Assessment of coral reef ecosystem status in the Pangkajene and Kepulauan Regency, Spermonde Archipelago, Indonesia, using the rapid appraisal for fisheries and the analytic hierarchy process

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Abstract

Coral reefs in the world's tropical and subtropical oceans have long been under considerable threat. The aims of this study were to identify the types of threat affecting coral reefs, to conduct a sensitivity analysis to assess the sustainability of coral reef ecosystems, and to suggest alternative strategies that should be deployed to improve the status of coral reef ecosystems in the Pangkajene and Kepulauan (PANGKEP) Regency, Spermonde Archipelago, Indonesia. The data obtained were analyzed using the rapid appraisal technique for fisheries (RAPFISH) and the analytic hierarchy process (AHP). The RAPFISH analysis identified 41 types of threat to the status of coral reef ecosystems, based on five indices: economic (51.92), social (47.33), technological (47.26), legal and institutional (45.60), and ecological (37.65). The averaged cumulative index of coral reef ecosystem sustainability was 45.95, within a threshold denoting a "less sustainable" status. The AHP analysis suggested that several alternative strategies are needed to improve the status of coral reef ecosystems, with greater prioritization of socialization, campaigns, and education, followed by law enforcement, selectivity in the use of fishing gear, rehabilitation of coral reef ecosystems, and restocking of fish in coral reefs. The findings of this

study can be used as points of reference when local policymakers begin to formulate appropriate strategies for the sustainable use of coral reef ecosystems.

Keywords: *Coral reef; Indonesia, Rapid appraisal for fisheries (RAPFISH); Analytic hierarchy process (AHP); Threat; Sustainability*

1. Introduction

Coral reefs provide vital habitats for diverse marine biota and sustain the Earth's marine ecosystems. Human activities' high dependence on coral reef ecosystems has led to potential threats to the reefs, with varying degrees of impact [1,2,3,4]. Coral reefs are typically concentrated in shallow waters, which places these habitats in danger of destruction caused by nearby human settlements [1,5].

In Southeast Asia, coral reef damage has been particularly severe; 88% of coral reefs in this region are endangered, of which approximately 50% are categorized as at high risk and 12% are categorized as at very high risk [1]. On the regional scale, the greatest threats to coral reefs occur in the Coral Triangle. The Coral Triangle, located in the waters of Indonesia, Malaysia, the Philippines, Timor-Leste, Papua New Guinea, and the Solomon Islands, is the world's center of marine biodiversity, particularly with regard to coral reefs [6]. In Pangkajene and Kepulauan (PANGKEP) Regency, Spermonde Archipelago, Indonesia, for example, coral reef coverage has declined significantly, at a degradation rate of 174 ha/yr [7]. The economic loss ensuing from the destruction of coral reefs was estimated to be USD 50.2 million/yr [8].

Threats to coral reefs are believed to indicate ascending future trends, including human population growth in coastal areas, the use of more efficient fishing technologies, increased fish consumption worldwide, land-based pollution, greater intensity of destructive fishing practices, coral bleaching, coral diseases, and other anthropogenic threats [5,6,10,11]. Based on their impacts, [11] classified the threats to coral reefs as global and local. Local threats (e.g., overfishing, destructive fishing, and eutrophication) can be managed at the local scale, whereas global threats [e.g., global warming, ocean acidification, and the El Niño–Southern Oscillation (ENSO) phenomenon] cannot. Local and global threats interact with one another to accelerate coral reef degradation [11,12].

The continuous decline in coral reef coverage may pose a serious threat to the long-term sustainability of coral reef ecosystems, leading to multidimensional problems for humanity and the environment. To address this issue, the utilization and management of coral reef ecosystems should be emphasized, with the consideration of ecological, socioeconomic, and institutional aspects, as stated in the ecosystem-based fisheries management (EBFM) framework [13,14] . According to the [13], the EBFM is an international fishery regime formulated to manage sustainable fisheries for the purpose of accommodating and gaining optimal benefits for current and future generations. This approach assesses scientific knowledge and addresses the uncertainty regarding the sustainability of marine resources, habitats, and stakeholders in marine ecosystems, as well as fulfilling one of society's ultimate goals. The EBFM framework's practical purpose is to assess and manage the impacts of ecological, social, and other outcomes related to human activities in the utilization of coral reef ecosystems [14].

This study had the following objectives: (1) to identify the various types of threat to the status of coral reef ecosystems in the PANGKEP Regency, Spermonde Archipelago, Indonesia; (2) to carry out a sensitivity analysis of the status of coral reef ecosystems by applying multidimensional scaling (MDS) approach; and (3) to formulate an appropriate and alternative policy that should be introduced to mitigate the deterioration of coral reef ecosystems. Two multidimensional appraisal techniques were applied as decision support tools: the rapid appraisal technique for fisheries (RAPFISH) and the analytical hierarchy process (AHP).

The RAPFISH is a multidisciplinary method for the analysis and evaluation of fisheries' sustainability using semi-quantitative scoring in five dimensions: ecological, economic, social, technological, and ethical/institutional. Detailed explanations of this technique have been provided by [16,17], and the statistical analysis is detailed in [17] and [18]. The RAPFISH has been used widely to assess the statuses of fisheries around the world (e.g. [19-25]). Recently, the RAPFISH has also been used to assess indicators of sustainable fishing communities in Cartagena (Spain) [26], to analyze the sustainability of marine ecotourism in Pangandaran Region, West Java Province of Indonesia [28], and to analyze the vulnerability of coral reefs in the coastal ecotourism area of Malang, Indonesia [29]. It is considered to be useful for the identification of the types of threat that jeopardize the sustainability of coral reef ecosystems.

Another essential assessment technique is the AHP, which is also useful for the formulation of appropriate and alternative policy strategies for the management of natural resources. The AHP is a convenient appraisal tool with valuable components used for problem mapping, the formulation of alternative solutions, the determination of priority scales, conflict resolution, participative decision making, and decision support tools; its application has numerous practical advantages and valuable features [30].

The RAPFISH and AHP are expected to be necessary for the production of valuable outputs in terms of the formulation of appropriate and alternative policy strategies to improve the status of coral reef ecosystems in the study area. Therefore, the results of this study will serve as a valuable reference for policy makers seeking to address coral reef ecosystem management in this region.

2. Materials and Methods

2.1. Study Site

This study centered on the PANGKEP Regency, Spermonde Archipelago, South Sulawesi Province, Indonesia. Observations and interviews were conducted in two subdistricts, Liukang Tuppabiring and Northern Liukang Tuppabiring, which encompass 10 inhabited islands: Salemo, Saugi, Karanrang, Badi, Sanane, Sarappo, Samatellu Lompo, Gondongbali, Pandangan, and Kapoposang (Fig. 1).

2.2. Data Collection

Primary data were collected by observation, interview, and distribution of RAPFISH score sheets to respondents, using purposive and proportional sampling [31]. Interviews were conducted with key individuals in the local community of fishermen, and with analysts and experts with various scientific backgrounds in marine ecology, society, economy, fishing technology, and coral reef management (legal and institutional dimension). The analysts/experts were from Hasanuddin University, Halu Oleo University, and the National Institute of Marine and Fisheries Sciences, Ministry of Marine and Fisheries, Indonesia. During the interviews, the analysts were asked to indicate their scores on prepared RAPFISH score sheets (Table 1).

Secondary data were collected from published reports and information obtained from institutions involved in coral reef management and supervision: the Faculty of Marine and Fisheries of Hasanuddin University, the Center for Coral Reefs Studies of Hasanuddin University, the Regional Department of Marine Affairs and Fisheries of the PANGKEP Regency, and the Central Bureau of Statistics.

2.3. Rapid Appraisal for Fisheries

The RAPFISH was developed at the University of British Columbia, Canada, and is used to evaluate the sustainability of fisheries with the application of a new multidisciplinary rapid appraisal technique. RAPFISH relies on the ordination of scored attributes grouped in several evaluation fields using multidimensional scaling (MDS). These fields, or dimensions, are ecological, economic, technological, social, and ethical/legal and institutional [14,16,17]. Each dimension is assigned specific attributes, or indicators, related to the sustainability of coral reefs, as specified by [12]. The attributes were then elaborated by referral to [16,32,33], as established in the principles and indicators approved by EAFM approaches [13].

Technically, each dimension of the RAPFISH has attributes and these attributes are compared with one another based on the level of threat to a coral reef ecosystem's status. The steps involved in RAPFISH application are detailed below.

2.3.1. Identification and determination of attributes

Based on a thorough review and compilation of all available data, 41 attributes were established in five dimensions: ecological (*n* = 8), economic (*n* = 7), social (*n* = 8), technological (*n* = 8), and legal and institutional (*n* = 10; Table 1). These attributes represent the various threats affecting the status of coral reef ecosystems in the PANGKEP Regency.

2.3.2. Definition and scoring of attributes

The second step of the analysis was to define and score the attributes in accordance with the RAPFISH [17,34], in which a "bad" score designates the worst condition for the coral reef ecosystem, and a "good" score signifies the most favorable condition. The scoring of attribute sets in this study was performed with reference to the method formulated by [34] and [35]. Each attribute's score depends on its position within the range of bad to good.

2.3.3. *Multidimensional scaling*

In MDS, similar points or objects are plotted close to one another, and dissimilar points or objects are plotted far from each other. Using the rotation axis, the positions of objects can be projected in the horizontal line, where the value of 0 is considered to denote a high threat and 100 is considered to denote a low threat. The steps of the ordination process are as follows:

a) Determination of two main reference points consisting of vertical (here, "good"/low threat) and horizontal ("bad"/high threat) midpoints of ordination.
b) Determination of an additional reference point ("anchor") for the stabilization of scoring.
c) Standardization of scores for each RAPFISH attribute, so that each attribute has a true weight and measurement scale differences among attributes are eliminated.
d) Calculation of the distances between RAPFISH points and reference points (good and bad scores) using MDS, i.e., calculation of the distance closest to the Euclidean distance, using the following equation [21]:

$$d_{1,2} = \sqrt{\sum_{i=1}^{n}(x_i - y_i)^2}, \qquad \text{(Eq. 1)}$$

where $d_{1,2}$ is the multidimensional Euclidean distance between two points, *n* is the number of points, and x_{i1} and y_i are the locations of each point on the *x* and *y* axes, respectively. The two MDS points are then projected in the two-dimensional Euclidean distance (D_{12}) using the following regression equation:

$$d_{12} = a + bD_{12} + e\ , \qquad \text{(Eq. 2)}$$

where *a* is the intercept, *b* is the slope, and *e* is the error.

The next step is regression analysis using an alternating least-square approach to squared distance scaling (ALSCAL) algorithm, available in statistical software such as SPSS Statistics [17]. Principally, this algorithm conducts iteration to minimize *e*. According to [19], the ALSCAL algorithm is executed in RAPFISH with automatic imposition, so that $a = 0$, as in the following equation:

$$d_{12} = bD_{12} + e. \qquad \text{(Eq. 3)}$$

e) Calculation of the stress value (a measure of goodness of fit in MDS) using the ALSCAL algorithm. This algorithm is used to optimize the distance of squared data from the original point (O_{ijk}) (d_{ijk}) in a three-dimensional point (*i*, *j*, *k*) framework, which is symbolized as stress (*S*), as described in the following equation:

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

In RAPFISH, MDS analysis is terminated when the stress (*S)* value is within a tolerable limit; the maximum acceptable value is 0.25 (25%) [21].

2.3.4. Rotation

Points obtained from RAPFISH scores were projected on the horizontal axis using rotation, with the extreme "bad" position assigned a value of 0 and the extreme "good" position assigned a value of 1. The RAPFISH also includes two "halfway" scores, which are mirror images of one another, for scaling of the vertical dimension, and a set of predefined anchor points to avoid vertical "flipping" of the MDS ordinates. The reference and anchor points have been described in detail by [18].

2.3.5. Index scale of sustainability

The index scale of the sustainability status of coral reef ecosystems in the study area was modified with reference to the index scaling proposed by [32]. The scale ranged from 0 to 100 and was divided into four categories (Table 2).

2.3.6. Sensitivity analysis

Sensitivity analysis was performed to determine which attribute contributed to the sustainability of the coral reef ecosystems with the greatest sensitivity. The effect level of each attribute on the sustainability index was assessed by leverage analysis of the RAPFISH scores to determine the level of ordination alteration when particular attributes were omitted from the data. The effect of each attribute was determined by observing the alteration of the root mean square (R^2) of ordination, particularly on the *x* axis, or the accountability scale. Transformation of the R^2 value at a higher level due to the omission of a particular attribute exerts a greater effect on the threat index; in other words, the attribute shows greater sensitivity for the management of coral reef ecosystems. Such high sensitivity levels are subsequently used to formulate recommendations for the conservation of coral reef ecosystems.

2.3.7. Monte Carlo Analysis

Uncertainties in RAPFISH analysis usually occur in the estimated score of each attribute and the contribution to the evaluation results. For this reason, Monte Carlo techniques of Rapfish are used to assess the uncertainty factor during the analysis [33]. Monte Carlo analysis was used to examine assessment errors caused by several factors, such as 1) inconsistency of assessment, 2) difference in assessment, 3) level of iterative stability, 4) data error, and 5) high S-values [18]. This method was also used to calculate the effects of random errors on the estimation of ordination values. The acceptability threshold for Stress (S) values was set at <25% and Squared Correlation (RSQ) ≈1 means that the RAPFISH calculation results can be accepted, otherwise RSQ ≈ 0 means the calculation results cannot be accepted [19,33].

2.4. Analytic Hierarchy Process

In addition to the RAPFISH framework, the data collected from respondents were analyzed using the AHP to examine policy alternatives and prioritization for improvement of the status of the coral reef ecosystem. The analytical steps were as follows.

To determine the hierarchy of policies in terms of coral reef ecosystem conservation, the two attributes with the uppermost sensitivity indices in each RAPFISH dimension were selected and analyzed using the AHP.

Each attribute was scored based on its relative importance for the five dimensions analyzed. The detailed steps and principles of the AHP are presented below.

2.4.1. Development of the AHP model

In the AHP model, the first step was to identify the problems and to structure them in the form of hierarchy trees (Fig. 2). Based on the decomposition of the problems, three hierarchies, or levels, were developed. The first hierarchy was the goal of the analysis. The second hierarchy consisted of the five dimensions of threat to the coral reef ecosystems. The third hierarchy comprised alternative policies aimed at mitigating the threats to the coral reef ecosystems. This model was used to analyze the five RAPFISH threat dimensions and to synthesize alternative strategies aimed at improving the coral reef ecosystem's status, based on the hierarchy levels.

2.4.2. Assessment of local stakeholders

The attributes of threats to coral reef ecosystems were prioritized at Hasanuddin University. The experience of stakeholders in the field of marine resource management and their proficiency in coral reef research were the primary reasons that they were considered to be local experts. During prioritization, several experts from academia and local governments were considered to be decision makers. They were selected based on their experience, skills, knowledge, and practices related to different dimensions of the threats to coral reefs.

2.4.3. Comparative judgment

Comparative judgment is an essential step in the AHP for element (alternative) prioritization. The relative importance of two elements (alternatives) are determined at a particular level (hierarchy), with respect to their effects on one of the elements (alternatives). Judgments are represented as a matrix of pairwise comparison using a standardized comparison scale. The scale used to demonstrate the relative importance of elements in the AHP is shown in Table 3.

In this study, in calculating the relative importance of elements i and j, a reciprocal axiom was employed; if the ratio of element i to element j is equal to 3, then element i is considered to be three times more important than element j. If the ratio is equal to 1, then element i and element j are equally important.

The distribution of these scores in a square matrix resulted in a reciprocal matrix [36], represented as follows:

$$A = [a_{ij}] = \begin{Bmatrix} 1 & a_{ij} \dots & a_{1n} \\ 1/a_{ij} & 1 \dots & a_{2n} \\ & & \vdots \\ 1/a_{1n} & 1/a_{2n\dots} & 1 \end{Bmatrix}, \qquad \text{(Eq. 5)}$$

where $A = [a_{ij}]$ represents the intensity of the decision maker's preference, compared with alternative a_{ij} and for all comparisons $i,j = 1,2,\dots n$. Decision makers' scores are expected to facilitate the comparison of alternatives in two rounds, until the scores may be considered stable. Stability was reached when a certain consensus on a sum of scores was achieved. In this case, comparative judgment was conducted using Expert Choice 11 software [37].

2.4.4. Synthesis of priority

In this step, the results of comparative judgment for each pairwise comparison matrix were analyzed. To determine local priority, the Eigen value was calculated. By multiplying the comparison scores for elements (alternatives) in each row of the reciprocal matrix and then taking the n^{th} root of that product, a good approximation of the element weight (EW) was generated for each alternative [38,39], as follows:

$$EW = \sqrt[n]{a_{ij} \times \dots \times a_{nj} \times \dots \times a_{nn}}.. \qquad \text{(Eq. 6)}$$

The weight in a column was summed, and the sum was used to obtain the normalized Eigen vector (w_{ij}) for that alternative, as shown by the equation:

$$w_{ij} = \frac{EW}{\Sigma Wij} \quad . \qquad \text{(Eq. 7)}$$

The importance of the elements in assessing the threats to the status of coral reefs was determined by the sum of the products of a_{ij} in each row and the normalized w_{ij} for each column [37,38], as follows:

$$nw_{ij} = \sum_{i,j}^{n} (a_{ij} \times w_{ij}). \qquad \text{(Eq. 8)}$$

In the consistent matrix, the nw_{ij} value for each element is an EW that determines its ranking within a set of alternatives (i.e., the importance or priority of elements increases with the nw_{ij} value). In this case, priority analysis was conducted using Expert Choice 11 software.

2.4.5. Logical consistency

In the AHP, logical consistency tests are performed to measure relative accuracy between element pairs. Values were obtained automatically using Expert Choice 11 software. The overall inconsistency index (ICR) was calculated to determine the level of acceptability of policy alternatives; ICRs < 0.10 are deemed acceptable [36].

3. Results

Data compilation revealed that the threats to the coral reef ecosystems in the PANGKEP Regency Spermonde Archipelago had 41 attributes (Table 1). Their sources were anthropogenic, biological, and natural factors, classified into the five RAPFISH dimensions (ecological, economic, technological, social, and legal and institutional). Dimensional *S* values ranged from 0.13 to 0.15 (Table 4). In the MDS, the *S* value was <0.25, indicating that the RAPFISH analysis conducted in this study fulfilled the statistical rule, and the confidence value of R^2 was between 0.94 and 0.95.

3.1. Assessment of Coral Reef Threats

3.1.1. Ecological dimension

The index value for the threats in the ecological RAPFISH dimension was 37.65 [Fig. 3(a)], falling between “less sustainable” and “sustainable” scores, but closer to the former. In the leverage analysis, the root mean square (RMS) values for the eight attributes indicated that the most sensitive attribute affecting the ecological dimension was the level of fishing exploitation (8.71), followed by the degree of coral reef destruction (7.15) and the concentration of total suspended solids (TSS) in the coral reefs (7.12; Fig. 4).

3.1.2. Economic dimension

RAPFISH ordination for the economic dimension yielded an index value for the threats of 51.92 [Fig. 3(b)]. Based on the sustainability scale, this value was within a fairly continuous category. Of the seven attributes in the economic dimension, leverage analysis showed that accessibility to markets posed the greatest threat (R^2 = 4.77), followed by the status of business capital (R^2 = 3.18; Fig. 4).

3.1.3. Social dimension

MDS ordination for the social dimension yielded an index value for the threats to coral reefs of 47.33 [Fig. 3(c)]. On the sustainability index, the social threats to coral reefs were categorized as "less sustainable," indicating that all attributes in the social dimension posed serious threats to the status of the coral reef ecosystems in the study area. Leverage analysis of the eight attributes in the social dimension showed that the three most sensitive attributes were the education level (R^2 = 4.89), public awareness (R^2 = 4.83), and poverty/no fixed income source (R^2 = 4.00; Fig. 4).

3.1.4. Technological dimension

The index value for the threats to coral reefs in the technological dimension was 47.26, meaning that the attributes fell into the "less sustainable" category [Fig. 3(d)]. Leverage analysis of the eight attributes revealed that the two main attributes influencing the status of coral reefs were the selectivity of fishing gear use (R^2 = 4.79) and intensity of destructive fishing practices (R^2 = 4.13; Fig. 4).

3.1.5. Legal and institutional dimension

The attributes in the legal and institutional dimension were in range of 25.01–50.00, with an index value of 45.60 [Fig. 3(e)]. The threats in this dimension were thus considered to be "less sustainable." Of the 10 attributes included in the leverage analysis, the two most sensitive for the status of coral reef ecosystems were law enforcement (R^2 = 3.70) and role models in the community (R^2 = 2.80; Fig. 4).

3.2. Uncertainties in the RAPFISH Analysis

The index values for the threats to coral reefs varied in each dimension (Fig. 4). However, the attributes were distributed relatively close to one another (Fig. 5), meaning that threats in multiple dimensions (i.e., ecological, economic, social, technological, legal and institutional) had similar impacts on coral reefs. The results of MDS and Monte Carlo analysis were also close to one another, supporting this evidence (Table 5). These results imply that factors such as scoring errors and diversity, data entry errors, and high *S* values, which have been considered to cause uncertainties in the RAPFISH analysis in previous studies [20,22], were all within acceptable levels in the present analysis. Therefore, the attributes of the threats analyzed in this study could be used to determine the status of coral reef ecosystems according to the rule of MDS. Additionally, the differences between the results from MDS and those of the Monte Carlo analysis were relatively small (<1.00), meaning that the level of error in the analysis was tolerable.

4. Discussion

4.1. Threats to Coral Reef Ecosystems

The values for the five dimensions indicate that the coral reefs in the PANGKEP Regency are generally regarded as "less sustainable." Here, based on the results described in section 3.1, we discuss the major factors in each dimension that threaten coral reef ecosystems (Fig. 6).

4.1.1. Ecological dimension

Fishing exploitation activities, destructive fishing practices (DFPs), and the sedimentation of terrestrial materials are considered to exert the greatest pressures on coral reefs. They are related closely to anthropogenic activities that take place both directly and indirectly close to coral reef areas.

4.1.2. Economic dimension

The greatest threat in the economic dimension was accessibility to the domestic and international markets. However, a policy aimed at providing business capital and technical assistance to traditional and small-scale fisheries, allowing them to increase their incomes, might also be necessary. In addition, a policy aimed at standardizing fisheries' commodity prices is necessary and should be implemented by the local government to ensure maximum profits for fishery personnel.

4.1.3. Social dimension

Poor education in the study area is a serious problem in terms of educational efforts to promoting the sustainable use of coral reef resources. The social survey showed that >90% of fishermen have only elementary-school educational levels. This low level of education may affect communities' behavior and perspectives on the use of coral reef resources. Higher education might provide fishery personnel with a better understanding of coral reef management.

The study findings imply that low education (R^2 = 4.89) is related to other attributes, such as low public awareness (R^2 = 4.83) and poverty/no fixed income source (R^2 = 4.00; Fig. 4). In some cases, the latter two attributes appeared to be driving factors in fishery personnel's decision to perform destructive fishing; interview data indicated that destructive fishing actions are usually perpetrated by fishery staff with poor education and awareness, and no alternative income.

4.1.4. Technological dimension

In practice, selectivity in fishing gear use and the intensity of DFPs play important roles in the degradation of coral reef ecosystems at the study sites. Our observations revealed that fishery personnel continue to use destructive fishing methods, despite their prohibition by local and national governments. Possible reasons for the persistent use of these methods include the lack of public awareness and poverty (social factors), low incomes and the absence of an alternative livelihood (economic factors), and weak law enforcement (a legal and institutional factor) [8,31]. Therefore, multidimensional approaches within the framework of the EAFM principles would presumably be effective in reducing DFPs and conserving the coral reef ecosystems at the study sites.

4.1.5. Legal and institutional dimension

Threats to coral reefs in this dimension derive from several factors, including ineffective law enforcement and the lack of role models in society for leadership on environmental issues. Additionally, to enhance law enforcement, the corruption of staff conducting field monitoring is a major issue to be addressed. For example, information regarding monitoring and surveillance activities is often passed in advance to the fishery workers who engage in DFPs, which makes it difficult for law officers to regulate DFPs in the sea.

4.2. The Current Status of Coral Reef Ecosystems

The achievement of coral reef ecosystem sustainability requires targeted efforts through the deployment of conservation strategies, so that these ecosystems can yield as many benefits as possible for current and future generations. In this study the index values for threats to the coral reef ecosystems in the five RAPFISH dimensions varied (Fig. 5). The overall value for the five dimensions was 45.95 (Fig. 5), indicating a "less sustainable" status of coral reef ecosystems in the PANGKEP Regency (Table 2). This status is due mainly to "less sustainable" scores in four dimensions social (47.33), ecological (37.65), legal and institutional (45.60), and technological (47.26); only the economic dimension was considered to be "sustainable" (51.92).

Based on the results of the RAPFISH analysis, the status of coral reef ecosystems in the study area may be expected to improve, progressing from "less sustainable" to "sustainable," through the implementation of appropriate management strategies. Such implementation should focus on the two attributes in each dimension with the highest sensitivity indices (i.e., 10 candidate attributes): the states of fishing exploitation and coral reef destruction, accessibility to markets, the status of business capital, the educational level, public awareness, the selectivity of fishing gear use, the intensity of DFPs, law enforcement, and the presence of role models in the community. The status of coral reef ecosystems is likely to be improved effectively through the prioritization of these 10 attributes.

4.3. Alternative Strategies for Coral Reef Conservation

The 10 attributes listed above were classified as the main problems that should be addressed to improve the status of coral reef ecosystems in the PANGKEP Regency. The recommended solution is to improve the sustainability of these ecosystems through the continuous implementation of 10 alternative strategies identified using the AHP (Fig. 6).

We recommend consistent implementation of the alternative policies based on their priority rankings. The policy of socialization, campaigning, and education (legal and environmental) had the highest value (0.161), followed by law enforcement (0.147), selectivity of fishing gear use (0.132), rehabilitation of coral reef ecosystems (0.125), restocking of fish in coral reefs (0.121), community empowerment (0.077), establishment of eco-friendly alternative livelihoods (0.067), business capital support (0.063), marine product certification (0.055), and institutional arrangements (0.052; Fig. 6). The ICR value in the AHP analysis was 0.04 (<0.10), meaning that the identification of these 10 alternative strategies was acceptable [36].

Based on the 10 alternative strategies, we recommend that the following measures be undertaken to improve the status of coral reef ecosystems in the PANGKEP Regency.

Community socialization, campaigns, and education: This strategy aims to improve knowledge and public awareness of the importance of coral reef ecosystems and attendant legal aspects, including environmental law. Presumably, the community will have access to sufficient information to gain full understanding. This study showed that many fishermen do not understand the precise ecological role of coral reef ecosystems. This lack of knowledge has led to low public awareness of the coral reef ecosystem's role in providing goods and services. Therefore, an increase in public awareness is anticipated to be particularly effective in pursuing the achievement of coral reef ecosystem sustainability.

Law enforcement and selectivity of fishing gear use: These two strategies can be implemented after implementation of the first strategy to gain broad public recognition of relevant issues. In practice, laws and regulations should be enforced and applied consistently to perpetrators of DFPs. This will create a deterrent so that the destructive activities may be gradually reduced. The selection of eco-friendly fishing gear should also be mandated to prevent the depletion of fish resources and preserve coral reef ecosystems. Local governments and relevant stakeholders should approach local fishery workers in a bid to persuade them to regulate their fishing gear, so that this strategy may be accepted and implemented by fishery personnel.

Rehabilitation of coral reef ecosystems and restocking of fish in coral reefs (reef gardens): These two alternatives have been practiced widely in some countries, including in eight Caribbean countries [40], where coral reefs are damaged and fish stocks are depleted. Technically, strategies for coral reef rehabilitation and fish restocking vary according to location; they depend greatly on the characteristics of the coral reef ecosystem and the existing conditions. In practice, these strategies require scientific evidence and insight, and should be undertaken following the precautionary principle of avoiding negative impacts on coral reef ecosystems and their surrounding environments. Therefore, the involvement and participation of researchers and experts in the fields of fisheries and coral reef resources are necessary to avoid pitfalls in planning and implementation.

Community empowerment for sustainable coral reef ecosystem management: This strategy aims to enhance the participation and empowerment of fishery personnel and other local stakeholders in terms of the coral reef and its ecosystem. In the implementation phase, this strategy requires field facilitators who provide technical assistance in preparing and arranging the management of coral reef ecosystems (e.g., planning, organizing, implementing, and controlling). In addition, the field facilitators will assist the local fishery personnel in identifying alternative livelihoods based on their skills and capacity. Successful deployment of this strategy is expected to increase fishery workers' incomes in addition to conserving the coral reef ecosystems.

Business capital support for traditional and small-scale fisheries: This strategy can be implemented if fishery personnel have alternative livelihoods or business plans that can serve as their main sources of income. Grant support is aimed at developing their sources of income and deterring them from DFPs that damage coral reef ecosystems.

Marine product certification for export markets: The purpose of eco-labeling is to signal to consumers the environmental and social effects of production and consumption, to catalyze change in purchasing behaviors, and ultimately to reduce negative environmental and social impacts [41]. The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) was established based on an international agreement among countries at the 1963 meeting of resolution for the World Conservation Union (IUCN) [42]. The CITES aims to protect and preserve wild endangered flora and fauna species in international trade. In 1978, the Government of Indonesia ratified the CITES agreement with Presidential Decree No. 43 [43].

The two incentives described above have been implemented in several countries and applied to international trade. In Indonesia, both incentives have also been implemented through international trade, but are less effective due to ineffective supervision and weak enforcement by legal officers and relevant agencies. Strict application of this strategy to domestic and international trade could minimize the overexploitation of coral reef resources.

Institutional arrangements for coral reef management: This strategy seeks to improve the capacities of managers and other stakeholders to respond to environmental, economic, and social issues related to coral reef ecosystems. To implement this strategy, field facilitators are necessary to empower the community in terms of capacity building. This strategy is expected to build a strong community-based institution, and is thus likely to play an important role in the conservation of coral reefs.

5. Conclusion

The coral reef ecosystems in the PANGKEP Regency, Spermonde Archipelago, Indonesia, are under serious threat from anthropogenic and natural factors. Based on the RAPFISH analysis, the use of coral reef ecosystems in the region is “less sustainable” from the ecological, social, technological, and legal and institutional aspects. The results of the AHP analysis provided an objective basis for the prioritization of 10 alternative strategies to improve the status of coral reef ecosystems in the region, with the highest priority placed on socialization, campaigns, and education, followed by law enforcement, selectivity of fishing gear use, rehabilitation of coral reef ecosystems, and restocking of fish in coral reefs.

Although the alternative strategies should be implemented effectively in order of priority, the various factors will interact with one another and continue to threaten the coral reef ecosystems in the future. We strongly recommend that local policymakers adopt strategies aimed at conserving the coral reef ecosystem. In practice, the findings of this study can serve as a reference for the appropriate formulation of strategies to ensure the sustainable use of coral reef ecosystems.

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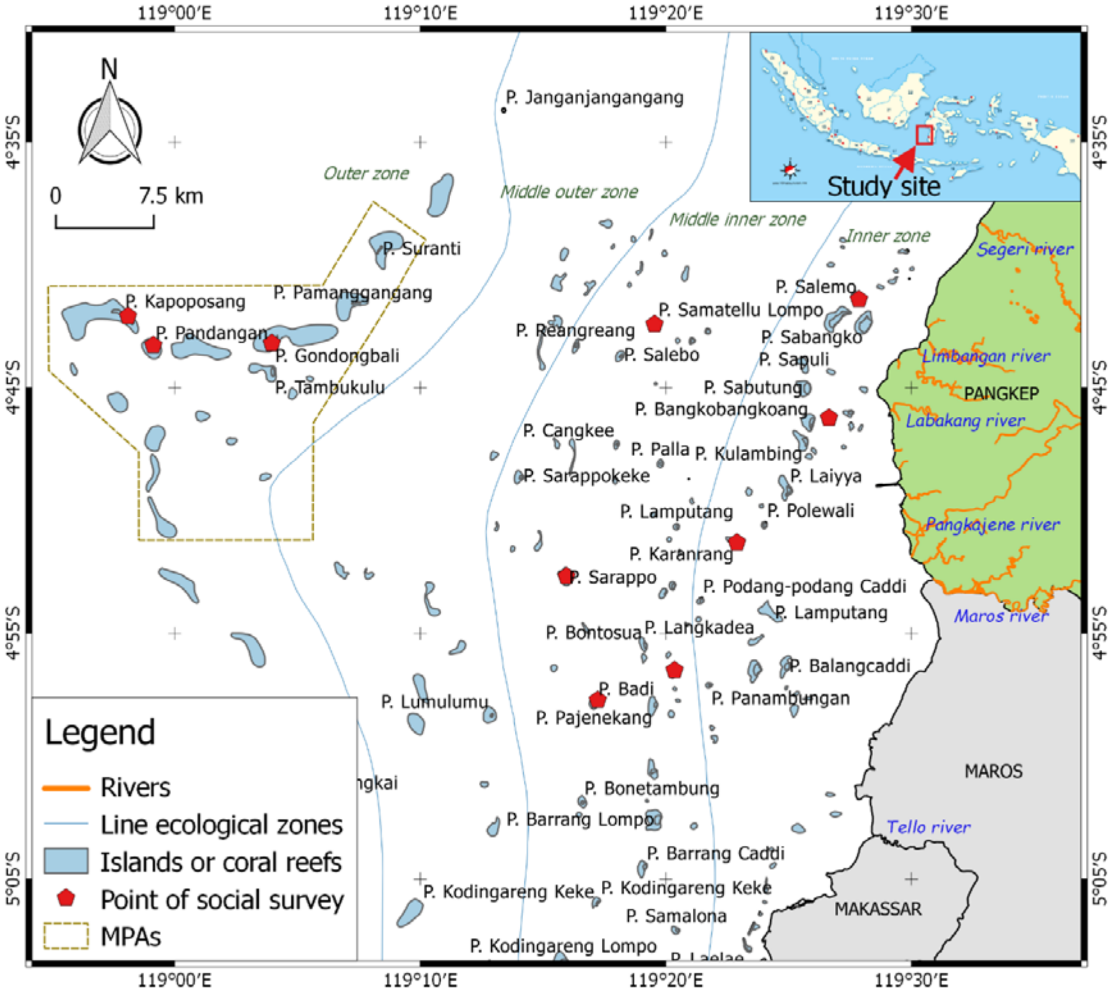

Fig. 1 Map of the study site, located in the islands of the PANGKEP Regency, Spermonde Archipelago, Indonesia. Of the 41 islands in the Spermonde Archipelago, 31 are inhabited. The sampling locations for this study were in the territories of eight islands and represented four coral zones: the inner, middle-inner, middle-outer, and outer zones.

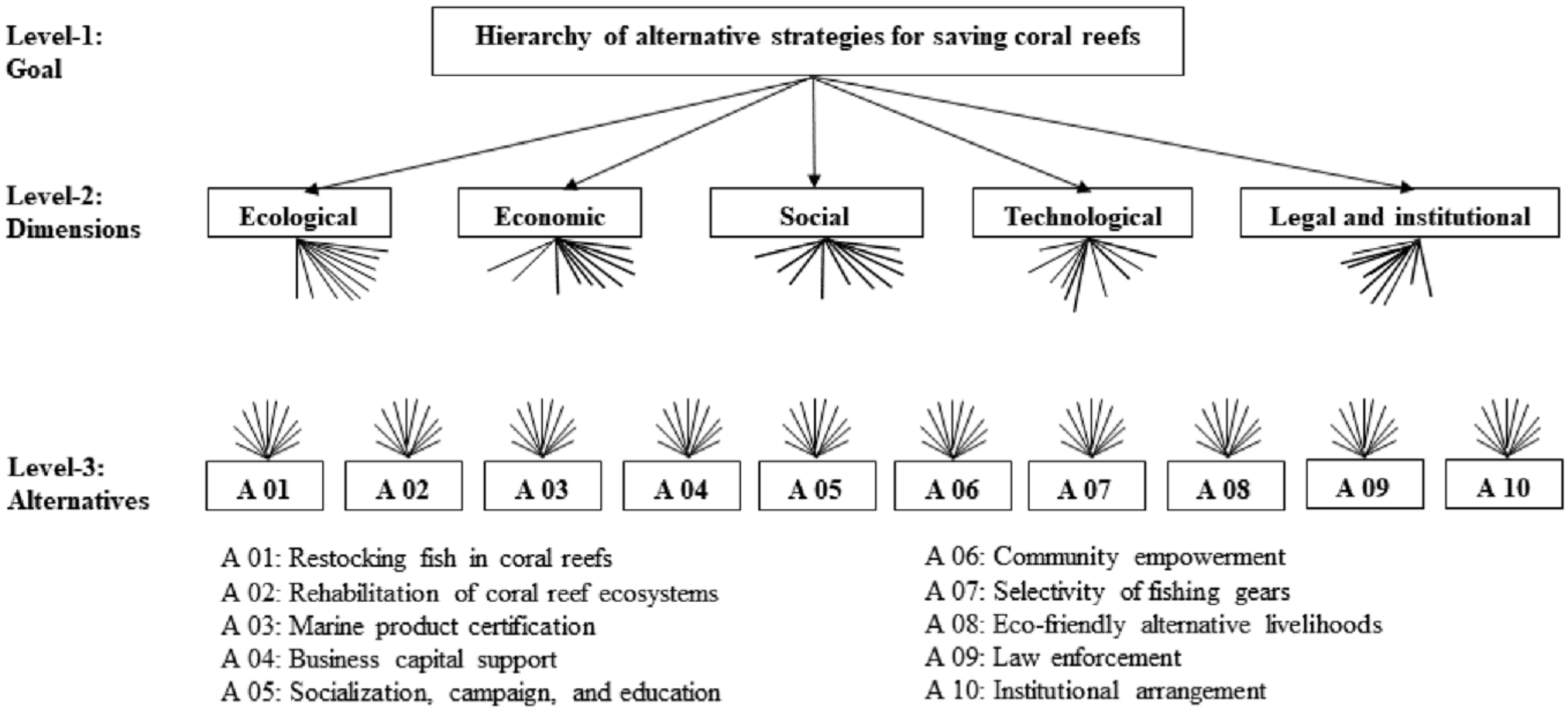

Fig. 2 Hierarchical model of the AHP Three levels, or hierarchies, are designated levels 1 (goal), 2 (RAPFISH dimensions), and 3 (alernative strategies for coral reef conservation). The 10 alternative strategies are: restocking of fish in coral reefs (A01); rehabilitation of coral reef ecosystems (A02); marine product certification (A03); business capital support (A04); socialization, campaigns, and education (A05); community empowerment (A06); selectivity of fishing gear use (A07); establishment of eco-friendly alternative livelihoods (A08); law enforcement (A09), and institutional arrangements (A10).

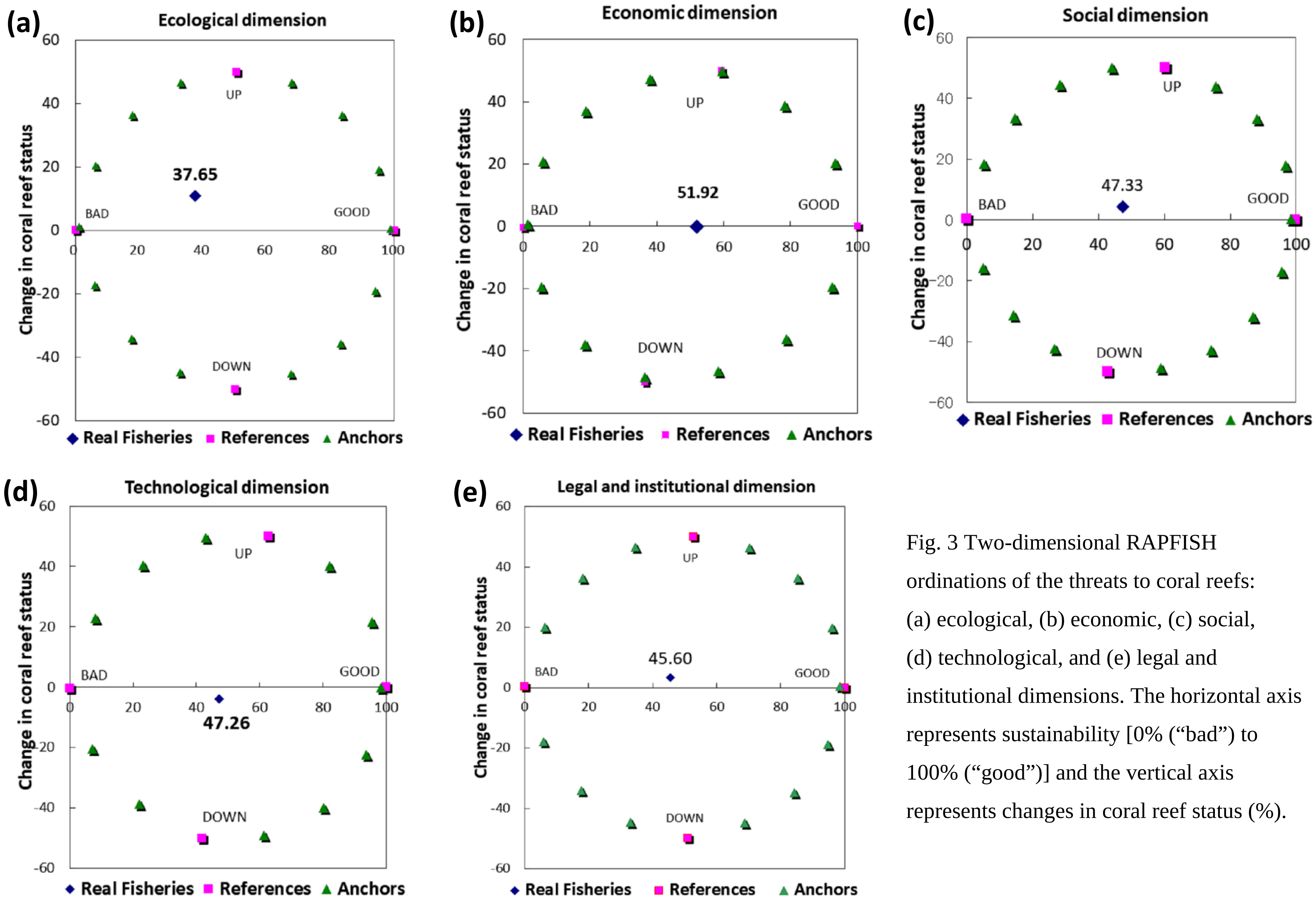

Fig. 3 Two-dimensional RAPFISH ordinations of the threats to coral reefs: (a) ecological, (b) economic, (c) social, (d) technological, and (e) legal and institutional dimensions. The horizontal axis represents sustainability [0% ("bad") to 100% ("good")] and the vertical axis represents changes in coral reef status (%).

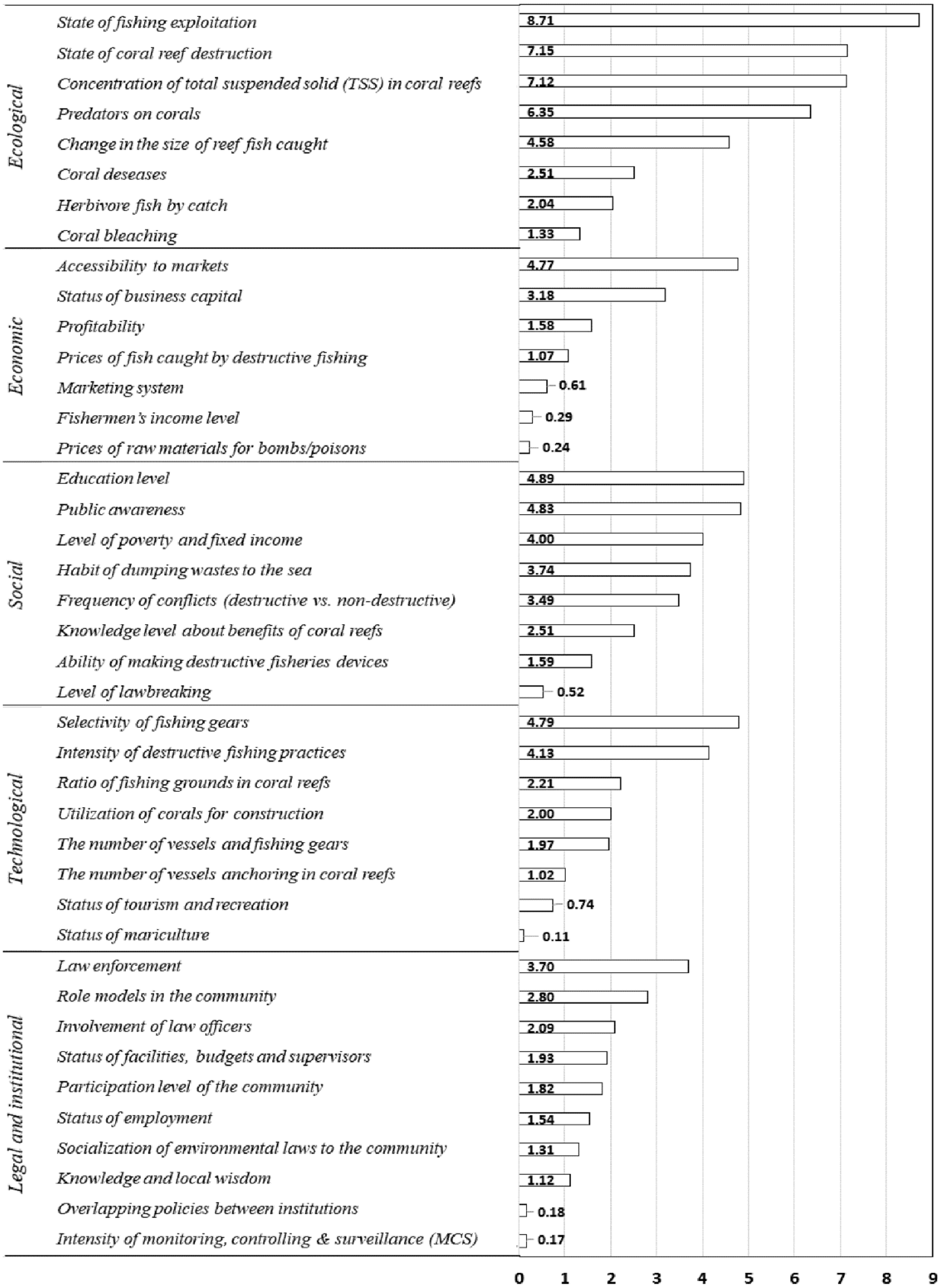

Fig. 4 Attribute leverage analysis of the RAPFISH ordinations for threats to coral reefs in the PANGKEP Regency, Spermonde Archipelago, Indonesia. Ecological, economic, social, technological, and legal and institutional dimensions, based on the standard error (%).

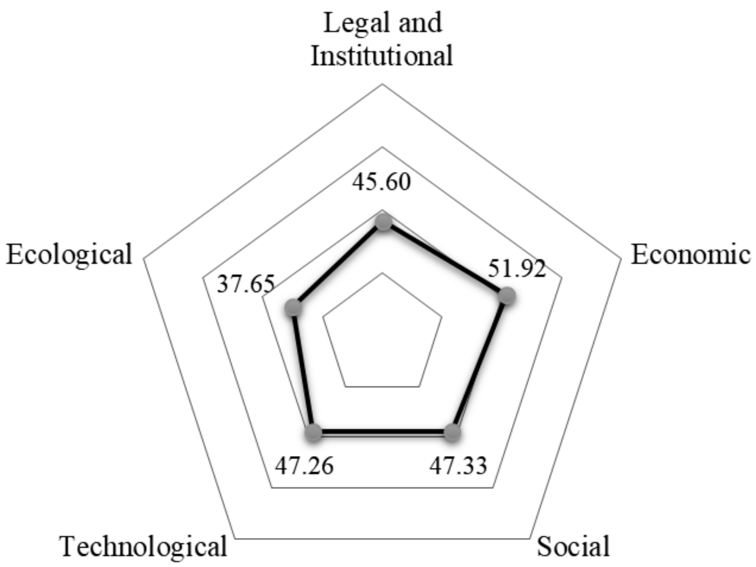

Fig. 5 Kite diagram of five dimensions of threats to coral reef ecosystems in the PANGKEP Regency, Spermonde Archipelago, Indonesia. Based on the threshold values listed in Table 2, the social, technological, ecological, and legal and institutional dimensions were regarded as "less sustainable," and the economic dimension was classified as "sustainable." The overall value for the threats was 45.95, indicating a "less sustainable" status of coral reef ecosystems in the PANGKEP Regency.

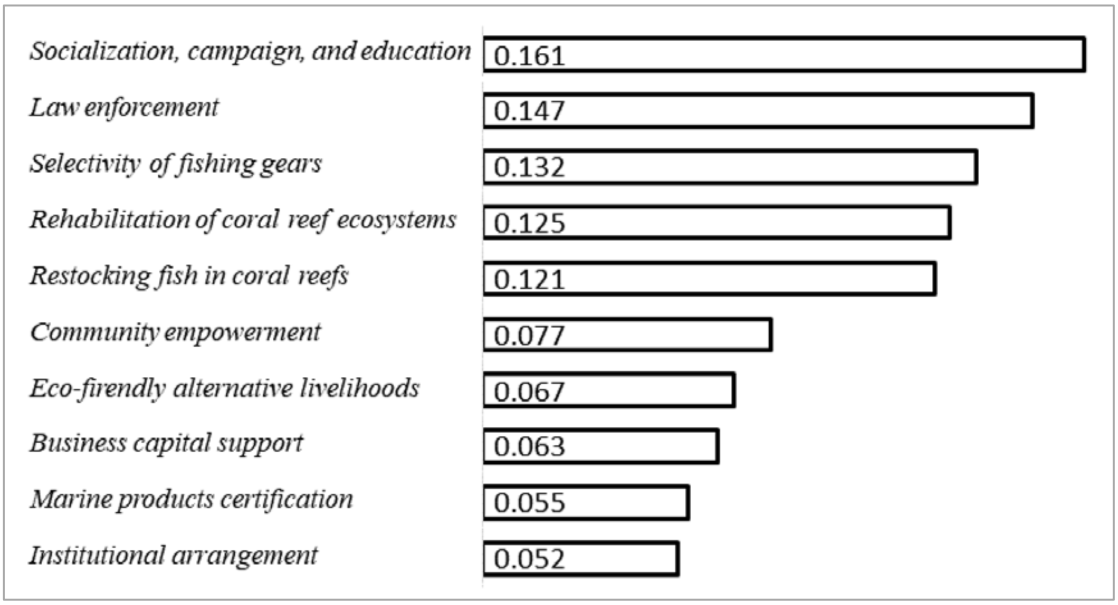

Fig. 6 Alternative strategies for improvement of the status of coral reef ecosystems in the PANGKEP Regency, Spermonde Archipelago, Indonesia, as described in Fig. 2. The ratio of inconsistency index (ICR) from the AHP analysis was 0.04 (<0.10), indicating acceptable identification of the 10 alternative strategies [36].

Table 1. Attributes of threats to the coral reef ecosystem in the PANGKEP Regency, Spermonde Archipelago, Indonesia, and RAPFISH scoring criteria. Scores range from bad (unsustainable; 0) to good (very sustainable; highest scores vary among attributes).

Attribute	Score scale	Remarks	Source
Ecological Dimension			
1. Concentration of total suspended solid (TSS) in coral reefs	0,1	Threshold for coral growth: >10 mg/L (0); ≤10 mg/L (1)	[44]
2. Predators on corals (i.e., crown-of-thorns starfish (COTs), starry puffer fish etc.)	0,1	COTs in coral reefs: >14 individuals/1000 m^2 (0); ≤14 individuals/ 1000 m^2 (1)	[45]
3. Herbivore fish by catch	0,1,2	The number of herbivore fish caught per trip: High>40% (0); moderate 10-40% (1); low 0-10% (2)	[33]
4. State of fishing exploitation	0,1,2,3, 4	Collapsed (0); high (1); moderate (2); low (3); balanced or equal (4)	[16]
5. Coral bleaching	0,1,2,3	% coral bleaching: ≥75-100% (0); 50-74.9% (1); 25-49.9% (2); <25% (3)	Modified from [46]
6. 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 [46]
7. Coral deseases	0,1,2,3	% coral deseases: ≥75-100% (0); 50-74.9% (1); 25-49.9% (2); <25% (3)	Modified from [46]
8. Change in the size of reef fish caught (for the last 10 years)	0,1,2	Declined substantially (0); decreased slightly (1); unchanged (2)	[33]
Economic Dimension			
1. Profitability	0,1,2,3	High profit (0); marginal profit (1); without gain or loss (2); little loss (3); large loss (4)	[33]
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 [33]

3. Accessibility to markets (domestic/international demand and price information)	0,1,2	International market (0); national market (1); local market (2)	[33]
4. Status of business capital	0,1,2,3	Loan capital (0); joint capital (1); grant capital (2); own capital (3)	Modified from [33]
5. Marketing system	0,1,2,3	Monopoly or government buyer (0); semi-closed (1); partially open market (2); fully open market (3)	[33]
6. Prices of raw materials for bombs/poisons	0,1,2,3	Very affordable (0); affordable (1); expensive (2); very expensive (3)	Modified from [33]
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 [33]
Social Dimension			
1. Knowledge level about benefits of coral reefs	0,1,2,3	None (0); low (1); moderate (2); high (3)	Modified from [33]
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)	[48]
3. Level of poverty and fixed income	0,1,2	High (0); moderate (1); low (2)	[33]
4. Public awareness	0,1,2	Low (0); moderate (1); high (2)	Modified from [33]
5. Level of lawbreaking	0,1,2,3, 4	Very high (0); high (1); moderate (2); low (3); very low (4)	Modified from [33]
6. 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 [33]
7. Frequency of conflicts (destructive versus non-destructive)	0,1,2	Frequent (0); seldom (1); none (2)	[32]
8. Ability of making destructive fishing devices	0,1,2,3	High (0); moderate (1); low (2); none (3)	Modified from [33]
Technological Dimension			
1. The number of vessels and fishing gears (for the last 10 years)	0,1,2	Increasing (0); unchanged (1); decreasing (2)	[48]
2. Intensity of destructive fishing practices (for the last 10 years)	0,1,2,3	High (0); medium (1); low (2); none (3)	[33]

3. Status of tourism and recreation	0,1,2,3	High (0); medium (1); low (2); none (3)	[33]
4. Selectivity of fishing gears	0,1,2,3	None (0); few (1); fair (2); many (3)	[33]
5. Ratio of fish grounds in coral reefs	0,1,2,3	75-100% (0); 50-74.9% (1); 25-49.9% (2); <25% (3)	Modified from [46]
6. The number of vessels anchoring in coral reefs	0,1,2	Many (0); few (1); none (2)	Modified from [33]
7. Utilization of corals for construction (for the last 10 years)	0,1,2,3	High (0); medium (1); low (2); none (3)	Modified from [33]
8. Status of mariculture	0,1,2,3	Very bad (0); bad (1); fair (2); good (3)	Modified from [33]
Legal and Institutional Dimensions			
1. Law enforcement	0,1,2,3	The level of legal violation: high (0); medium (1); low (2); none (3)	Modified from [12]
2. Overlapping policies between institutions	0,1,2,3	Numerous (1); fair (1); few (2); none (3)	Modified from [12]
3. Socialization of environmental laws to the community	0,1,2	Never (0); fair (1); frequent (2)	Modified from [33]
4. Involvement of law officers	0,1,2	Frequent (0); fair (1); never (2)	Modified from [12]
5. Status of facilities, budgets, and supervisors	0,1,2,3	Very limited (0), limited (1); fair (2); sufficient (3)	Modified from [48]
6. Participation level of the community in the management institutions	0,1,2	None (0); fair (1); frequent (2)	Modified from [33]
7. Intensity of monitoring, controlling, and surveilance (MCS)	0,1,2,3	Never (0); seldom (1); fair (2); frequent (3)	Modified from [33]
8. Role models in the community	0,1,2	A public figure who understands the environmental issues: Few (0); fair (1); many (2)	Modified from [33]
9. Knowledge and local wisdom	0,1,2	Little (0); fair (1); a lot (2)	[12]
10. Status of employment	0,1,2	Permanent (0); temporary (1); independent (2)	Modified from [33]

Table 2. Thresholds for index values used to assess the status of coral reefs (modified from [32]).

Threshold value of index	Status
0.00 - 25.00	Unsustainable
25.01 - 50.00	Less sustainable
50.01 - 75.00	Sustainable
75.01 - 100.00	Very sustainable

Table 3. Comparative judgment scale for the AHP (modified from [36]). The scale was used for quantitative evaluation to prioritize alternative strategies for improving the status of coral reef ecosystems.

Intensity of importance	Definition (Explanation)
1	Equal importance (Two activities contribute equally to the objective)
3	Moderate importance (Experience and judgment slightly favor one activity over another)
5	Strong importance (Experience and judgment strongly favor one activity over another)
7	Very strong or demonstrated importance (An activity is favored very strongly over another; its dominance demonstrated in practice)
9	Extreme importance (The evidence favoring one activity over another is of the highest possible order of affirmation)
2,4,6 and 8	(Intermediate values to reflect fuzzy options lying between the neighboring numbers)

Table 4. Values of stress and determination in all dimensions with iterations of 2. These values indicate the acceptability of the coral reef status analysis in this study (Stress (S) < 0.25, Squared Correlation (RSQ) ≈ 1).

Dimensions	Stress (S)	Squared Correlation (RSQ)
Ecological	0.13	0.94
Economic	0.15	0.94
Social	0.14	0.95
Technological	0.14	0.94
Legal and institutional	0.14	0.94

Table 5. Results of multidimensional scaling (MDS) and Monte Carlo analysis of five dimensions of threat to coral reef status, with differences and 95% confidence level.

Dimension	Results of MDS analysis	Results of Monte Carlo analysis	Difference
Ecological	37.65	38.18	0.53
Economic	51.92	51.28	0.64
Social	47.33	47.69	0.36
Technological	47.26	47.05	0.21
Legal and institutional	45.60	46.20	0.60