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Using a multi-criteria decision-matrix framework to assess the recovery potential of coral reefs in the South Western Indian Ocean

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A B S T R A C T

Over the last two decades, coral reefs have experienced dire declines due to intensifying anthropogenic disturbances and climate change. Defining and quantifying coral reef resilience now represents a critical management objective, but there is still little consensus on the approach and the indices to be used. In this study, we develop a multi-factor reef recovery index based on the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method to assess the vulnerability of several insular coral reefs in the South Western Indian Ocean (SWIO) from 2016 to 2018. We showed, that in the wake of a regional bleaching event in 2016, the most isolated reefs of Europa, which is characterized by low direct human impact had the highest recovery potential. On the contrary, islands that are more prone to direct human influence (*i.e.*, La Reunion and Rodrigues) displayed the lowest recovery potential.

1. Introduction

Coral reefs support the livelihoods of more than 275 million people worldwide (Burke et al., 2011). However anthropogenic impacts, such as ocean warming, pollution, or overfishing are now threatening the functioning and services provided by coral reefs (Bozec and Mumby, 2015; Burke et al., 2011; McWilliam et al., 2020), a trend that is amplified by the interactions between anthropogenic and natural disturbances (Hughes et al., 2018a, 2017). Much research in the last decades has focused on the drivers of coral reef resilience (Bellwood et al., 2004; Bruno and Selig, 2007; Hughes et al., 2018b), which is the ability of an ecosystem to maintain and/or return to its original state after disturbances. Resilience is supported by two distinct mechanisms: i) resistance, which is the capacity of an ecosystem to absorb stressors without changing its state, and ii) recovery, which is the capacity to return to its initial state after being modified (McClanahan et al., 2012; Nyström et al., 2008).

Over the last decades, many studies have assessed various coral reefs parameters to determine their overall ecosystem state, broadly documenting a decline of coral reef health worldwide. However, many empirical studies are based on a limited number of variables and do not explicitly consider coral reef resilience (see for example Kaufman et al., 2011). For instance, the most extensive effort to compile global trends on coral reefs has been made by the Global Coral Reef Monitoring Network (GCRMN) by the International Coral Reef Initiative (ICRI) as illustrated by many reports since 1998, including the latest "Status of Coral Reefs of the World: 2020" (Souter et al., 2021). GCRMN coral reef status assessment is currently based on hard coral cover (and composition when available), cover of fleshy algae and other benthic groups, as well as fish abundance and biomass (when available) (Souter et al.,

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2021). While these variables are valuable to determine coral reef health and to compare different reefs, they are not designed to assess resilience or more specifically recovery potential, and the GCRMN method does not provide a single index to reflect reef status.

Bolstering coral reef resilience represents a commonly cited management objective (Anthony et al., 2015), which has led to the formulation of "resilience based management" (RBM) as an applied concept in ecology (Mcleod et al., 2019). More precisely, according to Mcleod et al. (2019) RBM is defined as "using knowledge of current and future drivers influencing ecosystem function (*e.g.,* coral disease outbreak, changes in land-use, trade, or fishing practices) to prioritize, implement, and adapt management actions that sustain ecosystems and human well-being". Hence, the analysis of the spatial and temporal variation of reefs resilience, is crucial to inform RBM (Maynard et al., 2015).

In this context, indices that assess resilience can rely on a range of different attributes, but are commonly based on biological (*e.g.,* coral recruitment, coral diversity, abundance of resistant coral species, macroalgae abundance, herbivore biomass, coral diseases), anthropogenic (*e.g.,* human physical impacts, fishing pressure) and/or physical and chemical parameters (*e.g.,* sedimentation, pollution and temperature variability) that describe critical processes or their outcomes across a variety of scales (Fujita et al., 2013; Hédouin and Berteaux-Lecellier, 2014; McClanahan et al., 2012).

Any index with the goal of measuring ecological resilience should be able to synthetize the information derived from multiple parameters in order to represent a tool for decision-makers (Darling et al., 2019). Several synthetic indices have been developed to address the health or condition status of reefs (Ben-Tzvi et al., 2004; Kaufman et al., 2011; Lasagna et al., 2014) but only a few of these are directly designed to assess reef resilience using a set of ecological indicators that capture the dynamics of reefs' resistance and recovery (see Maynard et al., 2010). Indeed, to our knowledge, no indicator is yet available to specifically assess recovery potential. Thus, we sought to develop indicators that integrate across eight variables that are highlighted as excellent predictors of recovery potential, based on the published literature and expert opinions.

The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method is a multiple-criteria decision analysis framework, which ranks options on the basis of their relative distance from the most negative to the most positive solutions (Hwang and Yoon 1981). By employing relatively simple calculations, the TOPSIS methods can be widely applied by a variety of users and has been extensively used since the beginning of the 21st century in logistics, engineering, marketing, human resources, human health, and resource management (Behzadian et al., 2012). While the technique is not commonly employed in ecology to date, Parravicini et al (2012) used it to assess human impact on marine habitats and Parravicini et al. (2014) employed the TOPSIS approach to quantify the vulnerability of coral reef fish assemblages at a global scale. These examples demonstrate how multi-criteria analysis has the potential to be used to define a resilience index in a standardized, and widely applicable way.

Here we develop a multi-factor reef resilience index based on the TOPSIS method (Hwang and Yoon, 1981) to classify reefs according to their recovery potential (Behzadian et al., 2012; Parravicini et al., 2014). Specifically, using data from 18 reef regions in the South Western Indian Ocean (SWIO), we selected a range of indicator variables based on the literature and experts opinions. Although there is no unequivocal consensus on which parameters best quantify the resilience of reefs, the factors important for resistance and recovery are commonly not strongly correlated, thus warranting independent assessments of their dynamics (McClanahan et al., 2012). Since the objective of our study was to characterize recovery capacity, we selected the variables that were ranked as highly important to support recovery in McClanahan et al. (2012) and that were either available or rapidly collectable for our study locations. We then used the eight obtained variables in a multi-criteria decision matrix to compute measures of separation from ideal positive and negative solutions, thus quantifying the relative proximity of each site to the ideal solutions. We then superimposed the obtained results on existing data on reef recovery in the SWIO to evaluate whether the TOPSIS method can be an efficient tool to guide coral reef management actions that are needed given the vulnerability of these unique ecosystems.

2. Material and methods

2.1. Study sites

The present study was performed using data from several sites in the SWIO: Rodrigues and Reunion islands in the Mascarene Archipelago, Mayotte in the Comoro Archipelago and Glorieuses and Europa Islands in the Mozambique Channel (Fig. 1). A total of 18 sampling sites, located on outer slopes of the studied reefs, in 10–12 m depth were considered. Reunion Island (21° 07′ S, 55° 32′ E) is a volcanic island (*ca.* 70 km long and 50 km wide) located 700 km east of Madagascar. Fringing reefs line the island in a 12 km^2 area along 25 km of coastline on its western and southern coasts (Camoin et al., 1997; Montaggioni and Faure, 1980). Rodrigues (19° 43′ S, 63° 25′ E) is a small isolated island that is part of the Republic of Mauritius (18.3 km long and 6.5 km wide) and the easternmost of the Mascarene Islands. It is surrounded by an almost continuous reef covering ca. 200 km2 (Montaggioni and Faure, 1980; Rees et al., 2005). Both Rodrigues and Reunion island have been subject to intensifying coral bleaching over the last decades (see Hardman et al., 2007 at Rodrigues). Moreover, over the last three decades, Reunion Island experienced an ever-increasing urbanization of the coastal zone (Magnan and Duvat, 2018). This led to a noticeable eutrophication and a decrease in reef fish stocks (Naim, 1993; Chabanet et al., 1995), which has led in turn to an increase in algal cover compared to corals (Chazottes et al., 2002; Naim, 1993; Naim et al., 2013; Tourrand et al., 2013; Scopélitis et al., 2009). To address these issues, a multiple-use marine reserve (Réserve Naturelle Marine de La Réunion) was established at Reunion Island in 2007. The reserve covers an area of over 35 km^2 and it is divided into three levels of protection: areas open for human activities, restricted areas where only some traditional and commercial fishing activities are allowed, and sanctuaries where no activity is allowed (*i.e.,* no-take zones). While there is less human pressure in Rodrigues, the local government has implemented four marine reserves in the north of the island in 2007, to avoid overfishing. However, only partial management has been set up and fishing still occurs in these areas (Hardman et al., 2010; Pasnin et al., 2016). In addition, the South East Marine Protected Area (SEMPA) was designated as a Marine Protected Area (MPA) in 2009, which includes both inner and outer lagoons covering a total of 43.7 km^2 divided into different multiple-use zones including no-take zones (Fig. 1).

Mayotte is the oldest island of the Comoro Archipelago, located in the northern Mozambique Channel (12° 80′ S, 45° 10′ E) and is surrounded by one of the largest lagoons in the Indian Ocean (ca. 1500 km2, 15 km width and reaching 80 m depth; Chabanet, 2002; Dinhut et al., 2008). The lagoon is enclosed by a continuous barrier reef (Guilcher, 1971). In the face of anthropogenic disturbances related to increasing human population densities and environment disturbances (Ahamada et al., 2008; Dinhut et al., 2008), Mayotte's marine park (Parc Naturel Marin de Mayotte) was created in 2010. Glorieuses and Europa are part of the Îles Éparses, located in the north (11° 50′ S, 47° 30′ E) and south (22° 30′ S, 40° 30′ E) of the Mozambique Channel, respectively. Unlike the islands mentioned previously, these territories do not have permanent inhabitants and were classified as natural reserves in 1975 (Quétel et al., 2016). Although relatively free from local human impact, the reefs surrounding these islands have been affected by cyclones and the effects of climate change, and there has been a decrease in fish stocks probably linked to an increase in illegal fishing pressure in recent years, particularly on Glorieuses (Chabanet et al., 2016). A marine park has been created in 2012 at Glorieuses (Parc Naturel Marin des Glorieuses)

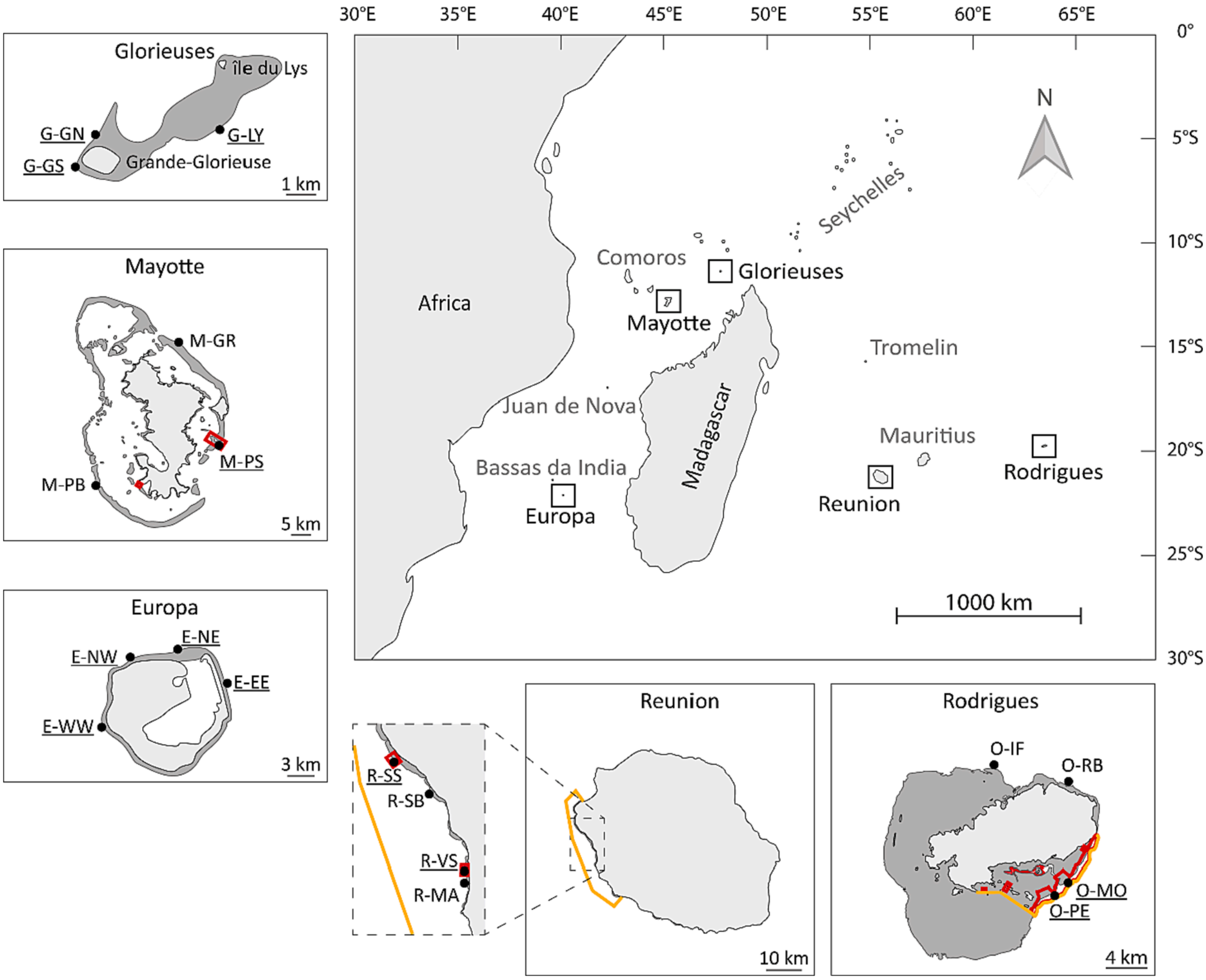

Fig. 1. Location of the 18 sampling sites in the South-Western Indian Ocean region. Land is in light-grey; reef flat is in dark grey; Marine Protected Areas are in orange; and No Take Zones are in red. The sampling sites are represented by black dots. Sites located within No Take Zones have their names underlined. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to develop sustainable human activities and transformed in a Natural Marine Reserve in 2021 (Quétel et al., 2016).

2.2. Sampling strategy

We selected eight variables based on their documented relevance for reef recovery, (Graham et al., 2015; McClanahan et al., 2012). These variables were: a) coral species richness, b) total and c) juvenile coral density, d) hard coral cover, e) proportion of stress-tolerant coral species cover, f) algal cover, g) herbivorous fish biomass and h) sea-surface temperature anomalies. Given the importance of coral recruitment for reef recovery, we also integrated recruitment rates based on the colonization of artificial substrata at Reunion and Rodrigues island (Jouval et al., 2019). The recruitment data was unavailable for other sites.

Coral densities (ind.m^{-2}) were estimated along three replicate belt-transect of 1 × 10 m using either benthic photographs (ca. 20 photographs per transect) at Reunion Island (in 2016), Rodrigues Island (in 2017) and Glorieuses (in 2015) or underwater visual censuses (UVC) at Mayotte (in 2016) and Europa (in 2016). Belt-transects were laid parallel to each other and to the coastline. In both cases, each coral colony was identified to the genus level and the maximum diameter was measured in the field or on photographs (which always included a length reference). The maximum diameter was used to distinguish adult corals (*i.e.,* mature colonies of greater than 5 cm diameter) from juveniles (*i.e.,* immature colonies of ≤ 5 cm diameter) (Penin et al., 2010).

The abundance of coral recruits was characterised at Reunion and Rodrigues islands using settlement tiles (Jouval et al., 2019), at the same sites where coral abundance, species richness and coral and algal cover were estimated. At each site, 20 unglazed terracotta tiles (10 × 10 × 2 cm) were deployed approximately 2 cm from the substrate using a stainless steel fixture anchored to the substrate (Adjeroud et al., 2007; Mundy, 2000). Tiles were immersed for six months during two austral summer periods (October 2015–March 2016, October 2016–March 2017). At the end of each immersion period, we retrieved, bleached and dried the tiles to expose the skeletons of coral recruits, which were identified and counted under a dissecting microscope.

For each sampling site, coral species richness was evaluated by the same co-author over a 45-minutes random prospection covering approximately 100 m^2 area. Censuses have been performed in 2012 at Glorieuses, 2016 at Reunion Island, 2014 and 2016 at Mayotte, 2016 at Europa and 2017/2018 at Rodrigues.

Coral and algal (macroalgae and turf) cover were defined in 2015 at Glorieuses, in 2016 at Europa and Mayotte and in 2016–2017 at Reunion and Rodrigues by using three replicate 20 m Line Intercept Transects (LITs; Loya, 1972) separated each other by 5 m and placed parallel to each other and the coastline, at the same locations as previously. Coral colonies were identified to the species level when possible. Each species was associated with one of the following life-history strategies: stress-tolerant, competitive, generalist, weedy or undetermined, following Darling et al. (2012). We then calculated the proportion of total coral area covered by stress-tolerant species.

Fish biomass was evaluated at all 18 sampling sites, in 2015 at Glorieuses, in 2016 at Europa and Mayotte, in 2017 at Reunion and in 2018 at Rodrigues. At each site, the species, number and total length of herbivorous fish was visually determined and noted during underwater visual censuses along three replicate belt-transects of 5 × 50 m, positioned around the benthic transects and laid parallel to the shoreline (Chabanet et al., 1995). A list of herbivorous fish species considered is presented in Supplementary Table S1. We then used these data to calculate the mean herbivorous fish biomass at each site (in kg.Ha^{-1}) using length-weight relationships from *Fishbase* (Froese and Pauly, 2018).

Considering the broad spatial scale of the present study, and the remoteness of some sites (*e.g.*, Glorieuses and Europa are inhabited islands) it was not possible to sample all sites simultaneously. Nevertheless, we were able to leverage the use of previously acquired data to obtain the most comprehensive dataset possible. As a consequence, differences obtained among sites could be influenced by temporal variation of measured variables. Considering that a mass bleaching event unfolded in the SWIO in 2016, this temporal mismatch may indeed affect our results; however, the only datasets that were collected prior to 2016 bleaching event were hard coral species richness in Glorieuses and in one site in Mayotte (M−GR), as well as coral abundance and cover in Glorieuses and Rodrigues, suggesting that any effects of the temporal mismatch would not have significant consequences for the broader outcomes of our analyses. Monthly averaged sea surface temperatures anomalies (SSTa) were obtained from the IRI/LDEO Climate Data Library (http://iridl.ldeo.columbia.edu) from November 1981 to December 2018 and for each island location. SSTa was calculated by subtracting the 1971–2000 monthly SST from the monthly SST values of the considered period (1981–2018) following Reynolds et al. (2002). Then, the proportion of months for which SSTa was equal or greater than 1 °C (*i.e.*, when the monthly SST greater than 1 °C compared to the temperatures recorded for the same month between 1971 and 2000) was calculated over the considered period. We refer to this variable as SSTa^{+1}.

2.3. Data analyses

We first explored the distribution of sites in the multidimensional space generated by the RI components using a Principal Component Analysis (PCA) to discriminate the 18 sites according to the variables used to describe the recovery capacity using the *FactoMineR* package (v.1.41; Lê et al., 2008) in R (R Core Team, 2018). We also examined the relationships between the RI components using pairwise Pearson correlations (Pearson correlations).

We then implemented the TOPSIS method (Hwang and Yoon, 1981; Hwang et al., 1993; Yoon, 1987) a multi-criteria analysis technique for identifying solutions from a panel of alternatives. The technique allows for the ranking of each site according to a score that represents a synthesis of the variables used to describe the recovery capacity. More precisely, the objective of the TOPSIS method is to classify alternative solutions according to their relative distance to two “ideal” (extreme), positive and negative solutions. The basic principle of the TOPSIS method is that the chosen alternative must have the shortest distance to the ideal positive solution, and thus the largest distance to the ideal negative solution. The method can be described as a series of six steps, summarized in Fig. 2 and detailed hereafter:

STEP 1: Definition of a multi-criteria decision matrix

$$M = \begin{matrix} & V_1 & V_2 & V_j \\ S_1 & & & \\ S_2 & & & \\ S_i & & & \end{matrix} \begin{pmatrix} x_{11} & x_{12} & x_{1j} \\ x_{21} & x_{22} & x_{2j} \\ x_{i1} & x_{i2} & x_{ij} \end{pmatrix} \quad (1)$$

where x_{ij} correspond to the value measured for variable V_j at site S_i.

STEP 2: Normalization of the multi-criteria decision matrix.

This step ensures that each variable has the same range: between 0 and 1.

$$n_{ij} = x_{ij} \Big/ \sqrt{\sum_{j=1}^{i} (x_{ij})^2} \quad (2)$$

where n_{ij} corresponds to the normalized value for variable V_j at site S_i.

STEP 3: Weighting of the normalized multi-criteria decision matrix.

To weight the variables according to their perceived importance for coral reef recovery, we conducted a survey through the “Coral-list” funded by the NOAA with the aim to rank each variable from 1 (low importance) to 5 (high importance; Supplementary Table S2), except SSTa^{+1} and recruitment rates which were added later in the analyses. A

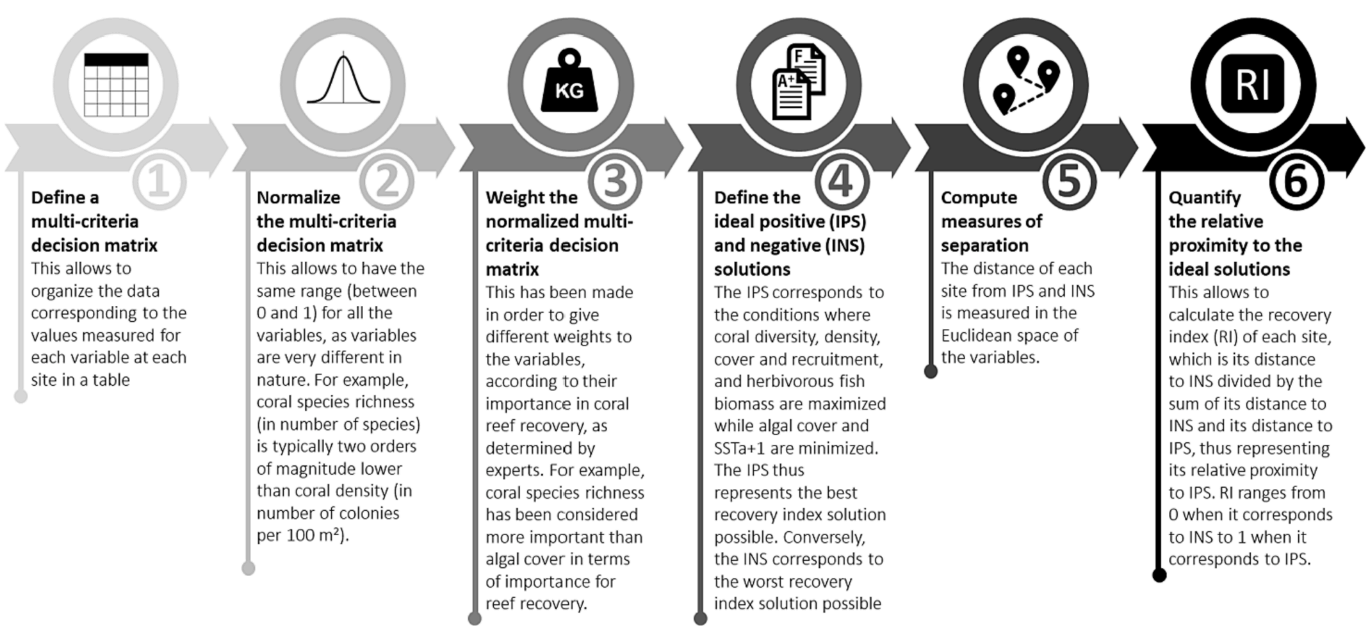

Fig. 2. Simplified flowchart of the six steps used to implement the TOPSIS method to calculate the recovery index (RI).

total of 23 recognised experts in coral reef ecology answered to our survey (Supplementary Table S2) and each variable was weighted as such:

$$v_{ij} = w_j \times n_{ij} \quad (3)$$

where w_j is the mean rank given by the experts to the variable V_j.

Recruitment rates (on artificial tiles) were weighted using the mean rank given to the juvenile coral density since both variables are related to coral recruitment. $SSTa^{+1}$ was weighted using the average weight of all the other variables. Using this method, the variables were weighted as follows: Stress tolerant coral species cover: 4.30; Coral species richness: 4.04; Juvenile coral density / recruitment rate: 3.95; $SSTa^{+1}$: 3.95; Herbivorous fish biomass: 3.86; Coral cover: 3.91; Total coral density: 3.8; Algal cover: 3.7.

STEP 4: Definition of the ideal positive and negative solutions.

Ideal positive (*IPS*) and negative (*INS*) solutions were defined as:

$$IPS = \left\{v_1^+, v_2^+, \ldots, v_j^+\right\} = \{(\max v_{ij} \mid j \in P) \ or \ (\min v_{ij} \mid j \in N)\} \quad (4)$$

$$INS = \left\{v_1^-, v_2^-, \ldots, v_j^-\right\} = \{(\min v_{ij} \mid j \in P) \ or \ (\max v_{ij} \mid j \in N)\} \quad (5)$$

where v_{ij} corresponds to the normalized and weighted elements of the multi-criteria decision matrix, *P* is for the variables expected to enhance reef recovery and *N* is for the variables expected to reduce reef recovery. Thus, the *IPS* corresponds to the conditions where coral diversity, density (total and juvenile), cover (total and stress-tolerant species), herbivorous fish biomass and coral recruitment rates are maximized while algal cover and $SSTa^{+1}$ are minimized. On the contrary, the *INS* corresponds to the conditions where algal cover and $SSTa^{+1}$ are maximized while coral diversity, density (total and juvenile), cover (total and stress-tolerant species), herbivorous fish biomass and coral recruitment rates are minimized. We performed two analyses: one using all 18 sites and one using only the eight sites of Reunion and Rodrigues islands for which recruitment rates data are available. Thus, two sets of ideal solutions (*IS*) were defined, hereafter referred to as IS_{Tot} and IS_{RR}, respectively.

STEP 5: Computing measures of separation.

The measures of separation of each alternative (*i.e.,* site) from the ideal positive and negative solutions were measured as its distance (*D*) from *IPS* and *INS*, respectively, in the Euclidean space of the variables:

$$D_i^+ = \sqrt{\sum_{i=1}^{j}\left(v_{ij} - v_j^+\right)^2} \ and \ D_i^- = \sqrt{\sum_{i=1}^{j}\left(v_{ij} - v_j^-\right)^2} \quad (6)$$

STEP 6: Quantifying the relative proximity to the ideal solutions.

$$RI_I = D_i^- / (D_i^+ + D_i^-) \quad (7)$$

The relative proximity to the ideal solution index (*RI*) ranges from 0 when the variable measure (v_{ij}) corresponds to *INS* (v_j^-; eq. (5)), and to 1 when the variable measure (v_{ij}) corresponds to *IPS* (v_j^+; eq. (4)).

2.4. Robustness of the RI index

As previously described, the ideal positive and negative solutions were calculated on the basis of the maximum and minimum values of each weighted variable at the 18 studied sites. However, these sites may be exposed to different disturbance regimes and environmental conditions, potentially biasing optimal solutions for different sites. To test the robustness of the TOPSIS analysis with respect to ideal solutions, we randomly generated 1000 *IPS* and *INS* for both analyses (using all the 18 sites and using only the eight sites of Reunion and Rodrigues islands for which recruitment data were available, *i.e., IS_{Tot}* and *IS_{RR}*) as follows:

- Generation of 1000 values from the 25 % extreme values of the distribution of the variable *j*:

$$IPS^{25} = \left\{v_1^{25+}, v_2^{50+}, \ldots, v_j^{25+}\right\} = \left\{\left(q_{75} < v_{ij} < q_{100} \middle| j \in P\right) \ or \ \left(q_0 < v_{ij} < q_{25} \middle| j \in N\right)\right\} \quad (8)$$

$$INS^{25} = \left\{v_1^{25-}, v_2^{50-}, \ldots, v_j^{25-}\right\} = \left\{\left(q_0 < v_{ij} < q_{25} \middle| j \in P\right) \ or \ \left(q_{75} < v_{ij} < q_{100} \middle| j \in N\right)\right\} \quad (9)$$

where q_{25} and q_{75} correspond to the first and the last quartiles, respectively.

Generation of 1000 values from the 50 % extreme values of the distribution of the variable *j*:

$$IPS^{50} = \{v_1^{50+}, v_2^{50+}, \ldots, v_j^{50+}\} = \{(q_{50} < v_{ij} < q_{100} | j \in P) \text{ or } (q_0 < v_{ij} < q_{50} | j \in N)\} \quad (10)$$

$$INS^{50} = \{v_1^{50-}, v_2^{50-}, \ldots, v_j^{50-}\} = \{(q_0 < v_{ij} < q_{50} | j \in P) \text{ or } (q_{50} < v_{ij} < q_{100} | j \in N)\} \quad (11)$$

Steps 5 and 6 were repeated for each of the 1000 iterations. For the measures of separation, we used equation (12), derived from equation (6):

$$D_i^+ = \begin{cases} 0, if \, v_{ij} > v_j^{25/50+} \\ \sqrt{\sum_{i=1}^{j}(v_{ij} - v_j^{25/50+})^2}, if \, v_{ij} \le v_j^{25/50+} \end{cases} \quad (12)$$

$$D_i^- = \begin{cases} 0, if \, v_{ij} < v_j^{25/50-} \\ \sqrt{\sum_{i=1}^{j}(v_{ij} - v_j^{25/50-})^2}, if \, v_{ij} \ge v_j^{25/50-} \end{cases}$$

For greater clarity, all abbreviations used in the manuscript are summarized in Table 1.

3. Results

The two first PCA axes explained 72.5 % of the variability in the components of the recovery potential variability measured among sites

Table 1
Abbreviations used to describe the Ideal Solutions (*IS*) according to the performed analyses.

Ideal solutions		Based on all 18 sites	Based on 8 sites (Reunion and Rodrigues islands)
Based on minimal/maximal values	Positive	IPS_{Tot}	IPS_{RR}
	Negative	INS_{Tot}	INS_{RR}
	Both	IS_{Tot}	IS_{RR}
Based on random sampling within the 25 % of extreme values of each variable distribution	Positive	IPS^{25}_{Tot}	IPS^{25}_{RR}
	Negative	INS^{25}_{Tot}	INS^{25}_{RR}
	Both	IS^{25}_{Tot}	IS^{25}_{RR}
Based on random sampling within the 50 % of extreme values of each variable distribution	Positive	IPS^{50}_{Tot}	IPS^{50}_{RR}
	Negative	INS^{50}_{Tot}	INS^{50}_{RR}
	Both	IS^{50}_{Tot}	IS^{50}_{RR}

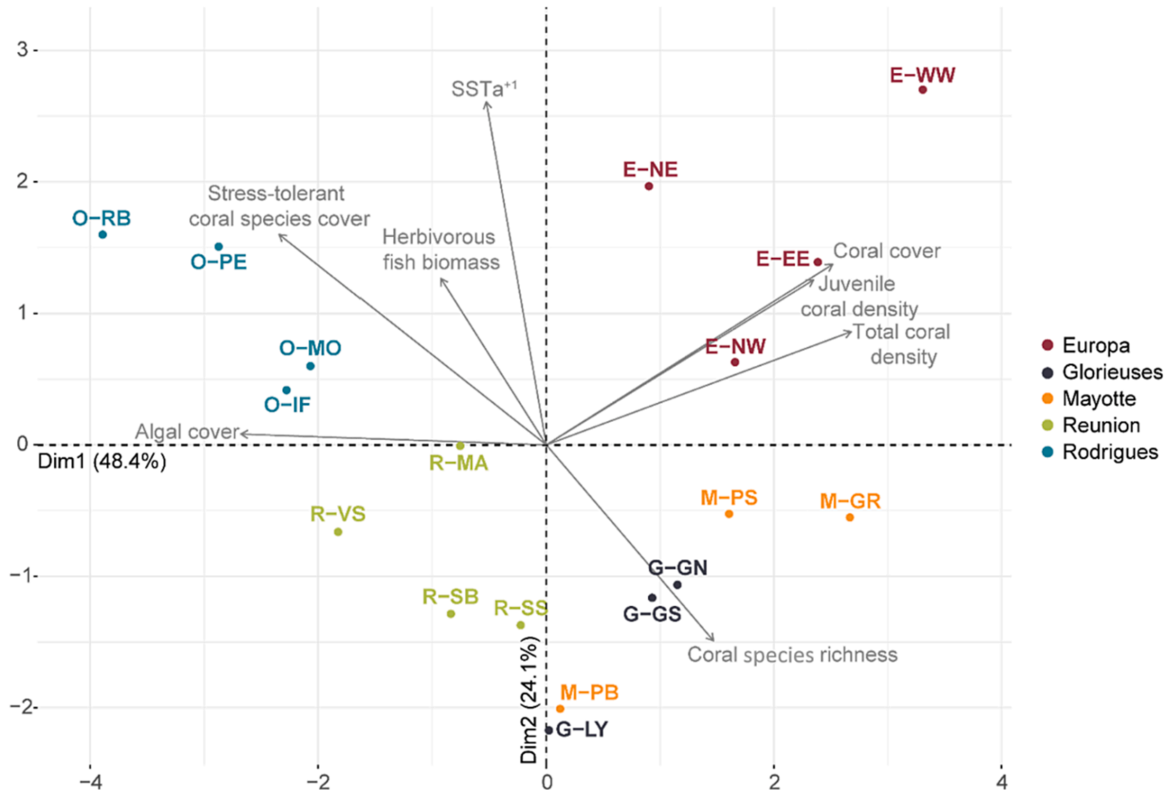

Fig. 3. Principal components analysis (PCA) of sites bases on the variables used to characterize the recovery potential of 18 reef sites in the SWIO.

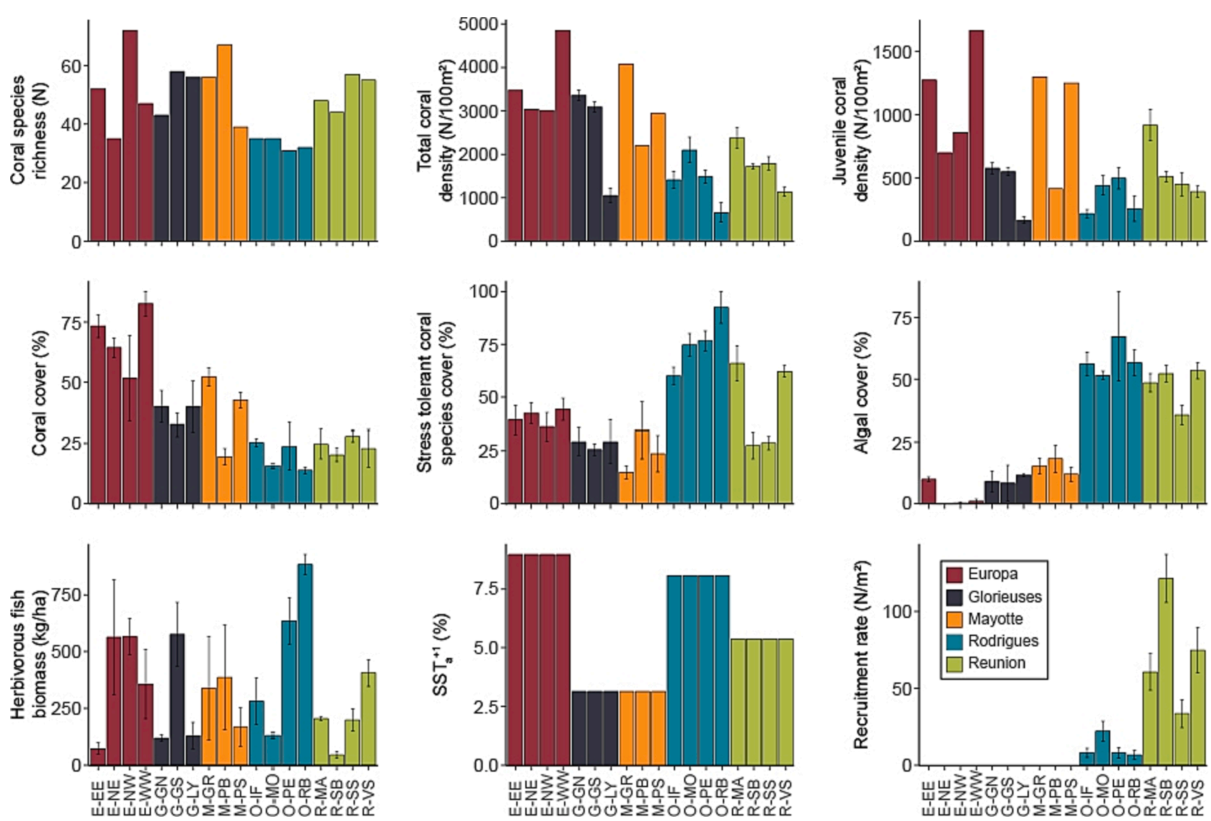

Fig. 4. Summary of the data obtained for each variable across the 18 study sites (mean ± SE). SE were not available for densities in Europa and Mayotte. Recruitment rates were not measured at Europa, Glorieuses and Mayotte.

(Fig. 3). Coral density (total and juveniles), coral cover (total and stress-tolerant species) and algal cover mainly contributed to the first axis of the PCA (ranging from 16 to 21 % for each variable) while SSTa^{+1} mostly contributed to the second axis (39 %). Sites at Europa, M−GR and M−PS at Mayotte, and G-GN and G-GS at Glorieuses were characterized by higher total coral cover and density and lower algal cover compared to sites at Rodrigues and Reunion (Figs. 3 and 4). Furthermore, Rodrigues and Europa sites exhibited higher percentages of stress-tolerant coral cover and higher SSTa^{+1} compared to Mayotte, Glorieuses and Reunion. Overall, the first axis of the PCA clearly separated the sites of the Mascarene Archipelago (Reunion and Rodrigues islands) from the sites of the Mozambique Channel (Europa, Glorieuses and Mayotte). The second axis discriminated the sites at Europa from the sites at Glorieuses and Mayotte within sites in the Mozambique channel, and the sites at Reunion from the sites at Rodrigues within sites in the Mascarene Archipelago.

Coral cover and density (total and juvenile) were positively correlated, while algal cover was negatively correlated to coral density (total and juvenile), coral cover and coral species richness (Fig. 5). Stress-tolerant coral species cover was negatively correlated with coral species richness and total coral density, while showing a positive correlation with algal cover and SSTa^{+1}. At both Rodrigues and Reunion, recruitment rates showed no significant correlations with other variables.

The TOPSIS analysis showed that the Europa sites, M−GR, and G-GS had the highest *RIs* (all *RIs* ≥ 0.5) (Fig. 6A), while sites at Reunion sites had lower recovery potential (average $RI = 0.31$; Fig. 6A and 6B). However, the south-western sites at Reunion (R-MA and R-VS) had a higher *RI* (0.36 in average) than the north-western sites (R-SS and R-SB; average $RI = 0.25$). The Rodrigues sites had more variable *RIs* ranging from 0.26 (O-IF) to 0.44 (O-RB; Fig. 6A and 6B).

The modification of the *IS* performed to test the robustness of the TOPSIS analysis with respect to ideal solutions by randomly sampling

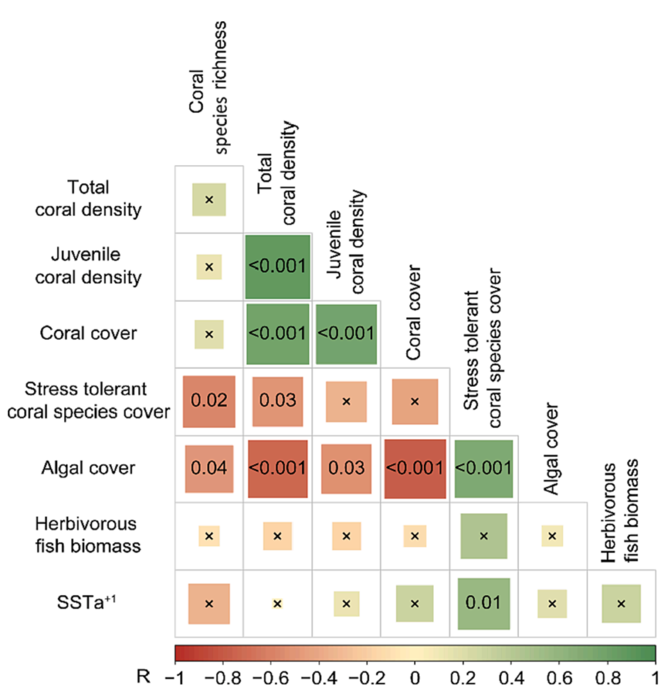

Fig. 5. Correlation matrix of variables used to characterize the recovery potential of the 18 studied sites. Square size and color shade are proportional to the absolute value of R. The color of the square depends on the sign of R: red, negative R; green, positive R. The correlation p-values are indicated inside each square (x corresponds to p greater than 0.05). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

within the 25 % of extreme values of each variable significantly modified the ranking of sites (Fig. 6A). In general, only five sites were found at the same position in more than 75 % of the cases in the IS_{Tot} and IS^{25}_{Tot} analyses (E-WW, E-NW, E-NE, R-SS and R-SB, respectively ranked in 1st, 2nd, 3rd, 16th and 18th positions in both IS_{Tot} and IS^{25}_{Tot} analyses; Table 2). There was less variation between analyses based on IS^{50}_{Tot} and on IS^{25}_{Tot} than between analyses based on IS^{25}_{Tot} and IS_{Tot} (Fig. 6; Table 2). Indeed, 14 sites maintained the same position in the two analyses based on IS^{50}_{Tot} and on IS^{25}_{Tot} (Fig. 6A). However, over the 1000 iterations performed with the IS^{50}_{Tot}, ranking of sites changed more frequently than in the IS^{25}_{Tot} analysis (Table 2).

The addition of recruitment rates at Rodrigues and Reunion had a strong influence on the *RI* (Fig. 6C). Recruitment rates were higher in Reunion (73 recruits.m^{-2} on average) than in Rodrigues reefs (11 recruits.m^{-2}; Fig. 4), thus moving 3 of the 4 sites at Reunion to the top of the ranking. The R-SB site had the lowest *RI* without taking recruitment rates into account ($RI = 0.21$; Fig. 6B) but had the highest *RI* when considering recruitment (122 recruitsrecruits.m^{-2} for this site; Fig. 4; $RI = 0.46$; Fig. 6C). When considering recruitment rate, the ranking of Reunion and Rodrigues sites remained relatively consistent between analyses based on IS^{25}_{Tot} vs IS_{Tot} and IS^{50}_{Tot} vs IS_{Tot} (Table 3).

The modification of the *IS* by taking the minimal and maximal values of only the sub-sample corresponding to the sites of Reunion and Rodrigues Islands (*i.e.,* IS_{RR}) led to significant changes in the ranking: only two sites maintained the same position with the IS_{Tot} and the IS_{RR} (Fig. 6B and Fig. 7A). As observed with IS_{Tot}, when adding recruitment rate, the ranking of Reunion and Rodrigues sites were consistent for IS^{25}_{RR} vs IS_{RR} and IS^{50}_{RR} vs IS_{RR} (Fig. 7B; Supplementary Table S3).

4. Discussion

We developed an ecological index that combines several variables related to recovery potential of a reef after disturbances into a single metric and applied this metric to reefs in the South Western Indian Ocean (SWIO). Using the TOPSIS method, which is rarely used in ecology (Behzadian et al., 2012), we computed a *Recovery Index* (*RI*) that characterizes sites throughout the SWIO based on variables such as coral cover, algal cover, recruitment rates, or SST anomalies. Based on the calculated *RI*, the island of Europa (south of the Mozambique Channel) had high recovery potential, regardless of the sites considered. *RIs* for Glorieuses and Mayotte (northern part of the Mozambique Channel) were highly variable among sites, whereas the Mascarene Islands (Reunion and Rodrigues) displayed the lowest *RIs*.

4.1. Recovery potential in the SWIO

Reefs around Europa are generally considered the healthiest and least impacted by direct anthropogenic pressures of the SWIO region (Chabanet et al., 2016; Quod et al., 2007). Accordingly, Europa was always at the top of the *RI* ranking, regardless of the TOPSIS analyses considered (based on IS_{Tot}, IS^{25}_{Tot} or IS^{50}_{Tot}). This is in agreement with the observed dynamics of reefs in the Mozambique Channel, where southern islands (including Europa) recover more quickly than the northern islands (including Glorieuses and Mayotte; Chabanet et al., 2016). This may be related to the warmer conditions in the north of the Mozambique Channel, which can induce more frequent bleaching episodes and mortality events (Chabanet et al., 2016). Concordantly, Europa was also the least affected island during the mass bleaching of 2016, especially on exposed reef slopes (Nicet et al., 2016; Bigot et al., 2019). Nevertheless, over the 1981–2018 period, Europa had the highest proportion of months for which the mean SSTs exceeded the monthly SSTs values (calculated over the 1971–2000 period) by at least 1 °C (SSTa^{+1}). This island thus displayed high variability in temperature, but with overall lower values than in nearby sites.

The sites in the north of the Mozambique Channel (*i.e.,* Glorieuses and Mayotte) were more heterogeneous in terms of described recovery.

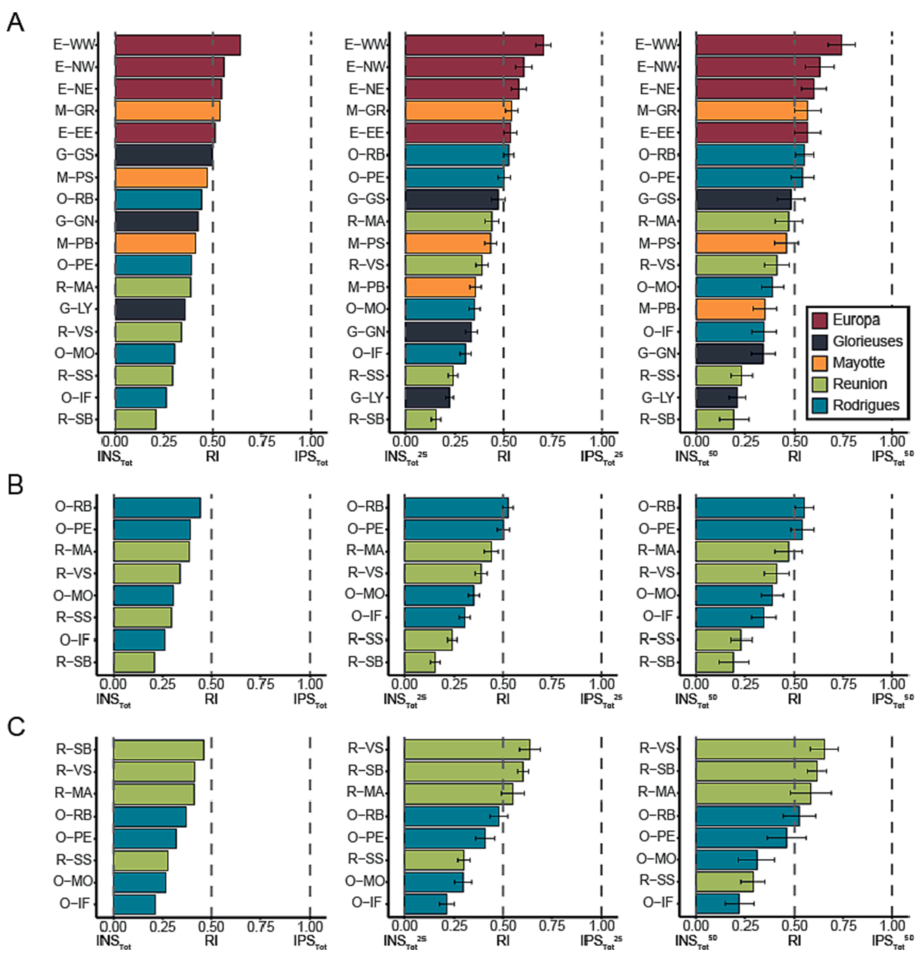

Fig. 6. Ranking of the reef sites according to their recovery potential evaluated through the TOPSIS relative index (*RI*). A) all sites without the *recruitment rate* variable; B) Rodrigues and Reunion, without the *recruitment rate* variable; C) Rodrigues and Reunion, including the *recruitment rate* variable. In each case, *INS*/*IPS* are based on the values measured from the 18 sampling sites (IS_{Tot}). The three columns show results from using the extreme values (left), the 25% quantiles (middle), and 50% quantiles of the distributions (right).

Several bleaching events have occurred over the last four decades in Mayotte (1983: Faure et al., 1984; 1998: Quod et al., 2002; 2010 and 2016: Nicet et al., 2016; Obura et al., 2018), which have strongly impacted outer reef slopes assemblages. Reefs in Mayotte are dominated by the genus *Acropora* (Obura et al., 2018), which is particularly sensitive to temperature-based stress (Hill et al., 2012; Darling et al., 2012, 2019). Despite this, Mayotte reefs have shown high levels of recovery after bleaching events, largely maintaining the dominance of *Acropora*, possibly due to high levels of connectivity (Obura, 2012; Obura et al., 2019) facilitated by the complex currents occurring in the north of the Mozambique channel (Crochelet et al., 2016), and that could be reflected in *RI* via high juvenile coral abundance. However, the recovery potential of these reefs may decrease in the future due to combined local and global stressors (Obura et al., 2018). The site with the highest *RI* (M−GR site) site that was located farthest from densely populated areas. It was also the only site for which hard coral species richness was assessed before the 2016 bleaching event. However, considering bleaching impact was low at this site (Nicet et al., 2016), it is unlikely that this has resulted in overestimating species richness compared to other sites of Mayotte. While it is not possible to evaluate if this high RI is directly related to lower anthropogenic impacts, the obtained results emphasize need to consider social aspects in RBM (Bruggemann et al., 2012; Mcleod et al., 2019).

At the northern extreme of the Mozambique Channel, Glorieuses had the lowest mean *RI* (0.34 compared to 0.60 for Europa and 0.44 for Mayotte), but *RI* was variable among sites, ranging from 0.22 to 0.47. Although considered relatively free from local human impact, Glorieuses' reefs had lower coral cover, lower coral densities (especially in juveniles), and higher algal cover than Europa. This is consistent with previous studies reporting relatively low hard coral cover, higher than usual soft coral cover, and high abundance of *Halimeda* calcareous green algae in contemporary assemblages (Chabanet et al., 2016; Schleyer et al., 2018). *Halimeda* green algae are abundant in sediments as well (*e. g.*, Prat et al., 2016). Moreover, from 2002 to 2015, a 25 % decline in fish biomass was observed, likely linked to an increase of illegal fishing pressure (Chabanet et al., 2016). Importantly, coral cover, abundance and species richness and herbivorous fish biomass in Glorieuses were all assessed before the 2016 bleaching event. Coral mortality was relatively high on the outer slopes following this event in Glorieuses, resulting in a loss of coral cover ranging from 10 to 50 % (Bigot et al., 2019; Nicet et al., 2016). As a consequence, calculated *RI* in Glorieuses might be slightly closer to IPS than they actually were at the time the other sites were sampled. This suggests that reefs in Glorieuses have a lower recovery potential, possibly related to their relatively low coral cover and high abundance of soft corals and *Halimeda* macroalgae, which raises concerns for their future and suggests that local management is of high priority in these islands.

The Mascarene Islands had lower *RI* scores than the islands in the Mozambique Channel (on average 0.36 compared to 0.48), but also showed high variability. At Rodrigues, two sites displayed a medium/high recovery potential (O-RB and O-PE, mean *RI* of 0.51) while the two others had low recovery potential (O-IF and O-MO, mean *RI* of 0.33); a difference predominantly driven by high herbivorous fish biomass and high relative cover by stress-tolerant corals observed in O-RB and O-PE. These differences in *RI* cannot be explained by the geographical position of the sites or their protection level. Despite the strong impact of bleaching in Rodrigues in 2016 (pers. obs.), the *RI*s measured were high for O-RB and O-PE, which suggests a good recovery potential at these

Table 2
Percentage of occurrence of each of the 18 sites at each TOPSIS ranking position (1 to 18) for the 1000 iterations of IS_{Tot}^{25} (top) and IS_{Tot}^{50} (bottom). White: 0 %; yellow: 0 < % ≤ 25; orange: 25 < % ≤ 50; light red: 50 < % ≤ 75; dark red: 75 < % ≤100. Diagonal values correspond to the positions observed for each site with the IS_{Tot}.

Position	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
E-WW	99.9	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E-NW	0.1	94.1	5.7	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E-NE	0	3.5	78.5	10.5	7.4	0.1	0	0	0	0	0	0	0	0	0	0	0	0
M-GR	0	0	5.5	41.4	31.2	16.1	5.8	0	0	0	0	0	0	0	0	0	0	0
E-EE	0	2.1	7.4	18.6	33.4	20.1	14.0	4.4	0	0	0	0	0	0	0	0	0	0
G-GS	0	0	0	0.1	0.2	1.6	10.7	69.3	13.2	4.9	0	0	0	0	0	0	0	0
M-PS	0	0	0	0	0	0	1.3	5.1	37.2	49.7	6.6	0.1	0	0	0	0	0	0
O-RB	0	0.2	2.9	29.1	14.8	52.2	0.8	0	0	0	0	0	0	0	0	0	0	0
G-GN	0	0	0	0	0	0	0	0	0	0	1.4	5.2	21.2	61.2	11.0	0	0	0
M-PB	0	0	0	0	0	0	0	0	0	0	0.1	52.4	38.1	9.4	0	0	0	0
O-PE	0	0	0	0.2	13.0	9.9	67.4	8.9	0.6	0	0	0	0	0	0	0	0	0
R-MA	0	0	0	0	0	0	0	12.3	48.6	39.1	0	0	0	0	0	0	0	0
G-LY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.4	92.6	0
R-VS	0	0	0	0	0	0	0	0	0.4	6.3	91.7	1.6	0	0	0	0	0	0
O-MO	0	0	0	0	0	0	0	0	0	0	0.2	40.7	40.7	18.4	0	0	0	0
R-SS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	92.6	7.4	0
O-IF	0	0	0	0	0	0	0	0	0	0	0	0	0	11.0	89.0	0	0	0
R-SB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100.0

Position	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
E-WW	95.0	4.3	0.6	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E-NW	4.1	54.2	23.3	14.6	2.9	0.7	0.2	0	0	0	0	0	0	0	0	0	0	0
E-NE	0	11.8	38.8	18.8	23.8	3.7	2.5	0.5	0.1	0	0	0	0	0	0	0	0	0
M-GR	0	5.0	14.0	23.5	15.3	14.7	21.0	5.3	0.8	0.3	0.1	0	0	0	0	0	0	0
E-EE	0	14.2	10.3	15.0	18.1	17.4	13.1	11.1	0.6	0.2	0	0	0	0	0	0	0	0
G-GS	0	0	0.2	0.9	3.4	9.1	8.0	27.7	18.3	24.1	4.9	2.4	1.0	0	0	0	0	0
M-PS	0	0	0	0	1.3	6.4	3.8	10.5	35.2	19.3	15.1	5.3	2.8	0.3	0	0	0	0
O-RB	0.7	5.3	7.3	16.3	16.0	28.2	16.8	6.3	2.8	0.3	0	0	0	0	0	0	0	0
G-GN	0	0	0	0	0	0	0	0	0	0.3	8.9	7.1	18.9	25.4	37.9	0.9	0.6	0
M-PB	0	0	0	0	0	0	0	0	0.1	0.5	3.0	16.6	21.7	33.5	23.1	1.5	0	0
O-PE	0.2	5.0	4.8	9.6	17.4	15.4	27.5	12.5	5.9	1.6	0.1	0	0	0	0	0	0	0
R-MA	0	0.2	0.7	1.2	1.8	4.1	6.7	24.4	24.8	33.5	2.4	0.2	0	0	0	0	0	0
G-LY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	23.0	40.7	35.8
R-VS	0	0	0	0	0	0.3	0.4	1.3	10.0	15.1	43.8	18.0	9.1	2.0	0	0	0	0
O-MO	0	0	0	0	0	0	0	0.4	1.4	4.7	20.7	45.9	17.8	8.7	0.4	0	0	0
R-SS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0	48.1	46.5	4.4
O-IF	0	0	0	0	0	0	0	0	0	0.1	1.0	4.5	28.7	29.9	34.3	1.2	0.3	0
R-SB	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	2.8	25.3	11.9	59.8

Table 3
Percentage of occurrence of each Reunion and Rodrigues site at each TOPSIS ranking position (1 to 8) for the 1000 iterations of IS_{Tot}^{25} (left) and IS_{Tot}^{50} (right). The analyses included the recruitment rate on artificial tiles. White: 0 %; yellow: 0 < % ≤ 25 %; orange: 25 < % ≤ 50 %; light red: 50 < % ≤ 75 %; dark red: 75 < % ≤100 %. Diagonal values correspond to the positions observed for each site with the IS_{Tot}.

Position	1	2	3	4	5	6	7	8
R-SB	24.2	61.1	14.7	0	0	0	0	0
R-VS	75.8	24.2	0	0	0	0	0	0
R-MA	0	14.3	81.0	4.7	0	0	0	0
O-RB	0	0.4	4.3	95.3	0	0	0	0
O-PE	0	0	0	0	100.0	0	0	0
R-SS	0	0	0	0	0	56.0	44.0	0
O-MO	0	0	0	0	0	44.0	56.0	0
O-IF	0	0	0	0	0	0	0	100.0

Position	1	2	3	4	5	6	7	8
R-SB	20.5	35.3	32.5	9.2	2.5	0	0	0
R-VS	60.6	36.5	2.8	0.1	0	0	0	0
R-MA	11.7	16.9	46.5	13.9	11.0	0	0	0
O-RB	7.2	8.7	12.5	71.4	0.2	0	0	0
O-PE	0	2.6	5.7	5.4	86.3	0	0	0
R-SS	0	0	0	0	0	43.4	45.8	10.8
O-MO	0	0	0	0	0	56.5	41.3	2.2
O-IF	0	0	0	0	0	0.1	12.9	87.0

sites, and matches previous observations by Hardman et al. (2008) that emphasize relatively high resilience of these reefs. However, data were collected between four months (coral cover) and two years (herbivorous fish biomass) after the bleaching event, *i.e.*, at different steps in the recovery process, which probably had an impact on the *RI* values.

Reunion reefs had the lowest measured *RI*s (0.30 compared to 0.42 on average in Rodrigues). The reefs around Reunion are geologically young and weakly developed, and close to the coast, the reef front being maximum 500 m apart from the coastline. This proximity leads to many anthropogenic pressures that compromise the recovery potential of these reefs: eutrophication, pollution, freshwater inputs or overfishing, which are known to hamper recovery (McClanahan et al., 2012) are particularly prevalent, especially compared to the nearly uninhabited Îles Éparses (Bigot et al., 2019; Naim et al., 2013; Riaux-Gobin et al.,

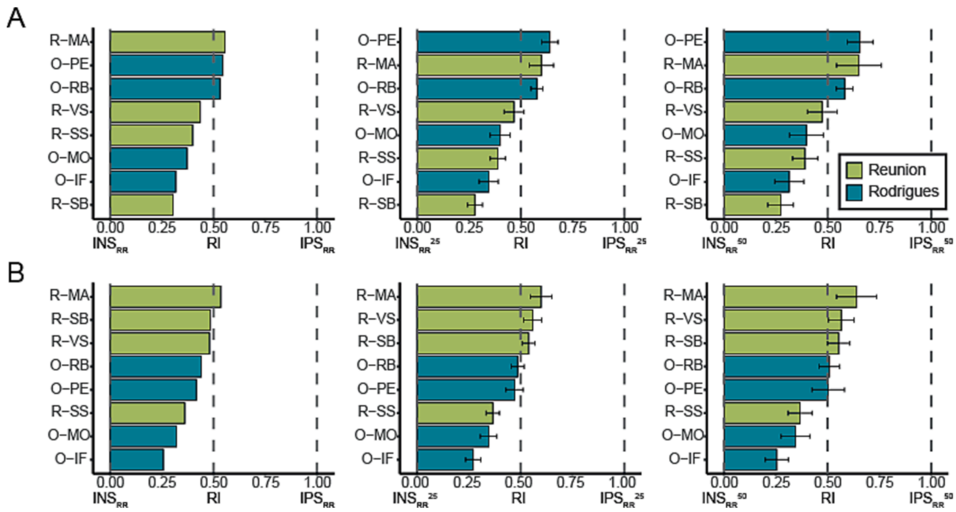

Fig. 7. Ranking of the Reunion and Rodrigues reef sites according to their recovery potential evaluated through the TOPSIS relative index (RI). A) without the recruitment rate variable; B) including the recruitment rate variable. In each case, INS/IPS are based on values measured from the eight sampling sites of Reunion and Rodrigues islands (ISRR). The three columns show results from using the extreme values (left), the 25% quantiles (middle), and 50% quantiles of the distributions (right).

2011). This is reflected in low total fish biomass on reef slopes compared with other studied islands, which can hamper recovery following severe disturbances (Graham et al., 2015). In contrast, frequent and strong cyclones and oceanic swell may have led to configurations of coral communities that benefit recovery. For example, wave-induced disturbance in 2007 has significantly reduced the cover of *Acropora* (Bigot et al., 2019), leading to an increased prevalence of stress-tolerant coral species at several sites, especially R-MA and R-vS This can partly explain the lower impact of the 2016 bleaching event on Reunion reefs compared to Rodrigues (Nicet et al., 2016; Obura et al., 2017). Overall, unlike Rodrigues, the variations in *RI* around Reunion were consistent with the geographical position of the sites: the reefs of Saint-Leu in the south (R-MA and R-VS) appear to have higher recovery potential than the reefs of La Saline in the north (R-SS and R-SB). However, as for Rodrigues reefs, these variations were not related to the protection status of the sites.

Overall, although our assessment is not based on temporally-replicated time-series, the ranking obtained using the TOPSIS method appears relatively consistent with responses of the studied sites to recent disturbances. However, results also revealed the overall absence of a relationship between reef recovery potential and the level of protection (outside or within a no-take zone or no-entry zone). Indeed, for Reunion, Rodrigues and Mayotte (where sites exhibit different levels of protection), the sites where fishing or human presence are excluded did not systematically vary in their *RI* scores compared to unmanaged sites.

4.2. The TOPSIS method: Strengths and limitations in the context of the reef recovery assessment

In order to be widely used, indices based on multi-criteria methods need to be easy to compute (Saaty and Ergu, 2015). In our case, this was particularly important since wide applicability across a large scale is desirable. From this perspective, the TOPSIS method seems interesting as its implementation does not require particular software (the entire method can be implemented using an excel data sheet or an R environment), analytical training, or computing power (Parkan and Wu, 1997).

The value of multi-criteria analyses hinges on a sufficient number of variables to highlight the problem to be solved (Saaty and Ergu, 2015). In our case, these variables were selected using two criteria: 1) their relevance to assess recovery potential, following McClanahan et al. (2012) and 2) the fact that they had to be easy to obtain, or ideally already available from previous studies. We used eight variables that are frequently measured in reef monitoring programs worldwide (see for example Chabanet et al., 2016; Heenan and Williams, 2013; Obura et al., 2017), and have been emphasized as relevant for reef recovery (McClanahan et al., 2012). While some of these variables are also relevant to assess reef health, we focused on factors influencing coral reef recovery, and weighted them using expert judgment. However, we also observed that the addition of coral recruitment rates measured on artificial tiles greatly changed the *RI* ranking of the sites in Reunion and Rodrigues, while stabilizing rankings when ideal solutions were randomly sub-sampled within the 25 to 50 % of extreme values of the variables. This suggests that addition of further uncorrelated variables would increase the robustness of the method. These variables could be related to nutrient load (pollution), sedimentation, connectivity, substrate suitability or coral growth rate (McClanahan et al., 2012), as well as more process-based variables that quantify coral reef ecosystem functioning (Brandl et al., 2019). However, these variables are challenging to collect over large geographical scales. The variables used in the present study allowed us to gather the state-of-the-art knowledge about reef resilience, were obtainable across large spatial scales, and proved relevant to cross-regional management.

The TOPSIS analysis showed that, when comparing *IS* based on minimum and maximum values ($IS_{\mathrm{Tot/RR}}$) to randomly sampled $IS^{25}_{Tot/RR}$ and $IS^{50}_{Tot/RR}$, *RI* values can differ substantially. This raises the question of which approach is most appropriate to compare alternatives. One of the classic shortfalls of TOPSIS is "rank reversal", where the addition of an alternative (in our case, another site) results in a significant change in the ranking by introducing new extreme values, which may lead to wrong decision-making (García-Cascales and Lamata, 2012; Wang and Luo, 2009). In the context of reef recovery, the rank reversal problem arises differently. An ideal solution for one site may be considered sub-optimal for another, therefore a variation in *IS*, regardless of its origin, will result in changing rankings. Yet, this variation reflects an ecological reality and it is an important element to be taken into account in the decision-making process. The re-sampling routine presented here, where variable values are not only taken from the extremes but from their extreme quantiles, may represent a viable solution to achieve more robust outcomes. The use of a variable *IS* could also provide a solution to the inherent lack of baseline data on the status of coral reefs. The establishment of a reference state (a "healthy" reference for recovery) requires long-term monitoring of reefs (which is rare), but even then, the reference state of a reef is constantly evolving and may be impossible to pinpoint. Comparing observed values with samples from the higher quantiles of the TOPSIS distribution may provide the most robust benchmark we can muster. The $IS^{25}_{Tot/RR}$ yielded a relatively stable ranking that was generally consistent with previous recovery dynamics on the studied reefs. Thus, it could provide a simple and effective solution to improve the TOPSIS robustness in applied ecological frameworks. Notably, rankings obtained with the $IS^{50}_{Tot/RR}$ were similar but not identical to those obtained with the $IS^{25}_{Tot/RR}$. However, the $IS_{Tot/RR}{}^{50}$ diverges strongly from the objective of comparing sites to an "optimal" reference. Indeed, using the $IS^{50}_{Tot/RR}$, ideal positive and negative solutions may haphazardly yield similar values. This may also explain why, for the $IS^{50}_{Tot/RR}$, the ranking of each site varied considerably across iterations.

Overall, the TOPSIS method based on a range of variables classically considered in reef monitoring programs appear to yield a meaningful index that can characterize reef sites based on their potential to recover from disturbance. Although the index is not yet optimized, particularly in terms of choosing the ideal solutions, it promises to be a valuable tool to support RBM. The presented index clearly avoided the issue of reflecting current health status rather than reef resilience, since strong recovery potentials were attributed to some reefs that were generally considered to be in poor health (*e.g.,* Rodrigues, which suffered from the severe 2016 bleaching event, resulting in low coral cover or coral density). To optimize this index and fully assess its potential, comparisons of empirical recovery rates with the obtained *RI*s from this study would be valuable. Although the index derived through the TOPSIS method cannot replace detailed multivariate data that describe coral reef processes through time, it may provide means to gauge potential trajectories of reefs based on widely accessible variables.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.109952.

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