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REVIEW

Strengthening resilience potential assessments for coral reef management

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Abstract

1. The persistence of diverse yet threatened ecosystems like coral reefs will require urgent action underpinned by effective assessments of resilience. Resilience potential assessments are commonly used to identify coral reefs likely to be more resilient to disturbances, based on indicators of state and function.
2. Assessments are intended to support decision-making, therefore, using principles from decision-science and indicator design theory, we evaluated the selection, design and analysis of indicators from 68 resilience potential assessments conducted between 2008 and 2022. These principles include justifying and testing indicators and aggregation approaches, representing key parts of the ecosystem, considering uncertainty and meaningful normalisation of indicators.
3. Although a broad range of indicators were typically evaluated, assessments rarely present structured processes to guide and justify indicator selection, such as selection criteria and conceptual models of ecosystem function. We also found that certain key ecosystem components that confer resilience were represented by indicators in almost all assessments, such as corals, herbivory, competition and reef structure. Other factors were rarely considered, such as abundance and diversity of key fish trophic groups other than herbivores, for example groupers and corallivores, other aspects of biodiversity and competitive interactions with corals. Reference points used to translate variables into resilience indicators were typically derived from the data, such as the highest indicator value of assessed sites. Ecologically meaningful thresholds, such as collapse or historic levels, were used less often as references. In most cases, indicators were not tested or validated against independent data, uncertainties were not presented, and there was a tendency to simplify results into composite indices to rank sites, without justifying aggregation methods.
4. Despite resource constraints, most resilience potential assessments collect quantitative data that are useful for coral reef management. However, the shortcomings identified can make indicator interpretation difficult, limiting the capacity to predict the resilience of the system and support decisions. Implementation of robust approaches drawn from indicator design and selection

theory can help strengthen resilience potential assessments of coral reefs and other ecosystems, ultimately improving the prospects of conservation.

KEYWORDS
assessment, coral reef, decision-support, ecosystem, indicator, management, resilience, resistance

1 | INTRODUCTION

Coral reefs are one of the most biodiverse and valuable ecosystem types in the world (Adey, 2000; Anthony et al., 2017) but are also among the most threatened (Bellwood et al., 2019; Burke et al., 2011; Halpern et al., 2015; Hoegh-Guldberg et al., 2017) due to climate-driven and local pressures increasing in magnitude and frequency (Anthony et al., 2017; Beyer et al., 2018; Costa et al., 2020). Effective assessments are critical to making informed decisions about reef management and conservation (Dixon et al., 2021; Obura et al., 2019; Pressey et al., 2017). A clear priority is identifying which reefs are likely to be more resilient to disturbances and therefore retain their biodiversity, ecosystem function and values (Darling & Côté, 2018; Hock et al., 2017; Macharia et al., 2016).

Resilience-based management takes a dynamic and adaptive perspective to enhancing natural processes that promote resilience and can include social and ecological dimensions (Gibbs & West, 2019; Harvey et al., 2018; Mcleod et al., 2019; Nyström et al., 2008). Ecological resilience is the capacity of an ecosystem to maintain or recover state, functioning and structure following a disturbance (see Box 1). Despite the potential of resilience-based management, it remains underused in reef management and conservation planning particularly in developing countries (Bates et al., 2019; Roche et al., 2018), in part due to difficulties operationalising the concept of resilience (Angeler & Allen, 2016; Maynard et al., 2010; Mumby et al., 2014). A clear definition of ecological resilience and the indicators to quantify it are necessary foundations for operationalisation in management (Box 1), but their interpretation and implementation vary globally (Lam et al., 2017; Maynard et al., 2017; Standish et al., 2014).

Early work to include resilience in management for example by Obura (2005), Obura et al. (2006), Salm et al. (2001), and West and Salm (2003) culminated in the first formalised method to assess the ecological resilience 'potential' of coral reefs, based on 61 resilience indicators (Obura & Grimsditch, 2009). *Resilience potential assessments* have since become the most widely used method for operationalising coral reef resilience globally (McLeod et al., 2021). The assessments can be used as decision-support tools providing reef managers with locally contextualised information to prioritise areas and actions for protection (Bachtiar et al., 2019; Ladd & Collado-Vides, 2013; McLeod et al., 2021).

Science for environmental decision-making and indicator design has developed over the last two decades (Bundy et al., 2019),

BOX 1 What is resilience and how can it be used in coral reef management.

"Resilience" was initially defined for ecosystems by Holling in the 1970s as the ability of systems to 'absorb change and disturbance and still maintain the same relationships between populations or state variables' (Holling, 1973). It has since been used in diverse ways for a range of complex systems. For example, "engineering resilience" is the rate of recovery to an ecosystem's original state following a perturbation, while "ecological resilience", applies to systems with multiple stable states, and relates to shifts to alternate states (Angeler & Allen, 2016; Nyström et al., 2008). Our definition aligns with Holling's statement, while still being contemporary: ecological resilience is the capacity of an ecosystem to maintain or recover state, functioning and structure following a disturbance (Cumming et al., 2017; Harvey et al., 2018; Roche et al., 2018; Standish et al., 2014).

Resilience has largely been an academic pursuit, due to challenges in making it operational for use by managers and policy makers (Maynard et al., 2010; Mumby et al., 2014; Obura, 2005; West & Salm, 2003). One proposal for a simple, practical path forward to make the concept of ecological resilience useful for management application is through resilience potential assessments. Resilience potential is a proxy for actual resilience and does not measure it directly. Instead, it tries to predict the 'potential' of reefs to respond to disturbances and has already been applied in several countries around the world (Lam et al., 2020; McLeod et al., 2021). This is generally done using quantitative indicators of ecosystem processes and features that influence resisting a disturbance (e.g. thermal sensitivity of coral community) and/or recovering from it (e.g. coral recruitment, herbivory). Multiple indicators are then typically combined into composite indices, and reefs ranked based on resilience potential, threats faced and other factors. Ecological aspects of resilience can also be considered alongside dimensions of socio-economic resilience and governance (Cinner & Barnes, 2019).

concurrent with developments in resilience science (Angeler & Allen, 2016; Cumming et al., 2017; Roff & Mumby, 2012). This body of theory could strengthen the capacity of resilience potential assessments and other indices of ecosystem condition and integrity (Grantham et al., 2020; Hill et al., 2022; Karr, 1981) to support management decisions. Multiple frameworks have been developed for designing, selecting, and evaluating indicators, including applications of decision theory (Possingham et al., 2001; Watermeyer et al., 2021), conceptual frameworks and formal selection criteria (Brown et al., 2021; Bundy et al., 2019; Failing & Gregory, 2003; Keith et al., 2013), and quantitative performance testing (Collen & Nicholson, 2014; Nicholson et al., 2012). Key considerations for indicator construction that emerge from these frameworks include having a clear definition of indicator objectives, consideration of uncertainty, transparency about methods for aggregating indicators into composites, selecting indicators based on explicit criteria and evidence, and testing indicator performance to understand their behaviour and predictive capacity. For instance, conceptual models that describe the key features, relationships and dynamics of a system can provide a foundation for indicator selection, ensuring representation of key components and reducing redundancy in indicator suites (Keith et al., 2013). This is particularly important given the push to use fewer variables mainly for practical reasons (Bang et al., 2021; Maynard et al., 2012; McClanahan et al., 2012).

Given the significant investment and widespread application of resilience potential assessments (McLeod et al., 2021), a review of their design and implementation is needed to ensure robust support for decision-making. We critically evaluated indicator selection, design and analysis of 68 resilience potential assessments conducted between 2008 and 2022 against guidelines and principles drawn from indicator science (including biodiversity conservation and fisheries management) and resilience potential assessments (Brown et al., 2021; Burgass et al., 2017; Lam et al., 2020; McLeod et al., 2021). Our objectives were to

1. identify the most commonly used resilience indicators and evaluate the representation of key ecosystem components that confer resilience;
2. identify areas for improvement in current resilience potential assessment methodologies by assessing how closely they align with best principles for indicator design and selection; and
3. provide recommendations to make resilience potential and other biodiversity and ecosystem assessments more systematic, robust and reliable, thereby enhance their applicability for use in management.

2 | METHODS

We compiled a list of assessments to review from three sources: (1) 65 resilience assessments compiled by McLeod et al. (2021) until April 2018, (2) a systematic review, and (3) ad-hoc searches and incidental finds. We located publications for 55 of the 65 assessments listed in McLeod et al. (2021). The systematic literature review was based on similar search terms and methods from McLeod et al. (2021) and searched for assessments published since April 2018. The search was conducted on Web of Science, Directory of Open Access Journals (DOAJ), and Google in April 2022, using the following search terms: reef AND resilience AND [assessment OR assess* OR monitoring]. Our search returned a total of 964 results (Google search limited to first 50 hits) across the three search topics, with 42 publications meeting our criteria for further review. We came across a further 20 assessments from ad-hoc searches and incidental finds, resulting in a total of 117 studies for further examination.

To qualify for inclusion in our analysis, resilience potential assessments had to: (1) examine the ecological resilience of coral reefs; (2) contain two or more ecological indicators, spanning more than one ecosystem component (see definition below and in Table S1: Glossary of key terms); (3) be quantitative or semi-quantitative; and (4) measure or infer how reefs would respond to disturbance in the future (Tables S2 and S3). These criteria and key characteristics helped to differentiate resilience potential assessments from related assessments such as state (e.g. Dahlgren et al., 2016; Safuan et al., 2021), vulnerability (e.g. Maina et al., 2016), risk (e.g. Bland et al., 2017; Obura et al., 2021) or pressure assessments (e.g. Magris et al., 2018; Williamson et al., 2021). In total, we identified 68 resilience potential assessments that were conducted between 2008 and 2022 across multiple publication types including journal articles, unpublished manuscripts, technical reports, field reports and summary documents (see list of assessments in Methods section of Supporting Information). Assessments were classed as either indicator-based (quantitative indicators) or model-based (using mechanistic and/or statistical models).

Criteria to evaluate resilience potential assessments were informed by prior knowledge of objectives and potential gaps from existing reviews and assessments (Gibbs & West, 2019; Lam et al., 2020; McLeod et al., 2021; Mumby et al., 2014; Roche et al., 2018). Using this information, we identified 28 criteria selected from relevant guidelines and principles from biodiversity indicator science (Bundy et al., 2019; Burgass et al., 2017; Failing & Gregory, 2003; Nicholson et al., 2012; Rowland et al., 2018), fisheries indicators (Brown et al., 2021; Nash & Graham, 2016) and other ecosystem assessment frameworks including the Red List of Ecosystems (RLE; Keith et al., 2013). The following details on the methods and results of each assessment were recorded (see Table S4 for exhaustive list of criteria):

1. *Metadata*: Location/country and region assessments were conducted (Marine Ecoregions of the World (MEOW) realms and provinces).
2. *Objective*: The stated assessment objectives such as measuring resilience potential, conducting other assessment(s) for example biodiversity or state, measuring real-time recovery and/or resistance, and so forth; whether the disturbance(s) that the assessment intends to measure resilience towards was clearly specified; and if a resilience definition was presented.

3. *Indicator selection*: The type and number of indicators used, and whether indicator-selection processes were explicitly reported, including whether a conceptual model (text or diagram) was presented to guide indicator selection; were indicators selected to represent resistance, recovery or both/neither, and were these groups actually assessed (scored) independently.
4. *Analysis and aggregation approaches*: How indicator results were presented, whether independently, aggregated into univariate indices or combined using multivariate analysis.
5. *Uncertainty*: Whether a measure of variance was presented alongside scores, and any mention of the quality of data and its effect on results including presenting qualitative or quantitative data quality scores.
6. *Performance testing*: Whether indicators were evaluated across a range of methods, including: capacity to detect change (using empirical or simulated data), sensitivity to changes in weights, redundancy among indicators which may influence the ability to detect trends, measurability and relevance to local reef contexts (Brown et al., 2021; Rowland et al., 2020; Shin et al., 2018); validation of resilience scores either by comparing them to actual disturbance responses or validating model outputs against independent datasets.
7. *Normalisation*: The process of scaling variables between 0 and 1, to convert them into meaningful indicators (Kaiser et al., 2021). We classified reference points used to normalise indicators into two categories: (i) Independent reference, which is any reference not derived from the data such as a 'healthy' benchmark, for example a pristine/remote reef, a reference state or time point, for example historical point before disturbance, or a meaningful resilience/functioning threshold, for example reef net accretion threshold; (ii) within dataset, that is references derived directly from the indicator data, for example highest indicator score across all surveyed sites or conversion to a relative-scale using the range of variable values.
8. *Weighting*: Whether indicators were weighted during aggregation, and the rationale used to determine weights.
9. *Management application*: How assessments informed management prioritisation and what indicators were linked to management interventions.

We developed a conceptual model to represent the main factors (features and processes) that confer resilience on coral reefs, based on theory on functioning and resilience (see Table S5 for justification for inclusion; McClanahan et al., 2012; Mumby et al., 2014; Nyström et al., 2008; Rogers, 2013; Timpane-Padgham et al., 2017). We illustrated this diagrammatically (Figure 1) following the approach of past resilience and ecosystem risk assessments (Bland et al., 2017; Lee et al., 2021; Obura et al., 2021; Obura & Grimsditch, 2009). We identified eight ecosystem components which affect the ability to maintain the dominance and functionality of the keystone taxonomic group, hard corals, including five essential components and three complementary components: Essential: (i) hard corals, (ii) fish, (iii) competitors to corals, (iv) abiotic environment, (v) reef structure; complementary: (vi) other biodiversity, (vii) corallivores, bioeroders and invasives, (viii) microbiome and symbiodinium. Complementary components were classed as such mainly due to difficulties with measuring them and less certainty regarding their influence on resilience. This sets three positive components (corals that create reef structure especially for fish) against destructive components such as competitors to corals (mostly macroalgae) and abiotic environment (mostly acute warming that bleaches corals). Each ecosystem component consists of sub-components, for example coral had abundance, diversity, condition (e.g. disease), reproduction, demography and thermal tolerance, and competitors to coral was split into abundance, competition level and herbivory (see Table S5 for full list).

We examined the representation of coral reef ecosystem components (Figure 1) in each assessment based on if any resilience indicators were used to represent them. If all the essential components and at least one of the three complementary components were represented, the assessment was considered effectively covered, but if none of the three complementary components were represented, the assessment was deemed to have complementary gaps. Herbivorous fish were usually included in assessments as proxy measures of food web disruptions to herbivory of macroalgae and were therefore considered as a subcomponent under competition to corals. Therefore, the fish component only considered non-herbivore fish groups and indicators.

3 | RESULTS

3.1 | Resilience assessment type

While resilience potential assessments have been conducted in every major tropical ocean basin, they are not evenly distributed, with most assessments conducted in the Western Indian Ocean ($n=12$), Western Coral Triangle (11) and Sunda Shelf (9), while no assessments were found for 16 of the 33 MEOW provinces (Figure 2, Table S6). Almost all assessments were empirical indicator-based assessments ($n=63$), while five were model-based (mechanistic, statistical or a combination). Most assessments were from journal articles ($n=30$) or technical reports ($n=24$).

Measuring resilience potential was stated as an objective by 90% of assessments, with 27% of resilience assessments being part of wider assessments such as biodiversity or state assessments (Figure S1). A definition of resilience was presented in 46 of the 68 assessments reviewed. The most common disturbance specified ($n=36$ assessments) was climate change related to thermal stress and bleaching (Figure S2), while 28 assessments did not specify the disturbance(s) they were assessing the resilience for. Resistance and recovery were scored separately in 20 assessments.

3.2 | Resilience indicator selection

Indicator selection criteria were presented in 19 of the 68 assessments, of which two presented an evaluation against the criteria.

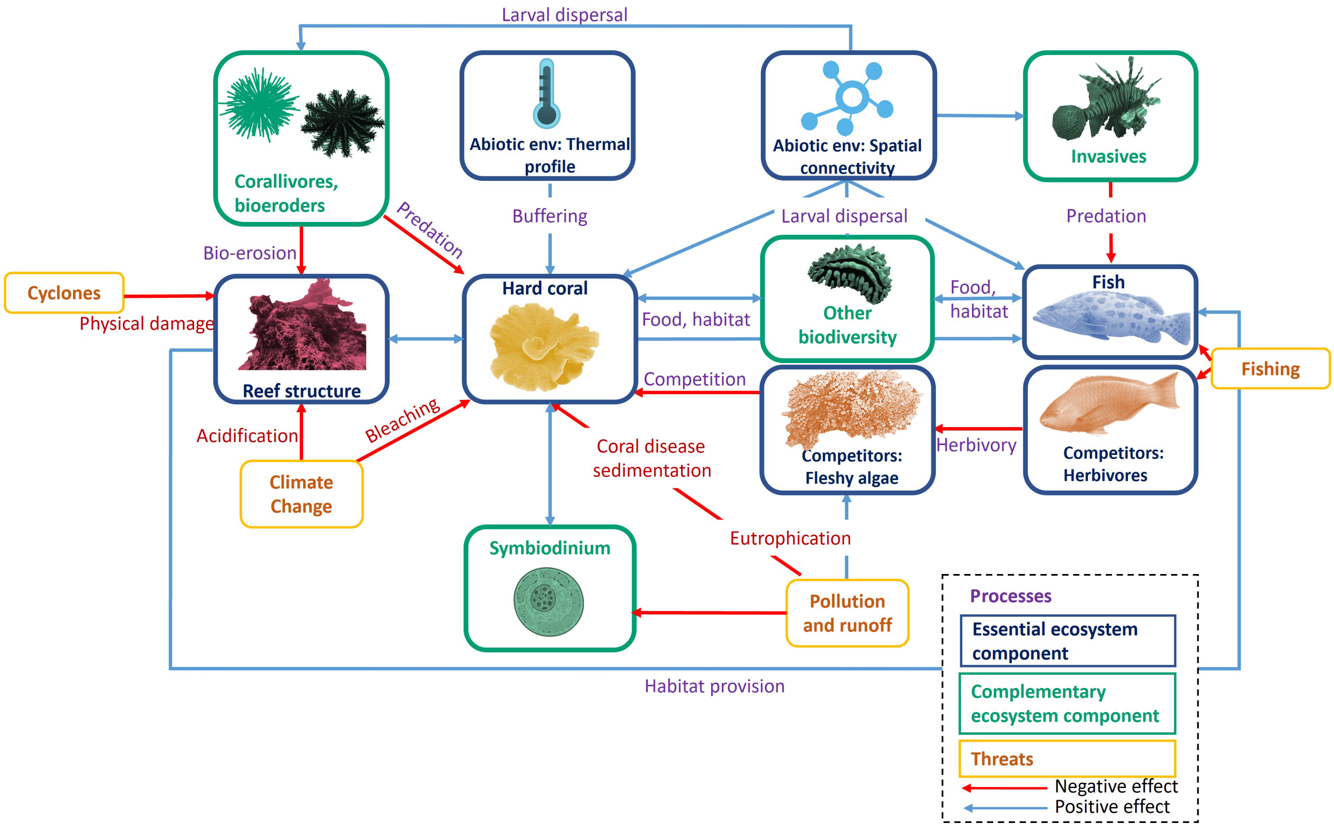

FIGURE 1 Conceptual model featuring the "essential" and "complementary" ecosystem components: features and processes that maintain ecological functioning and confer resilience for coral reef ecosystems, as well as some key pressures and the relationships between them. Thermal profile refers to the long-term temperature profile at a reef. Climate change affects multiple components to varying degrees, for example connectivity, but here we simplify it to show the two main direct impacts of climate change on corals with regards to acidification and bleaching.

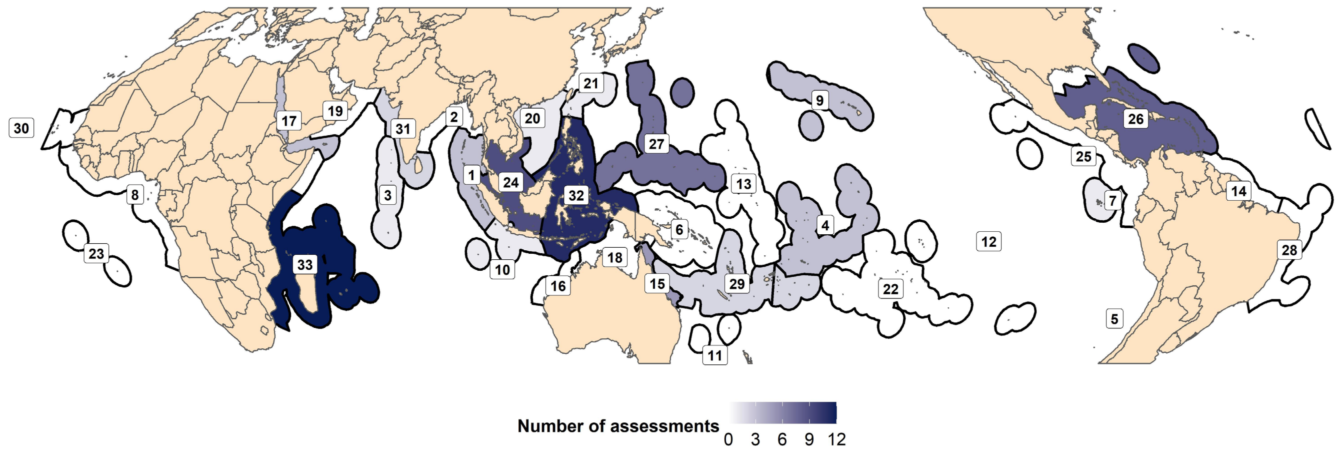

FIGURE 2 Coral reef-containing provinces according to the Marine Ecoregions of the World (Spalding et al., 2007), colour-coded by the number of resilience potential assessments analysed in this systematic review, from zero (white) to 12 (dark blue).

Most assessments ($n=30$) only provided references to support indicator selection (sometimes accompanied by a brief statement), while 12 assessments simply listed their indicators without providing any selection criteria, reference, or justification. A conceptual model of ecosystem functioning was not included in most assessments ($n=49$) but was described explicitly in text or diagrammatically in 16 and 3 assessments, respectively.

The five most-used indicators were coral abundance (including coral cover), coral recruitment, herbivore abundance, fleshy algae levels and substrate suitability (Figure 3, Table S7). Five assessments had incomplete or no information on the indicators used. All assessments (with a complete set of indicators) included a measure of corals (Figure 3). Competitors (competition) to coral was represented in 94% of assessments mainly by fleshy algae and herbivore (mainly

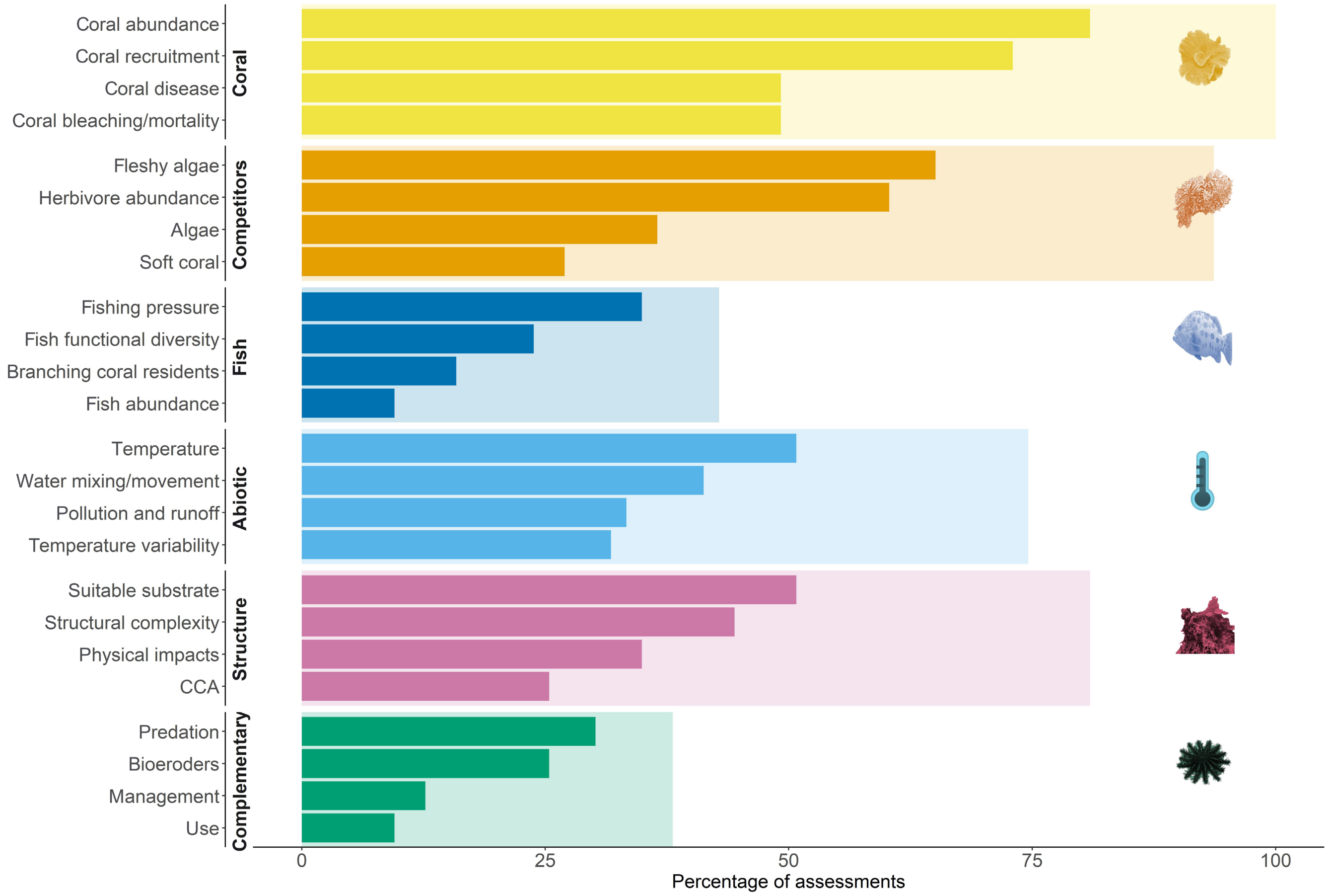

FIGURE 3 The percentage of resilience potential assessments in which resilience indicators and corresponding ecosystem components were represented. The pale, wide bars represent the total percentage of assessments where each ecosystem component was represented: coral, competitors to coral, fish, abiotic environment, reef structure and complementary components. The narrow bars within each show the four most frequently used indicators, ordered from highest to lowest. $n = 63$ assessments (five assessments did not provide a comprehensive indicator list and hence were excluded).

fish) abundance indicators. Non-herbivore fish abundance and diversity indicators were included in 41% of assessments, with fishing pressure as a proxy the most commonly used indicator.

Abiotic environmental indicators such as temperature variability, pollution and spatial connectivity were measured in 75% of assessments. Indicators of reef structure (habitat availability and quality) were included in 81% of assessments, for example suitable substrate and structural complexity. Additionally, 38% of assessments included indicators of complementary resilience components, with various indicators of corallivores such as crown-of-thorns, and indicators of bioeroders such as urchins. No assessments included a measure of the micro-biome or zooxanthellae/symbiodinium communities, and four assessments included other biodiversity (lobsters, plankton abundance and density of inverts such as mollusca, crustacea and polychaeta; Table S7).

Twenty-two assessments included indicators representing all five essential ecosystem components, of which 16 assessments covered all components (essential and complementary; Figure S3). Out of the assessments that did not cover all essential ecosystem components, five missed three components, 17 missed two and 19 assessments missed one component (most commonly fish, Figure S3).

Testing indicators was considered and/or done in 15 assessments, specifically indicator sensitivity ($n = 7$), redundancy ($n = 7$), measurability ($n = 2$) and relevance ($n = 1$). Validation of resilience scores was undertaken in seven assessments, out of which two were model-based. An additional five assessments discussed validating results, while 56 assessments did not present a consideration or test.

3.3 | Analysis and aggregation approaches

In ten assessments, the same data were used to calculate multiple indicators, while another ten did not clearly present the underlying data used for all indicators. Fifty-seven assessments did not present the issue of data quality in their publications, 11 assessments presented discussions regarding resolution (temporal and spatial) or measurement error, but no assessments included qualitative or quantitative data quality scores.

Variance, variation or uncertainty in indicator values was not presented in 39 assessments but was presented at the spatial-unit of assessment (e.g. reef or site) in six assessments. For the composite score, six assessments presented the variance at the spatial-unit. The most common intervals of variance included standard deviation, standard error, maximum and minimum values, and inter quartile range (IQR).

Resilience indicators were combined into a composite index in 50 of the 68 assessments, while nine assessments did not combine indicators, four assessments had uncertain methods, and five assessments used model-based approaches such as statistical and mechanistic models. Two assessments had unclear methods to derive composites, 44 summed or averaged indicator values to derive a single resilience score, and four used other methods such as geometric means of component scores, technique for order preference by similarity to ideal solution (TOPSIS), bootstrapping individual reef indicator values and principal component analysis. Most assessments presented the results of at least some individual indicators ($n=40$), with the rest presenting composite (aggregated) index results only ($n=28$). Of the 50 assessments that produced a composite index, the weighting scheme was unclear for 10 assessments, 29 used equal weights, 10 used unequal weights and one used multiple weighting schemes. Justification for weightings was not reported in 36 assessments, and this includes all but three of the equally weighted assessments (Figure S4).

3.4 | Normalisation

Fifty-four of the 63 indicator-based assessments normalised indicators, with the methods unclear in a further three assessments. Overall, 26 assessments used within-dataset references to normalise variables (e.g. against the highest variable score across all surveyed reef areas, or used the range of indicator values across survey sites to estimate or convert their indicators to a semi-quantitative ordinal scale), 16 used independent reference points (e.g. regional or global references of good and poor reef conditions, maximum and minimum possible values for an indicator, potential maximum resilience (maximum value of resilience index), or a reference temporal or spatial state). Thirteen assessments had unknown or unclear reference classes. Additionally, 15 of 17 assessments that undertook normalisation of aggregated final scores, did so by anchoring against the site with the highest score.

3.5 | Management application

Half of the assessments specified identifying management actions or areas in their objectives (Figure S1). Of the assessments with a management focus, two reported tangible management outcomes: no-anchoring sites in the Great Barrier Reef and a seascape zonation plan in Djibouti. Eighteen (18) assessments conducted analytical evaluations to provide management recommendations through query-based criteria approaches ($n=6$ assessments), calculation of management influence ($n=8$) and anthropogenic stress scores ($n=4$), and scenario-based modelling ($n=2$). Twenty-three (23) assessments provided detailed descriptive management recommendations, while 12 assessments made no connection to management applications.

A total of 67 management interventions were mentioned or suggested across all assessments, including those already implemented as well as those theoretically informed by the assessment results. We grouped them into eight broad types of management (Figure 4), with area-based approaches being the most popular ($n=28$ assessments), followed by water quality and fishery ($n=26$ assessments) interventions. The most common specific interventions included land-based pollution and sedimentation management ($n=22$), establishment of Marine Protected Area (MPA)/MPA networks ($n=19$), and restoration in the form of coral gardening ($n=13$; Figure 4).

A total of 24 management interventions were directly linked to 65 indicators across all the assessments which conducted a prescriptive management process (Table S8). The most common interventions included identifying areas to establish MPAs and No Take Areas ($n=12$ assessments), fishery management ($n=9$), and land-based pollution and sedimentation management ($n=9$; Table S9). Overall resilience potential levels were used to prioritise 13 interventions, and coral cover, fish biomass, herbivore fish biomass, and incidence of anthropogenic physical impacts indicators were used for six interventions (Table S8).

4 | DISCUSSION

Over the last 15 years, resilience potential assessments have been implemented in almost every major coral reef region in the world (Figure 2). While all assessments used established protocols, few applied (or reported use of) structured approaches for selection of indicators (e.g. Niemeijer & de Groot, 2008; Rice & Rochet, 2005). Implementing such approaches, as has been done in fisheries science (Shin et al., 2018), could improve clarity of purpose and remedy gaps in representation of ecosystem components. Our review also highlights the importance of producing indicators that can be interpreted meaningfully and reliably, which results from the choice of reference levels for normalisation, indicator aggregation approaches and consideration of uncertainty. We provide recommendations for improving resilience potential assessments, which can also be applied to other biodiversity and ecosystem assessments.

4.1 | Selection of resilience indicators

For assessments and indicators to be fit for use, a clear purpose needs to be articulated (Kaiser et al., 2021). While most of the assessments we reviewed defined resilience, almost half did not explicitly state the key disturbance(s) or threat(s) that reefs faced. This is important because different disturbances can impact reefs

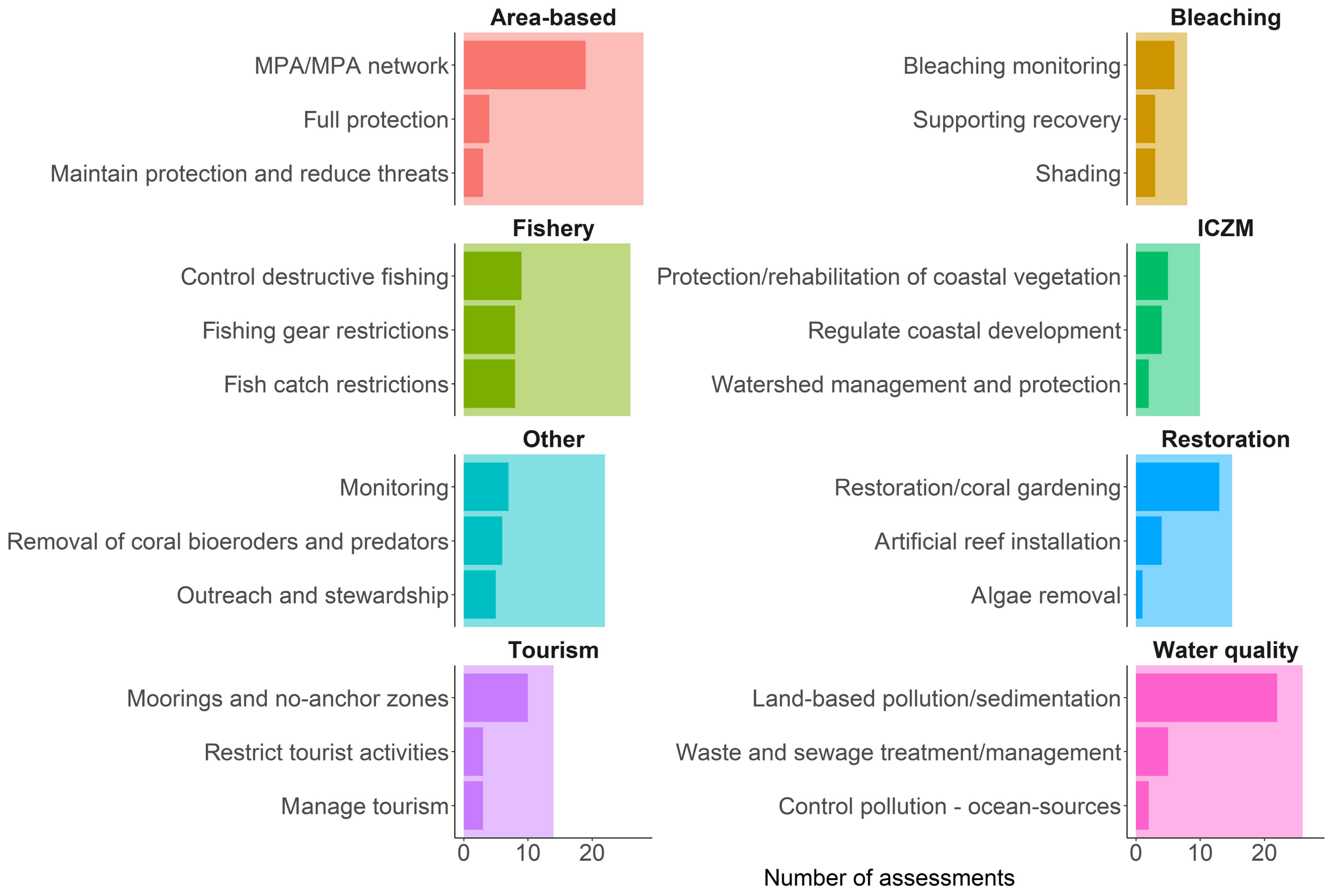

FIGURE 4 Management interventions used in management recommendation and prioritisation processes in resilience potential assessments, categorised by intervention type. The pale, wide bars indicate the total number of assessments that included each management type, while the bars within each category represent the top three most commonly used interventions.

in diverse ways, resulting in different ecological and management responses. Specifying the focus of the assessment can also help narrow down the resilience factors and indicators that need to be considered. Additionally, it is essential to recognise that resistance to and recovery from a disturbance such as bleaching are distinct processes and should be evaluated separately (Obura, 2005; West & Salm, 2003). This approach offers nuanced information about reef performance, for instance, a reef could have strong recovery potential but weak resistance.

Although a broad range of indicators were typically evaluated in the assessments, few described an explicit process for selecting them; in some cases, the indicators used were not listed clearly. Transparency and repeatability issues can arise due to the subjective nature of indicator selection, therefore reporting the selection process is important (Rice & Rochet, 2005), at the very least providing references to published studies (e.g. manipulative or field experiments) that demonstrate how ecological processes confer resilience in the focal region (for example Hughes et al., 2007; Mumby et al., 2007, 2013). A structured selection process can also provide a clearer understanding of what components of the reef ecosystem are reflected by specific indicators (Nash & Graham, 2016). Conceptual models of ecosystem functioning were rarely explicitly presented, though one was the basis of the original resilience assessment approach by Obura and Grimsditch (2009). Such models are integral in recognised assessment methods like the Red List of Ecosystems, as they can provide a transparent and shared understanding of ecosystem function, and can help identify crucial processes and features that require consideration (Rowland et al., 2018). Studies that use mechanistic models tend to develop and present good examples of cause-effect models (for example Bland et al., 2017; Bozec et al., 2022; Melbourne-Thomas et al., 2011).

To provide a more holistic view of ecological resilience, indicator selection should aim for comprehensive coverage (Mumby et al., 2014), and we provide a framework of key ecosystem components to consider when assessing resilience potential of coral reefs. However, as resilience assessments have evolved, they have tended towards using fewer indicators, due to practical reasons such as data availability and survey effort. This is supported by studies that compare results from different numbers of indicators (Bang et al., 2021; Maynard et al., 2012; McClanahan et al., 2012). Several assessments and methods consider and use a subset of 12 priority resilience indicators from McClanahan et al. (2012), but these smaller subsets risk missing important ecosystem components and factors important to management (Obura & Grimsditch, 2009). Unsurprisingly, corals (via indicators such as abundance/cover, diversity, thermal tolerance, condition, recruitment), and coral competition (algae cover, herbivore biomass/density) are well covered across all assessments. Coral and algae cover are considered essential ocean variables, and widely monitored and used in global status reporting of coral reefs, while herbivory is considered a critical reef resilience process (Miloslavich et al., 2018; Muller-Karger et al., 2018; Obura et al., 2019; Steneck et al., 2019). However, the majority of assessments were missing at least one essential ecosystem component, most commonly fish (abundance and diversity). Other major gaps in indicator groups were competitive interactions with corals, and measures of other biodiversity including coral predators and bioeroders. The complexity of collecting data is a barrier to including measures of the micro-biome and zooxanthellae communities, which are key components for driving resistance to warming and disease (Berkelmans & van Oppen, 2006).

4.2 | Indicator testing

Most assessments did not present any validation of their results, thus it remains uncertain whether predictions accurately reflect the resilience of the system (Gibbs & West, 2019; Roche et al., 2018). Testing is equally necessary for both indicator-based and model-based assessments, despite rarely being applied in the former. Rigorous testing of model fit and performance against independent empirical data, such as those conducted by Mellin et al. (2019) and Bozec et al. (2022), can provide robust results. There are a range of approaches to indicator testing, including empirical analysis. This involves assessing or monitoring reefs during and/or after disturbance events (e.g. bleaching), to assess whether resilience assessment results match observed resistance (i.e. did reefs with higher scores bleach less?). Composite scores as well as individual indicators can be tested using simple correlations or statistical generalised additive models or regressions. Testing the behaviour and performance of indicators can help elucidate correlations and redundancies among indicators, which is important as these may mask our ability to detect underlying trends (Brown et al., 2021). Testing can also ensure that differences in resilience potential between reef sites is accurately detected, particularly when there is uncertainty around the estimates and indicators are aggregated into a composite index (Mauro et al., 2021).

Our examination revealed that details on the sensitivity of resilience scores to weights, uncertainty, or data gaps and biases were generally not provided. Transparency around data quality, through subjective or quantitative data quality scores was generally missing. Inclusion will help guide data collection and monitoring efforts, inform indicator selection and allow for decisions which consider data uncertainty (Burgass et al., 2017; Collen et al., 2009).

4.3 | Analytical approaches

Most assessments used multiple indicators, thereby capturing multiple pathways to resilience. The aggregation of indicators into a composite resilience score (index) was often used for simplicity and ease of communication, but the methodological decisions made when aggregating indicators, such as the choice of aggregation method impact their performance (e.g. the use of geometric means, rather than an arithmetic mean can emphasise indicators with lower values) (Burgass et al., 2017; Greco et al., 2019; Rowland et al., 2018). Therefore, assessors must endeavour to present explicit details of the steps, decisions and assumptions used in constructing a composite index, including if there are multiple stages of aggregation. Constructing composite indices may generate bias, particularly if the same data is used to calculate multiple indicators, or if there is unequal representation of ecosystem components (Burgass et al., 2017; Rowland et al., 2018). Composite indices may also mask differences between sites through averaging effects (Munda & Nardo, 2009), which is an issue noted in several assessments where no single site emerged as uniquely different from the others.

It is important to consider how each indicator contributes to the overall resilience score, and we encourage assessors to present results for individual indicators, which is often not done. Alternative options to aggregating indicators may be more appropriate such as using the highest (or lowest) value when dealing with multiple indicators that fall under the same theme for example recovery potential (Keith et al., 2013; Reeves et al., 2007). This approach assumes that if a site scores well or poorly for one indicator, it is sufficient to influence recovery (Lam et al., 2020).

Another aspect to consider when aggregating indicators is weighting (Becker et al., 2017). From an ecological perspective, it is unlikely that the processes represented have the same influence on resilience, suggesting assessments should incorporate an unequal weighting scheme based on sound ecological theory (Gómez-Vega & Picazo-Tadeo, 2019; Maynard et al., 2010). However, in most composite indices reviewed here, indicators were weighted equally without explicit justification, suggesting the implications of this weighting scheme on the output were not fully considered. A few assessments used expert-derived, perceived importance of indicators from McClanahan et al. (2012), but to provide more quantitative weightings, assessors could draw from modelling studies which have tested the effect-size of indicators on resilience in different regions (e.g. Darling et al., 2019; Donovan et al., 2021; Graham et al., 2015). Some indicator-based assessments used innovative techniques to determine weights such as principal component analysis (Bachtiar et al., 2019) and sensitivity analysis (Gibbs & West, 2019). Unequal weighting can increase the confidence in the final index by tempering the effect of an indicator with weaker data (Burgass et al., 2017). Additionally, all assumptions, decisions and any testing on weightings should be properly recorded and communicated for repeatability and transparency in interpreting outputs (Brown et al., 2021; Burgass et al., 2017).

Variance intervals can be useful to interpret inter- and intra-site patterns and avoid a false sense of certainty (Rowland et al., 2021), but less than half the assessments presented them. At the spatial unit of assessment (e.g. reef site), measurement error or detectability biases can be estimated for each indicator, while considering the variance of the composite score provides insight into whether there was significant inter-indicator variability at a site. The variance around each indicator mean allows assessors to identify indicators with greater inter-site differences, and the contributing factors can be investigated with potential implications for management.

4.4 | Normalisation

The type of reference (or threshold) used to normalise variables into meaningful indicators of resilience requires careful consideration of the indicator purpose (Kaiser et al., 2021). Reference levels derived independently of the data can provide broader interpretation of indicators within a resilience context and help to differentiate these assessments from other well-accepted assessment types (e.g. state and risk) which often share indicators (Gibbs & West, 2019; Lam et al., 2020; Mumby et al., 2014; Roche et al., 2018). An important research gap is establishing standard global or regional thresholds for common indicators, which are linked to absolute resilience, but some work has been done on this, for example Karr et al., 2015 and the Healthy Reefs Initiative in the Mesoamerican barrier reef. Independent references still enable sites to be compared to one another, but importantly, also allow for comparisons beyond the study area (Mazziotta & Pareto, 2013). To allow different indicators to be more readily compared (Cherchye et al., 2007; Xu et al., 2020), ecosystem risk assessments like the Red List of Ecosystems anchor both lower and upper bounds during normalisation, with change in condition measured relative to collapse and historical level thresholds (Keith et al., 2013). Normalising indicators using within-dataset references for example against the highest indicator score across all assessed sites, makes interpreting final scores more complicated. If all reefs are in a poor condition, then some sites will get a high relative resilience score, which is misleading. Similarly, when all reefs are in good condition, some sites will artificially be classed as having a low resilience potential. For repeat surveys, having a moving reference can mask true changes in resilience potential. For instance, if the highest score for an indicator changes over time, a site's actual condition may improve but yield a lower relative resilience score. Some assessments excluded indicators based on low variation between sites, or because of low prevalence (e.g. disease or COTs; Maynard, 2019; Maynard et al., 2015). However, these indicators can still provide insights on absolute resilience levels. For example, in one assessment, macroalgae cover was excluded for having <1% cover at all sites, despite this being an important sign of strong resilience.

Several assessments employ a two-step normalisation process, normalising final site index (composite) scores against the highest site score to rank sites (Maynard et al., 2017; Salm et al., 2016, 2017). This is redundant, as sites can be ranked using un-normalised aggregate scores. Additionally, it further de-couples scores from the underlying data and introduces another level of pseudo (false)-variance between sites. We recommend that this step should be avoided.

4.5 | Management application

Linking indicators and associated thresholds to management actions is vital for effective management (see Anthony et al., 2015; Flower et al., 2017). We found the majority of assessments had management intent, but most provide descriptive management recommendations only. Some assessments conducted analytical prioritisations of management interventions using over sixty different indicators through query-based approaches, management influence scores and anthropogenic stress scores. But these approaches can be unstructured in the indicators used and how they are considered together. Approaches such as systematic conservation planning (Marxan) for establishing herbivore management areas (Chung et al., 2019), or a decision-tree framework for restoration (Gouezo et al., 2021), are structured and use strongly evidence-based thresholds (decision-triggers). This makes the outputs more amenable for decision-making processes (Addison et al., 2016; Ban et al., 2014; Cook et al., 2013).

Most resilience assessments collect quantitative data that are fundamentally useful for coral reef management and assessment, despite often being done under considerable resource constraints (McLeod et al., 2021). While some of the analysis may be sub-optimal in the context of resilience, if the data are accessible and available for use, they can be re-analysed to improve the accuracy of resilience potential assessments or contribute to broader assessments, such as systematic conservation planning and RLE assessments. The coral reef community has made significant strides in sharing data in recent years, with networks like the Global Coral Reef Monitoring Network bringing together data for regional and global initiatives (Wicquart et al., 2022), and we encourage assessors to continue this trend by making underlying data accessible to a wider audience.

5 | CONCLUSIONS

Effective assessments are critical to making informed decisions about the management and conservation of coral reefs. By capitalising on the latest developments in indicator theory and decision science for environmental management, the recommendations presented here (summarised in Box 2) can strengthen indicator selection, testing, aggregation and normalisation of resilience potential assessments. This can also contribute to establishing a globally

BOX 2 Key recommendations to consider when undertaking a resilience potential assessment. Studies in parentheses serve as the best examples of implementation of particular recommendations.

1. *Indicator selection*—Indicator selection should aim to represent a broad suite of ecosystem components for a more holistic view of ecological resilience.
    - Articulate a clear purpose of the assessment, include a resilience definition and state the relevant disturbance(s)/threat(s) being considered.
    - Use a conceptual model (ideally diagrammatic) to represent key local ecosystem components and resilience factors (Bozec et al., 2022).
    - Use structured approaches for selecting indicators, list all indicators clearly and include those with low prevalence (McClanahan et al., 2012; Thompson et al., 2020).
    - Represent the maximum number of ecosystem components feasible given available data (Ladd & Collado-Vides, 2013).
2. *Indicator testing*—Test the behaviour and performance of indicators to ensure predictions accurately reflect the resilience of the system.
    - Monitor reefs during and after disturbance events to assess agreement between resilience potential results and observed responses (Maynard et al., 2012).
    - Test sensitivity of resilience scores to considerations such as weights, uncertainty, data gaps and biases; assign data quality scores/rankings.
3. *Normalisation*—Carefully consider the type of reference (threshold) used to normalise variables into resilience indicators.
    - Determine and use locally or regionally relevant independent reference levels for indicators, for example meaningful resilience or functioning thresholds such as ideal states, historical conditions (Thompson et al., 2020).
    - Set both upper and lower bounds consistently for all indicators to make them comparable.
    - Avoid normalising (anchoring) aggregated final resilience scores.
4. *Composite indicators*—Carefully consider the methodological decisions, uncertainties and assumptions made when aggregating indicators into composites to determine whether it is appropriate/necessary.
    - Track and present results for individual indicators as well as composite indices.
    - Consider indicators separately for different aspects of resilience that is resistance/recovery (Cabral, 2014; Cowburn et al., 2019).
    - Check indicators aren't sharing input data, and check for correlations between indicators; avoid combining highly correlated indicators where possible.
    - Weightings: use robust methods for estimating weightings (e.g. contribution of each ecosystem component towards resilience, determined through quantitative approaches or expert elicitation), and justify all weights, including equal weighting (Jouval et al., 2023; Maynard et al., 2010).
    - Evaluate alternative options to aggregating indicators for example taking the highest (or lowest) value, or geometric means (Jouval et al., 2023; Thompson et al., 2020).
    - Present and explore variance levels for indicators and index scores to interpret inter- and intra-site patterns; select appropriate intervals based on the data distribution (Maynard et al., 2015).
5. *Management prioritisation*—Aim to link results from assessments to local management actions through a management prioritisation process.
    - Use structured approaches to prioritise management actions and areas, such as systematic conservation planning or decision-tree frameworks.
    - Include indicators that are considered manageable and define the expected relationship with the relevant management action (or pressure) (Ladd & Collado-Vides, 2013).

accepted standardised approach for assessing resilience potential, which can be regionally contextualised. This would lead to predictions that are more closely aligned with the absolute resilience of reefs and facilitate comparisons across different parts of the world, enhancing the robustness and reliability of the information provided to decision-makers, ultimately leading to more effective coral reef management.

AUTHOR CONTRIBUTIONS

Mishal Gudka conceived the original idea for the paper, which was then developed with critical input from Emily Nicholson. David Obura and Eric A. Treml also contributed key ideas throughout the project. Mishal Gudka and Emily Nicholson designed the methodology; Mishal Gudka conduced the literature review and data extraction; Mishal Gudka analysed the data with input on this and

visualisation from all authors; Mishal Gudka led the writing of the manuscript and all authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

All data extracted from reviewed assessments and R code to explore, analyse and visualise the data are openly available on Zenodo here: https://zenodo.org/doi/10.5281/zenodo.10622390 (Gudka, 2024).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Glossary of key terms.

Table S2. Criteria to differentiate resilience potential assessments from related assessments such as of state, vulnerability, risk, pressure. Priority—High indicates assessment must score affirmatively for all these criteria to be considered a resilience potential assessment.

Table S3. Key characteristics of various coral reef assessment types—Resilience, Resilience potential, State, Risk, Vulnerability, Threat/pressure.

Table S4. The key questions, criteria and categories used to evaluate resilience potential assessments in the review, including citations to justify their importance (the gap or principle they relate to), the response options and conditions/criteria for selecting the different options.

Table S5. Ecosystem components as illustrated in the conceptual model (Figure 1) with subset of corresponding sub-components and resilience factors (colours represent whether factors have a positive (blue), negative (red) or variable (black) effect on ecosystem component).

Table S6. Marine Ecoregions of the World provinces (Spalding et al., 2007) with the number of resilience potential assessments reviewed from each in brackets. Occasionally one assessment covered multiple provinces.

Table S7. Number of resilience potential assessments (No. assessments) each resilience indicator was used in (ordered by ecosystem component). Only considers assessments which had complete information on the indicators used ($n=63$).

Table S8. Management interventions informed by resilience, stress and management indicators across all the resilience potential assessments which conducted a prescriptive management process (26 assessments).

Table S9. Resilience, stress and management indicators used to inform management interventions across all the resilience potential assessments which conducted a prescriptive management process (26 assessments).

Figure S1. The frequency various objectives were stated across the reviewed resilience potential assessments ($n=68$ assessments). Assessments could have multiple objectives, or not state any clear objectives.

Figure S2. Number of resilience potential assessments that explicitly specified the resilience subject(s) (disturbance(s) or threat(s)).

Figure S3. Number of assessments with missing ecosystem components (grey bar) with the specific missing ecosystem components nested (coloured bars within grey bar).

Figure S4. The rationale and method used to determine indicator weights across all resilience potential assessments reviewed with composite indices ($n=50$). Multivariate analysis includes approaches like Principal Component Analysis, arbitrary is when no justification or explanation is provided, and unclear is when the method could not be determined from the information provided.

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