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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**

3  
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15  
16          **Abstract**

17          In Indonesia, the coral reef ecosystem in the Tiworo Strait Conservation Area (TSCA) faces various threats of  
18          natural and anthropogenic stressors that can damage the coral reef ecosystem's role 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  
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 = high threat), technological dimension (41.10 = high threat), and law and institutional dimension (26.83 =  
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

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

33

## 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;  
41 Zunino *et al.* 2021), coral diseases (Lapointe *et al.* 2019; Hazraty-Kari *et al.* 2021), nutrient enrichment (Lapointe  
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.*  
45 2018; Yasir Haya and Fujii 2019; Santavy *et al.* 2021). Given these conditions, coral reef ecosystems require  
46 urgent management, such as a marine protected area (MPA) approach (Mellin *et al.* 2016; Vaughan and Agardy  
47 2020; Hampton-Smith *et al.* 2021).

48 MPAs have become one of the most frequently employed marine management tools worldwide for  
49 conserving species and habitats, maintaining ecosystem functionality, and ensuring the sustainable use of marine  
50 resources (Pagiola *et al.* 2004; Vaughan and Agardy 2020). In Indonesia, the types and sizes of MPAs differ  
51 according to their conservation goals and targets. The Tiworo Strait is a medium-sized marine conservation area  
52 that located at the Southeast of the Sulawesi mainland in the center of the Coral Triangle Area, Indonesia (**Fig. 1**).  
53 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).

69         Remote-sensing technology has been used in a variety of coral reef studies, including the classification  
70 of benthic habitats (Zhang 2015; Roelfsema et al. 2018; Zhang et al. 2018; Molder et al. 2022), detection of  
71 changes in coral composition (Andréfouët et al. 2007; Hedley et al, 2016; Parsons et al. 2018; Purkis 2018;  
72 Nimalan et al. 2021) and benthic reflectance at the bottom (Lee et al. 2013; Barnes et al. 2014; Thompson et al.  
73 2017; Roelfsema et al. 2021) and estimation of coastal water bathymetry (Lyzenga et al. 2006; Mishra et al. 2006;  
74 Pacheco et al. 2015; Minghelli et al. 2021). Frequently, these studies only analyze changes in benthic habitat cover  
75 without identifying habitat status and types of threats.

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

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## 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 04°16'40"S – 04°32'20"S and 122°13'35"E – 122°32'40"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

106 it has a large surrounding reef flat compared to other islands within the TSCA, making it easy for Landsat satellite  
107 sensors to capture spectral responses reflecting seabed cover. Coral reefs off Pulau Tiga can represent the  
108 condition of reefs in the TSCA at large because all of its islands can be accessed directly by local and non-local  
109 fishermen. GT data were obtained using GPS for each type of seabed cover, which included live corals, dead  
110 corals, rubble, seagrass, and sand (Nurdin et al. 2015). *In-situ* data on bottom cover types were obtained using a  
111 GPS unit (latitude-longitude data) and snorkeling or SCUBA equipment (data on bottom cover types). GT data  
112 were applied to check the accuracy of the image classification results.

113

#### 114 *(ii) Social Surveys*

115 Socio-economic data were obtained through interviews and questionnaires as supporting information  
116 for image interpretation and Rapid Appraisal for Fisheries (RAPFISH) analysis. We used purposive sampling by  
117 selecting respondents according to types of fishery activities, occupations, academic positions, and stakeholder  
118 roles (Kothari 2004). To ensure the validity and currency of the data, we consulted with marine and fisheries  
119 scientists at the Faculty of Fisheries and Marine Science at Halu Oleo University. To strengthen the  
120 methodological assessment, we incorporated the opinions and perspectives of resource users (fishers), resource  
121 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*

127 Scattering and absorption of molecules by the atmosphere can decrease the quality of information in an  
128 image by up to 10%, depending on the spectral channels (Che and Price 1992). Atmospheric correction is  
129 therefore essential to minimize the effect of the atmosphere in multi-temporal images before comparing and  
130 analyzing the data (Hadjimitsis et al. 2010). Atmospheric correction was done for five series of Landsat imagery  
131 data using Dark Object Subtraction (DOS). In DOS, an absolute correction to the image is performed, such that

132 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*

136 Geometric correction for three series of Landsat imagery data was conducted using the same coordinate  
137 points (GCPs). Geometric correction aims to improve the accuracy of and minimize the geometric error in Landsat  
138 imagery data. Eight GCP points were chosen for geometric correction using order polynomial transformation and  
139 a nearest-neighbor interpolation algorithm (Afwani and Danoedoro 2019). The corrected image was considered  
140 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  
146 channels (bands) were selected because the band composites were considered the most appropriate for deducing  
147 the appearance of land cover. Red composites using band 3 (Landsat 5 TM/7 ETM) and band 4 (Landsat 8  
148 OLI/TIRS) are suitable for detecting dry land or soil. Green composites were used to detect chlorophyll in  
149 vegetation from band 2 (Landsat 5 TM/7 ETM) and band 3 (Landsat 8 OLI/TIRS). High chlorophyll  
150 concentrations on the mainland provided high reflection digital values and were shown as dark green colors.  
151 Water was detected using band 1 (Landsat 5 TM/7 ETM) and band 2 (Landsat 8 OLI/TIRS) in blue composites so  
152 that it could be depicted in blue.

153

#### 154 *d. Image Subsetting (Cropping)*

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

158

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

166 
$$\frac{k_i}{k_j} = a + \sqrt{(a^2 + 1)}, \quad (2)$$

167 
$$(DII)_{ij} = \ln(L_i) - \left[ \left( \frac{k_i}{k_j} \right) \times \ln(L_j) \right], \quad (3)$$

168 where  $i$  is the blue band,  $j$  is the green band,  $\sigma_{ii}$  is the variance of the blue band,  $\sigma_{jj}$  is the variance of the green  
169 band,  $\sigma_{ij}$  is the covariance between blue and green bands,  $\frac{k_i}{k_j}$  is the attenuation coefficient index ratio between  
170 blue and green bands, and  $L_i$  and  $L_j$  are the radiance pixels of blue and green bands, respectively.

171

172 *f. Classification, Ground Truth, and Reclassification*

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

179



180 g. *Post-Classification Process*

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

185

186 h. *Accuracy Assessment*

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

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

195 
$$\text{Producer accuracy } j = \frac{n_{jj}}{n_{+j}} \times 100\%, \quad (5)$$

196 
$$\text{User accuracy } i = \frac{n_{ii}}{n_{i+}} \times 100\%. \quad (6)$$

197 where  $n_{ij}$  is the number of observations at column  $j$  and row  $i$ ,  $n_{ii}$  and  $n_{jj}$  are the number of observations  
198 categorized in the thematic class of  $i$  and  $j$ , respectively,  $n_{i+}$  and  $n_{+j}$  are the number of observations classified in the  
199 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*

202 The Rapid Appraisal for Fisheries (RAPFISH) was developed at the University of British Columbia,  
203 Canada, and is used to evaluate fisheries sustainability with the application of a new multidisciplinary rapid  
204 assessment technique. The RAPFISH relies on the ordinance of assessed attributes that are grouped in several  
205 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*

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

$$236 \quad S = \sqrt{\frac{1}{m} \sum_{k=1}^m \left[ \frac{\sum_i \sum_j (d_{ijk}^2 - d_{ijk}^2)^2}{\sum_i \sum_j O_{ijk}^4} \right]}, \quad (7)$$

237 where m is the number of analysts or experts from various scientific backgrounds. In the RAPFISH method, MDS  
 238 analysis is terminated when the S value lies within a tolerable range, with an acceptable maximum value of 0.25  
 239 (25%) (Fauzi and Anna 2002).

240

241 *d. Rotation Process*

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

247

248 *e. Index Scale of Threats*

249 We used a modified index scale to assess threats to the sustainability of coral reef ecosystems based on  
 250 Pitcher and Preikshot (2001). Modifications included the following changes to descriptions of index levels: from  
 251 unsustainable to very high threats, from less sustainable to high threats, from somewhat sustainable to fewer  
 252 threats, and from sustainable to no threats. The threat index ranged from 0 to 100 and was divided into four  
 253 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

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

264

265 *g. Monte Carlo Analysis*

266 Monte Carlo analysis was used to analyze errors in the assessment of attributes caused by several  
267 factors, such as 1) inconsistency in assessment, 2) differences in the assessment, 3) level of iterative stability, 4)  
268 data errors, and 5) high stress values (Kavanagh and Pitcher 2004). This method was also used to calculate the  
269 effect of random errors on the process of estimating/calculating ordination values. The acceptable stress value was  
270 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  
279 channel was the highest (RSQ > 94%) compared to other ratios in the visible spectrum. This is coincident with the  
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**).

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

288           The Landsat multi-temporal images from 1994, 2002, 2013 and 2019 showed that coral reefs have  
289 changed over the 25-year period from 1994 to 2019, with a decline in live coral and increased dead coral and  
290 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  
291 for rubble, 53.06 ha for seagrass, and 49.41 ha for sand, implying relatively small proportions of damaged coral  
292 reefs (7.13%) and rubble (9.28%) compared to live coral (36.20%) (**Fig.4(a)**). The dominance of live coral is  
293 considered to benefit the marine ecosystem and local people. Live coral was widely distributed (in cyan) around  
294 the island, although some dead coral (in red) and rubble (in dark green) were also found in a small area.

295           There were significant changes in seabed cover from 1994 to 2003, particularly for live and dead coral  
296 and rubble (**Fig. 4(b)**; Table 5). The live coral area decreased significantly by 41.95%, from 78.30 ha in 1994 to  
297 45.45 ha in 2003. Dead coral doubled from 15.43 ha to 30.33 ha during the same period. The rubble area slowly  
298 increased by 48.43%, from 20.07 ha in 1994 to 29.79 ha in 2003. Seagrass decreased slightly by 3.10 ha, whereas  
299 sandy areas substantially increased from 49.41 ha in 1994 to 54.54 ha in 2003.

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

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

307           We observed three types of changes in benthic habitat cover over the 25-year period from 1994 to 2019:  
308 an increase, decrease, and fluctuative increase (Table 6). Visually, the greatest decrease in live coral cover

309 occurred between 1994 and 2003, with a reduction of 41.95%, followed by 2003–2013 (29.54%) and 2013–2019  
310 (18.28%). Conversely, the greatest increase in dead coral cover occurred between 2003 and 2013 (201.04%),  
311 followed by 1994–2003 (96.57%) and 2013–2019 (32.86%). Rubble cover increased throughout the study period,  
312 although the rate gradually decreased. Seagrass exhibited fluctuations in cover: a decrease of 5.84% from 1994 to  
313 2003, a slight increase of 3.79% from 2003 to 2013, and a decrease of 2.60% from 2013 to 2019. Similar to  
314 seagrass, sand cover fluctuated with a 10.38% increase from 1994 to 2003, a 16.64% decrease from 2003 to 2013,  
315 and a 12.81% increase from 2013 to 2019.

316 Live coral decreased dramatically by 89.77% from 78.30 ha in 1994 to 8.01 ha in 2019. By contrast,  
317 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.

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

323

## 324 **3.2. MDS Analysis**

325 Results of MDS analysis for the 37 threat attributes using the RAPFISH approach showed that the  
326 cumulative stress values for the five dimensions were all in the range of 0.11–0.12 (Table 8). As this range was  
327 below 0.25, the threat values were statistically valid and fulfilled statistical procedures with a significant interval  
328 (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**

330 The RAPFISH ordination results indicated that the coral reef threat level varied according to the threat  
331 dimension (**Fig. 6**). Threats to coral reefs from the ecological dimension contributed the most (16.87), followed by  
332 legal and institutional (26.83), economic (31.00), social (34.83), and technological (41.10) dimensions. Overall, the

333 average threat index was 30.13, indicating a high threat to coral reef ecosystems.

334           The leverage analysis indicated that the sensitivities of the threat attributes in the five dimensions varied  
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  
339 most sensitive attributes were “profitability” (5.83), “price of fish caught by destructive fishing” (5.78), and  
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***

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

### 357 **3.5. *Causal-loops Diagrams (CLDs) Model***

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

364 As shown in **Fig. 9**, there are three main CLDs variables: threats to coral reef ecosystems, sustainability  
365 of coral reef ecosystems, and changes in coral cover. In general, massive threats to coral reefs (i.e., ecological,  
366 economic, social, technological, and legal and institutional attributes) can affect the sustainability of coral reef  
367 ecosystems. Therefore, an appropriate strategy is needed to reduce pressure on coral reef ecosystems at the study  
368 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  
373 are in danger. Overall, the TSCA is classified in the "high threat" category, with an average index value of 30.16  
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  
384 trawling nets not only damages coral reefs but also depletes and damages aquatic biota (Kularatne 2020). These  
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  
401 between the community (fishermen) and local government should be pursued. In some countries, such as Fiji, Chile,  
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; (Erfteimeijer et al. 2012)).

415

#### 416 *Strengthening Local Institutions and Role Models*

417 Strong interactions between local fishers and their leaders (role models) can influence positive  
418 community behavior in terms of the use of natural resources. The conditions of coral reef ecosystems in the TSCA  
419 indicate destructive practices that are difficult to avoid. Leaders and role models in the local communities who are  
420 aware of the issues facing local fishers and the coral reef ecosystems should be given roles and responsibilities  
421 (Ho et al. 2016). Thus far, the roles of local community leaders have been taken over by village heads appointed  
422 by the local government, but most village heads do not have good environmental awareness. Strong local  
423 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  
436 analysis shows that a multidimensional threat has affected coral reefs during this period with an average threat  
437 index value of 30.13, which means that the threat status of coral reefs is categorized as high. This can be seen in  
438 the ecological dimension was the most sensitive dimension and was strongly influenced by threat level, with a  
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  
441 all stakeholders concerned with implementing the analyzed set of strategies. A multi-stakeholder collaboration  
442 model in the area can be the best option to improve coordination and cooperation in minimizing damage to coral  
443 reefs.

444

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450

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453

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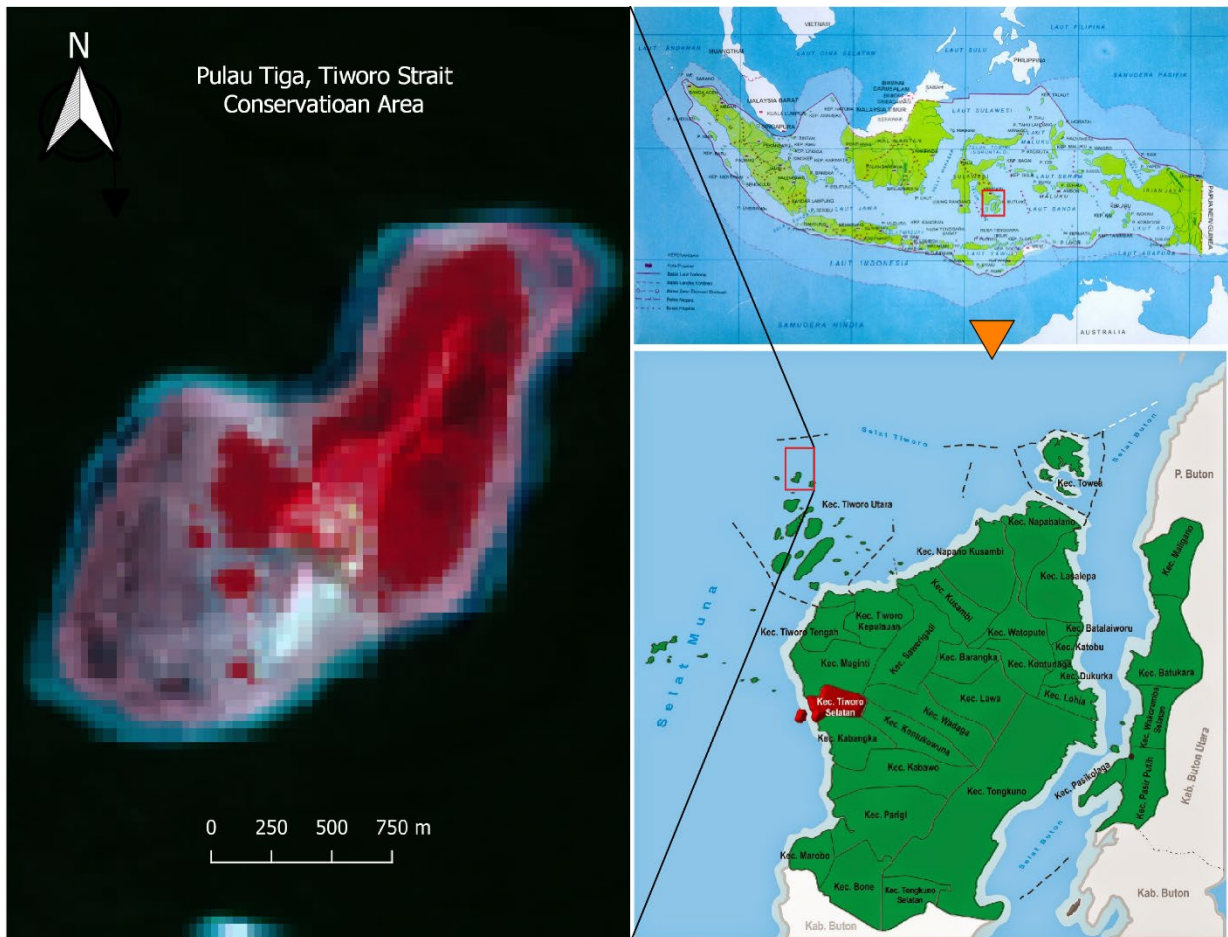
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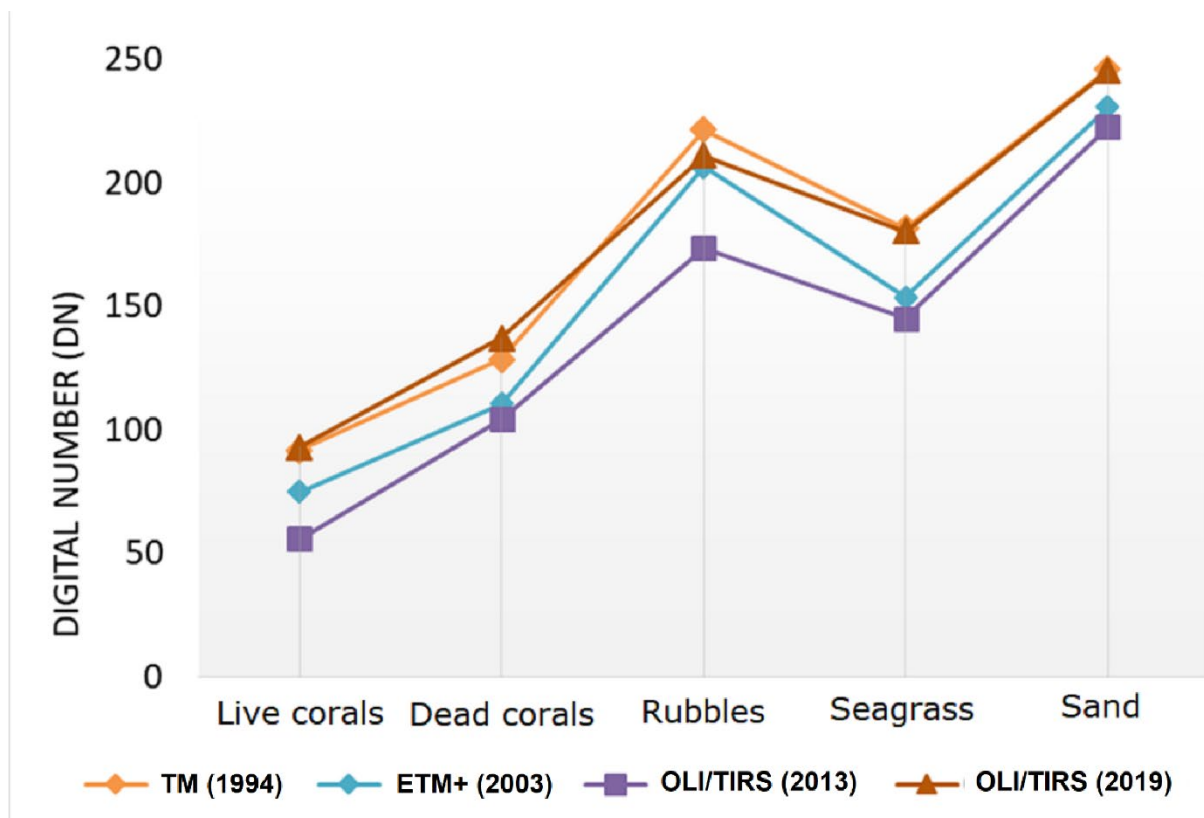
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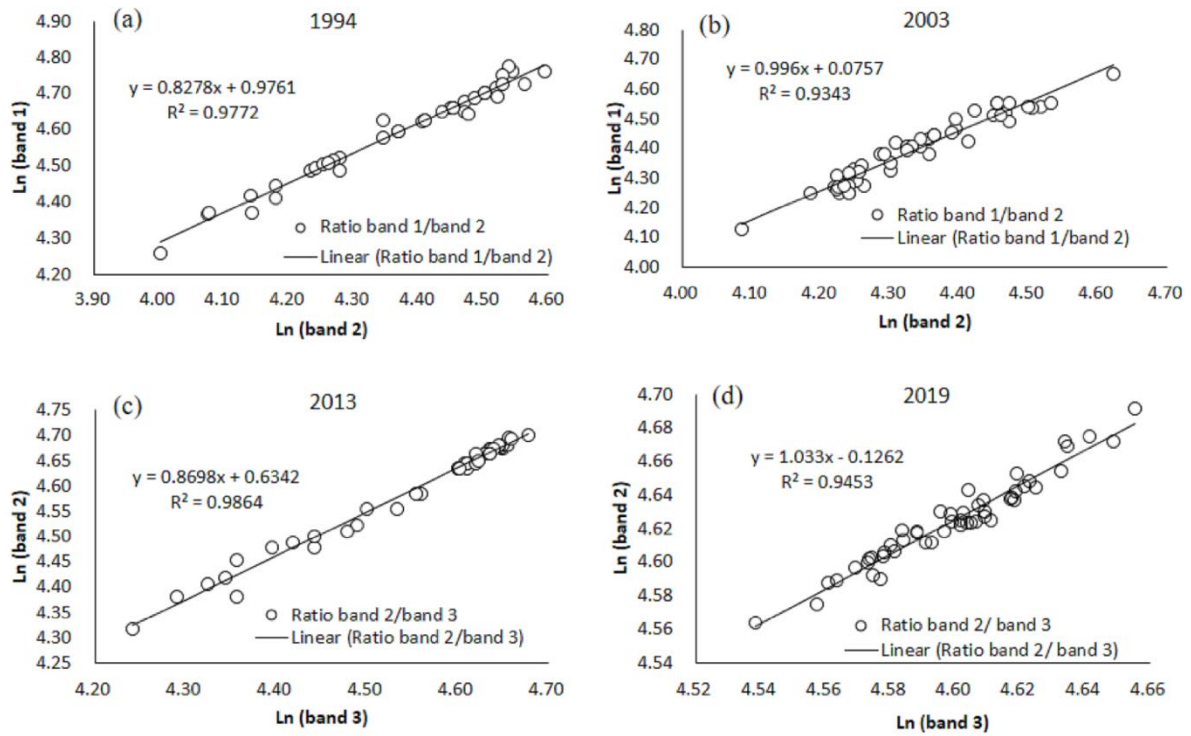
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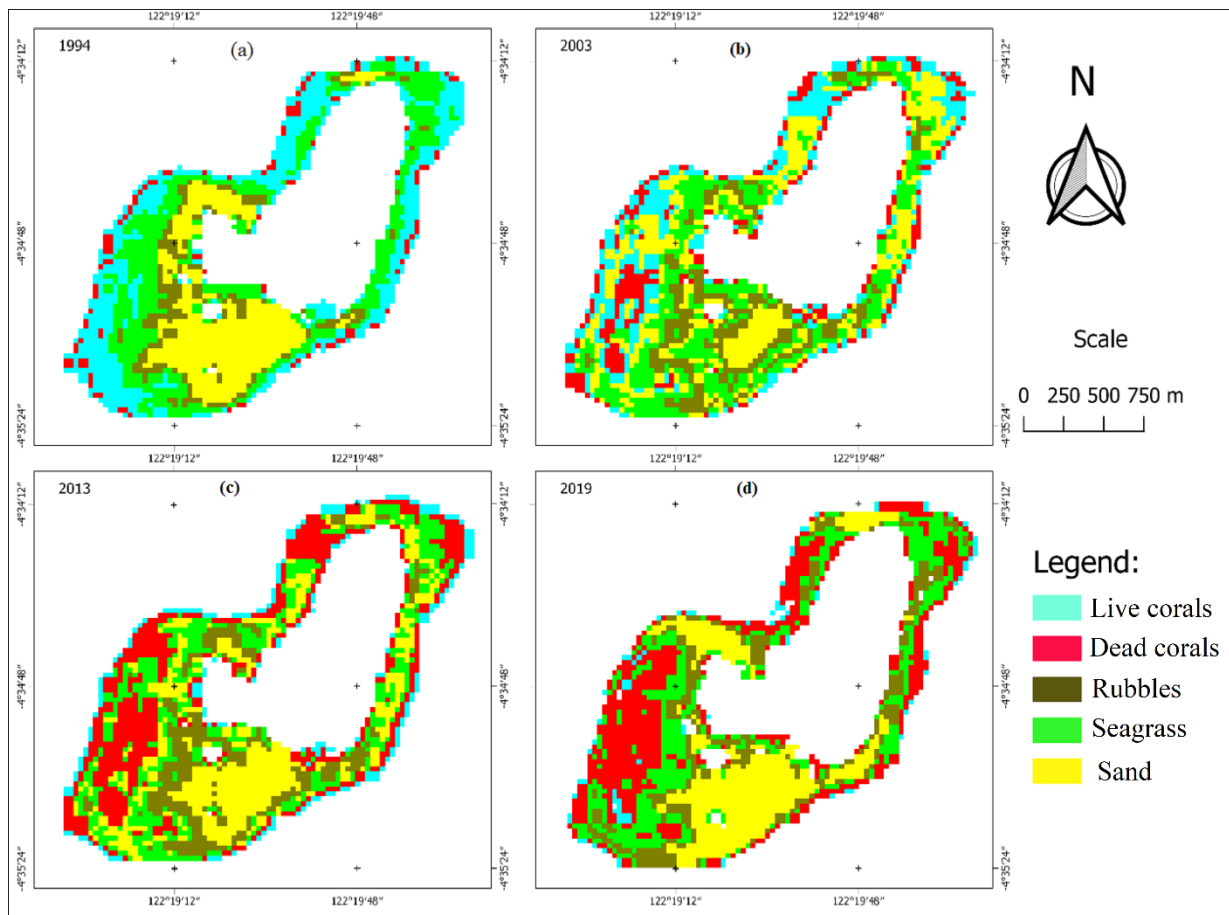
664 **Fig. 1** Study area located in the Tiworo Strait Conservation Area (TSCA) in the Muna Barat Regency of Southeast  
 665 Sulawesi in Indonesia.



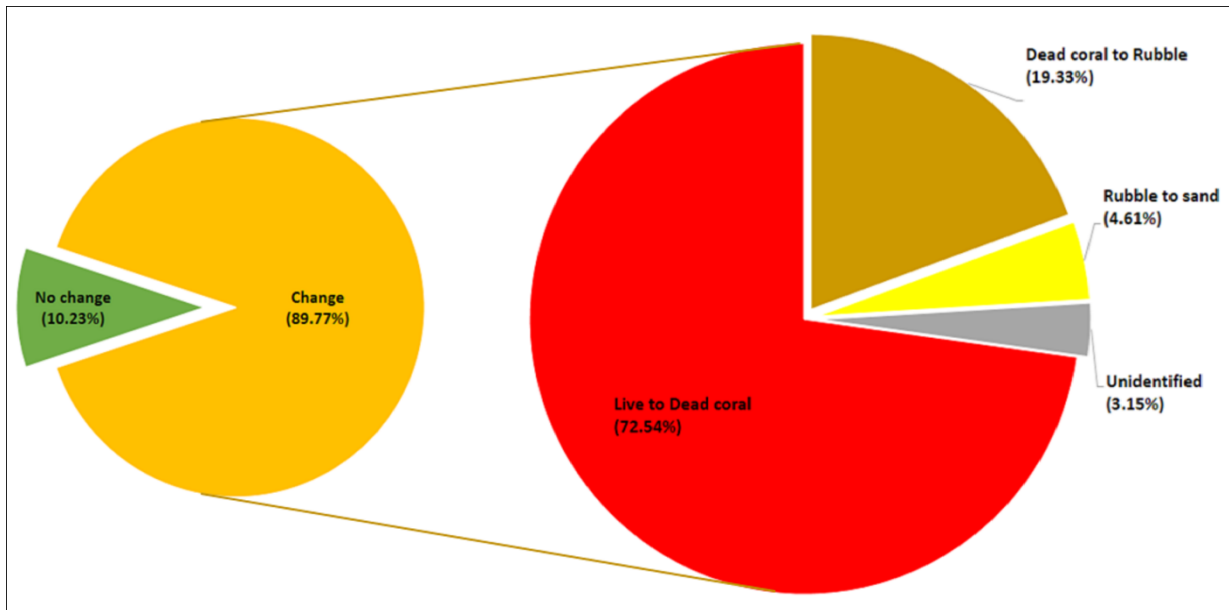
666 **Fig. 2** Spectral responses representing five types of seabed cover obtained by Landsat multi-sensor satellites in  
 667 1994 (Landsat 5 TM), 2003 (Landsat 7 ETM+), 2013 (Landsat 8 OLI/TIRS), and 2019 (Landsat 8 OLI/TIRS). Of  
 668 the five types of seabed cover, it can be seen that the three classes with the lowest response values—live coral,  
 669 dead coral, and seagrass—have object characteristics in which higher levels of electromagnetic radiation are  
 670 absorbed compared to rubble and sand. This causes the digital number (DN) values of the three types to be lower  
 671 than those of rubble and sand.



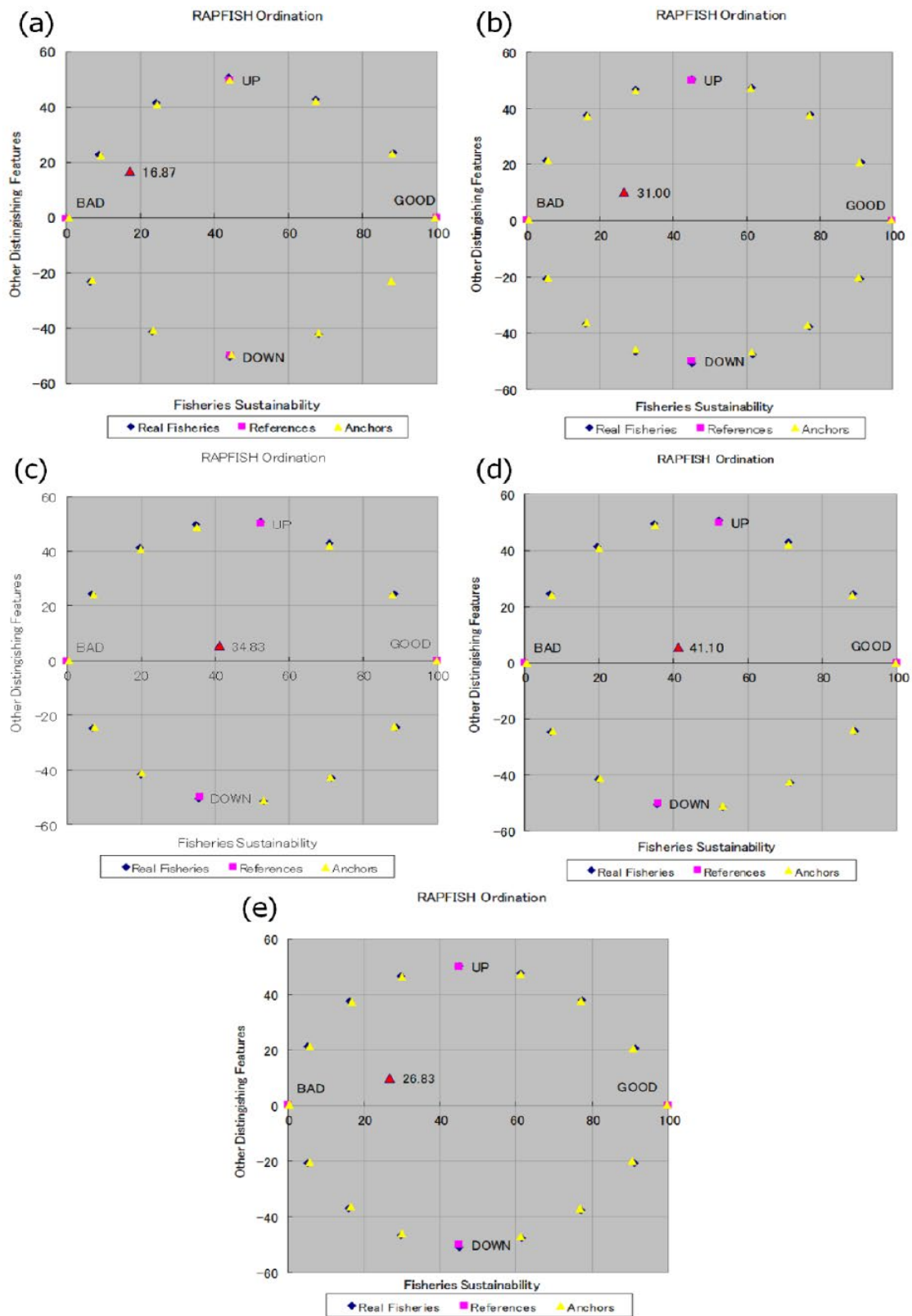
672 Fig. 3 Ratio of blue to green channels for multi-temporal Landsat imagery obtained in (a) 1994 (Landsat 5 TM),  
 673 (b) 2003 (Landsat 7 ETM+), (c) 2013 (Landsat 8 OLI/TIRS), and (d) 2019 (Landsat 8 OLI/TIRS). In the visible  
 674 light spectrum, because blue and green light can penetrate seawater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



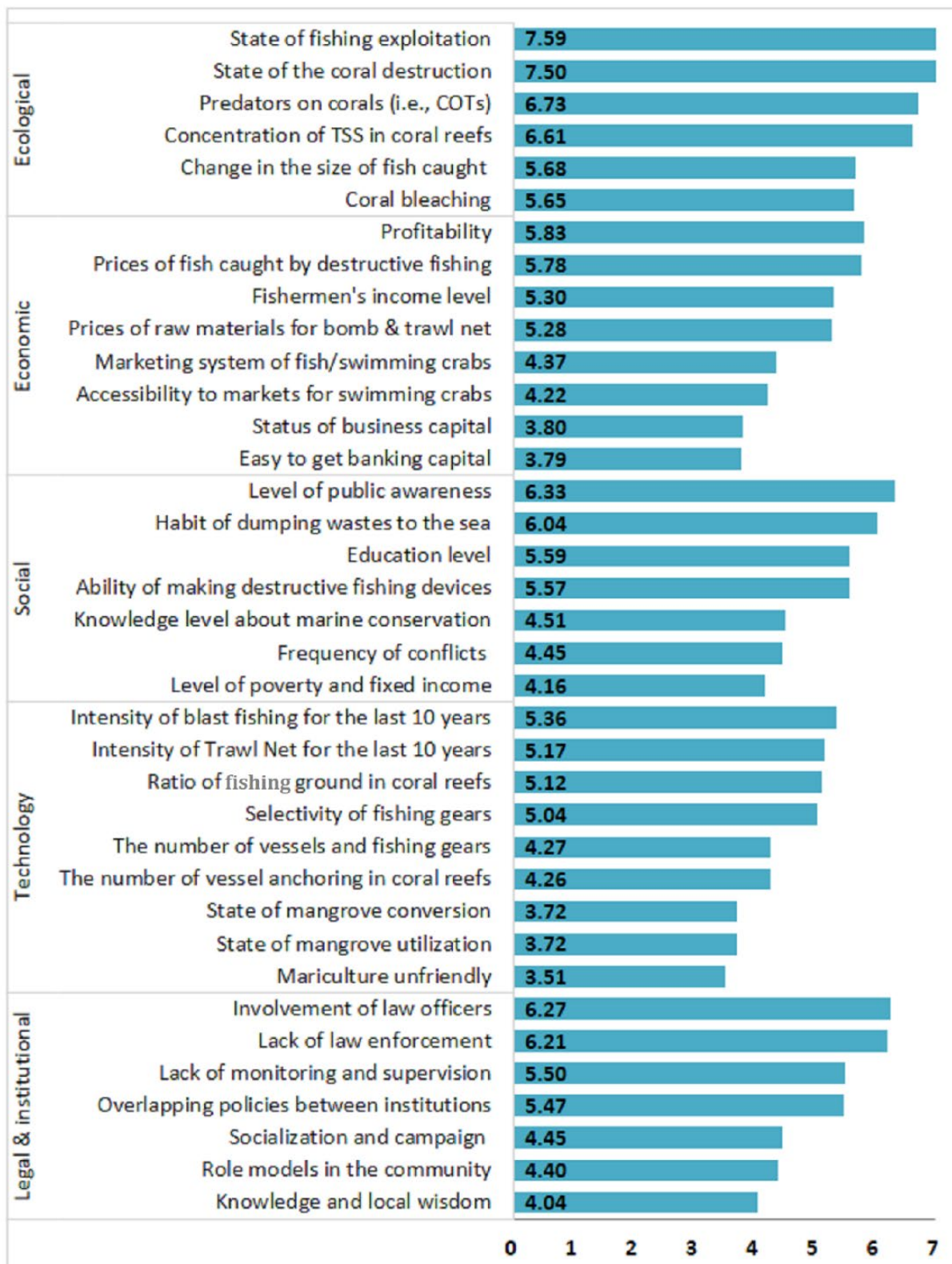
678 **Fig. 4** Distribution of changes in coral cover off Pulau Tiga within the TSCA according to Landsat multi-temporal  
 679 image data obtained over a 25-year period from 1994 to 2019.



680 **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).

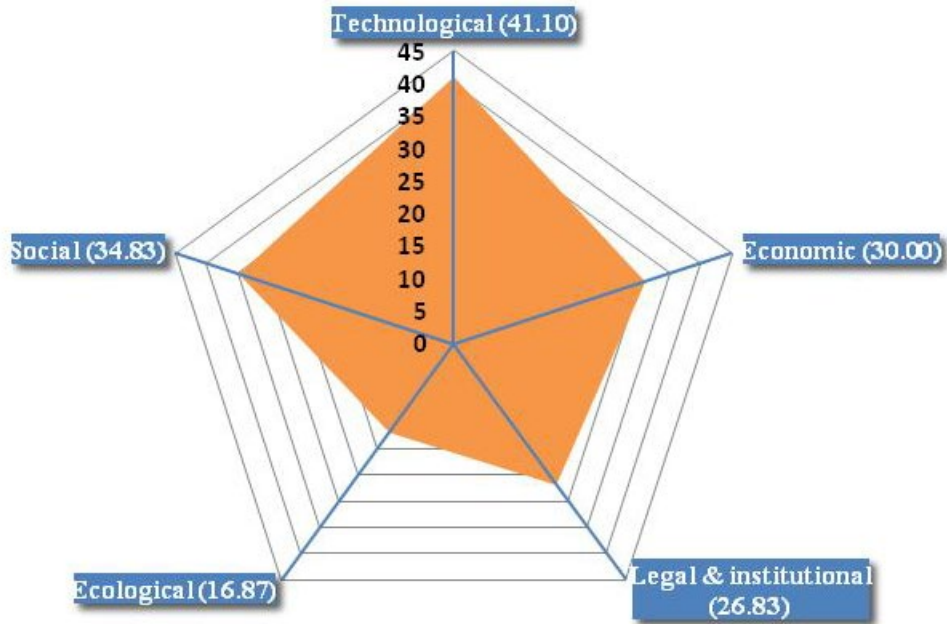


683 **Fig. 6** Two-dimensional Rapid Appraisal for Fisheries (RAPFISH) ordinations of the threats to coral reefs in the  
 684 TSCA, based on (a) ecological, (b) economic, (c) social, (d) technological, and (e) legal and institutional  
 685 dimensions. The horizontal axis represents sustainability [0%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

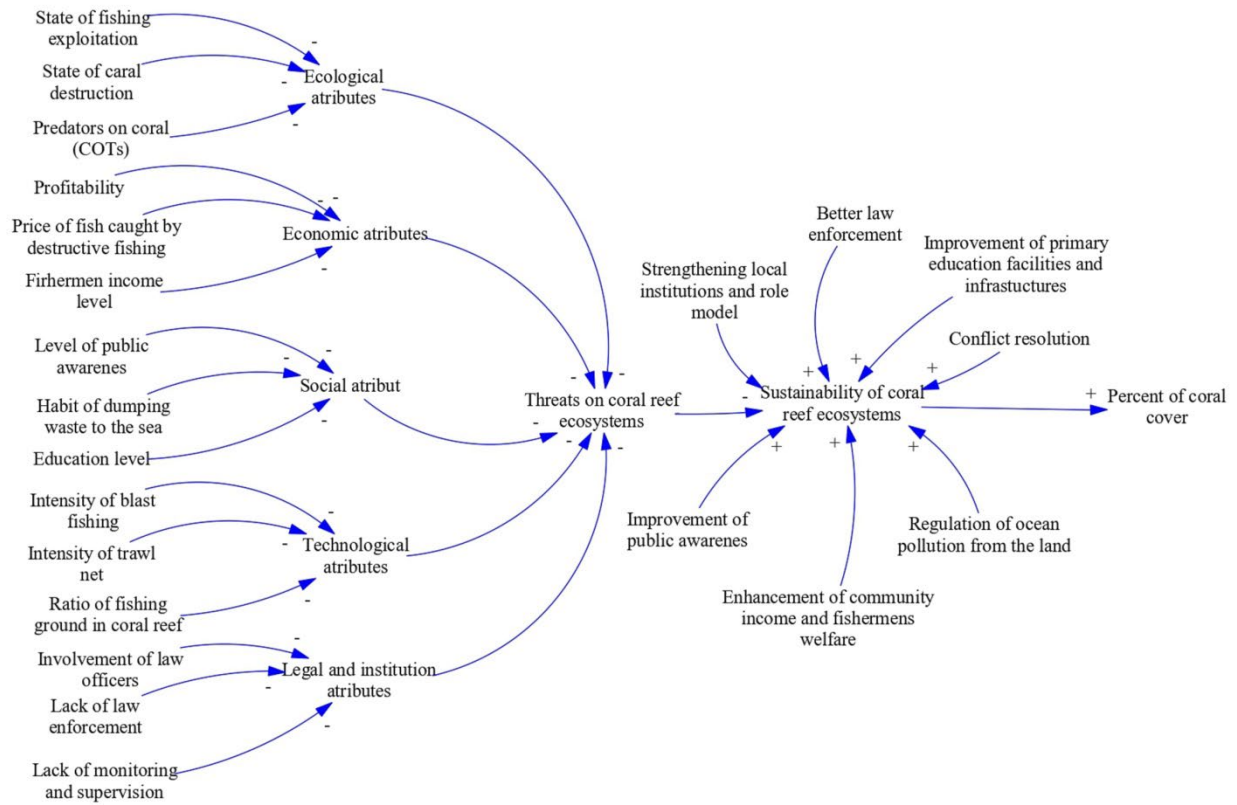


687 **Fig. 7** Attribute leverage analysis of the RAPFISH ordinations for threats to coral reefs in the TSCA. From the  
688 five dimensions analyzed (i.e., ecological, economic, social, technological, and legal and institutional), we  
689 obtained a root squared correlation (RSQ) value of 0.97, indicating that the analysis was acceptable.  
690





691 **Fig. 8** Kite diagram of the five threat dimensions to coral reef ecosystems in the TSCA. Based on the threshold  
 692 values listed in Table 4, the ecological dimension was regarded as under “very high threat” and the economic,  
 693 social, technological, and legal and institutional dimensions contributed to a “high threat” level. The overall value  
 694 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  
 696 the Tiworo Strait Conservation Areas (TSCAs)  
 697

698 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

699

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 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)

702

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

Attribute	Score scale	Remarks	Source/ references
<b><i>Ecological Dimension</i></b>			
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)	Erfteemeijer 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 <sup>2</sup> (0); ≤14 individuals/ 1000 m <sup>2</sup> (1)	Endean and Stablum (1973); Hoeksema (2012)
<b><i>Economic Dimension</i></b>			
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); easy (2)	Yasir Haya and Fujii (2019)
<b><i>Social Dimension</i></b>			
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)
<b><i>Technological Dimension</i></b>			
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, settlement, 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)
<b><i>Legal and Institutional Dimensions</i></b>			
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)

707 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

708

709 Table 5. Aerial estimates of major bottom types in 1994, 2003, 2013, and 2019 off Pulau Tiga within the Tiworo  
 710 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 %)

711



712 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	(-/+)

713

714 Table 7. Cumulative stress values and analysis of all dimensions. Values indicate the acceptability of the coral reef  
715 status analysis [Stress (S) < 0.25, root squared correlation (RSQ)  $\approx$  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

716

717