Ecological Indicators 162 (2024) 111988

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

A standard condition and threat indicator framework for benthic marine and estuarine condition assessment

Charles Cadier [a,*], Julieanne Blake [b], Mike Ronan [b], Maria Zann [b], Arnon Accad [c], Daniela Ceccarelli [d], Mary Chang [b], Guillermo Diaz-Pulido [a], Sabine Dittmann [e], Christopher Doropoulos [f], Caitlin Fleck [b], Paul Groves [g], Valerie Hagger [h], Catherine E. Lovelock [h], Taryn McPherson [b], Megan I. Saunders [f], Nathan J. Waltham [i], Maria Fernanda Adame [a,*]

[a] Coastal and Marine Research Centre, Australian Rivers Institute, School of Environment and Science, Griffith University, Nathan, QLD, 4111, Australia
[b] Department of Environment and Science, Queensland Government, Brisbane, QLD, 4000, Australia
[c] Department of Environment and Science, Queensland Herbarium and Biodiversity Science, Queensland Herbarium Brisbane Botanic Gardens Mt Coot-tha, Toowong, Brisbane, Queensland 4066, Australia
[d] Australian Institute of Marine Science, Townsville, QLD 4810, Australia
[e] College of Science and Engineering, Flinders University, Adelaide SA 5001, Australia
[f] Commonwealth Scientific and Industrial Research Organisation, St. Lucia, Australia
[g] Great Barrier Reef Marine Park Authority, Australian Government, Townsville, QLD, Australia
[h] School of Environment, The University of Queensland, Brisbane, Australia
[i] TropWATER, Centre for Tropical Water and Aquatic Ecosystem Research, and College of Science and Engineering, James Cook University, Queensland, Australia

A R T I C L E I N F O

Keywords:
Ecological monitoring
Management intervention
Stakeholders engagement
Framework development
Rapid assessment

A B S T R A C T

Marine and estuarine habitat degradation threatens ecosystem function and delivery of ecosystem services. An increasing number of management interventions aiming to improve ecological condition within impacted marine and estuarine habitats are being implemented. Monitoring the ecological outcomes of management interventions to evaluate their effectiveness supports adaptive management. However, the lack of a standardised set of indicators has impeded reliable assessment and knowledge sharing. The objective of this research project is to develop a cross-ecosystem standardised indicator framework to assess changes in benthic habitat conditions. The rapid Marine and Estuarine Condition Assessment Tool (MarECAT) was developed for Queensland, Australia; however, it can be applied elsewhere. A literature review was undertaken to identify indicators and metrics for habitat condition assessment that were reviewed by subject matter experts through a series of Technical Group meetings. Three indicator groups were identified based on the presence or absence of structural macrobiota attributes (i.e., macroflora, macrofauna, and substrate-dominated). The panel of experts endorsed a list of 42 condition indicators with associated metrics representing all ecosystem components, enabling a comprehensive assessment of habitat condition for a rapid assessment tool. A level of confidence nominated by practitioners was allocated to each condition indicator metric to inform the interpretation of assessments. Another outcome of the expert workshops was the endorsement of 10 threat indicators representing key pressures in marine and estuarine habitats, along with a specific assessment scale. The scoring method developed for the MarECAT will facilitate reliable assessment of management intervention outcomes and implementation of adaptive management to improve project success.

* Corresponding authors at: 5/6-10 Ann Maree close, Maroochydore, 4558, Queensland, Australia.
E-mail addresses: charles.cadier@griffithuni.edu.au (C. Cadier), f.adame@griffith.edu.au (M. Fernanda Adame).

https://doi.org/10.1016/j.ecolind.2024.111988
Received 27 November 2023; Received in revised form 29 March 2024; Accepted 1 April 2024
Available online 11 April 2024

1 Introduction

Marine and estuarine ecosystems provide many services that are highly valued by humans (Costanza et al., 1997), including storm protection, erosion and flood control, carbon sequestration, mitigation of coastal eutrophication, and nursery habitats for commercially important fisheries species, and are hotspots of biodiversity (Barbier et al., 2011, Barbier, 2019). Development of coastal areas and the associated impacts such as habitat loss, and pollution, adversely affect marine ecosystems (Crain et al., 2009). When ecosystems are impacted, the provision of ecosystem services may be reduced or completely lost. Marine protection may not always achieve the expected outcomes (Chaigneau and Brown, 2016); therefore, more interventionist management such as rehabilitation may be required to recover these services (Duarte et al., 2020). However, the effectiveness of these actions is questionable as a reliable assessment of management interventions is lacking for most projects. A successful assessment needs to be strategic, efficient, and meaningful by selecting adequate indicators.

An indicator can be defined as a measurable ecosystem attribute used to assess environmental conditions, changes or threats to environmental resilience, which can be linked to intervention goals and objectives (Heink and Kowarik, 2010). However, the use of one indicator in preference to another can result in different outcomes, which could have important consequences (Basconi et al., 2020). For instance, the assessment of coral reef condition using the number of fragmented and broken corals would not differentiate sites with high or low anchorage intensity, in contrast to the use of the number of overturned colonies which is a more effective indicator of anchorage pressure (Dinsdale & Harriott, 2004). In addition to condition indicators, threat indicators should also be assessed, since they are linked to condition and have the potential to cause an adverse change in habitat condition. Assessing threat indicators allows for the identification of key pressures in the area, which can inform management actions to improve habitat conditions (Scheltinga and Moss, 2007; Stelzenmüller et al., 2013). In many cases, threat management or pressure reduction is one of the most effective interventions required and may restore biophysical conditions (Auerbach et al., 2015; Carwardine et al., 2012). However, in other situations, more intensive interventions, such as rehabilitation, may be required. To date, marine monitoring programs have used a wide range of indicators and frameworks, hindering our capacity to compare their outcomes, and preventing knowledge-building from previous interventions (Cadier et al., 2020; Eger et al., 2022; Saunders et al., 2022). A set of reliable performance indicators and their integration into an assessment tool is yet to be agreed upon for marine and estuarine ecosystems.

There are inherent challenges in building a standardised set of indicators for marine and estuarine habitats. It is difficult to collect a comprehensive suite of metrics to measure indicators and develop a framework robust enough to present useful ecological information and simple enough to be applied by a wide range of practitioners (Eger et al., 2022). Habitat-based monitoring programs such as Seagrass Watch or Reef Check in Australia propose rapid assessment tools including a simple enough list of indicators and metrics that provide useful information on benthic habitat condition (Done et al., 2017; Mellors et al., 2008). However, these programs do not aim for a comprehensive assessment of the different ecosystem components, i.e. none include water quality or substrate dynamics, which are important indicators of of seagrass and coral reef conditions (Cooper et al., 2009; Suykerbuyk et al., 2016). Furthermore, each of these methods uses different indicators targeted to the habitat type, but this impedes comparison among habitats or ecosystems within a seascape. Monitoring programs targeting a focal water body, such as the Chesapeake Bay Program (USA) or the Reef 2050 Integrated Monitoring and Reporting Program (Great Barrier Reef, Australia), provide a comprehensive assessment of all ecosystem components within the investigated area (Great Barrier Reef Marine Park Authority & Queensland Government, 2015; Tango & Batiuk, 2016). However, these monitoring programs are specific to their water body, and therefore there is the need for a rapid and standardised assessment tool to facilitate global knowledge sharing from management intervention outcomes.

This tool should apply across both marine and estuarine benthic habitats due to their interdependence in the seascape and the fact that they share several key characteristics and monitoring requirements (Sheaves, 2009; Baldera et al., 2018; Vozzo et al., 2023). The development of such a tool requires collaboration with groups working across the spectrum of marine ecosystems, as knowledge exchange between practitioners can enrich the development of indicators and is key to the successful endorsement of the framework (Cvitanovic et al., 2015; Eger et al., 2022; Gann et al., 2019). Reviews of monitoring indicators have been recently published, and while each usually focus on one habitat type or one type of management intervention such as restoration, they are a valuable start to a standardised set of indicators (Bayraktarov et al., 2020; Cadier et al., 2020; Gatt et al., 2022). This tool will improve the tracking of the progress and effectiveness of management interventions, facilitating knowledge sharing and adaptive management implementation across multiple habitats (Saunders et al., 2022).

Here we describe the process for developing a standard set of condition and threat indicators, and associated metrics, to be integrated within a Marine and Estuarine Condition Assessment Tool (MarECAT) designed for Queensland, Australia. A framework for, and requirements of the proposed MarECAT tool, was provided by the Queensland Department of Environment and Science. The project addresses the need for a marine and estuarine monitoring tool in Queensland that is widely applicable and compatible with Queensland's Aquatic Ecosystem Rehabilitation Process and requires a comprehensive and evidence-based monitoring framework (Department of Environment and Science and Queensland, 2021). A key design element of MarECAT is to align with the freshwater monitoring tool, the Wetland Condition Assessment Tool (WetCAT; Department of Environment and Science, 2022). Australia has developed several policies and programs aimed at improving habitat condition, in particular regarding environmental offsets. Management interventions, including restoration, can be the result of offsetting requirements, such as Australia's federal biodiversity offset policy under the *Environment Protection and Biodiversity Conservation Act 1999* (Niner et al., 2017), carbon offsets with the Australian Blue Carbon method (Lovelock et al., 2022), and potentially nitrogen offset via water quality trading schemes (Smart et al., 2016). In Queensland, this includes policies and programs linked to the *Environmental Offset Act 2014* (Miller et al., 2015) and projects that generate carbon and co-benefits under the Land Restoration Fund (State of Queensland, 2020). Reliable assessments are therefore also needed to determine whether investments have achieved their intended outcomes.

The objectives of the MarECAT tool are to determine the outcomes of marine and estuarine habitat management intervention and/or habitat recovery. Therefore, the research objectives of this study were to 1) Review published indicators from scientific and monitoring programs sources to establish relevant indicators assessing changes in habitat condition, 2) Engage with stakeholders from diverse backgrounds and institutions to enrich and endorse the indicator framework, 3) Develop a classification of indicators and scoring methods for incorporation into MarECAT and which can be applied elsewhere. The outcomes of this work provide a basis towards a global standardised monitoring framework for marine and estuarine habitats.

2 Methods

The development of the indicator framework followed a four-step process described in the conceptual diagram (Fig. 1). A literature

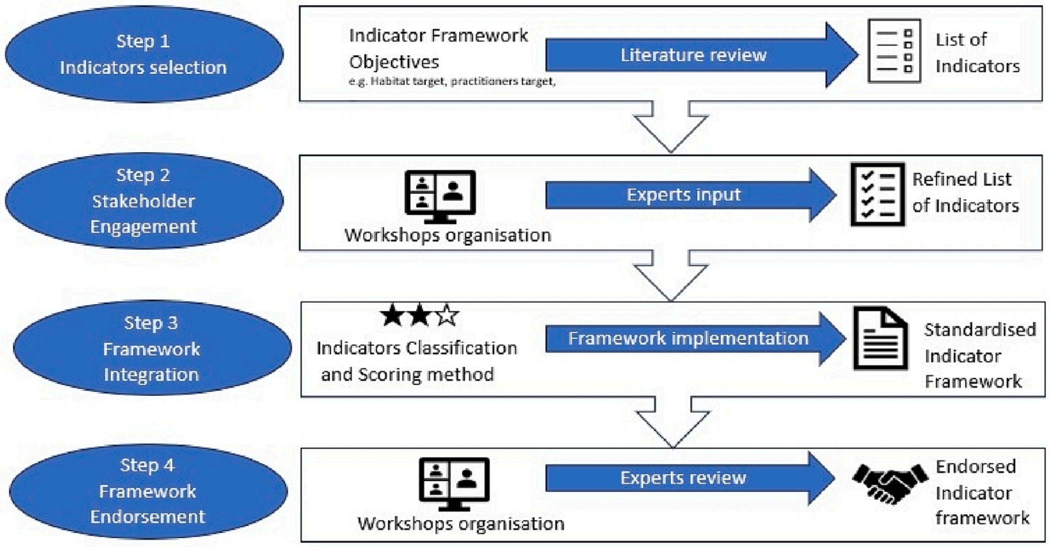

Fig. 1. Indicator framework development steps.

review was first implemented to obtain a list of potential indicators to be integrated in the framework. The indicators were then discussed with a panel of experts elicited during a series of workshops. Endorsed indicators were then classified and a scoring method was developed to produce a rating of habitat conditions and threats. This classification and scoring method was presented to the expert panel for discussion and final endorsement of the indicator framework.

2.1. Literature review

2.1.1. Habitats classification

Queensland's marine and estuarine benthic habitats have been classified into ninety-five habitat types by applying the principles and approach of the Queensland Intertidal and Subtidal Ecosystem Classification Scheme to Central Queensland (Department of Environment and Heritage Protection, 2017; Department of Environment and Science and Queensland, 2019– see Appendix A). The Scheme recognises that water column and benthic ecosystems need to be classified separately as the water column is a system in its own right, thus the typology of the MarECAT is a benthic typology (Department of Environment and Heritage Protection, 2017). One of the diagnostic attributes of this classification scheme, structural macrobiota, describes sessile habitat-forming species, the presence of which increases spatial complexity, modifies local environment conditions and leads to colonisation by a diverse assemblage of organisms (Lilley and Schiel, 2006). Here, the presence or absence of "structural macrobiota" was a key factor in defining three habitat types: macroflora-dominated, macrofauna-dominated, and absence of structural macrobiota (substrate–dominated). While there are many terms to describe habitat-forming species, structural macrobiota was kept for consistency with the Queensland Intertidal and Subtidal Ecosystem Classification Scheme.

2.1.2. Indicator literature review

A review of scientific literature outlining indicators for assessing conditions in marine and estuarine ecosystems was performed on Google Scholar and encompassed literature focused on supratidal forests, saltmarsh, mangroves, mudflats, sandy shores, rocky shores, seagrasses, macroalgae, shellfish reefs, coral reefs, sponge gardens. The search string consisted of the habitat type followed by "Australia" and "condition indicator", i.e. "seagrass" + "Australia" + "condition indicator", and the first 100 references were screened for inclusion with latest date of publication in 2022. The inclusion criteria were the use of indicators to assess marine or estuarine habitat condition, and applicable to a rapid assessment tool. The criteria excluded indicators used at landscape/seascape, those requiring high technology or expertise (e.g. isotopic models), not assessing habitat condition, specific to a stressor (e.g. climate change), and focused on a specific species. Indicators were also included from the review from Cadier et al. (2020) and Bayraktarov et al. (2020). Furthermore, a review of marine and estuarine ecosystem condition indicators used in Australian monitoring programs was conducted. The search was performed on Google, using the search string "habitat type" + "Australia" + "monitoring framework", and integrated regional and national programs. Metrics were determined for scoring the indicators. The metrics were aligned with indicators, i.e. metrics "flooding frequency" and "flooding inundation" were grouped within the indicator "tidal inundation". The indicators and metrics were incorporated into a list considered by subject matter experts.

The threat indicators were extracted from a previous framework assessing key stressors in estuarine, coastal, and marine ecosystems in Queensland (Scheltinga and Moss, 2007), and aligned with the existing threat indicators from the WetCAT (Department of Environment and Science, 2022). They were then integrated into a list considered by the expert panel, along with the specific spatial scale to which they are to be assessed (e.g. site scale, catchment scale).

2.2. Expert workshops

Workshops are among the most efficient tools to provide a collaborative space with diverse people for participatory conversations (Schuler et al., 1993). The workshop participants ('panel members') consisted of twenty-five experts from thirteen institutions of varied backgrounds, including universities, government-affiliated organisations, resource management organisations, and non-governmental organisations (Appendix B). The diverse backgrounds of the panel members aimed to reflect the diversity of researchers and practitioners likely to have an interest in the use of the MarECAT and expertise in the wide range of marine and estuarine habitat types of Queensland. A series of online workshops were held to discuss and seek technical validation and agreement on the indicators and metrics.

At the first workshop, the scope of the study was presented, and the habitat types included in the framework were discussed. Subsequent workshops were split across the three habitat classes, i.e. macroflora, macrofauna and substrate-dominated according to their expertise and interest of the panel members. These groups discussed condition indicators and metrics, the confidence levels attributed to each metric, threat indicators and specific assessment spatial scale. Throughout and in between workshops, an iterative process of discussion, revision, and reflection was utilised to refine the indicators and metrics. The last workshop presented the MarECAT for a final input round and endorsement of the tool.

3 Results

3.1. Literature review

The review originally screened 1200 papers from the literature, from which 84 were reviewed for potential selection in the study and led to the inclusion of 46 papers, including indicators to assess the condition of 11 habitat types representing all structural macrobiota categories (Fig. 2). The review also analysed indicators from 17 active monitoring programs (Appendix C). This review led to the extraction of 323 indicators. These indicators were compared to indicators extracted from previous reviews and after duplicates were removed, led to a final list of 350 indicators.

We grouped these indicators within an initial list of 64 condition indicators with associated metrics and classified them within 13 categories. For instance, the condition indicators “tidal inundation” and “energy magnitude” were classified within the category “water regime”. In turn, these categories are nested within themes: Water, Substrate, Plant, Animal, and Others. These categories and themes were based on the WetCAT condition assessment tool and capture the key physical, chemical and biological components that make up a marine or estuarine ecosystem. This initial categorised list of indicators was presented to the expert panel during the first workshop.

3.2. Outputs of expert’s workshops

3.2.1. Habitat types

At the first expert workshop, participants agreed on three groups based on structural macrobiota:

1) Structural Macroflora Habitats (Appendix D.1), those formed and dominated by plants (or macroflora) including tidal forests (e.g., *Melaleuca* spp.)., saltmarsh (e.g., *Sarcocornia* spp.), mangroves (e.g., Rhizophora spp.), seagrass (e.g., *Zostera* spp.), erect calcareous macroalgae (e.g., *Halimeda* spp.), and erect non-calcareous macroalgae (e.g., *Sargassum* spp.);
2) Structural Macrofauna Habitats (Appendix D.2**),** formed and dominated by animals, or macrofauna, and include hard branching coral (e.g., *Acropora* spp.), hard non-branching coral (e.g., *Porites* spp.), soft coral and other octocorallians (e.g., *Sarcophyton* spp.), shellfish reef (oyster, mussel, scallop), and other structural macrofauna (e.g., *Ascidia* spp.);
3) Substrate-Dominated Habitats (Appendix D.3), those lacking structural animals or plants and including sandy shores, mud flats, rocky shores, gravel, and boulders. The experts transferred turf and encrusting algae from structural macroflora to substrate-dominated habitats as they may dominate a habitat but are not considered structural species.

3.2.2. Condition indicator framework

Subject matter expert workshops led to the endorsement of a list of 42 condition indicators, for which a rationale is presented in Appendix E.1. These indicators can be measured with quantifiable parameters (Q metric) or estimated from nominal data (N metric). Another major output from these workshops was the inclusion of a confidence level for each of the metrics, associated with the result (adapted from Queensland Government and Queensland, 2015; Table 1). These confidence levels were aligned with the WetCAT and adapted to the MarECAT through inputs from the expert’ panel. It was agreed that practitioners were free

Table 1
Description of metrics confidence levels.

Metric confidence level	Description
Known	According to expert knowledge AND supporting evidence based on an accepted, published method.
Derived-High	According to expert knowledge OR an accepted method (but no expert has verified the score). This confidence rating could be used when using a “known” rating with caveats.
Derived-Moderate	Inadequate data sources/method combined with a strong assessment method/adequate data and/or expert knowledge.
Derived-Low	Inadequate sampling methods/frequencies and/or expert with low confidence in result.
Unknown	According to expert knowledge, the confidence in the assessment method and indicator score is yet to be determined.

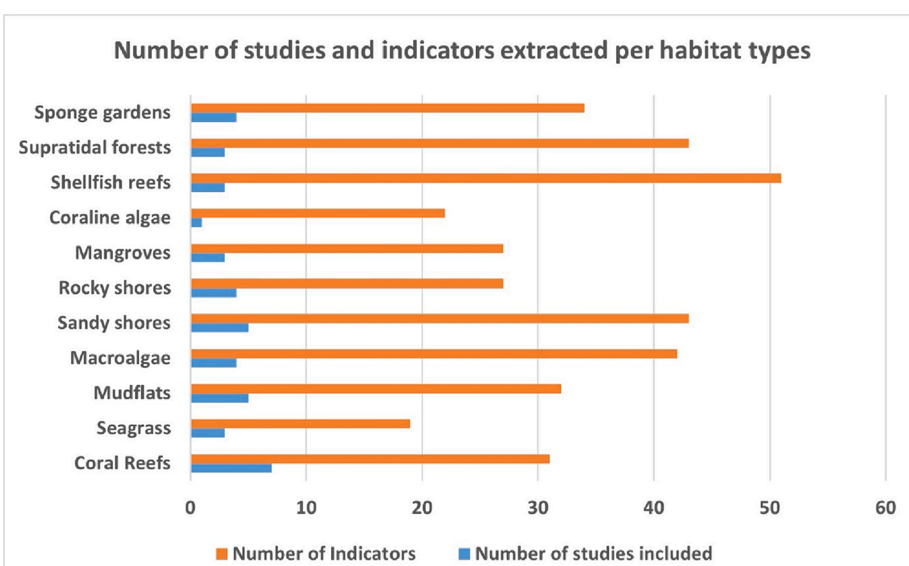

Fig. 2. Number of studies and indicators per habitat types extracted through the literature review process.

Table 2
Condition indicator table with themes, categories, indicators, habitat-type target, and assessment metrics with associated confidence levels. Q = Quantitative, N = Nominative, A = known, B = derived-high confidence, C = derived-moderate confidence, D = derived-low confidence, E = unknown confidence. Indicators and associated metrics specific of structural macroflora ([a]), structural macrofauna ([b]), and substrate dominated ([c]) habitats are indicated. References are provided in Appendix E2.

Categories	Condition Indicators	Metrics and Confidence level
		Water theme
C1 Water Regime	Tidal inundation[1]	• Flooding frequency (per unit of time, e.g., h/day) [1] **Q-A** • Flooding duration (per unit of time, e.g., h/inundation)[1] **Q-A** • Inundation depth (m)[1] **Q-A** • Visual determination of flooding * **N-D** • Time series of digital imagery displaying changes in flooding regime[2] **Q-C** • Presence of hard structures or constructions that modify the water regime e.g., bunds, walls, or roads ***N-C** • Presence of freshwater macrophytes as indicators of tidal restriction ***N-C**
	Energy magnitude[3]	• Wave Height (m) [3] **Q-A** • Wave period (s)[3] **Q-A** • Wave incidence direction* **N-C** • Wave Exposure Index[4] **Q-B**
C2 Water Quality	Temperature [5]	• Surface water temperature (°C)[5] **Q-A** • Benthic water temperature (°C)[5] **Q-A**
	Salinity [6]	• Water salinity (PSU)[6] **Q-A** • Vegetation type or salt deposits as indicators of salinity* **N-C**
	pH[7]	• Water pH[7] **Q-A**
	Turbidity [8]	• Total suspended sediment concentration (mg/L)[8] **Q-A** • Secchi disk depth (m)[8] **Q-A** • Water clarity observed as a measure of turbidity ***N-C**
	Dissolved oxygen (DO)[9]	• DO concentration (mg/L)[9] **Q-B** • Dead animals as indicators of low DO* **N-E** • Rotten smell as indicators of low DO* **N-D** • Dark black soils as indicators of low DO* **N-D**
	Nutrients [10]	• Nitrogen organic dissolved and total concentration (e.g., mg/L)[10] **Q-A** • Phosphorus organic dissolved and total concentration (e.g. mg/L)[10] **Q-A** • Carbon organic dissolved and total concentration (e.g. mg/L)* **Q-A** • Chlorophyll-a total concentration (e.g. mg/L)[11] **Q-A** • Algal blooms as indicators for potential excess of nutrients* **N-D** • Long term increase in macroalgal cover may indicate nutrient excess* **N-D**
	Acid sulphate runoff[12]	• Water pH for acid sulphate soils runoff[7] **Q-A** • Red stained soils and plants as indicators of iron leaching* **N-C** • Bright, clear blue water in pools* **N-C**
	Pollution [12]	• Pesticide or herbicide concentrations[13] **Q-A** • Heavy metal concentration[14] **Q-A** • Hydrocarbon concentration[3] **Q-A** • Microplastics concentrations* **Q-A** • Macroplastic occurrence* **N-C** • Slicks for hydrocarbons* **N-C** • Oil traces may indicate hydrocarbon pollution of water* **N-C**
		Substrate theme
C3 Substrate dynamics	Substrate elevation [18]	• Surface elevation (per unit of time, e.g., mm/yr)[15] **Q-A** • Sediment grain size (% fine vs % coarse grains)[16] **Q-A** • Lack of pneumatophore or shells on top of sediment, and fine substrate deposition may indicate accretion* **N-D** • Below ground root exposure and apparition of coarse substrate may indicate erosion[17] **N-E** • Time series of digital imagery displaying changes in vertical elevation or changes in the coastline[18] **Q-B** • Apparent shoreline dominant sedimentation process (accretion/stable/erosion)* **N-D** • Receding and/or slumping banks, beds, or bars as indicators of shoreline erosion* **N-D**
	Substrate disturbance [19]	• Vehicle tracks[19] **N-A** • Signs of animal pugging, trampling, digging and/or wallowing activity* **N-C** • Excavation and in-filling activity* **N-C** • Coral rubble[20] (% cover) **Q-B** • Anchor damage * **N-C** • Fishing bait digging activity (e.g., use of a yabbie pump)* **N-C** • Time series of digital imagery displaying substrate disturbance activity* **Q-B**
C4 Substrate composition	Temperature [21]	• Temperature (°C)[21] **Q-A**
	Salinity[22]	• Salinity (PSU)[22] **Q-A**
	Porosity[23]	• Soil porosity[23] **Q-A** • Soil bulk density (g/cm^3)[23] **Q-A** • Water content (%)[23] **Q-A** • Substrate firmness[24] **N-B**
	Grain size [23]	• Substrate grain size composition (%)[23] **Q-A** • Sediment texture[24] **N-C**
	Oxygen [25]	• Redox potential (mV)[26] **Q-A** • Oxic layer depth (cm)[27] **Q-A** • Sediment smell[24] **N-D** • Sediment colour[24] **N-C**
	Carbon and Nitrogen content [28]	• Organic matter content (%)[29] **Q-A** • Nitrogen density (g/cm^3)[28] **Q-A** • Organic carbon density (g/cm^3) [28] **Q-A**

(continued on next page)

Table 2 (*continued*)

Categories	Condition Indicators	Metrics and Confidence level
		• Greenhouse gas emissions (g/m^2/h)[28] **Q-A** • Sediment colour[24] **N-C** • Calcareous and non-calcareous substrate relative proportion (%)* **Q-A**
	Acid sulphate soils [12]	• pH[12] **Q-A** • Sediment colour [24]**N-D** • Red floccules in water and red-stained vegetation* **N-C**
	Pollution [12]	• Hydrocarbons concentrations (mg/g)[3] **Q-A** • Heavy metal concentrations (mg/g)[12] **Q-A** • Microplastics concentrations* (mg/g) **Q-A**
		Plant theme
C5 Vegetation composition	Cover [30]	• Algae total substrate cover (%)[31] **Q-A** • Relative percentage of fleshy macroalgae, turf algae and coralline algae vs total algae* **Q-A** • Time series of digital imagery displaying changes in vegetation cover[18] **Q-B** • [a]Tree density (ind/m^2)[32] **Q-A** • [a]Seagrass shoot density (ind/m2)[33] **Q-A** • [a]Vegetation cover (%)[22] **Q-B** • [a]Species composition (% cover)[33] **Q-B**
	Diversity [30]	• Macroalgae growth form OR functional form group occurrence[34] **N-C** • Halophytes species occurrence[35] **N-C** • [a]Species occurrence[32] **N-C** • [a]Species composition (%)[30] **Q-A** • [a]Species Richness[36] **Q-A** • [a]Species Evenness***Q-A** • [a]Species diversity (Shannon or Simpson's index) [33] **Q-A** • [a]Threatened species occurrence***N-C**
	[a]Growth form[32]	• [a]Aboveground biomass (kg/m^2)[33] **Q-A** • [a]Belowground biomass (kg/m^2)[33] **Q-A** • [a]Diameter at breast height (DBH) of trees (cm)[22] **Q-A** • [a]Tree basal area* **Q-A** • [a]Plant height (m)[22] **Q-A** • [a]Pneumatophore density (number/m^2)[37] **Q-A** • [a]Pneumatophore height (cm)* **Q-A**
	[a]Recruitment potential [32]	• [a]Seedling/Sapling/Sporophyte density (number/m^2)[32] **Q-A** • [a]Seed bank (seeds/m^2)[38] **Q-A**
C6 Vegetation threats	Vegetation health [32]	• Disease occurrence[39] **N-C** • Physical impacts occurrence***N-C** • Epiphyte occurrence (% cover, g cm^{-2})[40] **Q-A** • [a]Tree dieback occurrence[32] **N-B** • [a]Defoliation or browning leaves occurrence***N-C** • [a]Dead biomass on living tree (%)***Q-A** • [a]Insect attack occurrence[39] **N-C** • [a]Fungal disease occurrence[39] **N-C**
	Non-preferred flora[41]	• Non-preferred flora occurrence[41] **N-C** • Non-preferred flora habitat cover (%)[41] **Q-A**
		Animal
C7 Fauna composition	Abundance[3]	• Macrobenthos density (ind/m^2)[3] **Q-A** • Mobile invertebrate density (ind/m^2)* **Q-A** • Fish density (number per unit area)[31] **Q-B** • Macrobenthos dry biomass (g/m^2)[33] **Q-A** • Predator fish mean length (cm)[31] **Q-B** • Herbivory fish mean length (cm)* **Q-B** • Infauna traces* **N-D** • [a,c]Crab density (ind/m^2)[12] **Q-B** • [a,c]Burrow density (number/m^2)[19] **Q-A** • [a,c]Infauna mound density (number/m^2)[27] **Q-A** • [b]Hard coral cover (%)[31] **Q-A** • [b]Hard coral density (colony/m^2)* **Q-A** • [b]Soft coral cover (%)[31] **Q-A** • [b]Shellfish density (ind/m^2)[35] **Q-A** • [b]Shellfish benthic cover (%)[35] **Q-A**
	Diversity [30]	• Fish species occurrence[42] **N-C** • Fish species richness[33] **Q-A** • Fish species composition* **Q-A** • Long term increase in macroalgal cover may indicate reduced herbivory* **N-D** • Macrobenthos occurrence* **N-C** • Macrobenthos species richness* **Q-B** • Bird species occurrence[27] **N-C** • Bird species richness[33] **Q-A** • Bird species composition[43] **Q-A** • Infauna species composition* **Q-A** • Megafauna occurrence[29] **N-C** • Threatened species occurrence***N-C**
	[b]Growth form[31]	• [b]Reef areal extent (m^2)[44] **Q-A** • [b]Shell volume (cm^3)[35] **Q-A** • [b]Size frequency distribution mm (size), number or % per bin (size dist.)[35] **Q-A** • [b]Reef height (m)[35] **Q-A**

(*continued on next page*)

Table 2 (*continued*)

Categories	Condition Indicators	Metrics and Confidence level
	[b]Recruitment potential [31]	• [b]Reef relief***Q-A/N-C** • [b]Reef rugosity* **Q-A/N-C** • [b]Juvenile density (ind m^{-2})[31] **Q-A** • [b]Spatfall (spat/shell)[44] **Q-A** • [b]Relative proportion of population sexually mature (%)[44] **Q-A** • [b]Space availability (%)***Q-A**
	Functional groups [25]	• Macrobenthos functional groups relative percentage (%) [25] **Q-B** • Fish trophic and/or trait composition ***Q-B** • Birds' functional groups relative (%)[45] **Q-A**
	Habitat use [46]	• Megafauna activity[46] **N-C** • Threatened species activity* **N-C**
C8 Fauna threats	Fauna health [34]	• Megafauna scars***N-C** • Plastic occurrence in fauna digestive systems***N-C** • Disease occurrence***N-C** • [b]Crown of thorns feeding scars on corals* **Q-A** • [b]Physical damage on reef builders[34] **Q-A** • [b]Dead organism cover (%)[34] **Q-A** • [b]Bleached coral cover (%)[34] **Q-A** • [b]Bleached coral occurrence[34] **N-B**
	Non-preferred fauna [47]	• Fish parasite occurrence[33] **N-C** • Invasive macroinvertebrates occurrence* **N-C** • Invasive macroinvertebrates density (ind/m^2)***Q-A** • [a,c]Feral animal, rabbits, cane toad's occurrence[47] **N-C** • [a,c]Damage extent caused by feral animals***N-C** • [b]Crown of thorns starfish (COTS) density (ind/m^2)[34] **Q-B** • [b]COTS benthic cover (%)* **Q-A** • [b]COTS mean size (cm)* **Q-A** • [b]Drupella density (ind/m^2)[34] **Q-A** • [b]Mudworm (*Polydora* spp.) density (ind/m^2)[44] **Q-A**
		Other
C9 Litter	Debris [48]	• Litter type concentration (items/m^2)[48] **Q-A** • Status of litter (buried, submerged, stranded)[49]**N-A** • Artificial structure occurrence* **N-C**
	Illegal dumping*	• Illegal dumping type occurrence* **N-C** • Presence of oil slicks or slurries, hydrocarbon slicks or shimmering on sediments* **N-C** • Yellow/dying vegetation or presence of dead animals* **N-E**
C10 Extreme events	Fire regime [50]	• Ash deposits and burnt driftwood occurrence* **N-C**
	Storms(e.g., tropical cyclones, east coast lows) [51]	• Wooden debris mat following flooding* **N-C** • Dead and downed wood debris length* **Q-A** • Seagrass leaves mounded up on dunes* **N-E** • Scour by resuspension of sediment particles* **N-E** • Cyclone index[51] **Q-B** • Rubble cover (%)[20] **Q-A**
	Extreme emersion [52]	• Desiccation of intertidal plants and animals* **N-E** • Change in intertidal sessile fauna/flora upper tidal range* **N-E**
	Marine heatwave [53]	• Increasing events of harmful macroalgal blooms* **N-E** • Mass mortality of structural macrobiota such as mangroves, seagrasses, kelp forests, coral reefs and coralline algae* **N-B** • Time series of digital imagery displaying marine heatwaves impact on habitat habitat* **Q-A**
	Pest outbreaks [54]	• Crown of thorns outbreaks* **Q-A**

to choose which metrics they will measure to support the assessment of the condition indicators.

The indicator categories were similar among all habitat types; however, while indicators and associated metrics were similar for the water, substrate, and other themes, they differed for the plant and animal themes. The detailed indicator framework containing the proposed metrics to measure each indicator is presented in Table 2, with appropriate references for indicators and metrics to justify their inclusion (Appendix E2).

3.2.3. Threat indicators framework

The expert's workshop discerned 10 threat indicators representing the key stressors in marine and estuarine habitats in Queensland, along the specific scale required to assess each of them and a rationale for their inclusion (Table 3). The suggestion that threats were assessed at two scales: the habitat surrounding area (extent determined by the user) with a default distance of up to 1000 m from the edge of habitat (HS), and threats at the landscape/seascape scale (LS/SS) (1–5 km from the edge of the habitat depending on the indicator) was a major outcome of the expert's workshops. However, not all threat indicators have to be assessed at each scale, some may be more appropriate at HS, such as "Minor hydrological modifications", and others at LS/SS such as "Major hydrological modifications".

3.2.4. Indicator framework scoring method

The expert panel suggested that the MarECAT monitoring framework should require all indicators to be scored, unless there is a good reason not to. For condition indicators, a score of 5 indicates that the condition is the best possible while a score of 0 means that the condition is the worst possible (Burrows and Scott, 2020). The assessment of habitat condition can be performed as a Before/After intervention design, although the use of a control site is recommended, following a Before/After/Control/Intervention design (Stewart-Oaten et al., 1986).

An example of the implementation of this indicator framework is presented in the Blue Heart case study (**Text Box**). Threats are scored based on what is expected for each indicator at the specified scale at the project onset/monitoring event to provide context for assessment. A score of 5 indicates that the pressure is minimal, while a score of 0 means

Table 3
Threat indicators table with associated assessment scale and rationale for inclusion. HS = habitat scale (default of 1000 m from the edge of habitat), LS/SS = landscape/seascape scale (1–5 km from the edge of the habitat depending on the indicator).

Threat Indicators	Assessment Scale	Rationale
T1. Major hydrological modifications	LS/SS	Major hydrological modifications, such as dams in the catchments, which impacts key marine and estuarine physico-chemical parameters such as salinity.
T2. Minor hydrological modifications	HS	Minor hydrological modifications, such as tidal gates, which impacts key marine and estuarine physico-chemical parameters such as tidal inundation.
T3. Inflow from land activity	HS	Stormwater, sewage, or water releases from prescribed activities such as mines, can introduce large organic loads and contaminants, impacting biota through decreased dissolved oxygen and pollution
T4. Sediment resuspension	HS	Sediment resuspension may be caused by dredging, sand and gravel extraction, or beach nourishment activities, increasing turbidity which can lead to the loss of light dependent biota such as seagrass meadows
T5. Land Use	LS/SS	Land use such as intensive animal production can cause eutrophication events due to the release of high concentrations of nutrients and organic matter.
T6. Sea Use	LS/SS and HS	Sea use such as boating activities and aquaculture can cause disturbance to wildlife due to ship strike with megafauna or increased organic load in sediments impacting macrobenthos communities.
T7. Native habitat conversion	LS/SS and HS	Native habitat conversion includes both direct removal of areas of riparian or shoreline habitat and activities that disturb or damage habitat areas, such as coastal urbanisation, can cause the decline of coastal species
T8. Species collection and harvesting	LS/SS and HS	Species harvesting and collection through commercial and recreational fishing, bait collection and aquarium fish collection can greatly contribute to the decline of threatened and endangered species
T9. Non-preferred species	LS/SS and HS	Non-preferred species, including exotic or native species, can have significant effects on a system, resulting in the loss of native species, reductions in biodiversity and alterations to habitat
T10. Extreme events	LS/SS and HS	Extreme events such as marine heatwaves can have direct impact on fauna such as coral bleaching, but also indirect on sediment properties with loss of organic carbon from seagrass meadows

that the pressure is maximum. Threat indicators possess specific ratings and descriptions of the state of the pressure, providing information to allocate threat indicator ratings (Appendix F).

4. Discussion

The standardised set of indicators and metrics have been developed for inclusion in MarECAT, a rapid condition assessment tool across marine and estuarine habitats. The metrics used to measure the condition indicators are user-defined allowing flexibility in the choice of metrics used. This allows practitioners from multiple fields, with a wide range of expertise levels and budgets, to decide how to assess habitat condition. Engagement with stakeholders through workshops enabled the incorporation of expert input to facilitate the tool's endorsement.

An important part of condition assessment is the establishment of the habitat's benchmark condition against which the current status of the condition indicators can be assessed. The benchmark condition of a habitat should relate an observed state to a reference condition or ecological target (Smit et al., 2021). However, habitat conditions are not fixed and include dynamic ecosystem properties (White and Walker, 1997). Furthermore, the shifting baselines syndrome describes a persistent downgrading of perceived 'normal' environmental conditions with every sequential generation (Papworth et al., 2009; Jones et al., 2020). Therefore, the concept of a benchmark condition is difficult to frame. To overcome this issue, the assessment of a nearby, well-functioning protected area or regional average sharing a similar habitat type as the intervention site is recommended to set an appropriate ecological target of a normal habitat condition (Smit et al., 2021). The indicators are also applicable to assess habitat quality under environmental impact assessment and for selecting and monitoring offset sites. From this perspective, it is also important that region and habitat-specific benchmarking is used and stored in a readily accessible format similar to biocondition benchmarks for regional ecosystems (Burrows and Scott, 2020). This benchmark condition description is provided by the Queensland Intertidal and Subtidal Ecosystem Classification Scheme for each habitat type included in the MarECAT (Department of Environment and Science and Queensland, 2019). Standardisation allows for the comparison between sites and therefore the calculation of benefit can be ascertained (Maron et al., 2013).

One of the key aspects of the MarECAT indicators and metrics selection was their relevance for integration into a rapid assessment tool. Tidal inundation assessment provides relevant information regarding the hydrological suitability of a habitat for vegetation or fauna and requires relatively little data (Dibble & Meyerson, 2012; Van Loon et al., 2016). Belowground root exposure measurement enables a rapid assessment of the potential erosion that occurred in deforested mangrove habitats and is related to the loss of carbon and nitrogen content (Arias-Ortiz et al., 2021). Substrate composition metrics such as substrate firmness, texture, smell, and colour were tested and validated as part of a rapid protocol in mudflats to assess sediment condition in eutrophic estuaries (Hallett et al., 2019). Nonetheless, more precise measurements such as redox potential, soil bulk density, and organic matter content are also present in the indicator framework. Vegetation composition indicators have been more generally applied in monitoring programs, such as cover, diversity, and threats of seagrass or coral reef in the Seagrass Watch and the Eye on the Reef programs (McKenzie, 2003; Beeden et al., 2014). However, we also integrated indicators such as growth form and recruitment potential as they can be assessed visually with measurements of reef height or juvenile density and provide an essential assessment of habitat persistence, recruitment, and abundance (Baggett et al., 2015; Doropoulos et al., 2022). Finally, extreme event indicators are essential to assess the recovery of habitat condition, therefore, we included indicators such as the content and composition of ash in the water which provide relevant information on the impact of wildfires on water quality (Santín et al., 2015). The integration of indicators and metrics tested in the field and determined to provide relevant information on marine and estuarine habitat conditions contributes to the validity of the MarECAT indicator framework.

Selected condition indicators aim to cover the different ecosystem state variables to obtain a comprehensive assessment of ecosystem recovery (Mcdonald et al., 2016; Ruiz-Jaen and Aide, 2005). The scores obtained for each indicator can be compared over time to analyse changes in habitat conditions. For instance, a habitat may receive a low score in the condition indicator "Storms" after a cyclone due to the presence of wooden debris mats following flooding, scour by resuspension of sediment particles or seagrass leaves mounded up on dunes. However, with time, it is expected that the evidence for cyclone impacts will fade and the score of this condition indicator will increase as the habitat recovers. For a management intervention such as beach nourishment, the condition indicator "substrate elevation" is expected to receive a higher score after the intervention as one of the main outcomes of this project (Staudt et al., 2021). However, it is important to also monitor the condition indicator "fauna composition" and associated indicators such as "abundance" and "diversity" as beach nourishment may impact the intertidal invertebrate' population dynamics (Leewis et al., 2012). Therefore, all condition indicators have to be assessed and scored during the monitoring process to obtain comprehensive knowledge of the outcomes of management interventions and habitat resilience to extreme events.

Assessment of the indicators requires metrics that can be evaluated by practitioners with a variety of backgrounds and budgets and enable comparison of a project's outcomes (Stelzenmüller et al., 2013). This versatility is one of the main challenges in building a standardised set of indicators (Eger et al., 2022). Experts' inputs enabled the assignment of a specific degree of confidence to each metric presented in this indicator framework. This approach informs on the precision and reliability of the condition indicator evaluation, while allowing for the flexibility and ease-of-use of the indicators (Stelzenmüller et al., 2013). The choice of the confidence rating can be based on the funding for the project, as high confidence metrics are generally more expensive, time-consuming, and require expert skills, while low confidence metrics are generally faster and cheaper. The confidence in the metrics selected should also be associated with the objectives of the project. For instance, if the objective is to conserve a threatened species, then the level of confidence in the metric monitoring of this species should be high. Furthermore, some metrics may undergo spatial and temporal variations. For instance, macroalgal communities vary seasonally, biomass may be higher in summer than in winter, and diversity can be higher in shallow waters compared to deeper waters (Diaz-Pulido et al., 2007). Therefore, a justification of the rationale for the choice and sampling frequency of the metric used to evaluate condition indicators is essential to prevent bias or misunderstanding in reporting outcomes.

The challenge of grouping marine and estuarine habitats within the same monitoring framework was overcome by the choice of metrics that can be targeted towards the specific habitat type assessed. For instance, the successful recruitment of new individuals is essential for the recovery of structural macrofauna such as coral and shellfish reefs (Baggett et al., 2015; Doropoulos et al., 2022), and therefore it is important to include specific indicators and metrics to assess the condition of this habitat type. Furthermore, while the indicator "fauna health" applies to all habitat types, metrics such as "crown of thorns density" are designed for coral reef condition assessment (Beeden et al., 2014). The MarECAT is designed to compare the same habitat over time. Therefore, practitioners are required to determine the habitat type before any assessment is undertaken. The use of the presence or absence of structural macrobiota as a diagnostic attribute enables rapid visual recognition of habitat type categories by practitioners, which will guide them to define the indicators and metrics to assess the specific habitat condition. Besides structural macrobiota growth form and recruitment potential, indicators are similar for all habitat types and therefore will allow for project outcome comparisons across marine and estuarine ecosystems. This standard set of indicators across marine and estuarine habitats will be beneficial for future projects as lessons learned in one habitat can be applied to others (Eger et al., 2022).

Engagement of practitioners in the development of the set of indicators is one of the key aspects of this study. This has been outlined by other global monitoring programs such as the Mangrove Restoration Tool Tracker, which developed a set of ecological indicators to report for mangrove restoration projects (ttps://https://www.mangrovealliance.org/news/new-the-mangrove-restoration-tracker-tool/). Stakeholder engagement is essential for resource management issues, such as marine spatial planning success, regardless of the country (Zaucha and Kreiner, 2021). It is an important aspect of knowledge sharing, enabling understanding of site-specific ecological conditions. The inputs from practitioners in this study enabled the inclusion of a wide range of knowledge into the indicator framework, facilitating the refinement of the set of indicators and metrics. Stakeholder involvement contributes to the integration of knowledge into policy and decision-making processes (Lopes and Videira, 2013). Collaborative and participatory development of this indicator framework will contribute to the uptake of the MarECAT tool by the practitioner's community (Eger et al., 2022).

The approach outlined in this study can be widely applied and contribute to assessment of project activities globally. This tool will be made available online on the Queensland Department of Science Wetland Information website as a companion to the WetCAT tool. The MarECAT has the potential for modification and use by other jurisdictions. It can be used as a complementary tool to other existing global standardised indicator framework such as the Global Biodiversity Framework, for instance to track progress towards the Target 2 which focuses on effective restoration of degraded ecosystems (Phang et al., 2020; Hughes and Grumbine, 2023). The data provided by the MarECAT could also be valuable for other global monitoring frameworks such as the Global Ocean Observation System (https://goosocean.org/), or the Marine Biodiversity Observation Network (https://geobon.org/bons/thematic-bon/mbon/). This will facilitate the collection of information regarding the outcomes of management interventions and habitat resilience to extreme events and contribute to improving our knowledge of the current and future of marine and estuarine habitat conditions.

The set of indicators developed in this study is an important step towards a global standardised monitoring framework for all marine habitats to assess the ecological outcomes of management interventions and/or extreme events recovery. The application of a standardised monitoring framework could facilitate robust reporting of marine management outcomes and contribute to the efficient sharing of management intervention knowledge (Saunders et al., 2022). This would improve our knowledge of what works and does not work in natural resource management, enabling the application of adaptive management which is a key to management success (Saunders et al., 2020). In turn, this standard set of indicators could also facilitate the process of environmental accounting and promote financial incentives for management interventions (van Dijk et al., 2014). Therefore, a global standardised marine and estuarine monitoring framework would contribute to the upscaling of ecosystem conservation efforts to achieve global biodiversity, climate, and development targets.

Funding declaration

CC and MFA were funded by the Department of Environment and Science of the Queensland Government to develop the indicator framework for the MarECAT. CC was also funded by a Research Outputs and Excellence Scholarship from Griffith University to prepare this manuscript. MFA was funded by an Advance Queensland Industry Research Fellowship by the Queensland Government. CD and MIS were funded by a CSIRO Julius Career Award. CEL was supported by ARC award FL200100133.

CRediT authorship contribution statement

Charles Cadier: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julieanne Blake:** Writing – review & editing, Validation, Project administration, Data curation, Conceptualization. **Mike Ronan:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Maria Zann:** Writing – review & editing, Validation, Data curation, Conceptualization. **Arnon Accad:** Writing – review & editing, Validation, Data curation. **Daniela Ceccarelli:** Writing – review & editing, Validation, Data curation. **Mary Chang:** Writing – review & editing, Validation, Data curation. **Guillermo Diaz-Pulido:** Writing – review & editing, Validation, Data curation. **Sabine Dittmann:** Writing – review & editing, Validation, Data curation. **Christopher Doropoulos:** Writing – review & editing, Validation, Data curation. **Caitlin Fleck:** Writing – review & editing, Validation, Data curation. **Paul Groves:** Writing – review & editing, Validation, Data curation. **Valerie Hagger:** Writing – review & editing, Validation, Data curation. **Catherine E. Lovelock:** Writing – review & editing, Validation, Data curation. **Taryn McPherson:** Writing – review & editing, Validation, Data curation. **Megan I. Saunders:** Writing – review & editing, Validation, Data curation. **Nathan J. Waltham:** Writing – review & editing, Validation, Data curation. **Maria Fernanda Adame:** Writing – review &

editing, Validation, Supervision, Data curation, Conceptualization.

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

No data was used for the research described in the article.

Acknowledgement

The authors would like to acknowledge all participants of the Technical Group and the Reference Group who contributed to the development of the MarECAT indicator framework, including officers from the Department of Agriculture and Fisheries, Queensland, Grace Isdale from NRM South, Angus Thomspon from the Australian Institute of Marine Science, and Kylie McPherson, first author for the WetCAT.

Appendices.

Appendix A
Queensland Intertidal and Subtidal ecosystem classification Scheme. Habitat type classification using water level, biota and consolidation attributes

Water level	Biota	Consolidation	Habitat
Intertidal	Confirmed	Consolidated	Intertidal molluscs on consolidated substrate
		Unconsolidated	Succulent with herb
			Sedge
			Grass
			Bare areas above medium sea level
			Grass herb sedge undifferentiated
			Ceriops-dominated mangroves
			Rhizophora dominated mangroves
			Avicennia dominated mangroves
			Mixed mangroves
			Mangroves undifferentiated
			Other trees and shrubs
			Intertidal ovoid seagrass
			Intertidal wide strap seagrass
			Intertidal narrow strap seagrass
			Intertidal unspecified width strap seagrass
			Intertidal other seagrass
			Intertidal molluscs or unconsolidated or unknown substrate
		Consolidation unassigned	Intertidal coral
			Intertidal algae
			Other habitat-forming intertidal biota
	Unserveyed/absent	Consolidated	Intertidal high energy over consolidated substrate
			Intertidal high energy over intermediate substrate
			Intertidal low energy over consolidated substrate
			Intertidal low energy over intermediate substrate
		Unconsolidated	Intertidal high energy over boulders
			Intertidal low energy over boulders
			Intertidal unknown energy over boulders
			Intertidal high energy over gravel
			Intertidal low energy over gravel
			Intertidal unknown energy over gravel
			Intertidal high energy over mud below medium sea level
			Intertidal low energy over mud below medium sea level
			Intertidal substrate below higher astronomical tide with indeterminate tidal influence
			Intertidal mud above medium sea level
			Intertidal high energy over sand
			Intertidal low energy over sand
			Intertidal unknown energy over sand
			Intertidal unknown energy over mud
			Intertidal high energy over unconsolidated substrate of unknown structure
			Intertidal low energy energy over unconsolidated substrate of unknown structure
		Consolidation unassigned	Intertidal substrate of unknown consolidation outside channel
			Intertidal substrate of unknown consolidation inside channel
Subtidal	Biota confirmed	Consolidated	Hard branching coral on consolidated substrate in shallow to deep water
			Hard branching coral on consolidated substrate in very deep water
			Hard non-branching coral on consolidated substrate in shallow to deep water
			Hard non-branching coral on consolidated substrate in very deep water
			Hard undifferenciated coral on consolidated substrate in shallow to deep water
			Hard undifferenciated coral on consolidated substrate in very deep water
			Undifferenciated coral on consolidated substrate in shallow to deep water
			Undifferenciated coral on consolidated substrate in very deep water
			Soft corals and other octocorallians on consolidated substrate
			Subtidal oysters on consolidated substrate
		Unconsolidated	Hard branching coral on unconsolidated substrate in shallow to deep water
			Hard branching coral on unconsolidated substrate in very deep water
			Hard non-branching coral on unconsolidated substrate in shallow to deep water

(*continued on next page*)

Appendix A (*continued*)

Water level	Biota	Consolidation	Habitat
			Hard non-branching coral on unconsolidated substrate in very deep water
			Hard undifferenciated coral on unconsolidated substrate in shallow to deep water
			Hard undifferenciated coral on unconsolidated substrate in very deep water
			Undifferenciated coral on unconsolidated substrate in shallow to deep water
			Undifferenciated coral on unconsolidated substrate in very deep water
			Reefal gardens on unconsolidated substrate
			Subtidal wide strap seagrass
			Subtidal narrow strap seagrass
			Subtidal unspecified width strap seagrass
			Subtidal cylindrical seagrass
			Subtidal fern-like seagrass
			Ovoid seagrass in shallow water
			Ovoid seagrass in deep water
			Other seagrass in shallow water
			Other seagrass in deep water
			Scallop beds
			Subtidal oysters on unconsolidated or intermediate substrate
			Subtidal molluscs on unconsolidated or intermediate substrate
		Consolidation unassigned	Other subtidal forming habitat
			Erect calcareous algae
			Erect no-calcareous algae
			Encrusting algae
			Turf algae
			Other algae
			Octocorallians in very deep water
	Biota unsurveyed/absent	Consolidated	Calcareous consolidated or intermediate substrate
			Non-calcareous consolidated or intermediate substrate
		Unconsolidated	Boulders
			High energy over gravel
			Low energy over gravel
			High energy over mud
			Low energy over mud
			High energy over sand
			Low energy over sand
			Other unconsolidated or intermediate substrate
			High energy over unknown substrate in shallow to deep water
			Low energy over unknown substrate in shallow to deep water
			High energy over unknown substrate in very deep water
			Low energy over unknown substrate in very deep water

Appendix B

Expert panel participants and affiliation

Participant name	Affiliation
Catherine Lovelock	University of Queensland
Valerie Hagger	University of Queensland
Megan Saunders	CSIRO
Christopher Doropoulos	CSIRO
Tim Stevens	Griffith University
Guillermo Diaz-Pulido	Griffith University
Grace Isdale	NRM South
Arnon Accad	Queensland Herbarium and Biodiversity Science
Sabine Dittmann	Flinders University
Caitlin Fleck	DES Offsets
Nathan Waltham	James Cook University
Ralph Dowling	Queensland Herbarium and Biodiversity Science
Taryn McPherson	QPWS Marine Parks
Daniela Ceccarelli	AIMS
Angus Thompson	AIMS
Melanie Dixon	DAF
Jasmine Morton	DAF
Bart Mackenzie	DAF
Kylie Mcpherson	WetCAT Lead author

Appendix C
List of monitoring programs reviewed

Monitoring Program	Lead organisation	MarECAT Habitat Type
Moreton Bay Marine Park Monitoring Program	Department of National Parks, Recreation, Sport and Racing (NPRSR)	All Habitat types
Keppel Island monitoring program	AIMS	Structural macrofauna
North Queensland Bulk Port Corporation	James Cook University	Structural Macroflora
Ozcoast	Geoscience Australia, CSIRO, National Estuaries network	All Habitat types
Integrated marine Observing System (RIMREP)	CSIRO	Structural macrofauna
Ereefs (RIMREP)	CSIRO	Structural macrofauna
reef 2.0 (RIMREP)	CSIRO	Structural macrofauna
Crown of thorns starfish control program (RIMREP)	Great Barrier Reef Marine Park Authority	Structural macrofauna
Eye on the reef (RIMREP)	Great Barrier Reef Marine Park Authority	Structural macrofauna
Great Barrier Reef Marine Monitoring program (RIMREP)	Great Barrier Reef Marine Park Authority	Structural macrofauna
Long term monitoring program (RIMREP)	AIMS	Structural macrofauna
Long term Temperature Logger program	AIMS	Structural macrofauna
Weather stations	AIMS	Structural macrofauna
ReefCheck	Reef Check Foundation	Structural macrofauna
Seagrass Watch	Seagrass-Watch HQ	Structural Macroflora
Mangrove Watch	MangroveWatch	Structural Macroflora
Global Mangrove Watch	Global Mangrove Alliance	Structural Macroflora

Appendix D:. MarECAT habitat types

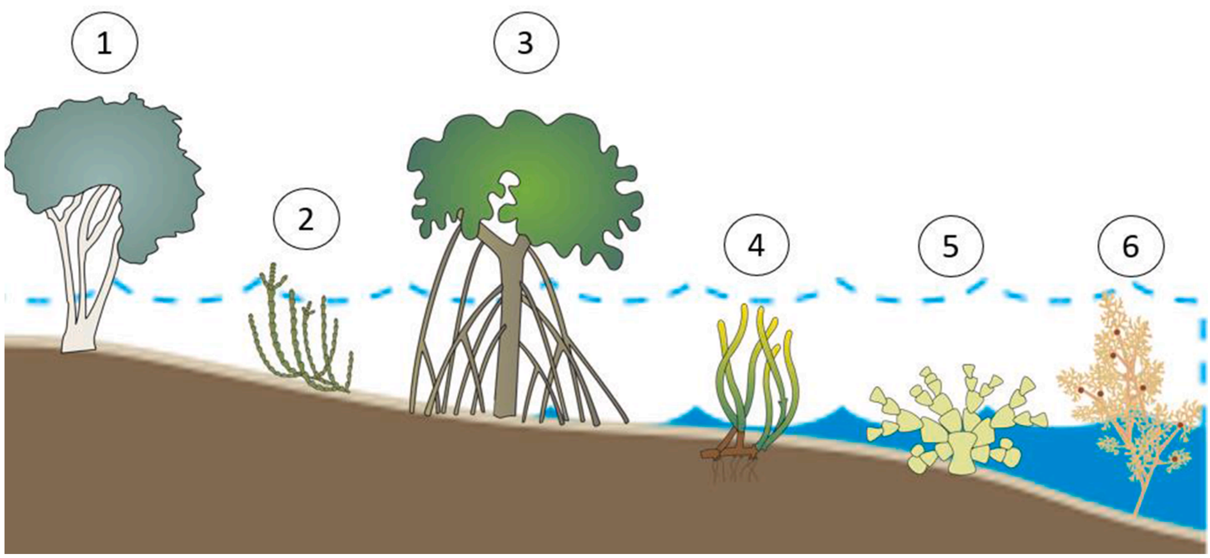

Fig. D1. Structural macroflora habitat types: 1) Supratidal Forest (e.g., Melaleuca spp.)., 2) Saltmarsh (e.g., Sarcocornia spp.), 3) Mangroves (e.g., Rhizophora spp.), 4) Seagrass (e.g., Zostera spp.), 5) Erect calcareous macroalgae (e.g., Halimeda spp.), 6) Erect non-calcareous macroalgae (e.g., Sargassum spp.).

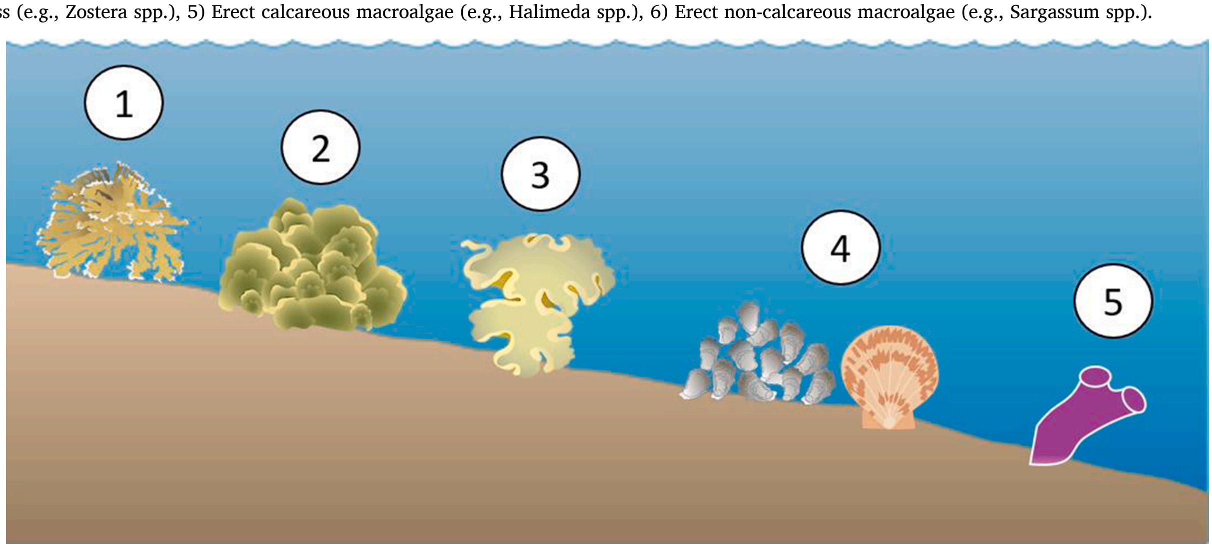

Fig. D2. Structural macrofauna habitat types: 1) Hard branching coral (e.g., Acropora spp.), 2) Hard non-branching coral (e.g., Porites spp.), and 3) Soft coral and other Octocorallians (e.g., Sarcophyton spp.) 4) Shellfish reef (oyster, mussel, scallop), 5) Other structural macrofauna (e.g., Ascidia spp.).

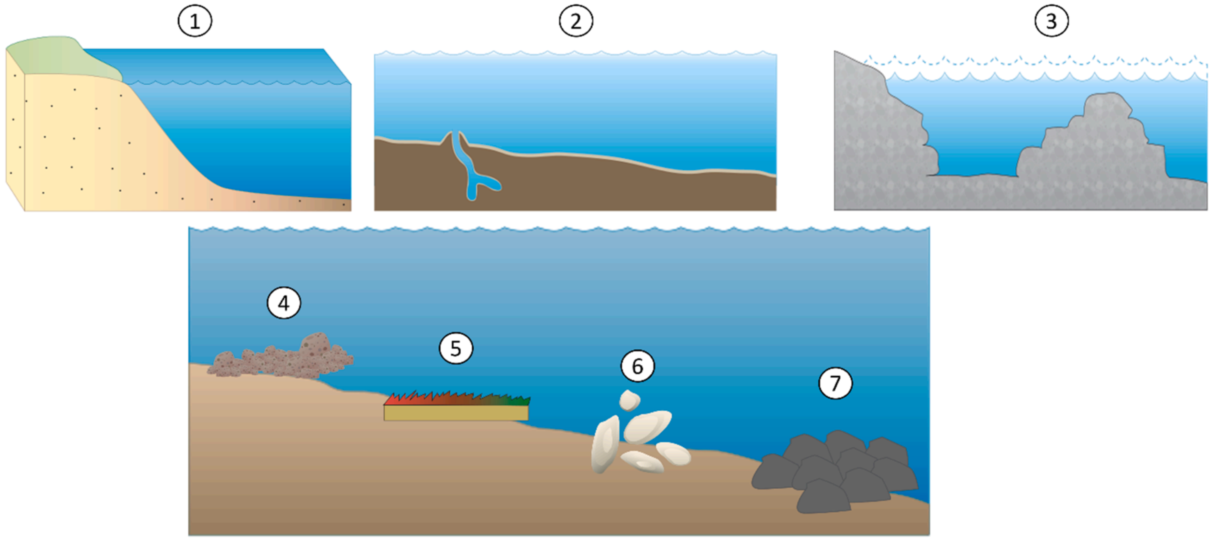

Fig. D3. Substrate dominated habitat types were based on the ecosystem types for Central Queensland, grouped by broad category tiers of non-structural macrobiota, thereafter by attributes of consolidation and substrate grain size /sediment texture: 1) Sandy shores, 2) Mud flats, 3) Rocky shores, 6) Gravel, 7) Boulders. Note that 4) Encrusting algae (e.g., crustose coralline algae) and 5) Turf algae (e.g., Lyngbya spp.) were both transferred from structural macroflora to substrate-dominated habitat types by the expert panel.

Appendix E:. MarECAT condition indicator framework

Table E1
Condition Indicators Rationale and References.

Categories	Condition indicators	Rationale
C1 Water Regime	Tidal inundation[1]	Tidal inundation controls the zonation of intertidal species. Restriction of tidal inundation can lead to the degradation of mangrove habitats.
	Energy magnitude[3]	Energy magnitude, such as wave exposure, affects benthic invertebrates communities.
C2 Water Quality	Temperature [5]	Water temperature has a physiological effect on species. Changes in water temperature can lead to coral reef habitat loss due to bleaching.
	Salinity [6]	Water salinity is an important ecological factor for chemical processes. Changes in salinity in estuaries can lead to a shift in species distribution.
	pH[7]	pH affects species' physiological processes. Changes in pH can lead to the inhibition of shell growth if it is too acidic.
	Turbidity [8]	Water clarity is a major determinant of the condition and productivity of an aquatic system. Increased turbidity can affect seagrass photosynthesis and decrease its productivity.
	Dissolved oxygen (DO)[9]	Water DO has a physiological effect on species. Hypoxia or anoxia conditions lead to major kills of marine and estuarine life.
	Nutrients [10]	Excessive loads of nutrients can cause the eutrophication of coastal waterways. This is caused by nutrient uptakes by algae blooms, and leads to hypoxia or anoxia conditions.
	Acid sulphate runoff[12]	Acid sulphate runoff reduce pH levels but it can also mobilise heavy metals which have additional toxic effects.
	Pollution [12]	High concentrations of heavy metals, pesticides, or other toxicants such as oil in coastal waters can lead to health problems in aquatic biota, including diseases and fish kills.
C3 Substrate dynamics	Substrate elevation [18]	Substrate elevation is an important ecological component, in particular for intertidal habitats. Changes in substrate elevation dynamics can lead to the erosion of the coastline and degradation of coastal habitats. Build-up of substrate elevation from increased sedimentation can smother structural macrobiota.
	Substrate disturbance [19]	Physical damages caused by substrate disturbance can lead to loss of substrate organic carbon, accelerated erosion and decrease in fauna abundance.
C4 Substrate composition	Temperature [21]	Coastal wetland canopy loss may lead to rise of substrate temperature and have direct effect on biogeochemical processes
	Salinity[22]	Sea level rise can lead to the salinisation of substrate and may significantly alter the composition, structure, and function of coastal wetlands.
	Porosity[23]	Substrate porosity is the amount of space in between particles. It is highly related to substrate water content, and to infauna species composition. Increased bioturbation activity can modify substrate porosity and alter biogeochemical processes.
	Grain size [24]	Substrate grain can be categorised by size. Higher mud content can be caused by substrate eutrophication, impacting substrate condition.
	Oxygen [25]	Substrate oxygen depletion due to eutrophication can lead to infauna kills.
	Carbon and Nitrogen content [25]	Carbon and Nitrogen content are important for biogeochemical processes. Higher organic carbon and nitrogen may cause substrate eutrophication and alter substrate condition.
	Acid sulphate soils [12]	Acid sulphate soils may cause acid run-off entering estuaries. The main effect of acid run-off is to reduce pH levels but it can also mobilise heavy metals which have additional toxic effects.
	Pollution [12]	High concentrations of heavy metals, pesticides, or other toxicants such as oil in coastal waters can lead to health problems in aquatic biota, including diseases and fish kills.
C5 Vegetation composition	Cover [30]	Vegetation cover represents their abundance. Macroalgae cover can be influenced by changes in water quality, and impact coral reef condition.
	Diversity [30]	Vegetation diversity is determined by the number of species in the habitat and their relative abundance. A decrease in species diversity could alter the resilience of the habitat.

(continued on next page)

Table E1 (*continued*)

Categories	Condition indicators	Rationale
	Growth form[32]	Growth form represents the structural aspect of the vegetation. Mangrove forests with low density but high diameter are considered mature forests, and therefore in good condition.
	Recruitment potential [32]	Recruitment potential is an essential aspect of the renewal of the vegetation. Lower juvenile densities may indicate that the conditions for vegetation growth are deteriorating.
C6 Vegetation stress	Vegetation health [32]	Vegetation health relates to the symptoms of direct threats to the vegetation. Mangrove diebacks may signify that hydrological condition have been altered.
	Non-preferred flora[41]	Non-preferred flora encompasses invasive species, or native species that may alter the condition of the habitat. For instance, sea level rise may cause mangrove encroachment in coastal freshwater habitats and saltmarsh.
C7 Fauna composition	Abundance[3]	Fauna abundance is an important component of their population dynamics. Changes in key fauna abundance, such as crabs in intertidal mudflats, may indicate heavy metal pollution or eutrophication of the habitat.
	Diversity [30]	Fauna diversity is determined by the number of species in the habitat and their relative abundance. A decrease in species diversity could alter the resilience of the habitat.
	Growth form[31]	Growth form represents the structural aspect of the fauna. A decrease in oyster shells volume may cause lower recruitment potential as large oysters have a high contribution to reproduction.
	Recruitment potential [31]	Recruitment potential is an essential aspect of the renewal of the benthic fauna. Lower juvenile densities may indicate that the conditions for fauna growth are deteriorating.
	Functional groups [25]	Fauna functional groups are based on species functional traits, here defined according to their behavioural, morphological, and physiological characteristics. Changes in benthic macrofauna functional groups are commonly reported as responses to changes in environmental conditions, particularly disturbances that affect sediment biogeochemistry and structure.
	Habitat use [46]	Habitat use by fauna communities may include nesting, foraging, scavenging, or other activities. Reproductive activities from turtles or shorebirds are a useful indicator of sandy beaches ecological conditions.
C8 Fauna threats	Fauna health [34]	Fauna health relates to the symptoms of direct threats to the fauna. The occurrence of bleached coral may indicate a change in water physico-chemical parameters threatening the condition of the reef.
	Non-preferred fauna [47]	Non-preferred fauna encompasses invasive species, or native species that may alter the condition of the habitat. For instance, damage caused by feral animals may cause sediment disturbance.
C9 Litter	Debris [49]	Marine debris is defined as any persistent solid material that is manufactured or processed and directly or indirectly, intentionally or unintentionally, disposed of or abandoned into the marine environment. Debris alter condition of flora organisms. Plastics can be detrimental to mangroves because of the risk of prolonged suffocation of pneumatophores, inhibiting growth and causing leaf loss. Degradation in microplastics leads to their entry into the food chain and accumulate in the body of fauna organisms.
	Illegal dumping*	Illegal dumping is the unlawful deposit of any type of waste material that is 200 L or more in volume, and commonly includes household rubbish and garden waste, household goods (such as whitegoods, TVs, mattresses, and furniture), building waste (construction and demolition materials), tyres, chemical drums, and paint tins or asbestos
C10 Extreme events	Fire regime [50]	Fire regime is defined by frequency, intensity, and season. Water quality can be impacted by the deposition of ash.
	Storms(e.g., tropical cyclones, east coast lows) [51]	Storm regime is defined by frequency, intensity and season. Cyclones can strip out foundation species such as coral reef.
	Extreme emersion event [52]	Extreme emersion events can be caused by events such as earthquakes. It can induce widespread mortality of intertidal species communities.
	Marine heatwave [53]	Marine heatwaves are discrete periods of anomalously warm water that can be defined by frequency, intensity and season.They are responsible for the collapse of foundation species such as coral reef.
	Pest outbreaks [54]	Pest outbreaks are defined as a shift in the biotic balance of the ecosystem. For instance, Crown of Thorns outbreak events are defined ecologically as those at densities high enough that starfish consume coral faster than it can grow.

Appendix E2. . Reference list for condition indicators and metrics

1. Van Loon, A.F., Te Brake, B., Van Huijgevoort, M.H. and Dijksma, R., 2016. Hydrological classification, a practical tool for mangrove restoration. *PLoS One*, *11*(3), p.e0150302.
2. Hickey, R., 2019. Tidal inundation modeling within GIS. *Journal of Coastal Conservation*, *23*(3), pp.599–606.
3. Denis-Roy, L., Ling, S.D., Fraser, K.M. and Edgar, G.J., 2020. Relationships between invertebrate benthos, environmental drivers and pollutants at a subcontinental scale. *Marine Pollution Bulletin*, *157*, p.111316.
4. Pepper, A. and Puotinen, M.L., 2009. GREMO: A GIS-based generic model for estimating relative wave exposure.
5. Water temperature - OzCoasts
6. Salinity - OzCoasts
7. Water pH – OzCoasts
8. Turbidity - OzCoasts
9. Dissolved oxygen - OzCoasts
10. Water column nutrients - OzCoasts
11. Chlorohyll a - OzCoast
12. Scheltinga, D.M., Moss, A., 2007. A framework for assessing the health of coastal waters: a trial of the national set of estuarine, coastal and marine indicators in Queensland. June 2007 Final report (condensed version).
13. Schaffelke, B., Mellors, J. and Duke, N.C., 2005. Water quality in the Great Barrier Reef region: responses of mangrove, seagrass and macroalgal communities. *Marine pollution bulletin*, *51*(1–4), pp.279–296.
14. Metal contaminants - OzCoasts
15. Cahoon, D.R., Lynch, J.C., Perez, B.C., Segura, B., Holland, R.D., Stelly, C., Stephenson, G. and Hensel, P., 2002. High-precision measurements of wetland sediment elevation: II. The rod surface elevation table. *Journal of Sedimentary Research*, *72*(5), pp.734–739.

16. Arias-Ortiz, A., Masqué, P., Glass, L., Benson, L., Kennedy, H., Duarte, C.M., Garcia-Orellana, J., Benitez-Nelson, C.R., Humphries, M.S., Ratefinjanahary, I. and Ravelonjatovo, J., 2021. Losses of soil organic carbon with deforestation in mangroves of Madagascar. *Ecosystems*, 24, pp.1–19.
17. Dai, W., Li, H., Zhou, Z., Cybele, S., Lu, C., Zhao, K., Zhang, X., Yang, H. and Li, D., 2018. UAV photogrammetry for elevation monitoring of intertidal mudflats. *Journal of Coastal Research*, (85 (10085)), pp.236–240.
18. Mackenzie, J.R., Duke, N.C. and Wood, A.L., 2016. The Shoreline Video Assessment Method (S-VAM): Using dynamic hyperlapse image acquisition to evaluate shoreline mangrove forest structure, values, degradation and threats. *Marine pollution bulletin*, *109*(2), pp.751–763.
19. Thompson, L.M. and Schlacher, T.A., 2008. Physical damage to coastal dunes and ecological impacts caused by vehicle tracks associated with beach camping on sandy shores: a case study from Fraser Island, Australia. *Journal of Coastal Conservation*, *12*, pp.67–82.
20. Kenyon, T.M., Doropoulos, C., Wolfe, K., Webb, G.E., Dove, S., Harris, D. and Mumby, P.J., 2023. Coral rubble dynamics in the Anthropocene and implications for reef recovery. *Limnology and Oceanography*, *68*(1), pp.110–147.
21. Zhao, X., Rivera-Monroy, V.H., Li, C., Vargas-Lopez, I.A., Rohli, R.V., Xue, Z.G., Castaneda-Moya, E. and Coronado-Molina, C., 2022. Temperature across vegetation canopy-water-soil interfaces is modulated by hydroperiod and extreme weather in coastal wetlands. *Frontiers in Marine Science*, *9*, p.543.
22. Grieger, R., Capon, S.J., Hadwen, W.L. and Mackey, B., 2021. Spatial variation and drivers of vegetation structure and composition in coastal freshwater wetlands of subtropical Australia. *Marine and Freshwater Research*, *72*(12), pp.1746–1759.
23. Valdemarsen, T., Quintana, C.O., Thorsen, S.W. and Kristensen, E., 2018. Benthic macrofauna bioturbation and early colonization in newly flooded coastal habitats. *Plos one*, *13*(4), p.e0196097.
24. Hallett, C.S., Valesini, F.J., Kilminster, K., Wells, N.S. and Eyre, B.D., 2019. A rapid protocol for assessing sediment condition in eutrophic estuaries. *Environmental Science: Processes & Impacts*, *21*(6), pp.1021–1037.
25. Lam-Gordillo, O., Mosley, L.M., Simpson, S.L., Welsh, D.T. and Dittmann, S., 2022. Loss of benthic macrofauna functional traits correlates with changes in sediment biogeochemistry along an extreme salinity gradient in the Coorong lagoon, Australia. *Marine Pollution Bulletin*, *174*, p.113202.
26. Przeslawski, R., Berents, P., Clark, M., Dittmann, S., Edgar, G., Frid, C., Hooper, G., Hughes, L., Ingleton, T., Kennedy, D., Nichols, S., Smith, J., 2020. Marine sampling field manual for grabs and box corers. In Przeslawski R, Foster S (Eds)., in: Field Manuals for Marine Sampling to Monitor Australian Waters. National Environmental Science Programme (NESP).
27. Dittmann, S., Baring, D.R., Lam-Gordillo, O., 2019a. Mudflat Condition Monitoring in Upper Gulf St Vincent. Final Report for the Adelaide and Mount Lofty Ranges Natural Resources Management Board. Flinders University College of Science & Engineering, Adelaide.
28. Iram, N., Maher, D. T., Lovelock, C. E., Baker, T., Cadier, C., & Adame, M. F. (2022). Climate change mitigation and improvement of water quality from the restoration of a subtropical coastal wetland. *Ecological Applications*, *32*(5), e2620.
29. Corrigan, S., Brown, A.R., Ashton, I.G., Smale, D.A. and Tyler, C.R., 2022. Quantifying habitat provisioning at macroalgal cultivation sites. *Reviews in Aquaculture*, *14*(3), pp.1671–1694.
30. McKenzie 2003 Draft Guideline for the rapid assessment of seagrass habitats in the western Pacific (QFS, NFC, Cairns)
31. AIMS, n.d. Reef monitoring sampling methods | AIMS [WWW Document]. URL https://www.aims.gov.au/docs/research/monitoring/reef/sampling-methods.html (accessed 6.6.22).
32. Mackenzie, J., Duke, N., 2009. State of the Mangroves Report: Burnett Mary Region. A descriptive account and condition assessment of estuaries, tidal wetlands and mangroves.Final Report to the Burnett Mary Regional Group. University of Queensland, Centre for Marine Studies, Brisbane
33. Cadier, C., Bayraktarov, E., Piccolo, R. and Adame, M.F., 2020. Indicators of coastal wetlands restoration success: a systematic review. *Frontiers in Marine Science*, *7*, p.600220.
34. Beeden, R.J., Turner, M.A., Dryden, J., Merida, F., Goudkamp, K., Malone, C., Marshall, P.A., Birtles, A. and Maynard, J.A., 2014. Rapid survey protocol that provides dynamic information on reef condition to managers of the Great Barrier Reef. *Environmental monitoring and assessment*, *186*, pp.8527–8540.
35. Baggett, L.P., Powers, S.P., Brumbaugh, R.D., Coen, L.D., DeAngelis, B.M., Greene, J.K., Hancock, B.T., Morlock, S.M., Allen, B.L., Breitburg, D. L. and Bushek, D., 2015. Guidelines for evaluating performance of oyster habitat restoration. Restoration Ecology, 23(6), pp.737–745.
36. D'Archino, R. and Piazzi, L., 2021. Macroalgal assemblages as indicators of the ecological status of marine coastal systems: A review. *Ecological Indicators*, *129*, p.107835.
37. Bishop, M.J., Byers, J.E., Marcek, B.J. and Gribben, P.E., 2012. Density-dependent facilitation cascades determine epifaunal community structure in temperate Australian mangroves. *Ecology*, *93*(6), pp.1388–1401.
38. Grieger, R., Capon, S. and Hadwen, W., 2019. Resilience of coastal freshwater wetland vegetation of subtropical Australia to rising sea levels and altered hydrology. *Regional Environmental Change*, *19*, pp.279–292.
39. https://wetlandinfo.des.qld.gov.au/wetlands/ecology/components/flora/mangroves/mangrove-dieback.html
40. Bryars, S., Collings, G. and Miller, D., 2011. Nutrient exposure causes epiphytic changes and coincident declines in two temperate Australian seagrasses. Marine Ecology Progress Series, 441, pp.89–103
41. Rumbelow, K., Speziali, A., Bloomfield, A., 2010. Working Towards a Statewide Inventory of Estuaries: Advancing the Inventory of Estuaries in Five NRM Regions of South Australia. Department of Environment & Natural Resources, Adelaide.
42. Hill, J., Loder, J., Reef Check Foundation Ltd. Reef Check Australia Survey Methods. (No. 2015). 2013.
43. Coen, L.D. and Luckenbach, M.W., 2000. Developing success criteria and goals for evaluating oyster reef restoration: ecological function or resource exploitation?. *Ecological engineering*, *15*(3–4), pp.323–343.
44. McAfee, D., McLeod, I.M., Boström-Einarsson, L. and Gillies, C.L., 2020. The value and opportunity of restoring Australia's lost rock oyster reefs. Restoration Ecology, 28(2), pp.304–314.
45. Rolo, V., Olivier, P.I. and van Aarde, R., 2017. Tree and bird functional groups as indicators of recovery of regenerating subtropical coastal dune forests. *Restoration Ecology*, *25*(5), pp.788–797.
46. Schlacher, T.A., Schoeman, D.S., Jones, A.R., Dugan, J.E., Hubbard, D.M., Defeo, O., Peterson, C.H., Weston, M.A., Maslo, B., Olds, A.D. and Scapini, F., 2014. Metrics to assess ecological condition, change, and impacts in sandy beach ecosystems. Journal of Environmental Management, 144, pp.322–335

47. Marshall, J.C., Blessing, J.J., Clifford, S.E., Negus, P.M. and Steward, A.L., 2020. Epigeic invertebrates of pig-damaged, exposed wetland sediments are rooted: An ecological response to feral pigs (Sus scrofa). Aquatic Conservation: Marine and Freshwater Ecosystems, 30(12), pp.2207–2220.
48. Winarni, N.L., Pradana, D.H., Ayujawi, S.A., Zackeisha, N., Anugra, B.G., Wulandari, Y. and Syachrudin, D., 2022. Problems in paradise: Mangrove bird communities impacted by litter in Jakarta Bay, Indonesia. *Ocean & Coastal Management*, *225*, p.106223.
49. Lippiatt, Sherry, Sarah Opfer, and Courtney Arthur. "Marine debris monitoring and assessment: recommendations for monitoring debris trends in the marine environment." (2013).
50. Santín, C., Doerr, S.H., Otero, X.L. and Chafer, C.J., 2015. Quantity, composition and water contamination potential of ash produced under different wildfire severities. Environmental Research, 142, pp.297–308.
51. Puotinen, M.L., 2007. Modelling the risk of cyclone wave damage to coral reefs using GIS: a case study of the Great Barrier Reef, 1969–2003. *International Journal of Geographical Information Science*, *21*(1), pp.97–120.
52. Schiel, D.R., Gerrity, S., Orchard, S., Alestra, T., Dunmore, R.A., Falconer, T., Thomsen, M.S. and Tait, L.W., 2021. Cataclysmic Disturbances to an Intertidal Ecosystem: Loss of Ecological Infrastructure Slows Recovery of Biogenic Habitats and Diversity. *Frontiers in Ecology and Evolution*, p.827.
53. Smith, K.E., Burrows, M.T., Hobday, A.J., King, N.G., Moore, P.J., Sen Gupta, A., Thomsen, M.S., Wernberg, T. and Smale, D.A., 2023. Biological impacts of marine heatwaves. *Annual review of marine science*, *15*, pp.119–145.
54. Babcock, R.C., Plagányi, É.E., Condie, S.A., Westcott, D.A., Fletcher, C.S., Bonin, M.C. and Cameron, D., 2020. Suppressing the next crown-of-thorns outbreak on the Great Barrier Reef. Coral Reefs, 39(5), pp.1233–1244.

*Variables integrated from experts inputs during Technical Group Workshops.

Appendix F: MarECAT threat indicator framework

Threat Indicators	Threat indicator rating (0–5) and description of state	Visual cues and other information
T1. Major hydrological modifications (LS/SS)	5) No major hydrological modifications and no major dam(s) affecting the habitat in the catchment.4) Major hydrological modifications are not likely and with no major dam(s) in the catchment.3) Major hydrological modifications are likely and no major dam(s) in the catchment.2) One major hydrological modification, but no major dam(s) in the catchment.1) Two to three major hydrological modification, but no major dam(s) in the catchment.0) More than three major hydrological modification, and/or major dam(s) in the catchment.	• Major land hydrological modifications, such as major impoundments (dams, weirs), irrigation systems (% Irrigated agriculture landuse from QLUMP mapping (Qld Land Use and Mapping Project), or drainage systems, which inhibit water from moving across the landscape. • Major sea hydrological modifications, including hardening of unconsolidated shoreline such as coastal defense, modification of substrate grain size and/or composition, presence of port/harbour/marina and related boating activity • Aerial photograph interpretation. • Barriers and instream structures (Department of Environment and Science) (des.qld.gov.au).
T2. Minor hydrological modifications (HS)	5) No hydrological modifications.4) Minor hydrological modifications are not likely (but evidence is not clear).3) Minor hydrological modifications are likely (but evidence is not clear).2) One minor hydrological modification is evident.1) Two to three minor hydrological modifications are evident.0) More than three minor hydrological modifications are evident.	• Impoundment density • Number of impoundments without effective fish ladders • Presence of entrance modifications • Presence of tidal barrage • Presence of artificial structures above the level of the natural substrate -piers, jetties, pipelines, boat ramps other terrain morphology modifications (constructed ridges and/or peaks, …) • Modifications in terrain morphology below the level of the natural substrate – dredged channels, holes, canal networks etc. • Recordings and observations of minor land hydrological modifications, such as roads, railways, fences, bunds, weed chokes, poor water quality, infilling, or earthen farm dams, which can inhibit the movement of water, and aquatic fauna, • Wetland hydromodifier mapping, • Intertidal and subtidal ecosystems of Central Queensland naturalness qualifier mapping – modified consolidation, terrain morphology, substrate composition, tidal inundation, substrate grain size (WetlandMaps) • Aerial photograph interpretation. • Water resource planning information for riverine systems - % annual proportion of flow deviation (APFD) • Barriers and instream structures (Department of Environment and Science) (des.qld.gov.au). • Wetland surrounding area < 1 km from the edge of the wetland • Catchment/Seascape assessment 1 km up to 5 km from the edge of the wetland
T3. Inflow from land activity (HS)	5) Inflow from modified landscapes is not evident.4) Inflows from modified landscapes are not likely.3) Inflows from modified landscapes are likely.2) < 4 inflows are evident.1) 4–18 inflows are evident.0) More than 18 inflows are evident.	· Inflow from land activity can alter water regimes, concentrate flows, scour soils/sediments, and introduce contaminants. · Stormwater, sewage, or water releases for prescribed activities such as mines are considered as inflow from land activity. · Information on the number of sewage plants without tertiary treatment, volume/number of sewage overflow events, percentage of area using septic systems (Cox et al. 2011) · Fish kill events can provide information on toxic water release. · Local government area (LGA) information about the extent of sewered versus unsewered residential areas.

(*continued on next page*)

(*continued*)

Threat Indicators	Threat indicator rating (0–5) and description of state	Visual cues and other information
		· Mapping layers of point sources, such as major roads, residential areas, resource and primary production/extraction activities, stormwater drains. · Licensed pollutant delivery sites (DES compliance pollution database) · Aerial photograph interpretation.
T4. Sediment resuspension (HS)	5) No sediment resuspension activities.4) Sediment resuspension activities are not likely (but evidence is not clear).3) Sediment resuspension activities are likely (but evidence is not clear).2)One sediment resuspension activity is evident.1) Two to three sediment resuspension activities are evident.0) More than three sediment resuspension activities are evident.	· Dredging in river system, sand and gravel extraction, and sand mining · Aerial extent of disturbed and untreated acid sulphate soils · Potential of estuary length adjoining with acid sulphate soils · Beach nourishment activities · Extreme wind wave induced sediment resuspension (Green and Coco 2013) · Broad scale sediment resuspension in catchment receiving waters – wind-driven wave resuspension of flood plume sediment.
T5. Land Use(LS/SS)	5) No intensive land use in the catchment4) 1—25 % intensive land use in the catchment3) 26–50 % intensive land use in the catchment2) 51–75 % intensive land use in the catchment1) 76 %-95 % intensive land use in the catchment0) 96–100 % intensive land use in the catchment	· Unsealed road density · Intensive agriculture on steep slopes · Percentage of catchment under intensive animal production · QLUMP mapping – reclassified by ALUM - primary landuse –1. Nature conservation 2. Native forestry production/ grazing 3. Dryland agriculture 4. Irrigated agriculture 5. Intensive use including urban and industrial · Australian Land Use and Management (ALUM) intensive land use (ALUM PRIMARY77 categories 3, 4 and 5). · Coastal population size · Percentage of catchment under ponded pastureland use · GIS and/or aerial photograph interpretation.
T6. Sea Use(LS/SS and HS)	5) No intensive sea use present.4) 1—25 % intensive sea use is present.3) 26–50 % intensive sea use is present2) 51–75 % intensive sea use is present.1) 76 %-95 % intensive sea use present.0) 96–100 % intensive sea use is present.	· Boating activity within the estuary · Number of boats moored. · Number of boats using a waterbody · Recreational usage index · Marine Parks zoning plans and designated areas within Highly Protected Areas – MNP and CP zones – Fish Habitat Areas – higher rating. · Marine Parks zoning plans and designated areas within habitat protection (mid rating) and general use zones – (lower rating) · Percentage of catchment under 'marine' aquaculture
T7. Native habitat conversion(LS/SS and HS)	5) Native habitat conversion is not evident (other than natural seasonal change).4) Very small area(s) of native habitat conversion is evident (e. g.,<5%).3) Small area(s) of native habitat conversion is evident (e.g., 5–25 %).2) Moderate area(s) of native habitat conversion is evident (e.g., 25–50 %).1) Much of the area is converted from native habitat (e.g., 50–75 %).0) Most of the area is converted from native habitat (e.g., >75 %).	· Clearing of native vegetation where it previously existed, as indicated by pre-clear vegetation mapping (i.e., current remnant vegetation and regrowth vegetation layer compared to preclear layer). · Percentage length of river system with no riparian vegetation · Percentage of catchment cleared · Percentage of estuarine riparian area modified · QLUMP cleared land or similar composite (e.g., Herbarium Integrated Vegetation Dataset). · Cartographic interpretation of contemporary imagery if required
T8. Species collection and harvesting(LS/SS and HS)	5) Collection or harvesting of is not evident.4) Collection or harvesting is not likely (but evidence is not clear).3) Limited collection or harvesting of wetland species is evident (e.g., limited to scientific collection).2) Minor evidence of collection or harvesting1) Moderate evidence of collection or harvesting (e.g., fishing spot).0) Strong evidence of collection or harvesting	· Commercial trawl usage of an estuary and adjoining coastal waters. · Marine Parks designated areas – (classify extractive uses and permitted zonings vs non extractive uses and highly protected areas). · Number of recreational fishers using an estuary and adjoining coastal waters. · Recreational and commercial bait (beachworm, bloodworm, bait fish, yabby, etc.) collector usage of an estuary and adjoining coastal waters. · Commercial line fishing usage of an estuary and adjoining coastal waters. · Commercial net and crab pots usage of an estuary and adjoining coastal waters. · Total commercial fisher catch from an estuary and adjoining coastal waters. · Coral trout abundance and size can be a good indicator of fishing pressure. · Commercial licensed collector (of aquarium fish, shell, coral, etc.) usage of an estuary and adjoining coastal waters. · Local knowledge on specific resource overexploitation. · DAF advice on licenses for fisheries and wildlife collection. · QPWS advice on wildlife collection. · NRM advice. · Cross check with evidence of infrastructure (e.g., jetties, and signage).
T9. Non-preferred species (LS/SS and HS)	5) Non-preferred species are not evident, such as cattle or feral pigs.4) Non-preferred wetland species are not likely (but evidence is not clear).3) Non-preferred wetland species affect < 5 % of the area of interest.2). Non-preferred wetland species affect 5–25 % of the area of interest.1) Non-preferred wetland species affect 26–50 % of the area of interest.0) Non-preferred wetland species affect > 50 % of the area of interest.	· Percentage of river system affected by aquatic weeds. · Presence of aquaculture facilities using marine species non-native to the region · Recordings or observations of site-specific, non-preferred fauna or vegetation, which may be native or exotic, or terrestrial or aquatic. · Exotic animals that inhabit (e.g., toads, fishes, or turtles) or regularly use (e.g., feral pigs, cattle, goats, horses) wetlands, including invasive animals. · Exotic non-preferred predators such as direct observations of dead or alive feral predators, such as fish, dogs, cats or foxes, or indirect

(*continued on next page*)

(*continued*)

Threat Indicators	Threat indicator rating (0–5) and description of state	Visual cues and other information
		observations such as predated birds and small mammals, scats, tracks, or burrows. · Native non-preferred predators, such as spangled perch, may predate other native fish in a wetland system that was previously isolated from predators. · Exotic plants that grow in wetlands, such as salvinia, water hyacinth, water lettuce, Singapore daisy, hymenachne, exotic typha, alligator weed, cat's claw creeper, willow, prickly Acacia, Noogoora burr or pasture grasses, including invasive plant. · Native non-preferred vegetation. For example, phragmites and most typha are native, but can be non-preferred where they dominate a system and influence ecology (e.g., reduces dissolved oxygen levels and prevents fish passage). · Noxious fish are listed under Queensland nd include several fish species, such as tilapia, carp and gambusia. · Declared animals are pests listed under Queensland legislation and include water buffalo and red-eared slider turtles. · Local knowledge, land use mapping. · DAF, NRM, LGA, QPWS advice. · Pestinfo. · WildNet.
T10. Extreme events(LS/SS and HS)	5) No extreme event recorded4) One extreme event is recorded, but neither frequent nor intense3) More than one extreme event is recorded, but neither frequent nor intense2). More than one extreme event is recorded, at least one of them being frequent1). More than one extreme event is recorded, at least one of them being frequent and intense0). Many extreme events are recorded, being frequent and intense	· Frequency and Intensity of extreme events · Marine Heatwaves · Cyclones · Storms · Floods · Sea level rise events · Emersion events · Bushfires · Oil spills · Use BOM data

References

Arias-Ortiz, A., Masqué, P., Glass, L., Benson, L., Kennedy, H., Duarte, C.M., Garcia-Orellana, J., Benitez-Nelson, C.R., Humphries, M.S., Ratefinjanahary, I., Ravelonjatovo, J., Lovelock, C.E., 2021. Losses of soil organic carbon with deforestation in mangroves of Madagascar. Ecosystems 24, 1–19. https://doi.org/10.1007/s10021-020-00500-z.

Auerbach, N.A., Wilson, K.A., Tulloch, A.I.T., Rhodes, J.R., Hanson, J.O., Possingham, H. P., 2015. Effects of threat management interactions on conservation priorities. Conserv. Biol. 29, 1626–1635. https://doi.org/10.1111/cobi.12551.

Baggett, L.P., Powers, S.P., Brumbaugh, R.D., Coen, L.D., DeAngelis, B.M., Greene, J.K., Hancock, B.T., Morlock, S.M., Allen, B.L., Breitburg, D.L., Bushek, D., Grabowski, J. H., Grizzle, R.E., Grosholz, E.D., La Peyre, M.K., Luckenbach, M.W., McGraw, K.A., Piehler, M.F., Westby, S.R., Ermgassen, P., 2015. Guidelines for evaluating performance of oyster habitat restoration. Restor. Ecol. 23, 737–745. https://doi.org/10.1111/rec.12262.

Baldera, A., Hanson, D.A., Kraft, B., 2018. Selecting indicators to monitor outcomes across projects and multiple restoration programs in the Gulf of Mexico. Ecol. Ind. 89, 559–571. https://doi.org/10.1016/j.ecolind.2018.01.025.

Barbier, E.B., 2019. The value of coastal wetland ecosystem services. In: Coastal Wetlands. Elsevier 947–964.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81, 169–193. https://doi.org/10.1890/10-1510.1.

Basconi, L., Cadier, C., Guerrero-Limón, G., 2020. Challenges in Marine Restoration Ecology: How Techniques, Assessment Metrics, and Ecosystem Valuation Can Lead to Improved Restoration Success, in: YOUMARES 9 - The Oceans: Our Research, Our Future. doi: 10.1007/978-3-030-20389-4_5.

Bayraktarov, E., Brisbane, S., Hagger, V., Smith, C.S., Wilson, K.A., Lovelock, C.E., Gillies, C., Steven, A.D.L., Saunders, M.I., 2020. Priorities and motivations of marine coastal restoration research. Front. Mar. Sci. 7, 484. https://doi.org/10.3389/fmars.2020.00484.

Beeden, R.J., Turner, M.A., Dryden, J., Merida, F., Goudkamp, K., Malone, C., Marshall, P.A., Birtles, A., Maynard, J.A., 2014. Rapid survey protocol that provides dynamic information on reef condition to managers of the great barrier reef. Environ. Monit. Assess. 186, 8527–8540. https://doi.org/10.1007/s10661-014-4022-0.

Burrows, A., Scott, P., 2020. BioCAT: a rapid tool to detect changes in native vegetation communities. Developed Using the Queensland Herbarium's BioCondition as the Foundation.

Cadier, C., Bayraktarov, E., Piccolo, R., Adame, M.F., 2020. Indicators of coastal wetlands restoration success: a systematic review. Front. Mar. Sci. 7, 1–11. https://doi.org/10.3389/fmars.2020.600220.

Carwardine, J., O'Connor, T., Legge, S., Mackey, B., Possingham, H.P., Martin, T.G., 2012. Prioritizing threat management for biodiversity conservation. Conserv. Lett. 5, 196–204. https://doi.org/10.1111/j.1755-263X.2012.00228.x.

Chaigneau, T., Brown, K., 2016. Challenging the win-win discourse on conservation and development: analyzing support for marine protected areas. Ecol. Soc. 21 https://doi.org/10.5751/ES-08204-210136.

Cooper, T.F., Gilmour, J.P., Fabricius, K.E., 2009. Bioindicators of changes in water quality on coral reefs: review and recommendations for monitoring programmes. Coral Reefs 28, 589–606. https://doi.org/10.1007/s00338-009-0512-x.

Costanza, R., D'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., Van Den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature. https://doi.org/10.1038/387253a0.

Crain, C.M., Halpern, B.S., Beck, M.W., Kappel, C.V., 2009. Understanding and managing human threats to the coastal marine environment. Ann. N. Y. Acad. Sci. https://doi.org/10.1111/j.1749-6632.2009.04496.x.

Cvitanovic, C., Hobday, A.J., van Kerkhoff, L., Wilson, S.K., Dobbs, K., Marshall, N.A., 2015. Improving knowledge exchange among scientists and decision-makers to facilitate the adaptive governance of marine resources: a review of knowledge and research needs. Ocean Coast. Manag. https://doi.org/10.1016/j.ocecoaman.2015.05.002.

Department of Environment and Heritage Protection 2017, Queensland Intertidal and Subtidal ecosystem classification scheme Version 1.0: Module 1—Introduction and implementation of intertidal and subtidal ecosystem classification, Queensland Wetlands Program, Queensland Government, Brisbane.

Department of Environment and Science, Queensland, 2019. Intertidal and subtidal ecosystem types of Central Queensland, WetlandInfo website, accessed 30 October 2023. Available at: https://wetlandinfo.des.qld.gov.au/wetlands/ecology/aquatic-ecosystems-natural/estuarine-marine/descriptions/.

Department of Environment and Science, Queensland, 2021. Aquatic Ecosystem Rehabilitation Process, WetlandInfo website, accessed 23 November 2023. Available at: https://wetlandinfo.des.qld.gov.au/wetlands/management/rehabilitation/rehab-process/.

Department of Environment and Science, 2022, WetCAT: A Condition Assessment Tool for Measuring Event Recovery and Rehabilitation in Palustrine and Lacustrine Wetlands in Queensland, Version 1.0, June 2022, Queensland Wetlands Program, Queensland Government, Brisbane.

Diaz-Pulido, G., McCook, L.J., Larkum, A.W.D., Lotze, H.K., Raven, J.A., Schaffelke, B., Smith, J.E., Steneck, R.S, 2007. Vulnerability of macroalgae of the Great Barrier Reef to climate change. In: Climate change and the Great Barrier Reef (eds. Johnson, JE & Marshall, PA). Great Barrier Reef Marine Park Authority & Australian Greenhouse Office Townsville, pp. 153-192.

Dibble, K.L., Meyerson, L.A., 2012. Tidal Flushing restores the physiological condition of fish residing in degraded salt Marshes. PLoS One e46161. https://doi.org/10.1371/journal.pone.0046161.

Dinsdale, E.A., Harriott, V.J., 2004. Assessing anchor damage on coral reefs: a case study in selection of environmental indicators. Env Manage 33, 126–139. https://doi.org/10.1007/s00267-003-3056-9.

Done, T., Roelfsema, C., Harvey, A., Schuller, L., Hill, J., Schläppy, M.L., Lea, A., Bauer-Civiello, A., Loder, J., 2017. Reliability and utility of citizen science reef monitoring data collected by reef check Australia, 2002–2015. Mar. Pollut. Bull. 117, 148–155. https://doi.org/10.1016/j.marpolbul.2017.01.054.

Doropoulos, C., Gómez-Lemos, L.A., Salee, K., McLaughlin, M.J., Tebben, J., Van Koningsveld, M., Feng, M., Babcock, R.C., 2022. Limitations to coral recovery along an environmental stress gradient. Ecol. Appl. 32, e2558.

Duarte, C.M., Agusti, S., Barbier, E., Britten, G.L., Castilla, J.C., Gattuso, J.P., Fulweiler, R.W., Hughes, T.P., Knowlton, N., Lovelock, C.E., Lotze, H.K., Predragovic, M., Poloczanska, E., Roberts, C., Worm, B., 2020. Rebuilding marine life. Nature 580, 39–51. https://doi.org/10.1038/s41586-020-2146-7.

Eger, A.M., Earp, H.S., Friedman, K., Gatt, Y., Hagger, V., Hancock, B., Kaewsrikhaw, R., Mcleod, E., Moore, A.M., Niner, H.J., Razafinaivo, F., Sousa, A.I., Stankovic, M., Worthington, T.A., Bayraktarov, E., Saunders, M., Vergés, A., Reeves, S., 2022. The need, opportunities, and challenges for creating a standardized framework for marine restoration monitoring and reporting. Biol. Conserv. 266 https://doi.org/10.1016/j.biocon.2021.109429.

Gann, G.D., McDonald, T., Walder, B., Aronson, J., Nelson, C.R., Jonson, J., Hallett, J.G., Eisenberg, C., Guariguata, M.R., Liu, J., Hua, F., Echeverría, C., Gonzales, E., Shaw, N., Decleer, K., Dixon, K.W., 2019. International principles and standards for the practice of ecological restoration. Second Edition. Restor Ecol 27, S1–S46. https://doi.org/10.1111/rec.13035.

Gatt, Y.M., Andradi-Brown, D.A., Ahmadia, G.N., Martin, P.A., Sutherland, W.J., Spalding, M.D., Donnison, A., Worthington, T.A., 2022. Quantifying the reporting, coverage and consistency of key indicators in mangrove restoration projects. Front Forest Glob Change 5, 1–15. https://doi.org/10.3389/ffgc.2022.720394.

Great Barrier Reef Marine Park Authority & Queensland Government. 2015. Reef 2050 Integrated Monitoring and Reporting Program Strategy. Great Barrier Reef Marine Park Authority, Townsville, Queensland, Australia.

Hallett, C.S., Valesini, F.J., Kilminster, K., Wells, N.S., Eyre, B.D., 2019. A rapid protocol for assessing sediment condition in eutrophic estuaries. Environ. Sci.-Pro Imp. 21, 1021–1037. https://doi.org/10.1039/c9em00141g.

Heink, U., Kowarik, I., 2010. What are indicators? on the definition of indicators in ecology and environmental planning. Ecol. Ind. 10, 584–593. https://doi.org/10.1016/j.ecolind.2009.09.009.

Hughes, A.C., Grumbine, R.E., 2023. The Kunming-Montreal global biodiversity framework: what it does and does not do, and how to improve it. Front. Env. Sci. 11 https://doi.org/10.3389/fenvs.2023.1281536.

Jones, L.P., Turvey, S.T., Massimino, D., Papworth, S.K., 2020. Investigating the implications of shifting baseline syndrome on conservation. People Nat. 2, 1131–1144. https://doi.org/10.1002/pan3.10140.

Leewis, L., van Bodegom, P.M., Rozema, J., Janssen, G.M., 2012. Does beach nourishment have long-term effects on intertidal macroinvertebrate species abundance? Estuar. Coast. Shelf Sci. 113, 172–181. https://doi.org/10.1016/j.ecss.2012.07.021.

Lilley, S.A., Schiel, D.R., 2006. Community effects following the deletion of a habitat-forming alga from rocky marine shores. Oecologia 148, 672–681. https://doi.org/10.1007/s00442-006-0411-6.

Lopes, R., Videira, N., 2013. Valuing marine and coastal ecosystem services: an integrated participatory framework. Ocean Coast. Manag. 84, 153–162. https://doi.org/10.1016/j.ocecoaman.2013.08.001.

Lovelock, C.E., Adame, M.F., Bradley, J., Dittmann, S., Hagger, V., Hickey, S.M., Hutley, L.B., Jones, A., Kelleway, J.J., Lavery, P.S., Macreadie, P.I., Maher, D.T., McGinley, S., McGlashan, A., Perry, S., Mosley, L., Rogers, K., Sippo, J.Z., 2022. An Australian blue carbon method to estimate climate change mitigation benefits of coastal wetland restoration. Rest Ecol. 1–15 https://doi.org/10.1111/rec.13739.

Maron, M., Rhodes, J.R., Gibbons, P., 2013. Calculating the benefit of conservation actions. Conserv. Lett. 6, 359–367. https://doi.org/10.1111/conl.12007.

Mcdonald, T., Gann, G.D., Jonson, J., Dixon, K.W., 2016. International standards for the practice of ecological restoration – Including principles and key concepts. First Edition: December 2016. SER in collaboration with SER Australasia.

McKenzie, L., 2003. Guidelines for the rapid assessment and mapping of tropical seagrass habitats. Cairns, QFS, NFC, p. 46.

Mellors, J.E., McKenzie, L.J., Coles, R.G., 2008. Seagrass-watch: engaging torres strait islanders in marine habitat monitoring. Cont. Shelf Res. 28, 2339–2349. https://doi.org/10.1016/j.csr.2008.03.041.

Miller, K.L., Trezise, J.A., Kraus, S., Dripps, K., Evans, M.C., Gibbons, P., Possingham, H. P., Maron, M., 2015. The development of the Australian environmental offsets policy. Conservation 42, 306–314. https://doi.org/10.2307/26320630.

Niner, H. J., Milligan, B., Jones, P. J. S., & Styan, C. A., 2017. Realising a vision of no net loss through marine biodiversity offsetting in Australia Ocean Coast Manag, 148, 22–30. doi: 10.1016/j.ocecoaman.2017.07.006.

Papworth, S.K., Rist, J., Coad, L., Milner-Gulland, E.J., 2009. Evidence for shifting baseline syndrome in conservation. Conserv. Lett. 2, 93–100. https://doi.org/10.1111/j.1755-263x.2009.00049.x.

Phang, S.C., Failler, P., Bridgewater, P., 2020. Addressing the implementation challenge of the global biodiversity framework. Biodivers. Conserv. 29, 3061–3066. https://doi.org/10.1007/s10531-020-02009-2.

Queensland Government, Queensland, 2015, Groundwater dependent ecosystem FAQs, WetlandInfo website, accessed 1 February 2021. Available at: https://wetlandinfo.des.qld.gov.au/wetlands/facts-maps/gde-background/gde-faq/.

Ruiz-Jaen, M.C., Aide, T.M., 2005. Restoration success: how is it being measured? Restor. Ecol. 13, 569–577. https://doi.org/10.1111/j.1526-100X.2005.00072.x.

Santín, C., Doerr, S.H., Otero, X.L., Chafer, C.J., 2015. Quantity, composition and water contamination potential of ash produced under different wildfire severities. Environ. Res. 142, 297–308. https://doi.org/10.1016/j.envres.2015.06.041.

Saunders, M.I., Doropoulos, C., Bayraktarov, E., Babcock, R.C., Gorman, D., Eger, A.M., Vozzo, M.L., Gillies, C.L., Vanderklift, M.A., Steven, A.D.L., Bustamante, R.H., Silliman, B.R., 2020. Bright spots in coastal marine ecosystem restoration. Curr. Biol. 30, R1500–R1510. https://doi.org/10.1016/j.cub.2020.10.056.

Saunders, M.I., Waltham, N.J., Cannard, T., Sheppard, M., Fischer, M., Twomey, A., Bishop, M., Boody, K., Callaghan, D., Fulton, B., Lovelock, C.E., Mayer-Pinto, M., McLeod, I.L., McPherson, T., Morris, R., Pomeroy, A., Ronan, M., Swearer, S., Steven, A. (2022). A roadmap for coordinated-scale coastal and marine ecosystem restoration. Report to the Reef and Rainforest Research Centre, Cairns, Queensland.

Scheltinga D. M. and Moss A., 2007. A framework for assessing the health of coastal waters: a trial of the national set of estuarine, coastal and marine indicators in Queensland. Environmental Protection Agency Queensland, prepared for the National Land & Water Resources Audit, Canberra.

Schuler, D., Namioka, A. (Eds.), 1993. Participatory design: Principles and practices. CRC Press, Boca Raton, FL. S.

Sheaves, M., 2009. Consequences of ecological connectivity: the coastal ecosystem mosaic. Mar. Ecol. Prog. Ser. https://doi.org/10.3354/meps08121.

Smart, J. C. R., Hasan, S., Volders, A., Curwen, G., Fleming, C., & Burford, M. (2016). A tradable permit scheme for cost-effective reduction of nitrogen runoff in the sugarcane catchments of the Great Barrier Reef. Report to the national environmental science Programe. Reef and Rainforest Research Centre Limited, Cairns, Australia.

Smit, K.P., Bernard, A.T.F., Lombard, A.T., Sink, K.J., 2021. Assessing marine ecosystem condition: a review to support indicator choice and framework development. Ecol. Ind. 121, 107148 https://doi.org/10.1016/j.ecolind.2020.107148.

State of Queensland, 2020. Land restoration fund co-benefits Standard. Queensland Government, Australia.

Staudt, F., Gijsman, R., Ganal, C., Mielck, F., Wolbring, J., Hass, H.C., Goseberg, N., Schüttrumpf, H., Schlurmann, T., Schimmels, S., 2021. The sustainability of beach nourishments: a review of nourishment and environmental monitoring practice. J. Coast. Conserv. 25, 1–24. https://doi.org/10.1007/s11852-021-00801-y.

Stelzenmüller, V., Breen, P., Stamford, T., Thomsen, F., Badalamenti, F., Borja, Á., Buhl-Mortensen, L., Carlstöm, J., D'Anna, G., Dankers, N., Degraer, S., Dujin, M., Fiorentino, F., Galparsoro, I., Giakoumi, S., Gristina, M., Johnson, K., Jones, P.J.S., Katsanevakis, S., Knittweis, L., Kyriazi, Z., Pipitone, C., Piwowarczyk, J., Rabaut, M., Sørensen, T.K., van Dalfsen, J., Vassilopoulou, V., Vega Fernández, T., Vincx, M., Vöge, S., Weber, A., Wijkmark, N., Jak, R., Qiu, W., ter Hofstede, R., 2013. Monitoring and evaluation of spatially managed areas: a generic framework for implementation of ecosystem based marine management and its application. Mar. Policy 37, 149–164. https://doi.org/10.1016/j.marpol.2012.04.012.

Stewart-Oaten, A., Murdoch, W.W., Parker, K.R., 1986. Environmental impact assessment:" pseudoreplication" in time? Ecology 67, 929–940. https://doi.org/10.2307/1939815.

Suykerbuyk, W., Bouma, T.J., Govers, L.L., Giesen, K., de Jong, D.J., Herman, P., Hendriks, J., van Katwijk, M.M., 2016. Surviving in changing seascapes: sediment dynamics as bottleneck for long-term seagrass presence. Ecosystems 19 (2), 296–310. https://doi.org/10.1007/s10021-015-9932-3.

Tango, P.J., Batiuk, R.A., 2016. Chesapeake Bay recovery and factors affecting trends: long-term monitoring, indicators, and insights. Reg. Stud. Mar. Sci. 4, 12–20. https://doi.org/10.1016/j.rsma.2015.11.010.

van Dijk, A., Mount, R., Gibbons, P., Vardon, M., Canadell, P., 2014. Environmental reporting and accounting in Australia: Progress, prospects and research priorities. Sci. Total Environ. 473–474, 338–349. https://doi.org/10.1016/j.scitotenv.2013.12.053.

Van Loon, A.F., Te Brake, B., Van Huijgevoort, M.H.J., Dijksma, R., 2016. Hydrological classification, a practical tool for mangrove restoration. PLoS One 11, e0150302.

Vozzo, M.L., Doropoulos, C., Silliman, B.R., Steven, A., Reeves, S.E., ter Hofstede, R., van Koningsveld, M., van de Koppel, J., McPherson, T., Ronan, M., Saunders, M.I., 2023. To restore coastal marine areas, we need to work across multiple habitats simultaneously. P. Natl. Acad. Sci. USA 120, e2300546120. https://doi.org/10.1073/pnas.2300546120.

White, P.S., Walker, J.L., 1997. Approximating nature's variation: selecting and using reference information in restoration ecology. Restor. Ecol. 5, 338–349. https://doi.org/10.1046/j.1526-100X.1997.00547.x.

Zaucha, J., Kreiner, A., 2021. Engagement of stakeholders in the marine/maritime spatial planning process. Mar. Policy 132. https://doi.org/10.1016/j.marpol.2018.12.013.