures.
27	Therefore, the sustainability of coral reefs in the TSCA-one of the most important marine conservation sites in the

- 28 Coral Triangle Marine Eco-region should be the primary priority for all stakeholders. Appropriate policies and 29 supervision in the field must be carried out rigorously and measurably, implementing the analyzed set of strategies.
- 30

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

34 1. Introduction

35 Over the past four decades, numerous studies have identified the trend of continuous coral reef 36 degradation due to natural and anthropogenic pressures. These pressures include enhanced local pollution of 37 coastal areas (Burke et al., 2011; Häder et al., 2020; Randazzo-Eisemann et al., 2021), overfishing (Moussa et al., 38 2019; Nichols et al., 2019), destructive fishing practices (Yasir Haya and Fujii 2020; Hampton-Smith et al. 2021), 39 sea surface temperature (Hughes et al. 2018; Ngoc 2019), climate change and subsequent ocean warming 40 (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 41 42 et al. 2019; Adam et al. 2021), and other anthropogenic threats (Burke et al. 2011; Mellin et al. 2016; Hoegh-43 Guldberg et al. 2019; Hein et al. 2021). Degradation of coral reefs leads to a loss of their ecological and economic 44 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 45 urgent management, such as a marine protected area (MPA) approach (Mellin et al. 2016; Vaughan and Agardy 46 47 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, 54 mangroves, seagrass, and fish, with a total area of around 27,936 ha (KKJI-KP3K, 2019). Because of this potential, 55 the Tiworo Strait was designated as a conservation area by the local government of the Muna Regency and has 56 become one of the most critical marine conservation sites in the Coral Triangle of Southeast Sulawesi, Indonesia. 57 Nevertheless, the coral reefs in the Tiworo Strait Conservation Area (TSCA) are thought to have experienced 58 massive degradation due to pressure from various environmentally unfriendly activities.

59 The primary sources of coral reef degradation are local anthropogenic factors i.e., blast fishing, trap 60 fishing (locally known as "Bubu"), and bottom-trawling net practices (locally known as "Dogol"). These three 61 fishing practices are considered environmentally unfriendly because they overly exploit fishery resources and 62 violate conservation rules (Gorris 2016; Chan and Hodgson 2017; Kularatne 2020) thus allegedly reducing coral 63 cover in this area. Information on coral reef changes in the TSCA, which is desperately needed for habitat 64 management, is not yet available. However, the combination of remote-sensing technology, in-situ data, and social 65 surveys can provide alternative approaches for monitoring changes in reef composition at high spatial and 66 temporal resolution (Andréfouët et al. 2003; Foo and Asner 2019; Chen et al. 2022). These approaches can 67 facilitate monitoring in remote areas that are not directly accessible including coral reef ecosystems (Purkis 2018; 68 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.

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81	
82	2. Materials and Methods
83	2.1. Study Site
84	The study site was located in the TSCA, Muna Barat Regency, in the Southeast Sulawesi Province of
85	Indonesia, geographically located between $04^{\circ}16'40"S - 04^{\circ}32'20"S$ and $122^{\circ}13'35"E - 122^{\circ}32'40"E$ (Fig. 1). The
86	Tiworo Strait was declared a MPA through a Decree of the Muna Regent (No.157/2004) and has a total area of
87	27,936 ha. For the last several decades, fishermen, fishing boat workers, seaweed and fish cage farmers, small-
88	scale crab entrepreneurs, traders, and grocers living near the TSCA have depended on the marine resources in the
89	Tiworo Strait.
90	2.2. Data Sources
91	2.2.1. Satellite Imagery Data
92	Landsat TM data consist of seven spectral bands with a spatial resolution of 30 m for bands 1–5 and 7.
93	Landsat ETM+ data consist of eight spectral bands with a spatial resolution of 30 m for bands 1–7. Landsat 8 data
94	have nine spectral bands with a spatial resolution of 30 m for bands 1-7 and 9. Landsat TM, ETM+, and
95	OLI image classifications with a spatial resolution of 30 m can be used to examine the cover of five seabed
96	substrates: live coral, rubble, sand, dead coral, and seagrass. Satellite imagery data used in this study were
97	obtained from multi-temporal and multi-sensor Landsat imagery from 1994, 2002, 2013, and 2019. Landsat
98	imagery data is freely downloadable from US Geological Survey-USGS (2019). The types and characteristics of
99	Landsat imagery are summarized in Table 1.
100	
101	2.2.2. Field Data
102	(i) Ground Control Points and Ground Truthing Data
103	Aside from coral observations, coordinate points as ground control points (GCPs) and for ground
104	truthing (GT) were determined using global positioning system (GPS). GCPs at the location were typically road

105 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.

113

114 (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).

122

123 2.3. Data Analysis

124 2.3.1. Image Processing

125

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

126 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,

133 signals recorded for each object by the sensor are a result of atmospheric scattering (Chavez 1996).

134

135 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).

141

142 c. Image Composites

143 True color in Landsat 5 TM and Landsat 7 ETM images is displayed with a RGB (red:green:blue) band 144 composition of 3:2:1, whereas that in Landsat 8 OLI/TIRS images is displayed as RGB = 4:3:2 [38,40]. This band 145 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 146 the appearance of land cover. Red composites using band 3 (Landsat 5 TM/7 ETM) and band 4 (Landsat 8 147 OLI/TIRS) are suitable for detecting dry land or soil. Green composites were used to detect chlorophyll in 148 vegetation from band 2 (Landsat 5 TM/7 ETM) and band 3 (Landsat 8 OLI/TIRS). High chlorophyll 149 150 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 151 152 that it could be depicted in blue.

153

154 *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.

159 e. Application of the Depth Invariant Index

160 The objective of the depth invariant index (DII) algorithm is to improve the accuracy of object 161 information (color) at the sea bottom in an image (Lyzenga 1981, 1985). We created at least 30 polygons in a 162 training area assumed to comprise coral reefs in the study area. The data obtained were analyzed in terms of 163 variance and covariance for blue and green bands. The variance and covariance were then used to determine the 164 attenuation coefficient to clarify the results of coral reef image classification using the following equations:

165
$$a = \frac{(\sigma i i - \sigma j j)}{2\sigma i j},$$
 (1)

166
$$\frac{ki}{kj} = a + \sqrt{(a^2 + 1)},$$
 (2)

167 (DII)ij = ln(Li) -
$$\left[\left(\frac{ki}{kj}\right) \times ln(Lj)\right]$$
, (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, $\frac{k_i}{k_j}$ 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.

171

172 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.

180 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.

185

186 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:

194
$$Overall\ accuracy = \frac{\sum_{i=1}^{k} n_{ij}}{n} \times 100\%, \tag{4}$$

195
$$Producer\ accuracy\ j = \frac{n_{jj}}{n_{+j}} \times 100\%,\tag{5}$$

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

200

201 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,

206	technology, social, ethics/law, and institutions (Pitcher and Preikshot 2001; Alder et al. 2002; Fletcher 2006).
207	Each dimension is assigned a specific attribute, or indicator, associated with the threat to coral reefs, as
208	determined by Kennedy et al. (2013). Attributes are then parsed with reference to Pitcher and Preikshot (2001),
209	Susilo (2003), and RAPFISH (2019).
210	Technically, the stages of data collection and processing in RAPFISH are as follows: (i) identification
211	and determination of threat attributes, as defined according to the principles of the ecosystem approach to fisheries
212	management, (ii) definition and scoring of attributes, (iii) field verification and consultation with fisheries
213	scientists/experts, (iv) data processing, (v) scientific justification, and (vi) RAPFISH analysis (Pitcher 1999). The
214	RAPFISH procedure included data tabulation, data entry into the RAPFISH program, running the RAPFISH
215	program, analysis of multi-dimensional scaling (MDS), sensitivity analysis, Monte Carlo analysis, and
216	interpretation of results based on the threat index and sustainability status.
217	
218	a. Identification and Determination of Attributes
219	Thirty-seven threat attributes were identified from a thorough review of all available data. The collected
220	attributes were classified into five dimensions: six attributes in the ecological dimension, eight attributes in the
221	economic dimension, seven attributes in the social dimension, nine attributes in the technological dimension, and
222	seven attributes in legal and institutional dimension (Table 3; (Pitcher and Preikshot 2001)). These attributes
223	represent the variation in threats to the sustainability of coral reefs in the TSCA.
224	
225	b. Defining and Scoring Attributes
226	The second step in the analysis was defining and scoring attributes in RAPFISH (Pitcher and Preikshot 2001;
227	Kothari 2004). A "bad" score designates the worst possible condition of a coral reef ecosystem, and a "good" score
228	signifies the most favorable condition. Scoring was performed based on the method formulated by Good et al. (1999)

229 and Hershman et al. (1999).

230

231 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:

236
$$S = \sqrt{\frac{1}{m} \sum_{k=1}^{m} \left[\frac{\sum_{i} \sum_{j} (d^2_{ijk} - d^2_{ijk})^2}{\sum_{i} \sum_{j} O^4_{ijk}} \right]},\tag{7}$$

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).

240

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241 d. Rotation Process
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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).

247

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).

254

255 f. Sensitivity Analysis

256

Sensitivity analysis was done to determine which attribute was most sensitive to the sustainability of coral

²⁴⁸ e. Index Scale of Threats

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).

264

265 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).

271

272 **3.** Results and Discussion

273

274 3.1. Change in Coral Reefs

275 The digital number obtained by Landsat multi-sensors is relatively small for the categories of live coral, 276 dead coral, and seagrass, implying higher absorption of visible spectrum radiation (i.e., blue, green, and red 277 channels) by the seabed compared to rubble and sand (Fig. 2). Therefore, the three categories appear darker in an 278 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 279 280 results in numerous previous studies stating that the ratio of blue to green channels has a better ability to detect 281 seabed cover, including coral reefs (El-Askary et al. 2014; Lillesand et al. 2015; Nurdin et al. 2015). Therefore, 282 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

318 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.

323

324 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.

329

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 334 335 greatly (Fig. 7). In this study, attributes that were ranked first to third in terms of contribution to index value in each 336 dimension were selected as the most sensitive attributes. For the ecological dimension, the top three most sensitive 337 attributes were "state of fishing exploitation" with a sensitivity score of 7.59, followed by "state of coral destruction" 338 (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 339 340 "fishermen's income level" (5.30). For the social dimension, "level of public awareness" had the highest sensitivity 341 score (6.33). The second and third highest scores were for "habits of dumping waste into the sea" (6.04) and 342 "education level" (5.59). For the technological dimension, the three most sensitive attributes of nine attributes were 343 "intensity of blast fishing for the last 10 years" (5.36), followed by "intensity of trawl net fishing for the last 10 344 years" (5.17) and "ratio of fishing ground to coral reef area" (5.12). Of the seven attributes analyzed in the legal and 345 institutional dimension, those with the highest index scores were "involvement of law officers" (6.27), "lack of law 346 enforcement" (6.21), and "lack of monitoring and supervision" (5.50).

347 The 15 attributes were classified according to their high sensitivity values within each dimension for 348 consideration among the TSCA's stakeholders regarding coral reef management. These 15 attributes were also the 349 basis for developing technical programs and activities for conservation.

350 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).

357 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.

369 3.6. Strategies to reduce threats to coral reef ecosystems

370 Long-term changes in the TSCA's coral reefs during the 25-year period from 1994 to 2019 have 371 influenced the ecological, economic, and social sustainability of the surrounding communities. Coral reefs off 372 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 30.16 373 374 (Fig. 8). The most highly sensitive and influential threat index was the ecological dimension, with an index value of 375 16.87. Attributes of the ecological dimension must be seriously considered by all stakeholders if restoration of the 376 TSCA's coral reefs were to occur. Critical attributes of the other dimensions i.e., law and institutional, economic, 377 social, and technological must be addressed with appropriate policies and programs to prevent further degradation 378 of the TSCA's coral reef ecosystems. We offer the following suggestions based on our results to reduce the threat 379 status from highly threatened to threatened, and even to low threat levels.

380

381 Better Law Enforcement

382

Fair and firm law enforcement of illegal and destructive fishing activities is necessary. This is based on

383 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 384 385 destructive fishing activities are enabled by a ready supply of materials and a lack of monitoring facilities and 386 personnel.

- 387
- 388

Improvement of Primary Education Facilities and Infrastructure

389 Lack of education and awareness within the local communities is a distinct, persistent problem. In some 390 cases, destructive fishing behaviors are taken up by those with little education or awareness and no alternative 391 livelihoods (Destructive Fishing Watch 2003). There is a shortage of teachers and there are no high schools in the 392 TSCA area. More than 80% of the local fishers possess only a junior high school education level (Statistics of 393 Muna Barat Regency 2019). Low levels of education significantly affect the understanding of coral reef resources 394 and result in misconduct. Higher levels of education may promote a better understanding of the principles of 395 sustainable coral reef management.

396

397 Enhancement of Community Income and Fishermen's Welfare

398 In addition to market and supply factors, low wages earned by fishermen are a strong contributing factor 399 to destructive fishing practices. The imbalance of profits received by fishermen and intermediary buyers/traders is 400 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, 401 402 St. Lucia, Brazil, the Philippines, and other Pacific countries, collaborative management has been considered a 403 success, especially in small-scale fisheries (d'Armengol et al. 2018). Success depends primarily on i) conducive 404 social and institutional conditions, ii) market access and user dependence on resources, iii) local institutional 405 characteristics, and iv) equitable distribution of benefits in the use of resources.

406

407 Regulation of Ocean Pollution from the Land

408

Agricultural land use and mangrove forest conversion in the Tondasi coastal area contributes to its

409 increasing turbidity and sedimentation. Besides muddiness, increased turbidity in the Tondasi coastal area affects 410 shallow water habitats, particularly coral reefs, off the surrounding islands. Most coral reefs off the surrounding 411 islands (near the mainland) were found to be mostly dead, disrupting their ability to function as habitat for fish 412 and other marine organisms. Implementation of coral reef rehabilitation programs for habitat recovery in this area 413 will be difficult because one of the limiting factors for healthy coral growth is an excessive concentration of 414 suspended sediments (>10 mg/L; (Erftemeijer et al. 2012)).

415

416 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.

424

425 Conflict Resolution

426 Managing and defining zones in the TSCA is necessary to accommodate various economic, social, and 427 environmental interests (Day et al. 2019). The Tiworo Strait as a marine conservation area has not yet 428 implemented a zoning system, such as core zones and sustainable fishing zones. The implementation of zones 429 needs to be accompanied by socialization within the local communities so that all parties support and follow the 430 guidelines.

431

432 4. Conclusion

433 There were significant changes in live coral, dead coral, and rubble cover in the TSCA during the 1994–
434 2019 period. By analyzing satellite images, our results showed that the area of live coral decreased dramatically

435 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 436 index value of 30.13, which means that the threat status of coral reefs is categorized as high. This can be seen in 437 the ecological dimension was the most sensitive dimension and was strongly influenced by threat level, with a 438 439 threat index of 16.87 (very high threat status). If local threats continue without preventative measures, coral reefs 440 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 441 model in the area can be the best option to improve coordination and cooperation in minimizing damage to coral 442 443 reefs.

444

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450

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

665 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 ($0.45-0.52 \mu m$) and band 2 is the green band ($0.53-0.61\mu m$), whereas in Landsat 8 OLI/TIR, band 2 is blue ($0.450-0.515 \mu m$) and band 3 is green ($0.525-0.600 \mu m$).



678 Fig. 4 Distribution of changes in coral cover off Pulau Tiga within the TSCA according to Landsat multi-temporal

679 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
- 681 coral reef area was transformed (left pie chart): 72.54% from live to dead coral, 19.33% from dead coral to rubble,
- 682 4.61% from rubble to sand, and unidentified changes (3.15%) (right pie chart).



683 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

686 represents changes in coral reef status (%).

	State of fishing exploitation	7.59						
e	State of the coral destruction	7.50						
ogic	Predators on corals (i.e., COTs)	6.73						
colo	Concentration of TSS in coral reefs	6.61						
ш	Change in the size of fish caught	5.68						
	Coral bleaching	5.65						
	Profitability	5.83						
	Prices of fish caught by destructive fishing	5.78						
<u>e</u>	Fishermen's income level	5.30						
Eo	Prices of raw materials for bomb & trawl net	5.28						
con	Marketing system of fish/swimming crabs	4.37						
Ξ.	Accessibility to markets for swimming crabs	4.22						
	Status of business capital	3.80						
	Easy to get banking capital	3.79						
	Level of public awareness	6.33						
	Habit of dumping wastes to the sea	6.04						
ocial	Education level	5.59						
	Ability of making destructive fishing devices	5.57						
S	Knowledge level about marine conservation	4.51						
	Frequency of conflicts	4.45						
	Level of poverty and fixed income	4.16						
	Intensity of blast fishing for the last 10 years	5.36						
	Intensity of Trawl Net for the last 10 years	5.17				-		
~	Ratio of fishing ground in coral reefs	5.12						
log	Selectivity of fishing gears	5.04						
out	The number of vessels and fishing gears	4.27						
ect	The number of vessel anchoring in coral reefs	4.26						
_	State of mangrove conversion	3.72						
	State of mangrove utilization	3.72						
	Mariculture unfriendly	3.51						
-	Involvement of law officers	6.27						
No	Lack of law enforcement	6.21						
tut	Lack of monitoring and supervision	5.50						
nsti	Overlapping policies between institutions	5.47					1	
Š	Socialization and campaign	4.45						
gal	Role models in the community	4.40						
L	Knowledge and local wisdom	4.04						
		0 1	2	2	4	5	6	7
		0 1	2	5	4	5	0	/

687 Fig. 7 Attribute leverage analysis of the RAPFISH ordinations for threats to coral reefs in the TSCA. From the

688 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.



- 695 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)

698 Table 1. Types and characteristics of Landsat image data

No.	Satellite	Sensor	Resolution (m)	Acquisition	Path/Row
1.	Landsat 5	ТМ	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

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

701 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	Flowering plants, generally found intertidal areas
	boundary	and reef flats
Sand	Yellow and red	Sediment from carbonate origin (dead corals and
		skeleton for calcifying organisms)

703 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	0,1	COTs in coral reefs:	Endean and
(i.e., crown-of-thorns		>14 individuals/1000 m^2 (0); ≤ 14	Stablum (1973);
starfish (COTs), starry		individuals/ 1000 m ² (1)	Hoeksema (2012)
Economic Dimension			
1. Profitability	0,1,2,3	High profit (0); marginal profit (1); without	RAPFISH (2019)
5	- , , , ,-	gain or loss (2); little loss (3); large loss (4)	
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)
 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); chean (3): Very chean (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	0,1,2,3,4	Very high (0); high (1); moderate (2); low	Modified from
	wastes to the sea		(3); very low (4)	RAPFISH (2019)
6.	Frequency of conflicts	0,1,2	Frequent (0); seldom (1); none (2)	Modified from
	(destructive versus non-			Susilo (2003)
	destructive)			
7.	Ability of making	0,1,2,3	High (0); moderate (1); low (2); none (3)	Modified from
	destructive fishing			RAPFISH (2019)
	devices			
Te	chnological Dimension			
1.	The number of vessels	0,1,2	Increasing (0); unchanged (1); decreasing	Statistics of Muna
	and fishing gears (for		(2)	Barat Regency
	the last 10 years)			(2019)
2.	Intensity of blast	0,1,2,3	High (0); medium (1); low (2); none (3)	RAPFISH (2019)
	fishing for the last 10			
	years			
3.	State of mangrove	0,1,2,3	High (0); medium (1); low (2); none (3)	RAPFISH (2019)
	utilization (fire woods,			
	construction, etc.)			
4.	Selectivity of fishing	0,1,2,3	None (0); few (1); fair (2); many (3)	RAPFISH (2019)
_	gears			
5.	Ratio of fishing	0,1,2,3	75-100% (0); 50-74.9% (1); 25-49.9% (2);	Modified from
~	grounds in coral reefs	0.1.0	<25% (3)	RAPFISH (2019)
6.	The number of vessels	0,1,2	Many (0) ; few (1) ; none (2)	Modified from
-	anchoring in coral reefs	0 1 2 2	$H^{2}_{1}(0) = \frac{1}{2}(1) + \frac{1}{2}(2)$	RAPFISH (2019)
7.	State of mangrove	0,1,2,3	High (0) ; medium (1) ; low (2) ; none (3)	Modified from
	conversion (fishpond,			RAPFISH (2019)
0	settelement, buildings)	0 1 2 2	$H_{1}^{2} = 1$ (0), $m = \frac{1}{2}$ (1), $1 = \frac{1}{2}$ (2), $m = \frac{1}{2}$ (2)	\mathbf{D} A DEICH (2010)
0.	for the last 10 years	0,1,2,5	$\operatorname{High}(0); \operatorname{medium}(1); \operatorname{low}(2); \operatorname{hohe}(3)$	KAPFISH (2019)
0	Mariculture unfriendly	0122	V_{am} (b); b); (1); (2); c); (2); (2); (3); (3); (3); (3); (3); (3); (3); (3	Modified from
9.		0,1,2,5	Very bad(0), bad(1), fall(2), good(3)	PAPEISH (2010)
	and Institutional Dim	ansians		KAITISII (2019)
1	I ack of law	0.1.2.3	The level of legal violation: high (0):	Modified from FAO
1.	enforcement	0,1,2,5	medium (1) : low (2) : none (3)	(1005)
2	Overlapping policies	0123	Numerous (1) : fair (1) : few (2) : none (3)	(1))
2.	between institutions	0,1,2,5	(1), for (1), for (2), hole (3)	(1995)
3	Socialization and	012	Never (0) : fair (1) : frequent (2)	Modified from
5.	campaign of the public	0,1,2	(0), iai (1), itequein (2)	RAPFISH (2019)
	awareness			(2017)
4.	Involvement of law	0.1.2	Frequent (0) : fair (1) : never (2)	Modified from FAO
	officers	•) -)		(1995)
5.	Lack of monitoring and	0,1,2,3	Never (0); seldom (1); fair (2); frequent (3)	Modified from
	supervision by	-)))-		RAPFISH (2019)
	community			
6.	Role models in the	0,1,2	A public figure who understands the	Modified from
	community		environmental issues:	RAPFISH (2019)
	•		Few (0); fair (1); many (2)	
7.	Knowledge and local	0,1,2	Little (0); fair (1); a lot (2)	Modified from
	wisdom			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

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 %)	

710 Strait Conservation Area (TSCA).

Change of bottom types Type of Type of 1994 to 2003 Ratio 2003 to 2013 Ratio 2013 to 2019 Ratio change classes (ha) (%) (ha) (%) (ha) (%) 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 (-/+)

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

714 Table 7. Cumulative stress values and analysis of all dimensions. Values indicate the acceptability of the coral reef

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

status analysis [Stress (S) < 0.25, root squared correlation (RSQ) \approx 1].

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