C2. Imam Bachtiar

by Imam Bachtiar

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Practical Resilience Index for Coral Reef Assessment

Imam Bachtiar[1,2]*, Suharsono[3], Ario Damar[4], and Neviaty P. Zamani[5]

[1]*Department of Math and Science Education, Faculty of Teacher Training and Education, University of Mataram, Kota Mataram 83125, Indonesia*

[2]*Department of Magister Pendidikan IPA, Program Pascasarjana, University of Mataram, Kota Mataram 83125, Indonesia*

[3]*Research Center for Oceanography, Indonesian Institute of Sciences, Jakarta 12710, Indonesia*

[4]*Department of Aquatic Resources Management, Faculty of Fisheries and Marine Science, Bogor Agricultural University, West Java 16680, Indonesia*

[5]*Department of Marine Science and Technology, Faculty of Fisheries and Marine Science, Bogor Agricultural University, West Java 16680, Indonesia*

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Abstract – Assessing coral reef resilience is an increasingly important component of coral reef management. Existing coral reef resilience assessments are not practical, especially for developing countries. South-east Asian countries have been using line-intercept-transect (LIT) in coral reef monitoring for a long time. The present study proposes an index for assessing coral reef resilience based on data collected from the LIT method. The resilience index formula was modified from an existing resilience index for soil communities developed by Orwin and Wardle. We used an ideal resilient coral reef community as a reference point for the index. The ideal coral reef was defined from data collected from 1992 to 2009. Six variables were statistically selected for the resilience indicators: coral functional group (CFG), coral habitat quality (CHQ), sand-silt cover (SSC), coral cover (COC), coral small-size number (CSN), and algae-other-fauna (AOF) cover. Maximum values of five variables were determined as the best state, while the maximum value of CSN was determined from 1240 data-sets of Indonesian reefs. The resilience index performed well in relation to changes in COC, AOF, and SSC variables. Managers can use this tool to compare coral reef resilience levels among locations and times. This index would be applicable for global coral reef resilience assessment.

Keywords – recovery, food security, reef health, indicators, monitoring

1. Introduction

Coral reef ecosystems are increasingly affected by global climate change (Kleypas et al. 1999; Hoegh-Guldberg et al. 2007) and human-induced stress and disturbances (Jackson 1997; Jackson et al. 2001). Coral reef management can mitigate the potential impact of these disturbances by improving coral reef resilience (Hughes et al. 2007; Hoegh-Guldberg et al. 2007) regardless of its ecological limitations (Mora et al. 2016). Ecological resilience in terms of capacity to recover from disturbance to the same level of organization (Holling 1973) is increasingly important in coral reef management. The theory of resilience has improved to the point where it should be able to be implemented in coral reef management practices (Nystrom et al. 2008).

Resilience assessment of coral reef ecosystems, however, is still at a development stage (Lam et al. 2017). At present, two methods have been available for measuring coral reef resilience. Obura and Grimsditch (2009) provided a comprehensive method which included 61 variables and 5 protocols. This large number of variables and protocols requires significant financial support and considerable expertise, unlikely to be available in developing countries. Maynard et al. (2010) developed a more practical method in assessing coral reef resilience. This only needs a discussion forum to collect data based on the personal judgment of managers, scientists, policy makers, and other important stakeholders. This method could be very practical in many countries, but it needs people with sufficient knowledge in coral reef ecology. In many developing countries where coral reef scientists are rare, the Maynard method might still be hard to implement. McClanahan et al.

*Corresponding author. E-mail: imambachtiar@unram.ac.id

(2012) listed 11 key factors of coral reef resilience, but how the factors will be used in management is not yet formulated. Cumming et al. (2016) reviewed resilience theory on social-ecological systems that might be very difficult to use in management because of its complexity. A new practical resilience assessment is therefore needed for coral reef management in developing countries with few coral reef ecologists.

The aim of the present study was to formulate an index for assessing the resilience state of a coral reef ecosystem using multivariate data extracted from line intercept transects (LIT). LIT has been widely used and extensively learned about in the region of ASEAN countries, including Indonesia (English et al. 1994; Suharsono 2008). This method would be practical in resilience assessment of the ASEAN countries. Despite the range of multivariate data available from LIT (Marsh et al. 1984; English et al. 1994), the majority of extracted data is merely living coral cover (%). Coral reef managers mostly did not know how to integrate multivariate data into a single interpretation of the quality of a coral reef ecosystem. Lam et al. (2017) found that existing coral reef resilience assessment and monitoring programs differ as much as 75%. Here, we show that data collected on an ordinary monitoring program can also be used in resilience assessment. Coral reef resilience is defined as recovery potential to a coral predominated community. When using the resilience index developed in the present study, a coral reef manager will be working with multivariate data but interpreting them in a univariate way.

2. Methods

Data collection

The present study used monitoring data collected by the Research Center of Oceanography (RCO), Indonesian Institute of Sciences (*Bahasa Indonesia,* LIPI). All the collected data were taken from LIT methods by trained- and supervised-researchers of the same institution. Data were collected within the period of 1992–1998 and 2009; all 1240 transects were 10 m length. This long period may provide samples of the best and the worst coral reefs resilience levels in Indonesia. In the first period LIT were laid at various depths, from 3 to 15 m; in the second period LIT were at ~5 m depth. All positions of transect sites in 2009 were recorded aboard using GPS (Global Positioning System).

The resilience index calculation is based on a transect unit. The LIT data used in the present study could spatially represent the coral reefs of Indonesian waters (Fig. 1). Data collected in 2009 encompassed coral reefs of the Indian Ocean (Tapanuli Tengah, Nias, Nias Selatan, Mentawai), Indonesian Seas (Sunda Strait, Karimata Strait, Makassar Strait, Java Sea,

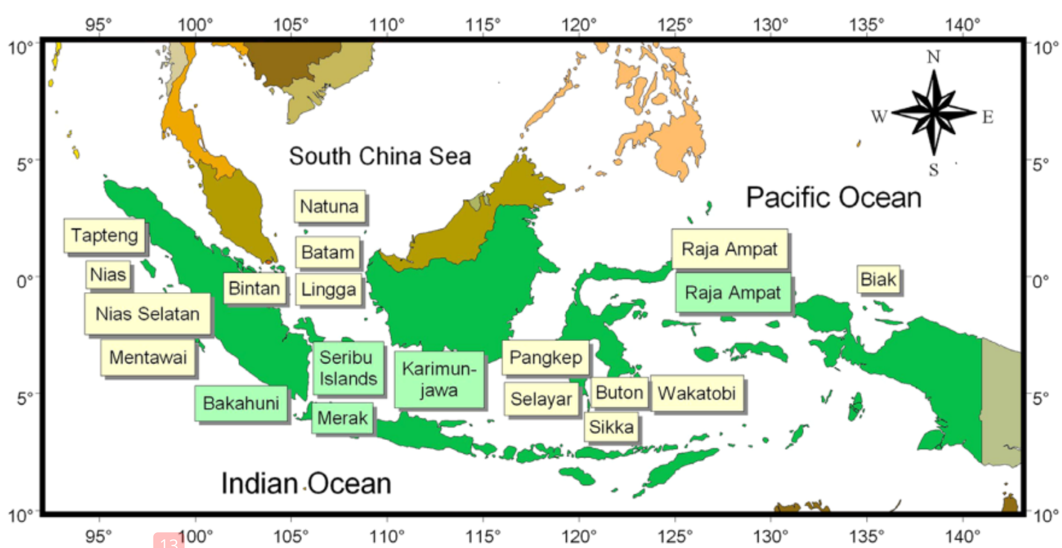

Fig. 1. Locations of data collection used in the present study. Locations with green background showed data collected in 1992–1998, light-brown background showed data in 2009

Flores Sea, Arafura Sea), South China Sea (Natuna, Bintan), and Pacific Ocean (Biak, Raja Ampat). The older data (1992–1998) added locations at the Java Sea (Seribu Islands, Karimun Jawa), Sunda Strait (Bakahauni, Merak) and Raja Ampat. The older data provided some reference to earlier coral reef conditions when anthropogenic impacts were smaller and the intervals between natural disturbances (bleaching) were longer. These data were all used to compose the "resilient coral reef" as the reference point in the formulation of the resilience index.

Data analysis

The coral reef resilience index used in this study was a modification of the soil community resilience index developed by Orwin and Wardle (2004). The modification included redefining indicator variables and constructing a single reference (control) community. The original formula of the Orwin and Wardle (2004) index was

$$RS_t = \left[\frac{2(|D_0|)}{(|D_0|)+(|D_x|)}\right] - 1$$

RS_t = Resiliece index at t, D_0 = difference between before and after disturbance at control community, D_x = differerence between before and after disturbance at impact community.

The ecological index modification has two main processes, i.e. determining indicator variables and building the formula. Indicator variables were identified from a literature review and classified into six resilience components: biological legacy, structural legacy, and mobile link (Lundberg and Moberg 2003), coral reef regimes (productivity), herbivory, and water quality. These variables are briefly discussed in this paper and listed in Table 1.

(a) Biological legacy, i.e. surviving coral colonies. It has been long understood that coral species exhibit different resistance to the same disturbance (Brown and Suharsono 1990; Ninio and Meekan 2002). Surviving colonies could enhance recolonization of opened spaces from both larvae produced (Miller and Mundy 2003; Starger et al. 2010) and vegetative propagation (Golbuu et al. 2007; Williams et al. 2008). Biological legacy is therefore related to biological diversity (Peterson et al. 1998) and larval dispersal. In the present study, diversity at genera level (coral genera richness, CGR) and functional level (coral functional group, CFG) were used to represent biological diversity. Species richness is hard to determine on LIT since coral taxonomists are rare in many developing countries (Erdinger and Risk

Table 1. Indicator variables used in development of the coral reef resilience index

Components	Variables	Unit	Justifications	References
a) Biological legacy (Biodiversity)	Coral genera richness (CGR)	# genera	High resistance, surviving colonies contribute to sexual and asexual recruitment	Miller and Mundy (2003); Williams et al. (2008); Starger et al. (2010)
	Coral functional group (CFG)	# life form	Functional diversity augment robust community	Bellwood et al. (2004)
b) Structural legacy (Complexity)	Coral massive and sub-*mas-sive* cover (CMS)	% CM+CS covers	High resistance, high habitat complexity, but low water quality	Erdinger and Risk (2000); Ninio and Meekan (2002)
	Unsuitable settlement substrate (SSC)	% sand and silt covers	Inhibit coral settlement and growth	Hodgson (1990); Babcock and Davies (1991)
c) Mobile link (Recruitment)	Coral colony size (CCS) classes; 10 cm interval	#size classes	Continuing recruitment increase recovery	Peterson et al. (1998)
	Coral small-size colonies (CSN); D ≤ 10 cm	#small colonies	Existing recruitment enhance recovery	Van Moorsel (1985); Golbuu et al. (2007)
d) Productivity (Regimes)	Coral cover (COC)	% coral cover	Healthy coral reef, high productivity	Done (1992); Hughes (1994)
	Algal total cover (ATC)	% algal cover	Unhealthy reef, low herbivory	Done (1992); Hughes (1994); Bahartan et al. (2010)
	Other fauna cover (OTF)	% OTF cover	Unhealthy reef, low productivity	Tkachenko et al. (2007); Cruz et al. (2016)
e) Herbivory	Macroalgal cover (AMC)	% cover	Unhealthy reef, low herbivory	Hughes et al. (2007); Roff and Mumby (2012)
f) Water quality	Coral acroporiid cover (CAC)	% acroporidae cover	Good water quality, rapid recovery, but low habitat complexity	Done (1982); Erdinger and Risk (2000); Roff and Mumby (2012)

2000). It is assumed that adequate coral larval recruitment will occur with sufficient coral colonies.

(b) Structural legacy, i.e. habitat complexity and settlement substrate availability. A complex habitat provides a suitable substrate for larval settlement, hosts fish diversity (Wilson et al. 2007), and maintains herbivory processes (Ledlie et al. 2007). Previous studies measured habitat complexity using a spatial index (Rogers et al. 1983), surface index (Robert and Ormond 1987), or visual assessment (Wilson et al. 2007). In the present study, habitat complexity was indicated by abundance of massive- and sub-massive- corals (CMS). Both coral life forms are structurally resistant to biological and physical disturbances when other coral life forms (branching, foliose, encrusting, etc.) become rubble. Availability of settlement substrate is also very important to facilitate sexual coral recruitment. Measuring unsuitable settlement substrate (USS) is easier than the opposite, since some suitable settlement substrates may have been temporarily occupied by benthic community.

(c) Mobile link, i.e. incoming mobile organism. Planulae larvae are one of the important mobile link organisms that facilitate coral recolonization. Incoming fish and other benthic larvae and juveniles are also important but indirectly related to coral recolonization and therefore do not directly affect coral reef recovery. In the present study, coral colony size was chosen as an indicator of incoming coral recruitment. When recruitment is continuing, the range of the coral colony size should be wide. This condition could be indicated by the number of colony size classes (coral colony size-classes, CCS), at 10 cm intervals. The abundance of the smallest colony size (≤ 10 cm) could also indicate current coral recruitment. Indicator variable of coral small-size number (CSN) is chosen to represent the mobile link, coral recruitment or colonization. Marsh et al. (1984) provided a formula for measuring colony diameter on a line transect which is too complex for coral reef managers. In this study, colony size was defined as the length of colony size at the intercept. This approach would not affect the results of the study as colony size measurement was not one of the objectives. Confounding data on CSN might happen whether it comes from recruitment or coral fragment. This could also be neglected since index as an ecological indicator will be working on a macro scale instead. McClanahan et al. (2012) also recognized coral size distribution as important factor in coral reef resilience.

(d) Intensity of herbivory is an important factor controlling algal abundance on reefs. Using herbivorous fishes as an indicator variable of herbivory intensity, however, might not be very appropriate. Phase-shift could happen without reduction on herbivorous fishes abundance, e.g. in the Great Barrier Reefs (Cheal et al. 2010). Important herbivores are dependent on the composition of the algal community (Fox and Bellwood 2008; Hoey and Bellwood 2008). Redundancy of herbivory roles between herbivorous fishes and sea urchins could also vary among locations (Carpenter 1990). A coral reef could still maintain its resilience in conditions of low abundance of herbivorous fishes, when sea urchins are sufficiently abundant (Hughes 1994). Furthermore, important herbivory could be carried out by non-herbivorous fishes, such as *Platax pinnatus* (Bellwood et al. 2006). In the present study, abundance of macroalgae (AMC) and total algal abundance (ATC) were used as indicator variables of herbivory. Both indicator variables could represent the impact of herbivory intensity and nutrient availability (Littler et al. 2006).

(e) Ecosystem productivity. Coral reefs exhibit multi-stable states with different productivity levels. Highly productive coral dominated communities could shift into alternate stable states which are predominated by macroalgae (Hughes 1994), soft corals (Fox et al. 2003), or anemone (Tkachenko et al. 2007). Indicator variables that represent the productivity of a coral reef ecosystem are COC (coral cover), OTF (other fauna cover), and ATC (algae total cover). A high productivity coral reef should be high in COC but low in OTF and ATC variables.

(f) Water quality. While temperature, chlorophyll and turbidity can be easier to measure than nutrients and contaminants in reef waters, they still require more specialized equipment and training, difficult to access in a developing country. To simplify assessment, a bioindicator can be chosen to represent water quality. Particular coral species such as *Acropora* have been linked with good water quality (Done 1982; Erdinger and Risk 2000). Thus the cover acroporid corals (CAC) were used as an indicator variable of good water quality.

Among the 11 variables in Table 1, there were variables that need to be combined. There were variables having small abundance but high variances, i.e. algae total cover (ATC), macroalgae cover (AMC), and other fauna cover (OTF). These variables are ecologically important but statistically too small to detect their effect. ATC, AMC and OTF variables were therefore combined as one variable AOF (algae and other fauna) so that its importance will not be neglected in statistical analysis.

There were also variables with contrasting characteristics. Coral massive + sub-massive (CMS) cover and coral acroporid cover (CAC) play different roles in ecosystem resilience. High CMS cover could indicate high coral reef complexity but it could also indicate poorer water quality and slow recovery. Massive and sub-massive corals found on inshore reefs are relatively tolerant to low water quality from sedimentation and land-based pollution (Erdinger and Risk 2000). In contrast, high CAC could indicate less coral reef complexity but also indicates rapid recovery (Ninio and Meekan 2002). Both CMS and CAC are equally important in determining coral reef resilience.

Combining CMS and CAC into a single variable CHQ (coral habitat quality) needs a special approach, based on existing studies on Indo-Pacific reefs. Cumulative coverage of CMS and CAC has a maximum value of 100%. It was therefore assumed that the best resilience of a coral reef would be composed of 50% of CMS and 50% of CAC. This composition ensures rapid coral recovery as CAC (Ninio and Meekan 2002) promotes high growth rates and adaptation (Guest et al. 2016), and CMS promotes habitat complexity by maintaining the abundance and diversity of herbivorous fishes (Ledlie et al. 2007; Guest et al. 2016). CHQ is mathematically calculated as follows:

$$CHQ = \sqrt{CAC*(CMC+CSC)}$$

CAC=coral *Acropora* cover, CMC=coral massive cover, CSC=coral sub-massive cover

Algal and other fauna (AOF) was defined to integrate AMC, ATC and OTF. Data of Indonesian coral reefs showed that each AMC, ATC and OTF variables have a very high coefficient of variability, i.e. 349%, 87%, and 140% respectively. The three variables were then pooled into a new variable, AOF, which is the sum of total algal cover (ATC) and other fauna cover (OTF). Macroalgal cover (AMC) is part of the ATC. They were separately measured as different variables since macroalgae predominance has been shown to be the most common phase shift condition on coral reefs (Hughes 1994; Hughes et al. 2007).

Statistical analysis was applied to refine indicator variables. Pearson correlation index was calculated to identify redundancies among variables. Non-parametric multivariate statistics, BEST (Biological Environmental STepwise) analysis was applied to find the best combinations in variable reduction for several correlated variables. BEST is a multivariate tool to select environmental variables or species that best explain community pattern. Reduction of the number of variables could be carried out using BEST analysis, as long as its correlation coefficient is higher than 95% (Clarke et al. 2008). Prior to data analysis, data were transformed into log (x + 1) and normalized, since some variables had different scales. PCA (Principal Component Analysis) was performed to weight each indicator variable based on its contribution to the first principal component, as suggested in Primpas et al. (2010). All multivariate statistics were carried out using Primer 6 version 6.1.13 software.

3. Results

Refining indicators

After grouping the five indicator variables (CAC and CMS as CHQ; AMC, ATC, and OTF as AOF), there were 8 remaining indicator variables of coral reef resilience. Among these, three variables were interdependently related, i.e. COC, AOF and SSC. Potentially, coverage of COC and AOF is dependent on the coverage of SSC, i.e. sand and silt covers. Maximum cover of COC and AOF is 100%, when SSC is zero. The maximum cover of COC and AOF decreases with increasing SSC.

Among 8 indicator variables of the resilience index, many variables showed significant correlation, as the number of data was robust (N = 1240 transects). Two pairs of variables showed a considerably high correlation index. Correlation indices between CFG and CGR was 0.691, and between COC and CCS was 0.833 (Table 2). The number of variables needs to be reduced, to avoid redundancy and to improve its applicability without significant reduction in the quality of the index.

BEST analysis provided combinations of seven and six variables that may be used to reduce the number of variables. The highest priority for omission is the coral genera richness (CGR) due to difficulties in underwater genera identification. From the BEST combinations (Table 3), while six or seven variables do not reduce the performance very much, in contrast there is a huge difference in the effort spent on measurement. It was decided to omit CGR and CCS from indicators of coral reef resilience. Leaving out CGR and CCS variables the index still maintained representativeness of each resilience component, CFG represents biodiversity and CSN represents mobile link resilience components.

Table 2. Matrix of correlation coefficients among eight resilience variables (N = 1060)

	CGR	CFG	SSC	CHQ	CCS	CSN	COC	AOF
CGR	1.000							
CFG	**0.691**	1.000						
SSC	-0.224	-0.277	1.000					
CHQ	0.299	0.550	-0.222	1.000				
CCS	0.343	0.382	-0.287	0.395	1.000			
CSN	0.512	0.443	-0.155	0.055	0.015	1.000		
COC	0.511	0.526	-0.389	0.478	**0.833**	0.175	1.000	
AOF	0.046	0.023	-0.113	-0.100	-0.280	0.123	-0.313	1.000

Table 3. Combinations of seven and six variables provided by BEST analysis

No.	Number variables	Correlation index	Variable combinations	Omitted variable
1	7	0.992	CGR, SSC, CHQ, CCS, CSN, COC, AOF	CFG
2	7	0.991	CFG, SSC, CHQ, CCS, CSN, COC, AOF	CGR
3	7	0.990	CGR, CFG, SSC, CHQ, CCS, CSN, AOF	COC
4	7	0.988	CGR, CFG, SSC, CHQ, CSN, COC, AOF	CCS
5	6	0.974	CGR, SSC, CHQ, CSN, COC, AOF	CFG, CCS
6	6	0.973	CGR, SSC, CHQ, CCS, CSN, AOF	CFG, COC
7	**6**	**0.973**	**CFG, SSC, CHQ, CSN, COC, AOF**	**CGR, CCS**
8	6	0.971	CFG, SSC, CHQ, CCS, CSN, AOF	CGR, COC
9	6	0.970	CHQ, CCS, CSN, SSC, COC, AOF	CGR, CFG
10	7	0.969	CGR, CFG, CHQ, CCS, SSC, COC, AOF	CSN

Defining a reference community

An ideal 'resilient' coral reef must be set up as a reference community of the index. It must show a maximum value of resilience index, which happens when it has maximum values in all six indicator variables. On the other hand, a 'non-resilient' coral reef must have a minimum value of index. Among the six indicator variables, the maximum and minimum theoretical values of five variables are known. Coral cover (COC), for example, theoretically has a minimum and maximum value of 0.00 and 100.00% respectively (Table 4). Coral functional group (CFG), i.e. coral life form, theoretically between 0–13 groups, as it has been standardized in English et al. (1994). The theoretical maximum value of one variable, CSN, however, was not known. The maximum value of CSN was therefore determined from 1240 transects. Since its maximum value from transects was 23 colonies, the maximum value of CSN was set up at 25, which has a very low probability of occurrence (0.048%).

Formulating resilience index

The coral reef resilience index uses a single reference community, the ideal resilient coral reef community, i.e. a community with the best (maximum) values in all n indicator variables. Orwin-Wardle index modification resulted in a coral reef resilience index as described in Eq. 1.

$$RI_j = \sum_{i=1}^{n}\left[\frac{2(|X_i max - X_i min|)}{(|X_i max - X_i min|)+(|X_{ij} - X_i min|)} - 1\right] \quad (1)$$

RI_j = Resilience index of transect j, $X_i max$ = maximum value of variable X_i, $X_i min$ = minimum value of variable X_i,

Table 4. Variable composition of the "super coral reef" as the reference point of the resilience index assessment

Resilience indicator	From transects	Unit	Minimum	Maximum
1) Coral Functional Group (CFG)	0–10	Group	0	13
2) Sand and Silt cover (SSC)	100–0	%	100	0
3) Coral Habitat Quality (CHQ)	0–42	%	0	50
4) Coral Small-size Number (CSN)	0–23	Colony	0	25
5) Coral Cover (COC)	0–100	%	0	100
6) Algae-Other-Fauna cover (AOF)	100–0	%	100	0

Table 5. Weighting factors of the indicator variables

Indicator variables	PC 1
CFG	-0.560
SSC	0.204
CHQ	-0.423
CSN	-0.430
COC	-0.520
AOF	0.103

X_{ij} = real value of X_i at transect j.

Using data of the resilient coral reef, the formula for the coral reef resilience index is defined as follows.

$$RI=\Big[\Big(\frac{2(13-0)}{(13-0)+(13-CFG)}-1\Big)+\Big(\frac{2(50-0)}{(50-0)+(50-CHQ)}-1\Big)+\Big(\frac{2(25-0)}{(25-0)+(25-CSN)}-1\Big)+\Big(\frac{2(100-0)}{(100-0)+(100-COC)}-1\Big)-\Big(\frac{2(100-0)}{(100-0)+(SSC-0)}-1\Big)-\Big(\frac{2(100-0)}{(100-0)+(AOF-0)}-1\Big)\Big] \quad (2)$$

Each indicator variable in Eq. 2 might have a different magnitude of contribution to the index, as they could have different variances. Indicator variables need to be weighted to improve index sensitivity. PCA was performed to objectively weight each of the resilience indicators. PCA showed that the PC1 contributed 47.7% of the total variances. This number determined its liability to be used as a weighting factor. Variables were weighted using PC1 as listed in Table 5.

Weighting of indicator variables changed the index value. The maximum value of the resilience index was 1.930, while the minimum was -0.200. A correction factor is required to ensure that the minimum value was close to 0.000, i.e. when a coral reef was 100% covered by SSC (sand and silt). The final formula of the coral reef resilience index is as Eq. 3 or 4.

$$RI=\Big[0.56\Big(\frac{2(13-0)}{(13-0)+(13-CFG)}-1\Big)+0.42\Big(\frac{2(50-0)}{(50-0)+(50-CHQ)}-1\Big)+0.43\Big(\frac{2(25-0)}{(25-0)+(25-CSN)}-1\Big)+0.52\Big(\frac{2(100-0)}{(100-0)+(100-COC)}-1\Big)-0.20\Big(\frac{2(100-0)}{(100-0)+(SSC-0)}-1\Big)-0.10\Big(\frac{2(100-0)}{(100-0)+(AOF-0)}-1\Big)+0.20\Big] \quad (3)$$

$$RI=\Big[0.56\Big(\frac{26}{13+(13-CFG)}-1\Big)+0.42\Big(\frac{100}{50+(50-CHQ)}-1\Big)+0.43\Big(\frac{50}{25+(25-CSN)}-1\Big)+0.52\Big(\frac{200}{100+(100-COC)}-1\Big)-0.20\Big(\frac{200}{(100)+(SSC-0)}-1\Big)-0.10\Big(\frac{200}{(100)+(AOF-0)}-1\Big)+0.20\Big] \quad (4)$$

Using the present index, a single transect has a theoretically resilience index between 0.000 and 2.130, but we hardly find coral reef with a resilience index more than 1.00. Assessment of ~1240 transects from Indonesian reefs revealed a range between 0.021 and 1.070, with an average (± SD) of 0.468 ± 0.225, and a median of 0.469. Proportion of transects with a resilience index ≥ 1.000 was only 0.403%. This proportion is very small and not usually found in natural habitats. Furthermore, resilience index assessment on a reef must be carried out using more than one transect, as such assessment needs replications. From the present data, at any location (site) with a minimum of three transects, there was no reef with an average resilience index of ≥ 1.000. The highest average resilience index (± SD) found was 0.976 ± 0.107. Theoretically, we rarely encounter any reefs with a resilience index ≥ 1.000.

Validating resilience index

Comparing resilience index with COC, AOF and SSC showed a positive relationship between the increase of COC and an increase in the resilience index. On the other hand, an increase in AOF and SSC coincided in a decrease in the resilience index. Recovery of a coral dominated community depends on the composition of the coral community and the other two opposing factors, AOF and SSC. This suggests that coral cover alone may not be a good measure of coral reef resilience since it does not necessarily show diversity of coral functional group and coral recruitment.

The resilience index provides a more meaningful metric for assessment of resilience levels than coral cover, although regression analysis for both variables COC and AOF shows its significant dependency. Resilience index increases with increasing coral cover but decreases with increasing algal-other-fauna and sand-silt covers (Fig. 2). Coral reefs with poor coral cover (< 25%) show a wide range of resilience levels, from 0.021 to 0.663. Coral reefs with algal cover > 50%, however, have a resilience index range between 0.100 and 0.802. This high resilience index was found at a transect in Biak (BIALT11) which has 36.0% COC and 52.4% AOF. Coral reef with the best resilience index (1.000) may still have AOF about 0 and 17%, with coral cover ranging from 71.0 to 89.70%.

The present resilience index is also readily applicable for extreme situations. An extreme reef which is covered by 100% sand and silt (SSC) will have a resilience index of 0.000. This means that such a reef would never be recolonized

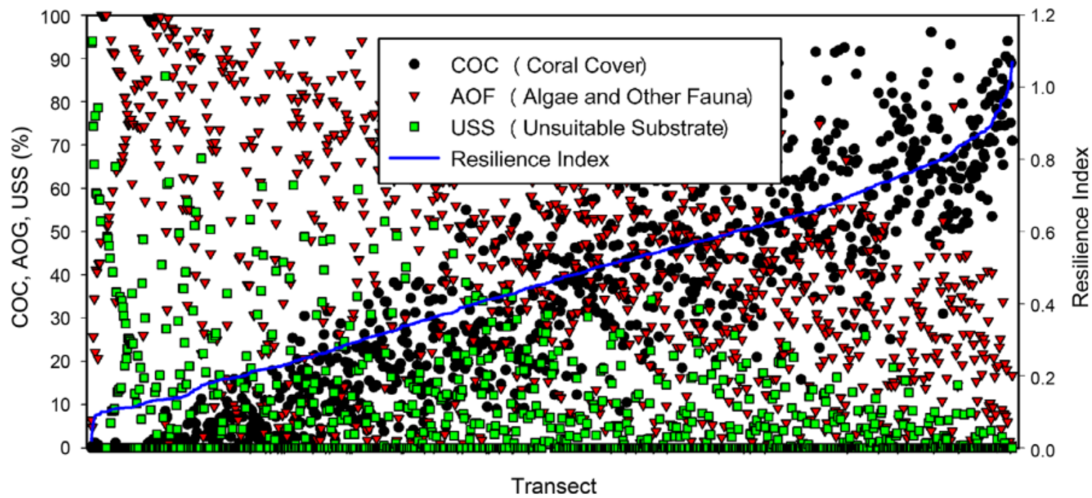

Fig. 2. Performance of resilience index in relation to COC, AOF, and SSC

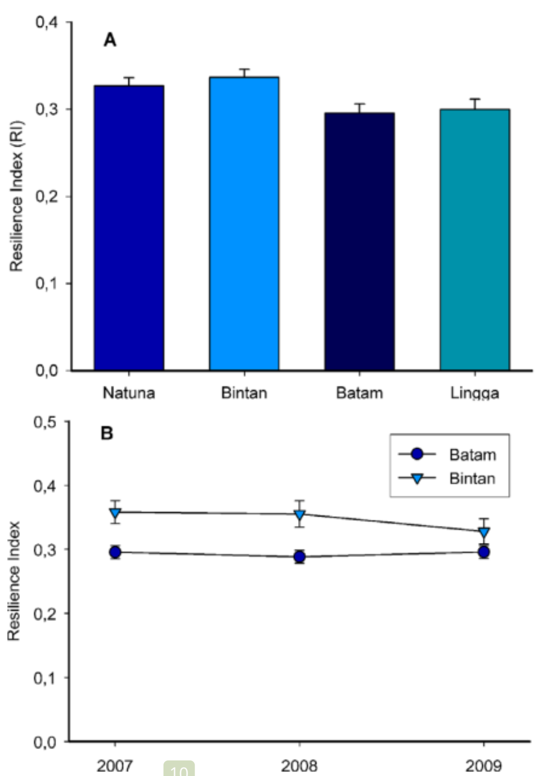

Fig. 3. Comparison of coral reef resilience indices among locations (A) and times (B). Error bars indicate 1 SE

by coral communities. A transect with 100% algal or soft coral (AOF) covers will have a resilience index of 0.047, while a transect that has 100% ruble cover will have a resilience index of 0.094. Regarding these situations, coral population recovery is still possible and dependent on other ecological processes.

The present index can be used to compare the resilience status of coral reefs among locations and times. Fig. 3A shows coral reef resilience indices among four locations in the Province of Kepulauan Riau, Indonesia. Using this index we could also determine that coral reef resilience was significantly different among the four locations ($F = 3.935$, $df = 3{,}225$, $P < 0.01$). Coral reef resilience is dynamic as a results of its interaction with fluctuating stress and disturbances from the surrounding environment over time. Fig. 3B shows how the present index compares temporal variation in coral reef resilience. These figures confirmed the practical uses of the index to detect resilience variation spatially and temporally.

4. Discussion

The present study shows that assessment of coral reef resilience level can be carried out using LIT data. Using this index, managers are able to more objectively compare resilience levels spatially among coral reefs and more accurately make decisions on coral reef management. They could also describe temporal variation of the resilience level to predict future trends for management purposes.

The present resilience index is merely ecological resilience. Several authors have proposed employing a more complicated resilience measurement which covers not only ecological but also physical oceanography, social factors, and management practices (Maynard et al. 2010; Obura and Grimsditch 2009; Cumming et al. 2016). Such coral reef resilience measurements are more comprehensive than the present study, but they are also impractical for coral reef managers. The present study provides a complementary resilience index to Maynard's index. The Maynard's index provides a broad assessment of the resilience state, while this present resilience index focuses on ecological assessment.

The resilience state represented by the index may only operate maximally under good management practices. Improper management could impose additional stress and disturbances on coral reefs. The resilience index should be viewed as the resilience state of coral reef ecosystems at the time of assessment. A resilience index will likely decrease in response to disturbances, due to reduction in coral cover, loss of coral functional groups, increasing coverage of rubble, or increasing algae and other fauna cover.

The present index is very practical. A coral taxonomist or biologist is not always available in many provinces in Indonesia. Coral genera richness (CGR) is therefore omitted from the operational resilience indicators. Obura and Grimsditch (2009) resilience assessment uses 61 indicators covering ecological, social, physical, and management factors. This complex resilience measurement would require a high level of financial support and a lot of expertise. On the other hand, the use of the present index can be utilized by nearly all coral reef managers with basic training experience in the LIT method and a spreadsheet computer program.

The resilience index enable managers to make the right management decisions. When SSC is high due to coastal erosion, a possible management response is to deploy suitable settlement substrate to reduce SSC cover, for example concrete blocks (Bachtiar 2002) or reef balls (Bachtiar and Prayogo 2010). However this would only be practical if erosion or the disturbance could be reduced over the long term.

The index may be used as an alternative and predictive measurement of coral reef recovery after disturbance. Recovery of the ecosystem may be measured in terms of time to return to a former pre-disturbance resilience index. Conventional recovery time has mostly been measured as returning coral cover (Golbuu et al. 2007; Gilmour et al. 2013; Graham et al. 2015) and community composition or species diversity (Brown and Suharsono 1990; Done et al. 1991; Smith et al. 2008). Returning coral cover could take place over a decade, but returning species diversity might need many decades. The present index supports the efforts of Timpane-Padgham et al. (2017) to integrate resilience metrics in coral reef restoration efforts. Using the resilience index, coral reef recovery does not only mean recovery of coral cover but also functional group diversity, habitat quality and recruitment.

The present resilience index would be globally applicable, since reference points of all variable indicators were theoretically their maximum values. Only the CSN value was determined from data collected from Indonesian waters. Since many Indonesian waters show the best places for coral growth (Tomascik et al. 1996) and center of coral diversity (Veron et al. 2009), it might be inferred that the best in Indonesia might also represent the best state worldwide. This means that the maximum value of CSN on the index would also be the maximum value in most other coral reef areas in the world. Furthermore, the index can be easily adapted to various transect lengths by using new CSN values related to the transect length, for example 30 or 50 meter length. The CSN variable is additively linear to transect length.

The resilience index needs to be interpreted in relation to a specific disturbance. Carpenter et al. (2001) advised that resilience measurement should clearly compare the resilience of 'what to what'. Interpretation of the resilience index used in this study should be developed for that purpose. When a coral reef with a resilience index of 0.450, for example, is reduced to 0.250 due to coral bleaching, the length of time for recovery to its former state is important. Time series data from permanently laid LIT, particularly in areas of mass coral mortality related to bleaching, will assist in further development and interpretation of the resilience index. It is recommended that the index should be validated through application by coral reef researchers from other Indo-Pacific regions.

In the future, index interpretation should also be developed in relation to human-induced acute disturbances, such as blast fishing and ship grounding. Index interpretation in relation to chronic disturbance might be best used as a warning signal of a potential greater ecological loss if it is accompanied by an acute disturbance. This system of resilience index assessment needs to be developed as a standard protocol.

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PAGE 3

PAGE 4

PAGE 5

PAGE 6

PAGE 7

PAGE 8

PAGE 9

PAGE 10

PAGE 11