Australian Government

Great Barrier Reef Marine Park Authority

Queensland Government

Monitoring coral reefs within the Reef 2050 Integrated Monitoring and Reporting Program:

Final Report of the Coral Reef Expert Group

Schaffelke, B.[1], Anthony, K.[1], Babcock, R.[2], Bridge, T.[3,4], Carlos, E.[5], Diaz-Pulido, G.[5], Gonzalez-Rivero, M.[1], Gooch, M.[3], Hoey, A.[3], Horne, D.[6], Kane, K.[7], McKenzie, C.[8], Merida, F.[6], Molloy, F.[6], Moon, S.[8], Mumby, P.[9], Ortiz, J.C.[1], Pears, R.[6], Phinn, S.[9], Ridgway,T.[10], Roelfsema, C.[9], Singleton,G.[11], Thompson, A.[1]

[1] Australian Institute of Marine Science
[2] CSIRO
[3] James Cook University
[4] Queensland Museum
[5] Reef Catchments Natural Resource Management
[6] Great Barrier Reef Authority
[7] North Queensland Bulk Ports
[8] Association of Marine Park Tourism Operators
[9] University of Queensland
[10] Great Barrier Reef Foundation
[11] Dawul Wuru Aboriginal Corporation

The Great Barrier Reef Marine Park Authority acknowledges the continuing sea country management and custodianship of the Great Barrier Reef by Aboriginal and Torres Strait Islander Traditional Owners whose rich cultures, heritage values, enduring connections and shared efforts protect the Reef for future generations.

Published by the Great Barrier Reef Marine Park Authority

ISBN 9780648589211

A catalogue record for this publication is available from the National Library of Australia

This publication should be cited as:

Schaffelke, B., Anthony, K., Babcock, R., Bridge, T., Carlos, E., Diaz-Pulido, G., Gonzalez-Rivero, M., Gooch, M., Hoey, A., Horne, D., Kane, K., McKenzie, C., Merida, F., Molloy, F., Moon, S., Mumby, P., Ortiz, J.C., Pears, R., Phinn, S., Ridgway,T., Roelfsema, C., Singleton,G., and Thompson, A. 2020, *Monitoring coral reefs within the Reef 2050 Integrated Monitoring and Reporting Program: final report of the coral reef expert group*, Great Barrier Reef Marine Park Authority, Townsville.

Front cover image: Underwater reefscape view at Lodestone Reef, Townsville region. © Commonwealth of Australia (GBRMPA), photographer: Joanna Hurford.

Australian Government
Great Barrier Reef Marine Park Authority

Great Barrier Reef Marine Park Authority
280 Flinders Street Townsville | PO Box 1379 Townsville QLD 4810
Phone: (07) 4750 0700
Fax: 07 4772 6093
Email: info@gbrmpa.gov.au

www.gbrmpa.gov.au

Acknowledgements

Essential additional information and analyses to support the recommendations were provided by seven commissioned desktop studies (provided as Supplementary Reports) which were authored by some members of the Coral Reef Expert Group and the following scientists:

- Yves-Marie Bozec
- Carolina Castro-Sanguino
- Alistair Cheal
- Michael Emslie
- Carla Ewels
- Eric Lawrey
- Sebastian Lopez-Marcano
- Camille Mellin
- Patricia Menendez
- Erin Peterson
- Marji Puotinen

Supplementary Reports (provided separately)

Commissioned desktop studies to inform the design recommendations.

S1. Practical taxonomy for coral reef monitoring under the Reef 2050 Integrated Monitoring and Reporting Program. Russ Babcock and Thomas Bridge

S2. Practical Taxonomy for monitoring of coral reef macroalgae under the Reef 2050 Integrated Monitoring and Reporting Program. Guillermo Diaz-Pulido

S3. Synopsis of current coral reef monitoring on the Great Barrier Reef. Alistair J Cheal and Michael J Emslie

S4. Model to Inform the Design of a Reef 2050 Integrated Monitoring and Reporting Program. Camille Mellin, Ken Anthony, Erin Peterson, Carla Ewels and Marji Puotinen

S5. Statistical power of existing AIMS long-term reef monitoring programs. Angus Thompson and Patricia Menendez

S6. Novel technologies in coral reef monitoring. Manuel Gonzalez-Rivero, Chris Roelfsema, Sebastian Lopez-Marcano, Carolina Castro-Sanguino, Thomas Bridge, Russ Babcock

S7. Coral reef models as assessment and reporting tools for the Reef 2050 Integrated Monitoring and Reporting Program: A review. Yves-Marie Bozec and Peter J. Mumby

S8. Monitoring Site Planner – Choosing where to monitor coral reefs on the Great Barrier Reef. Eric Lawrey, Aaron Smith, Gael Lafond, Marc Hammerton

1.0 Executive Summary

This report provides recommendations for the design of the coral reef theme of the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP).

The design recommendations were based on published information, expert knowledge of members of the RIMReP Coral Reef Expert Group, specifically commissioned desktop studies and reviews (available as separate Supplementary Reports), and further out-of-session work.

This foundational information for guiding the recommendations provided:

- the identification of actions within the Reef 2050 Plan relevant to coral reef ecosystems;
- the clarification and definition of information requirements of managers and stakeholders;
- an agreed conceptual model of system understanding of coral reef ecosystems — including drivers, pressures, impacts and management responses;
- a summary of current knowledge of status and trends of coral reef attributes;
- synopses of current monitoring and modelling activities relevant to coral reef ecosystems;
- evaluations of the adequacy of current monitoring and modelling of proposed coral reef indicators to achieve the objectives of RIMReP, including an identification of gaps; and
- a review and evaluation of new monitoring technologies for their potential to increase efficiency of future monitoring.

The design process strove to anticipate future changes (for example, change of needs, advancements in technology), however, the Coral Reef Expert Group clearly acknowledged that the recommended design is for a 'RIMReP version 1.0', which will evolve and continually adapt and improve over the duration of the Reef 2050 Plan.

Based on the foundational information and expert knowledge, the Coral Reef Expert Group recommends:

- A suite of indicators, considered to most effectively monitor the condition of coral reef ecosystems to provide information essential to track the effectiveness of the ecosystem-oriented actions associated with the Reef 2050 Plan.
  The selection was based on a set of decision criteria and includes widely used indicators with demonstrated value for condition and trend assessments, process studies and development of ecological models.

- An efficient, hierarchical design with three spatial scales:

  – Broad-scale, whole-of reef monitoring: for example, remote sensing-based shallow water reef classification, general reef area habitat map, and aerial reef-wide assessments of bleaching extent.

- Medium-scale monitoring: for example, regular structured monitoring at fixed, 'backbone' sites for reporting of trends in condition and resilience; reactive surveys at local to regional scale, for example for the assessment of extent and severity of disturbances).

- Site-specific, small-scale monitoring: for example, selected 'sentinel' or 'reference' sites for sampling additional indicators, testing and validation of new technology, process studies; specific early warning sites (such as Eye-on-the-Reef Tourism Weekly sites, sites in the crown-of-thorns starfish outbreak initiation area).

- An initial selection of fixed sites for the medium-scale 'backbone' coral reef monitoring, based on the outputs of a specifically developed multi-criteria analysis tool (Monitoring Site Planner). For this recommendation report, the Monitoring Site Planner was applied using a set of initial criteria:
  - spatial attributes (Natural Resource Management regions which could be used as reporting regions for RIMReP, Marine Park zoning, reef bioregions of the Great Barrier Reef);
  - environmental gradient data (climatology of summer and winter temperatures, annual mean Secchi depth, annual mean non-algal particulates, annual mean chlorophyll, maximum annual current flow); and
  - the amount of historic data available (in years) for each of the reefs that have been monitored.

  The Monitoring Site Planner can be further refined for a final site selection for the RIMReP implementation, for example by determining different weightings between criteria, adding additional criteria, and adding 'must have' sites. These decisions would be best made in close consultation between key RIMReP stakeholders and the Coral Reef Expert Group. The advantage of using the interactive Monitoring Site Planner for future design refinement is that trade-offs between various criteria can be easily evaluated and visualised.

- A sampling strategy using methods ready for immediate application and recommendations for a phased implementation of additional sites, new technologies and increased inclusion of community and citizen monitoring.

Additional recommendations were made for developing a modelling suite for data integration, analyses, reporting and prediction of future state. Specific requirements and priorities should be articulated during the RIMReP implementation phase.

Contents

1.1 List of Tables

1.2 List of Figures

2.0 Background and design considerations

The Great Barrier Reef, like all coral reef ecosystems globally, is vulnerable to climate change and ocean acidification, and is under significant direct pressure from human activities. Monitoring and reporting coral reef condition and trends is essential to understand the extent and rate of any changes, especially those that might lead to a loss in resilience, and to inform management actions. High quality observational data will also support research to better understand cause and effect relationships that are vital to build and validate ecological models that will be required for forecasting and decision support into the future.

2.1 Objectives of the Reef 2050 Integrated Monitoring and Reporting Program

The *Reef 2050 Long-Term Sustainability Plan* (Reef 2050 Plan) provides an overarching strategy for managing the Great Barrier Reef (the Reef). It contains actions, targets, objectives and outcomes to address threats and protect and improve the Reef's health and resilience, while allowing ecologically sustainable use. The Reef 2050 Plan has been developed in consultation with partners, including Traditional Owners and the resource, ports, fishing, agriculture, local government, research and conservation sectors.

A key component of the Reef 2050 Plan is the establishment of the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP). RIMReP will provide a comprehensive and up-to-date understanding of the Reef — the values and processes that support it and the threats that affect it. This knowledge is fundamental to informing actions required to protect and improve the Reef's condition and to drive resilience-based management.

There are currently over 90 monitoring programs operating in the Reef World Heritage Area and adjacent catchment. These programs have been designed for a variety of purposes and operate at a variety of spatial and temporal scales. The comprehensive strategic assessments of the World Heritage Area and adjacent coastal zone — both of which formed the basis for the Reef 2050 Plan — identified the need to ensure existing monitoring programs align with each other and with management objectives. RIMReP will fulfil this need.

RIMReP will provide information across the seven themes that make up the Reef 2050 Plan outcomes framework. The themes are ecosystem health; biodiversity; water quality; heritage; community benefits; economic benefits and governance.

The intent of RIMReP is not to duplicate existing arrangements but to coordinate and integrate existing monitoring, modelling and reporting programs across disciplines. For example, the *Reef 2050 Water Quality Improvement Plan* underpins the Reef 2050 Plan's water quality theme, and RIMReP will form a key part of the new integrated program.

As the driver of resilience-based management under the Reef 2050 Plan, RIMReP's primary purpose is to enable timely and suitable responses by Reef managers and partners to emerging issues and risks and enable the evaluation of whether the Reef 2050 Plan is on track to meet its outcomes, objectives and targets.

RIMReP's vision is to develop a knowledge system that enables resilience-based management of the Reef and its catchment, and provides managers with a comprehensive understanding of how the Reef 2050 Plan is progressing (see**RIMReP will** be central to ensuring decisions regarding the protection and management of the Reef are based on the best available science, consistent with the principles of transparency and accountability, and underpinned by a partnership approach.

Figure 1 for a program logic).

Three goals for the knowledge system are that it is:

- ***Effective*** in enabling the early detection of trends and changes in the Reef's environment, inform the assessment of threats and risks, and drive resilience-based management.
- ***Efficient*** in enabling management priorities and decisions to be cost effective, transparent, and based on cost-benefit and risk analyses.
- ***Evolving*** based on the findings of Great Barrier Reef Outlook Reports, new technologies and priority management and stakeholder needs.

RIMReP will be central to ensuring decisions regarding the protection and management of the Reef are based on the best available science, consistent with the principles of transparency and accountability, and underpinned by a partnership approach.

Figure 1. RIMReP program logic. Each of the three goals has associated development and implementation objectives as well as foundational inputs.

2.2 Relevant *Reef 2050 Long-Term Sustainability Plan* targets, objectives and outcomes

The recommended design for the RIMReP coral reef monitoring theme will deliver knowledge, information and data that will enable some level of reporting against the following relevant outcomes, objectives and targets of the Reef 2050 Plan (Commonwealth of Australia, 2015):

Reef 2050 Plan Ecosystem Health theme outcome statement:

'The status and ecological functions of ecosystems within the Great Barrier Reef World Heritage Area are in at least good condition with a stable to improving trend.'

Relevant objectives:

- **EHO2** The World Heritage Area retains its integrity and system functions by maintaining and restoring the connectivity, resilience and condition of marine and coastal ecosystems.
- **EHO3** Trends in the condition of key ecosystems including coral reefs, seagrass meadows, estuaries, islands, shoals and inter-reefal areas are improved over each successive decade.

Relevant target:

- **EHT5** Condition and resilience indicators for coral reefs are on a trajectory towards at least good condition at local, regional and Reef-wide scales.

Reef 2050 Plan Biodiversity Theme outcome statement:

'The Reef maintains its diversity of species and ecological habitats in at least a good condition with a stable to improving trend.'

Relevant objectives:

- **BO4** Indices of biodiversity are in good or very good condition at Reef-wide and regional scales.
- **BO5** Reef habitats and ecosystems are managed to sustain healthy and diverse populations of indicator species across their natural range.

Relevant target:

- **BT5** Trends in populations of key indicators species and habitat condition are stable or improving at Reef-wide and regionally relevant scales.

Recent advice prepared for the 2020 review of the Reef 2050 Plan[1], however, it highlighted that the current ambitious ecosystem health and biodiversity outcome statements of

[1] http://www.environment.gov.au/marine/gbr/reef2050/mid-term-review

maintaining good or very good condition and an improvement in values are no longer realistic under the projections of climate change and ongoing local pressures (Roth et al., 2017).

A potential future revision of Reef 2050 Plan outcomes statements, objectives and targets is not expected to require a substantial revision of the recommended RIMReP coral reef monitoring program. The Coral Reef Expert Group design recommendation is based on principles of using robust, widely applied and accepted indicators for evaluations of coral reef condition and trends, hierarchical sampling and adaptive continuous improvements (see below).

A challenge will remain to report in a scientifically rigorous and practical manner against the qualitative statements of 'good' and 'healthy' for the condition of the Reef's values. This will likely evolve over the maturing of RIMReP and. For example, RIMReP will be informed by future recommendations on the identification of key species for reef function to be developed by a recently commenced two-year research project (National Environmental Science Program Tropical Water Quality Hub Project 4.6 — Recommendations to maintain functioning of the Reef[2]) and by other research — for example, on defining reef 'aesthetics' (Vercelloni et al., 2018) and by the continuous development of reporting metrics for existing long-term programs (Thompson et al., 2016).

2.3 Information needs for Great Barrier Reef management

Management information needs and approaches for the application of monitoring data to report the condition and trends of coral reef-associated values and attributes have been variously described (McClanahan et al., 2012; Hedge et al., 2013; Flower et al., 2017). An overview of useful, albeit ambitious, long-term monitoring objectives for the Reef is restated here (from Hedge et al., 2013). This was used as an initial basis for the indicator selection and the design recommendation:

- Determine trends in coral reef condition, community composition, recruitment and growth rate of inshore, midshelf and offshore reefs at higher spatial and temporal coverage than at present, including at impacted sites.
- Determine trends in coral reef resilience indicators (after McClanahan et al., 2012): resistant coral species, temperature variability, nutrients, sedimentation, coral diversity, herbivore biomass, physical human impacts, coral disease, macroalgae, recruitment, fishing pressure, crustose coralline algae and crown-of-thorns starfish.
- Determine coral larval production, transport and settlement between reefs to identify source and sink reefs and connectivity.
- Measure extent, frequency and intensity of impact effects as well as recovery from exposure of coral reefs to rising sea level, flood plumes, cyclones, sediments, nutrients, pesticides, ocean acidification, crown-of-thorns starfish, clearing and modifying coastal habitat, dredging activities and increased sea and air temperature (refer also to Table 3 for list of pressures prioritised by the Coral Reef Expert Group for attribution of observed changes and impact-specific reporting).

[2] https://nesptropical.edu.au/index.php/round-4-projects/project-4-6/#

- Measure trends in incidence of coral disease.
- Predict crown-of-thorns starfish outbreak initiation and progression of outbreak wave through early warning monitoring based on crown-of-thorns starfish numbers, water quality and flood events.
- Determine level of crown-of-thorns starfish and *Drupella* predation on coral throughout the Reef.

In-depth discussions with staff of the Authority (the Authority) and other stakeholders, as well as a specifically commissioned report (Udy, 2017), provided further guidance on what type of coral reef monitoring information would support the identified five main categories of management use:

1. Tactical - responding to an event or incident (e.g. vessel grounding, flood, cyclone, coral bleaching, crown-of-thorns) e.g. by estimating spatial extent of impact/change and informing on potential response options.
2. Operational (prioritisation of compliance effort, moorings, permit assessments) e.g. by reporting trends in condition and resilience of coral reefs.
3. Strategic planning (e.g. zoning, policy development) e.g., by comparing condition of coral reefs with threats.
4. Quantifying effectiveness of management actions e.g. by quantifying changes in coral relative to management action.
5. Reporting to community and stakeholders (e.g. report cards, Outlook reports, web and social media) e.g. by reporting changes in extent or condition of coral reefs at regional scale (also desire to report at Reef-wide and local scale).

Information about the condition and trends of coral reefs is a fundamental component of the assessment of heritage values in the Great Barrier Reef Outlook Report (Great Barrier Reef Marine Park Authority, 2019). The Biodiversity section of the Outlook Report includes assessments of coral reefs as key habitats and of corals, other invertebrates and bony fishes as key species. The Ecosystem Health section of the Outlook Report also includes assessments of key ecological processes associated with coral reef communities, such as microbial processes, particle feeding, primary production, herbivory, predation, symbiosis, recruitment, reef building, competition and connectivity, and reporting of current condition and trends in outbreaks of coral disease and of crown-of-thorns starfish populations. Assessments of the condition and trend of coral reef habitat and coral communities were made with a high level of confidence, based on ‘adequate high-quality evidence’, which reflects the availability of fit-for-purpose data from monitoring and research projects. All other assessment components relevant to this RIMReP theme were assessed based on limited or very limited evidence. The Great Barrier Reef Region Strategic Assessment (Great Barrier Reef Marine Park Authority, 2014) used the same coral reef habitat and biodiversity key values and attributes for a Reef-wide evaluation of the effects of large-scale drivers of change (climate change and economic growth, for example) and human activities.

Data and condition and trend assessments from current coral reef long-term monitoring programs are also included as essential elements in existing reports cards[3].

The Outlook Report habitat and species values and processes guided the RIMReP Coral Reef Expert Group in the selection of indicators recommended to be used in the RIMReP coral reef monitoring (see below).

3.0 RIMReP Coral Reef Expert Group tasks

The Coral Reef Expert Group (CREG) was one of eight expert groups, which all followed a prescribed process to recommend a design for their thematic component. The tasks of the expert groups included:

- Synopsis of the theme, to include discussion on current state, primary drivers, pressures and responses using DPSIR framework.
- Review of all current monitoring and modelling activities relevant to the expert group theme.
- Identify candidate indicators that can be monitored and would provide information about trend, status or forecasting of value or the system.
- Evaluation of the adequacy and confidence of current monitoring and modelling of candidate indicators, determined by their ability to meet the objectives of the RIMReP and management needs provided by the Authority.
- Identification and discussion of gaps and opportunities in current monitoring and modelling of such indicators.
- Evaluation of new monitoring technologies for their potential to increase efficiency or statistical power and their compatibility with long-term datasets.
- Recommendations for monitoring design including consideration of:
    - Primary indicators
    - Continuity of data sets
    - How the design addresses management needs
    - Modification to existing programs
    - Costing
    - Transition strategies

[3] http://www.reefplan.qld.gov.au/measuring-success/report-cards/; http://healthyriverstoreef.org.au/report-card-results/; http://riverhealth.org.au/report_card/ehi/; http://ghhp.org.au/report-cards/2016; http://wettropicswaterways.org.au/report-card-2017/

4.0 Current understanding of coral reef systems and status on the Great Barrier Reef

4.1 Coral Reef Systems on the Great Barrier Reef

Coral reefs are highly interconnected ecosystems. Organisms, attributes and processes respond to a multitude of external factors, often including complex mechanisms. Various conceptual and qualitative models have described the links and relationships between organisms, the environmental and external drivers on coral reefs (e.g. Fabricius, 2011; Dambacher et al., 2013; Anthony et al., 2013; Kuhnert et al., 2014; Great Barrier Reef Marine Park Authority, 2014; Flower et al., 2017). The illustration of ecological processes and key attributes of coral reefs in Flower et al. (2017) was used as a starting point for the RIMReP design process (**Figure 2**). Based on the available conceptual models and expertise in the Coral Reef Expert Group a working conceptual model was collated, based on the principles of the Driver, Pressure, State, Impact and Response (DPSIR) (**Figure 3**).

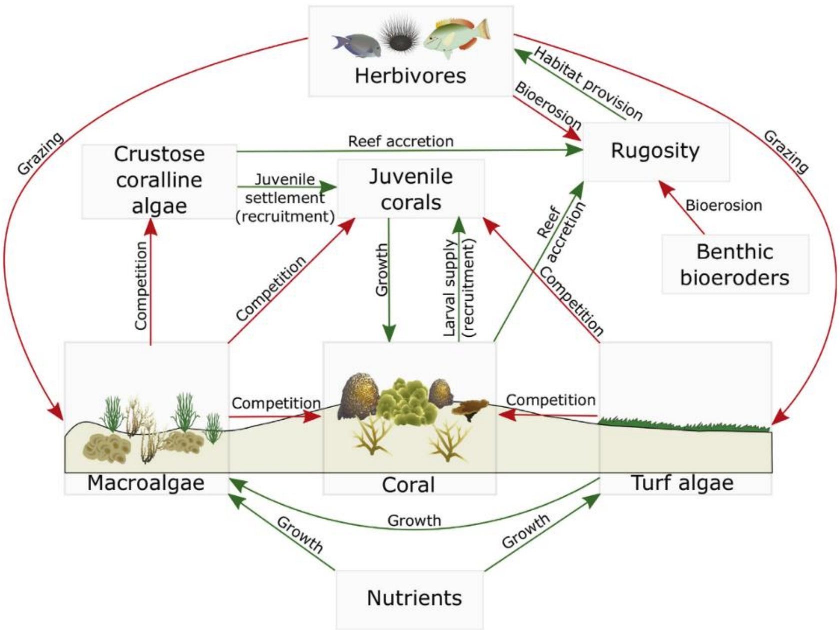


Figure 2. Illustration of the main ecological processes, attributes and feedbacks on a coral reef (reproduced from Flower et al. (2017).[4]

[4] Note that coral predation, for example by Crown-of-thorns starfish, is omitted in this diagram.

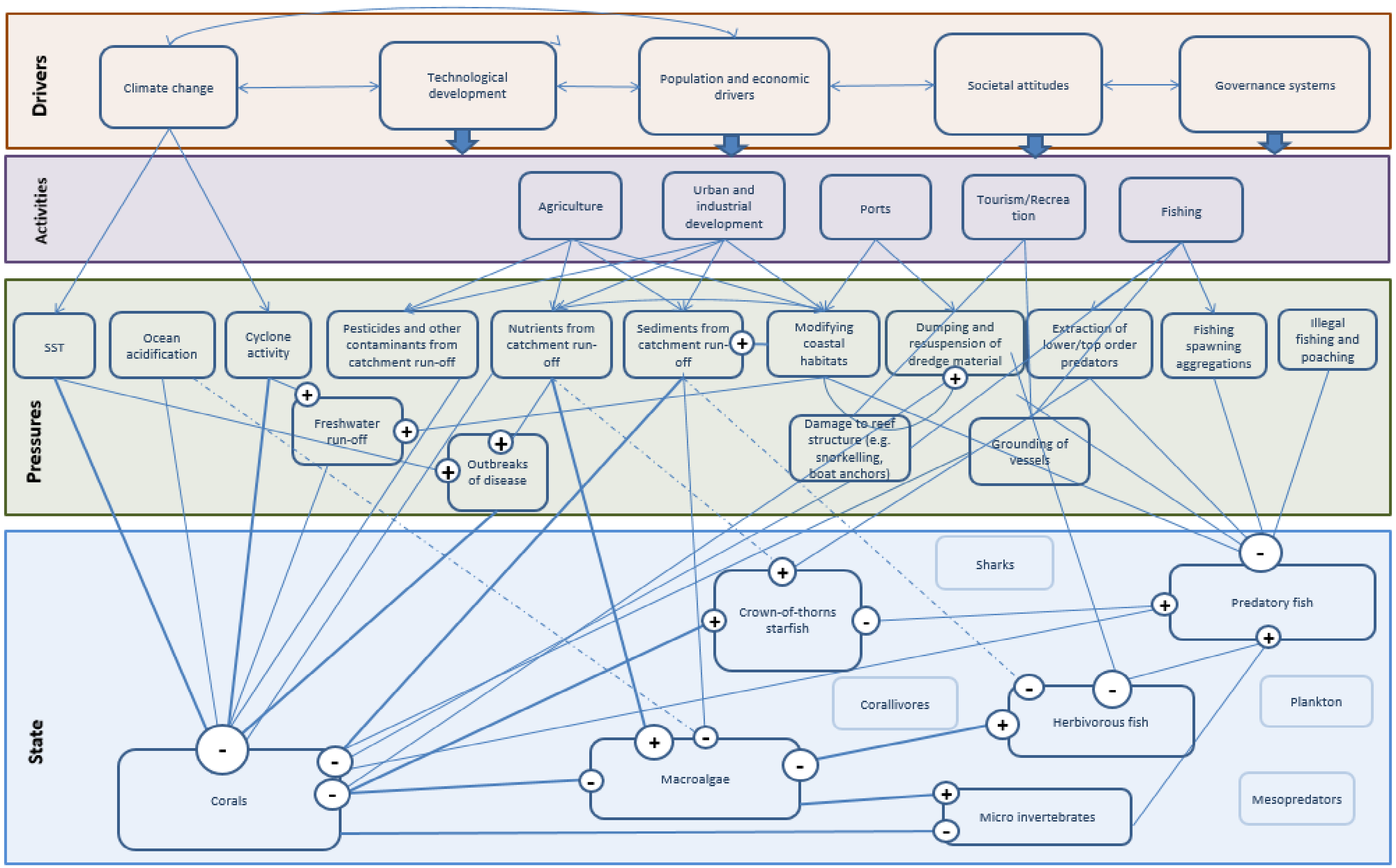


Figure 3. Illustration of the relationships of attributes of coral reef ecosystems with external pressures, activities and drivers to assist with indicator selection for the coral reef monitoring under RIMReP

4.2 Current status of coral reef systems on the Great Barrier Reef

Long-term data on indicators of coral reefs condition are essential to understand the context of short-term trends as coral reefs go naturally through cycles of disturbance and recovery. Observed long-term trends generally reflect the regional histories of disturbance. An updated analysis of the coral cover data, the most widely reported indicator for the condition of coral reef benthos, from the Australian Institute of Marine Science's (AIMS) Long-Term Monitoring Program to May 2018 showed clear differences in coral cover trends in three different regions of the Reef **(Figure 4**).

Coral cover on reefs in the Northern region was in early 2017 less than half of what it was in 2013, due to mortality caused by two severe cyclones, an ongoing crown-of-thorns starfish outbreak and severe coral bleaching in 2016. Mean coral cover on survey reefs in the northern Reef was very low in 2017 (about 10 per cent), which has not been observed before in the AIMS 30-plus year time series.

Coral cover on reefs in the Central region has been generally lower than in the other two regions. Cover decreased to the lowest level on record in 2012 (De'ath et al., 2012), following the impact of tropical cyclone Yasi in 2011, and then recovered rapidly up until 2016. Surveys in 2018 found coral cover had declined to 14 per cent due to coral bleaching in 2016 and again in 2017 and increasing activity of the crown-of-thorns starfish as the current wave of outbreaks moves south.

Coral cover in the Southern region was affected by severe tropical cyclone Hamish in 2009 causing extensive damage. From 2009-2016, there were no severe cyclones and few recorded outbreaks of crown-of-thorns starfish in the Swains or Capricorn-Bunker sectors, enabling the coral cover on reefs in those sectors to increase. However, many of the southern Swain reefs have current intense crown-of-thorns starfish outbreaks. Reefs in the Pompey sector were close to the path of tropical cyclone Marcia (February 2015) which set back recovery. These same reefs were also affected in March 2017 by tropical cyclone Debbie. Mean coral cover on reefs in the Southern region declined for the first time in seven years, dropping from 33 per cent in 2017 to 25 per cent in 2018.

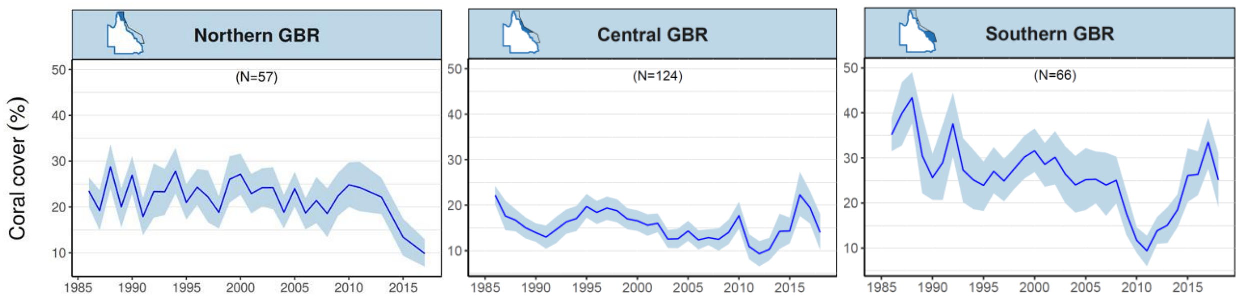


Figure 4. Trends in mean hard coral cover for the whole Great Barrier Reef and the Northern, Central and Southern regions, based on Bayesian hierarchical models. N indicates the number of reefs contributing to the analyses; blue shading represents 95 per cent certainty (Source: AIMS website, https://www.aims.gov.au/reef-monitoring/gbr-condition-summary-2016-2017)

The long-term record shows the cumulative impact of multiple disturbances. However, the impacts of the 2016 and 2017 mass bleaching events were extreme, especially in the northern region of the Reef. Scientific publications analysing these impacts and the ecological responses from are starting to become available (for example, Hughes et al., 2017a; 2018; Kennedy et al., 2018).

Status and trends of the condition of Reef inshore reefs are assessed as part of the Marine Monitoring Program (MMP)[5]. In 2017, the reported coral reef condition index, which aggregates several indicators for the condition of coral reef benthos, declined across all regions due to the impacts of high temperatures and cyclone Debbie in 2017 (Thompson et al., 2018, see **Figure 5**). This ends a period of recovery from 2014 to 2016, which in turn followed a decline from 2011 to 2014, due to the cumulative impact of tropical cyclones, outbreaks of crown-of-thorns starfish and a period of high river discharge carrying increased loads of nutrients and sediments to the Reef.

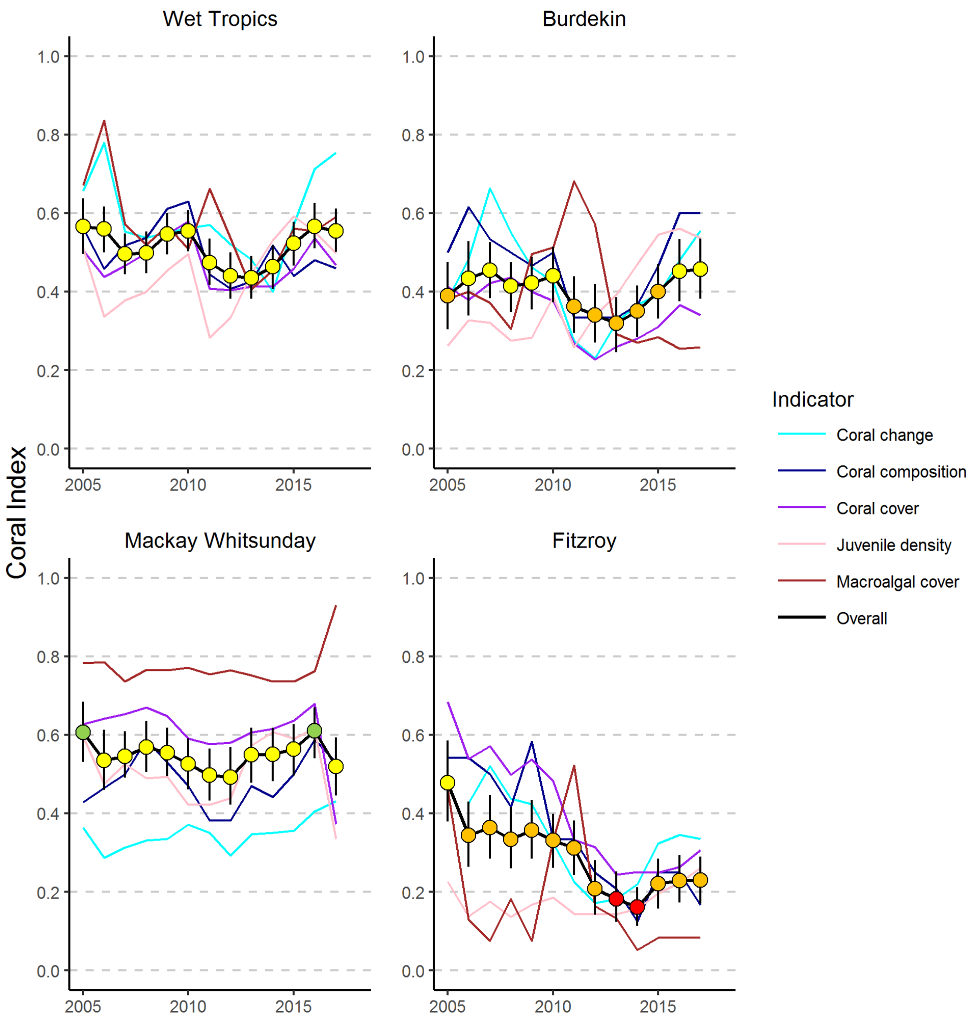


Figure 5: Regional coral index as reported by the Marine Monitoring Program to 2017 (Source: Thompson et al., 2018). The regional coral index is derived from the aggregate of metric scores for indicators of coral community health (see legend)

[5] http://www.gbrmpa.gov.au/managing-the-reef/how-the-reefs-managed/reef-2050-marine-monitoring-program

Other datasets on the condition of coral reefs are collected by James Cook University (JCU) as part of the inshore zoning monitoring (Williamson et al., 2016), and by the Authority as part of the Eye on the Reef program[6], which includes the joint Field Management Program's in-water Reef Health and Impact Surveys (RHIS[7]), as well as observations for situational awareness and early warning about disturbances by tourism operators and the public. These data are currently not formally or regularly reported. An exception was the use of RHIS data for an assessment of the 2016 mass bleaching event (Great Barrier Reef Marine Park Authority, 2017). One of the challenges RIMReP needs to solve is the meaningful integration of various and dispersed data sources to provide relevant information for the management of the Reef.

Cumulative impacts of multiple pressures are shaping coral reef communities; these are often a combination of local or regional water quality pressures and global pressures, such as increasing temperature and ocean acidification (reviewed in Schaffelke et al., 2017; Wolff et al., 2018). In an environment of frequent disturbances, the persistence of coral communities depends on resilience, which is the product of resistance to pressures and ability to recover during periods of low disturbance (Anthony et al., 2015).

The recovery from the presently low coral cover in the northern Reef can currently not be predicted because it is the first time a decline of this magnitude has been recorded in that region. Analysis of the long-term monitoring data have shown that between seven and 10 years is required for coral cover to return to pre-disturbance levels, though a further three to five years is needed for recovery of community composition (Johns et al., 2014). Fast recovery and complete reassembly within around 10 years may occur on reefs with a high proportion of tabulate *Acropora* corals (Johns et al., 2014). While fast-growing tabulate corals are important for fast recovery of three-dimensional reef structure (Ortiz et al., 2014), taxa with this growth form are generally more sensitive to a range of disturbances compared to other corals (Osborne et al., 2011; Berkelmans et al., 2012).

However, it needs to be highlighted that while some reefs can rebound, provided further disturbance does not intervene, other reefs can suffer phase shifts, and the drivers of these shifts are poorly understood (Graham et al., 2015). Recent analysis of the AIMS long-term dataset also showed that some reefs subjected to major heat stress events can exhibit slow rates of coral recovery, even if the bleaching is not severe (Osborne et al., 2017).

Another factor of concern is the prevalence of coral disease on already stressed and impacted reefs. Following the 2002 heat stress event on the Reef, a 20-fold increase in white syndromes were observed in some regions (Willis et al., 2004) and reefs with the slowest rates of recovery exhibited highest levels of coral disease. Coral disease is a symptom of chronic ecosystem-level stress, and similar to the 2002 event, recent higher prevalence of coral diseases was confirmed at some reefs in February 2017. Though the links between thermal stress and bleaching are clear, and bleaching events can be predicted accurately, links between thermal stress and disease outbreaks are less well understood. Previous studies have also shown that thermally stressed corals are more

[6] http://www.gbrmpa.gov.au/managing-the-reef/how-the-reefs-managed/eye-on-the-reef
[7] http://www.gbrmpa.gov.au/managing-the-reef/how-the-reefs-managed/eye-on-the-reef/reef-health-and-impact-survey

susceptible to disease (Miller et al., 2009; Mydlarz et al., 2009; Burge et al., 2014) and modelling based on climate model projections of future ocean temperatures predict that corals will become increasing susceptible to disease, resulting in as much coral mortality from disease as bleaching in the coming decades (Maynard et al., 2015).

A recent study at Beaver Reef in the northern Reef tagged 100 colonies of tabular acroporids and followed the effects of the 2017 coral bleaching event and a simultaneous white syndrome outbreak on the population over a year (Brodnicke et al., 2019). Results from this monitoring provided insights into the rate at which healthy corals become bleached and diseased, and how fast bleached and diseased colonies suffer mortality. Coral disease exacerbated mortality in bleached corals, demonstrating the additive effects of these two processes on population demographics.

Useful long-term data series (for example, the AIMS Long-Term Monitoring Program, JCU's Effects of Zoning on Inshore Reefs, and various research projects) are available to support status and trend assessments for coral reef-associated fish. Marked spatial differences in assemblage composition are apparent for most major groups of fishes, including butterflyfishes, damselfishes, parrotfishes, surgeonfishes, rabbitfishes and large predatory fishes such as coral trout, snappers and emperors (Williams and Hatcher, 1983; Russ, 1984; Gust et al., 2001; Hoey and Bellwood, 2008; Emslie et al., 2010; 2012; 2017; Cheal et al., 2012). Cross-shelf variation in fish assemblages was generally greater than latitudinal variation and was conspicuous across all taxa, latitudes and year. Cross-shelf differences in reef fish assemblage structure are most likely related to differences in habitat structure, which have differential effects on settlement preferences and survival of larval fish, and to persistent environmental gradients from coast to shelf edge, such as water quality, wave exposure, and depth.

Most knowledge about coral reefs of the Reef (and indeed about most reefs around the world) is derived from diver-based studies and surveys, and hence has focused on shallow water reef, mostly to a depth of 20 metres. The currently accepted assumption is that mesophotic reefs (at a depth of 30 to 150 metres) are less biodiverse than shallow-water reefs. However, this assumption might change with increasing ability to explore these deep-water ecosystems. Recent expedition-style surveys using remote underwater vehicles found unexpected taxonomic richness of deep-water corals (Englebert et al., 2017), including high abundance and large size of staghorn corals in the upper mesophotic zone (about 30 to 70 metres depth) (Muir et al., 2015). Staghorn coral form important, three-dimensional reef habitat on shallow reefs. However, it still debated how much mesophotic and shallow reefs on the Reef are connected and whether coral reefs in deep water may be genetic and biodiversity refugia (see Bongaerts et al., 2010; 2017) as they are less exposed to major pressures such as thermal stress and storm damage than their shallow counterparts.

Like shallow water coral reef benthic assemblages, reef fish assemblages of the Reef have also shown substantial temporal variation (Emslie et al., 2012, 2017). Changes in reef fish abundance and diversity have largely resulted from natural disturbances which reduced the amount of live coral cover (i.e. cyclones, crown-of-thorns starfish, and bleaching). However, the largest and most dramatic changes were associated with disturbances that not only reduced live coral cover, but also severely decreased three-dimensional habitat complexity

(Emslie et al., 2008; 2014). Despite numerous and often severe impacts from natural disturbances, fish assemblages of the Reef appear largely resilient and have maintained an ability to recover quickly from perturbations, whilst maintaining distinct sub-regional assemblages (Cheal et al., 2008; Emslie et al., 2008; Emslie et al., 2015; Mellin et al., 2016b; Wilson et al., 2009). However, the increasing frequency of severe disturbances predicted under climate change scenarios (Cheal et al., 2017 and references therein) may fundamentally alter the ability of fishes to recover from such disturbances. For example, in an unusual sequence of severe and widespread cyclones on the Reef between 2009 and 2011, there were record declines in reef fish abundance and species richness over 1,000 kilometres of the central and southern outer Reef (Cheal et al., 2017). This study also highlighted that such sequences of particularly intense cyclones may become more common in the coming decades, with serious ramifications for the resilience of reef fishes.

The expansion of the area of 'no-take' marine reserves (Marine National Park and Preservation zones) under the *Great Barrier Reef Marine Park Zoning Plan 2003* has increased population sizes of exploited fishes inside their boundaries (Russ et al., 2008; Emslie et al., 2015). More surprisingly, it has also contributed to reef fish resilience, ensuring the maintenance of important ecological functions essential to recovery following disturbances (Mellin et al., 2016b). In particular, 'no-take' zones also retain benefits for exploited fish stocks in the face of strong tropical cyclones that are predicted to occur with greater frequency in the coming decades (Emslie et al., 2015).

Other components of the coral reef ecosystem are either not regularly monitored (for example, mobile invertebrates, except for crown-of-thorns starfish) or not regularly reported (for example, status and trends of other benthos such as sponges and macroalgae – noting that macroalgae abundance is included in the MMP coral index).

Monitoring of crown-of-thorns starfish population numbers provides good information about location, severity and progression of the current population outbreak, which commenced around 2010 (Pratchett et al., 2014). The data are also used to inform the Authority's current crown-of-thorns starfish control program[8] and are the foundation for the development of crown-of-thorns starfish population and connectivity models to improve management and control options in the future (for example, Hock et al., 2014; 2016; Mellin et al., 2016a; Vanhatalo et al., 2017). However, there is no formal integrated reporting of crown-of-thorns starfish monitoring data, which are collected by the AIMS Long-Term Monitoring Program, the joint Field Management Program and tourism operators. Regular reporting of crown-of-thorns starfish numbers is provided in the Long-Term Monitoring Program's survey reports[9]. Crown-of-thorns starfish densities and spatial progression of outbreaks over time are also visualised in an animation (1985-2017)[10].

However, the monitoring methods used (visual counts), while giving useful indications for the presence of adult starfish, are limited in their ability to accurately measure population numbers at low densities and of small size classes (for example, MacNeil et al., 2016). Due

[8] http://www.gbrmpa.gov.au/about-the-reef/animals/crown-of-thorns-starfish/what-is-the-short-term-strategy
[9] https://www.aims.gov.au/docs/research/monitoring/reef/latest-surveys.html#Latest sector reports
[10] https://www.aims.gov.au/docs/research/biodiversity-ecology/threats/cots-animation.html

to these limitations it is difficult to obtain reliable early warning signals of outbreaks. This may be improved by using modern techniques such as analyses of eDNA in water or in crown-of-thorns starfish predators (Uthicke et al., 2015, 2018; Doyle et al., 2017).

5.0 Priority indicators to monitor coral reef systems on the Great Barrier Reef

A wide variety of indicators are currently used in coral reef monitoring and have been evaluated for their usefulness to report on condition and trend of coral reef ecosystems (diagnostic indicators) and to predict recovery potential after disturbances (prognostic or resilience indicators) (McClanahan et al., 2012; Flower et al., 2017). Many of these indicators are currently being applied in coral reef monitoring in the Reef (summarised by Cheal and Emslie, 2018 - see Supplementary Report S3).

For the selection of recommended indicators for the RIMReP coral reef monitoring the Coral Reef Expert Group used the following decision criteria to assess a candidate indicator's capability to:

1. Provide **tactical information** for management (to inform incident assessment and/or response).
2. Provide **operational information** for management (to inform actions, assessments, decisions).
3. Contribute to **policy development** and **strategic planning** (trends, cause-effect).
4. Evaluate the **effectiveness of management** actions/responses.
5. Describe **condition, trend**, potential **resilience** and status of key processes
6. **Attribute causes** of change in condition (state).
7. Contribute **information across themes**.
8. Ensure **continuity of historical data sets** and build on existing programs.

As a further overarching principle, recommended indicators are widely used in research and monitoring (for example, response to pressures is relatively well understood), and will deliver information for various purposes and contexts, including to build and validate models, such as ecosystem models to predict future states, risk assessment and decision support models. A list of priority indicators that are recommended to form the backbone of RIMReP's coral reef monitoring is in **Table 1**. A longer list including other relevant indicators is in **Appendix 1** – these indicators may be included in more detailed monitoring activities, for example at 'reference' or 'sentinel' sites (discussed further below).

Table 1. Priority indicators recommended for monitoring under the RIMReP coral reef theme (see Appendix 1 for full list of indicators) against key values and processes reported in the Great Barrier Reef Outlook Report 2014. Note that resolution (for example, taxonomic, spatio-temporal) of each indicator is considered further below in the recommendation section. Indicator type categories: C= indicator for condition and trend assessments, R = resilience indicator, P = indicator for process understanding/attribution

Value/Process (as per Great Barrier Reef Outlook Report)		Priority indicator	Measured/ derived?	Justification for selection	Type
Hard and soft corals		Coral cover and composition	y	Most widely used indicator of coral reef condition and trend[11], selected as essential ocean variable (EOV)[12]. Coral cover increase during periods free from acute disturbances as resilience indicator (recovery).	C R P
	Recruitment Connectivity	Number of juveniles	y	Indicator of condition and trend and resilience, widely monitored[11]	C R P
	Recruitment Connectivity	Recruitment tiles	y	Resilience indicator, process understanding of reef connectivity	R P
	Reef Building	Rugosity/3d structure	y	Indicator of condition and trend, and of habitat quality	C P
		Reef size and extent	y	Baseline indicator of condition- i.e. where and how large is the area of potential living coral reef	C
		Accretion vs erosion assessment	y	Reef accretion/erosion is important for resilience assessments and affected by environmental pressures (temperature, water quality, ocean acidification)	C R P
		Coral bleaching	y	Key pressure on reef condition	C R P
	Microbial processes	Coral disease	y	Key pressure on reef condition, widely monitored[11]	C R P
	Particle feeding	Community composition of particle-feeding benthos	Derived	Indicator of condition and trend	C
Macroalgae		Abundance, cover	y	Widely used indicator of coral reef condition and trend[11], selected as essential ocean variable (EOV)[12] Increasing macroalgal cover may indicate loss of resilience.	C R P
		Turf heights/canopy heights	y	Suggested as useful resilience indicator as turf height affects coral recruitment	R

[11] E.g. identified as key variable in the Global Coral Reef Monitoring Network (Jackson et al., 2014).
[12] By the Global Ocean Observing System (GOOS), http://goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114

		Ratio of crustose coralline algae/ turf algae/ fleshy algae	Derived	Crustose coralline algae are important for coral recruitment, the ratio is suggested as a useful measure of recruitment substratum quality	R
Primary production		Abundance and community composition of benthic primary producers	Derived	May be reported to indicate condition and trends in trophodynamics of coral reef ecosystems	C P
Fish		Counts and size of reef fish	y	Widely used indicator of fish biodiversity, selected as essential ocean variable (EOV)[12]	C P
		Counts and size of reef-associated pelagic fish	y	Widely used indicator of fish biodiversity, selected as essential ocean variable (EOV)[12]	C P
	Herbivory	Biomass of herbivorous fish	Derived	Herbivores are an important control factor of coral/macroalgal competition and coral recruitment	C R P
Mobile invertebrates	Predation	Abundance of crown-of-thorns starfish	y	crown-of-thorns starfish population outbreaks are a major cause of coral cover decline.	C R P
	Herbivory	Counts of key herbivores (e.g. sea urchins)	y	Herbivores are an important control factor of coral/macroalgal competition and coral recruitment	C R P

Two commissioned desktop reviews gave more detailed recommendations about the taxonomic resolution for the invertebrate and macroalgae indicators identified in **Table 1** (Babcock and Bridge, 2018 - Supplementary Report S1; Diaz-Pulido, 2018 - Supplementary Report S2).

Due to the size and biodiversity of the Reef and the remoteness of many of the coral reefs, a hierarchical monitoring approach, with a strong focus on integration of data from various sources, is considered to be the most practical option to achieve the goals of RIMReP. A key consideration with regard to monitoring methods was the recommendation to use imagery as the common 'currency' for benthos assessments. Future monitoring would ideally move from human-based to automated image analysis to greatly expand the scope and timeliness of monitoring programs on the Reef. This can only be achieved when data standardisation and compatibility among methods is assured. To support the design recommendation, Babcock and Bridge (2018, Supplementary Report S1) reviewed knowledge and options for classification frameworks that would allow different data to be integrated in an unambiguous and ecologically valid way between various monitoring approaches.

Typically, finer taxonomic resolution at the species level is aspired to as it would provide the greatest amount of detail. However, it is not always achievable due to factors such as image resolution and expertise of observers (Carleton and Done, 1995), the lack of which can lead to greater error rates in identification. Conversely, coarser levels of classification (e.g. functional groups) may be less prone to error due to image quality and the requirement for less expertise and training, but they may also result in important trends and processes being overlooked. However, studies of both taxonomic sufficiency and the utility of functional group approaches (for example, Mouillot et al., 2013, Madin et al., 2016) conclude that, while species level identifications may be the gold standard, loss of information due to use of higher level classification schemes is likely to be relatively minor for assessments of condition and trends of ecological communities. Similar conclusions have also been drawn in relation to classification of mobile organisms, such as fish (Richardson et al., 2017).

Standardised classification schemes, or 'vocabularies', have been developed in a number of regions around the world. Ideally, such schemes are flexible enough to include useful high-resolution classifications where possible while also providing a consistent common framework at lower levels. One such approach recently developed in Australia is the Collaborative and Automated Tools for Analysis of Marine Imagery (CATAMI) Classification Scheme (Althaus et al., 2015). The CATAMI Classification Scheme combines coarse-level taxonomy and morphology, and is a flexible, hierarchical classification that bridges the gap between habitat/ biotope characterisation and taxonomy, acknowledging limitations when describing biological taxa through imagery.

While the CATAMI Classification Scheme has not been widely used in coral reef monitoring, Babcock and Bridge (2018) recommend that the scheme is considered for adoption in RIMReP, after a workshop including representatives of various monitoring programs be convened in order to arrive at a consensus around exactly how to implement a standardised approach and integrate it into RIMReP reporting mechanisms.

Table 2 describes the recommendation for the taxonomic resolution of benthic coral reef macroalgae (Diaz-Pulido, 2018).

Table 2. Level of taxonomic resolution recommended for the monitoring of benthic coral reef algae under RIMReP

Level of taxonomic resolution	Benefits	Limitations
One grouping, 'macroalgae'	Requires no expertise, quick, easy to implement, relatively expensive, access to large data sets.	Limited information on processes driving change, no resolution to distinguish between algal types [e.g. benign (e.g. protection from bleaching, crown-of-thorns starfish) vs. harmful (e.g. coral competitors)]. No information on other groups, e.g. turfs.
Major macroalgal categories 'macroalgae', 'algal turfs' and 'crustose coralline algae'	Relatively quick, not so expensive, little expertise required, includes key algal groups important for reef functioning: • crustose coralline algae: indicator of potential to build solid carbonate frameworks, accretion, settlement inducers. • Algal turfs: highly productive, most abundant component, food for grazers.	Limited info on processes driving change, some expertise required to assess categories, more time needed to analyse data. No resolution to distinguish between types of macroalgae (e.g. benign vs. harmful).
Functional form approach — seven major groups, including macroalgae, algal turfs, crustose coralline algae	Includes key algal groups important for reef functioning (as above). More resolution of the macroalgae category, e.g. differentiate leathery/canopy forming macroalgae, which are key for fish and invertebrates.	Few studies have used this approach, expertise required, more time required to analyse data. Still provides limited info on processes.
Phylum, order or family	Useful in physiological studies and reef metabolism.	Not widely applied in reef algae, limited resolution in some groups, no distinction between benign and harmful species. Taxonomic expertise required.
Genus-level	Provide insights into dynamics (e.g. differential effects of cyclones/hurricanes, grazing, nutrients, seasonality, etc.).	Taxonomic expertise required and training, time consuming.
Species-level	Provides insights into drivers of community dynamics, estimates of species diversity (important for conservation). Differentiation between harmful and benign taxa. Species can be grouped at different levels.	Considerable taxonomic expertise required and training, time consuming. Increased time required to analyse data.
Recommended: Combination of major algal categories and genus- level	Provides insight into drivers of community dynamics, used successfully in a number of	Time-consuming, requires expertise and training

for key genera (to be determined, but would include e.g. *Sargassum*, *Lobophora*)	studies, flexible and adjustable to expertise available	Suggested future improvements are automation, e.g. using the CoralNet automatic classifier
Suggested additions		
Canopy height as a good indicator of coral recruitment competition. Easy to measure but cannot use photos to determine this		
Calcification stations For assessment of growth, calcification, marginal growth or expansion has occurred, skeletal density etc. Similar to erosion blocks used by the National Oceanic and Atmospheric Administration of the United States (now tested in the Reef).		

In addition to the indicators recommended to be measured as part of a future RIMReP coral reef monitoring program, the Coral Reef Expert Group considered a long list of potential pressures on the Reef, provided by the Authority. Selecting from this long list, key pressures were identified that would be important for reporting of coral reef condition, trend and resilience and/or for process understanding or cause/effect attribution (**Table 3**). These are: cyclone activity/impact, sea temperature, stream flow, outbreaks of crown-of-thorns starfish populations and coral disease. Measures for the latter two pressures are recommended as priority indicators in the RIMReP coral reef monitoring component (see Error! Reference source not found.).

Table 3. List of key pressures (alphabetical order) that potentially affect coral reef condition, trend and resilience. Availability of data for these pressures would support analysis and reporting of coral reef indicators. Pressures in italic font are included in recommended coral reef indicators (see Error! Reference source not found.). Blue shaded cells were identified as high priority pressures for coral reefs. Pressures in bold print were identified as essential explanatory variables for regular analyses and attribution of trends in coral reef indicators

Pressure	**How would these be used for reporting and analyses?**	**Level of detail required**
Altered ocean currents	Attribution of changes in coral recruitment, connectivity. Most likely as case study.	tbd
Cyclone activity	Essential for attribution of regional coral cover decline.	Data from operational cyclone impact model (Puotinen et al., 2016)
Damage to reef structure	Attribution of local coral cover decline, most likely as part of specific control/impact studies or compliance monitoring.	tbd
Disposal and resuspension of dredge material	Input variable for specific control/impact studies or compliance monitoring.	tbd
Dredging	As above	
Extraction - fishing in spawning aggregations	Fisheries/harvest data would support analyses of changes in coral reef fish population data. Most likely as case study/research project.	tbd

Extraction - lower order predators		
Extraction - top order predators		
Grounding large vessel	Attribution of local coral cover decline, most likely as impact assessments, or specific control/impact studies.	tbd
Grounding small vessel		
Increased freshwater inflow	Essential for attribution of regional coral cover decline. Has in the past been used as proxy for sediments and nutrients from land run-off.	Stream flow data from QLD Government https://water-monitoring.information.qld.gov.au/
Marine debris	Specific research on effects of marine debris on coral reef organisms. Derelict fishing line has been associated with higher levels of coral disease (Lamb et al., 2016), and could be used as indirect indicator for fishing pressure	tbd
Modifying supporting terrestrial habitats	Studies on paddock-to-reef continuum. Most likely as case study/research project.	tbd
Nutrients from catchment run-off	Studies on paddock-to-reef continuum. Most likely as case study/research project.	Paddock to Reef end of catchment loads data, eReefs model.
Ocean acidification	Prediction of coral reef resilience. Most likely as case study/research project.	Local to regional scale
Outbreak or bloom of other species	Reporting of occurrence of outbreaks. Most likely for specific case studies/research projects.	Outbreaks of nuisance algae would be observed by recommended RIMReP coral reef monitoring
Outbreak of crown-of-thorns starfish	Essential for attribution of regional coral cover decline. Also for specific case studies/research projects.	Recommended as indicator of RIMReP coral reef monitoring
Outbreak of disease	Essential for attribution of regional coral cover decline. Also for specific case studies/research projects.	Recommended as indicator of RIMReP coral reef monitoring
Pesticides from catchment run-off	Studies on paddock-to-reef continuum. Most likely as case study/research project.	Paddock to Reef end of catchment loads data, eReefs model.
Sea temperature increase	Essential for attribution of regional coral cover decline.	As high resolution as possible
Sediments from catchment run-off	Studies on paddock-to-reef continuum. Most likely as case study/research project.	Paddock to Reef end of catchment loads data, eReefs model.

6.0 Evaluation of the adequacy of current monitoring of coral reef systems on the Great Barrier Reef

6.1 Synopsis of existing monitoring programs

Coral reef monitoring in the Reef has over 30 years of history. An inventory of all existing environmental monitoring programs on the Reef was recently undertaken by (Addison et al., 2015). Monitoring was defined as 'the repeated and systematic collection of data through time'. For inclusion in the inventory, environmental monitoring programs had to meet the following criteria:

- Location: monitoring occurs in the World Heritage Area or neighbouring catchments.
- Current: at least one monitoring event has occurred in the last five years, with some indication that the monitoring will continue in the future (dependent on funding).
- Relevant to the Reef 2050 Plan: the values monitored address at least one of the Reef 2050 Plan's environmental or socio-economic values and attributes (for example, coral reef condition), or one of the threats identified through the Reef 2050 Plan.
- Publicly available: monitoring results are publicly accessible through scientific publications, government/institutional reports, online databases, or are available upon request from data custodians (Addison et al., 2015).

Addison et al. (2015) identified 16 existing programs that specifically monitor coral reef habitats on the Reef. This collation was further refined by Cheal and Emslie (2018 - Supplementary Report S3), focusing on three main objectives:

- Collate information about indicators measured, techniques used, spatio-temporal design, and reporting processes (building on the Reef monitoring inventory by Addison *et al*. 2015);
- Identify which of the candidate indicators are not covered in existing programs; and
- Discuss potential limitations of current designs (building on Addison et al. 2015).

The additional review reduced the 16 programs identified in Addison et al. (2015) to 15 by merging two sub-activities of the 'Effects of management zoning on inshore reefs of the Great Barrier Reef Marine Park' program. The reviewed 15 Reef coral reef monitoring programs were (see **Figure 6** for a map of sites):

1. Effects of management zoning on inshore reefs of the Marine Park (JCU). [red triangle symbols in **Figure 6,** 'RAP Fish and benthos (JCU)']
2. Long-Term Monitoring Program: Reef monitoring (AIMS). [orange pentagon and purple triangle symbols in **Figure 6**, 'RM' and 'RMRAP'].
3. Long-Term Monitoring Program: effects of management zoning (AIMS) [red diamond and purple triangle symbols in **Figure 6**, 'RAP' and 'RMRAP']. Note that manta tow survey data are available from a larger number of reefs than those represented on the map in **Figure 6**.
4. Eye on the Reef: rapid monitoring (the Authority, using reef visitors and traditional owners) — no fixed sites.

5. Eye on the Reef: reef health and impact surveys (the Authority, using individuals from varied groups that may include university-trained scientists) — no fixed sites.
6. Eye on the Reef: tourism weekly monitoring surveys (the Authority and tourism industry, using tourism operators).
7. Reef Check (Reef Check Australia, using volunteers that may include university trained scientists) — no fixed sites.
8. Marine Monitoring Program: inshore (AIMS) [pink square triangle symbols in **Figure 6**, 'IN'].
9. Gladstone Harbour monitoring (AIMS).
10. North Queensland Bulk Ports Corporation monitoring: Abbot Point, Mackay and Hay Point (AIMS and private consultants). [red star symbols in **Figure 6**, 'AP']
11. Reef Life Survey (Reef Life Survey, using recreational divers and university trained scientists) — no fixed sites.
12. Coral Watch (University of Queensland, using citizen scientists) — no fixed sites.
13. Crown-of-thorns Starfish Outbreak Management Program (Reef and Rainforest Research Centre and the Authority, Association of Marine Park Tourism Operators) — no fixed sites
14. Catlin Seaview Survey (University of Queensland).) [turquoise circle symbols in Figure 6, 'Catlin Seaview 3+ surveys'].
15. Recovery of the Reef (Earthwatch andAIMS, using university trained scientists and citizen scientists). [One site only, Orpheus Island, not represented in **Figure 6]**.

6.2 Adequacy and gaps of existing monitoring programs

Cheal and Emslie (2018, see Supplementary Report S3) identify which RIMReP candidate indicators are covered in existing Reef coral reef monitoring programs and discuss potential limitations of current designs. Additional details about the methods used in each of the major existing monitoring program are summarised in Mellin et al. (2018, Supplementary report S4). The authors group existing programs broadly into two complementary approaches and recommend that both, taking into consideration the limitations of each, should be integrated into the future RIMReP design:

- **Structured programs** to provide high quality, high resolution, and mostly quantitative data from regular sampling at fixed locations, mostly carried out by university-trained scientists.
  The logistical requirements of these structured programs can limit their spatial extent (both within and among reefs), but current programs have been especially useful for reporting condition and statistically valid trends at local, regional and Reef-wide scales trends, for attribution of changes to pressures and for supporting/enabling research on process understanding.
- **Reactive survey programs** using rapid assessment techniques by large numbers of observers of varying levels of training and experience. Reactive survey programs can be conducted at larger numbers of reefs, reef zones and habitats, but are often un-repeated and use qualitative rather than quantitative assessments.
  The spatially more extensive sampling of reactive surveys programs can provide

an early warning signal and information of the extent and severity of disturbance events (e.g. coral bleaching, cyclones, crown-of-thorns starfish outbreaks). The robustness of temporal trend information from reactive survey programs that repeat observations at fixed sites may be limited due to haphazard sampling regimes and sampling error between multiple observers, which has not been quantified for most of these programs.

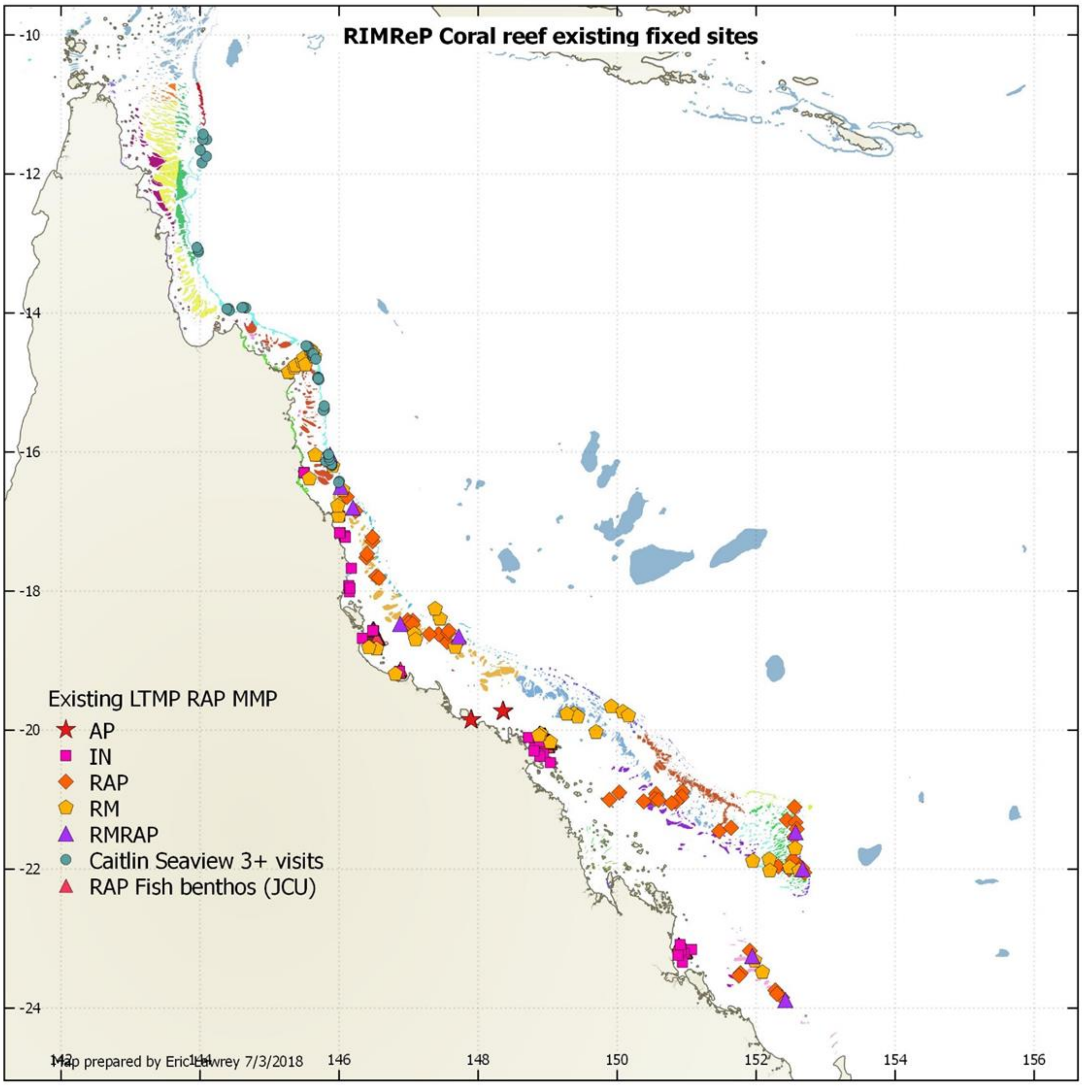


Figure 6. Map of sites of existing coral reef monitoring programs that use fixed sampling sites Note that programs 6 and 9 are missing on the map. See text above for further explanations.

The following dot-points (in no particular order of importance) summarise further findings and identified gaps in the existing program from Cheal and Emslie (2018) that will inform the RIMReP design:

Strength of existing programs:

Indicators:

- Most proposed RIMReP candidate indicators of target organisms are covered to some extent by at least one existing program, but often at a relatively coarse level.
- Most programs document cover of hard corals, their growth forms and a range of measures of hard coral health and disease, but only a limited subset identify hard corals to a fine taxonomic resolution (genus) or provide robust indicators of their population/community structure (juvenile counts, size structure, diversity/composition etc.).
- Of the environmental pressure candidate indicators, two with high priority, 'outbreaks of crown-of-thorns starfish' and 'outbreaks of disease', were best covered among programs: most monitored these pressures.

Reporting and quality control:

- All programs reported their results in some form; online, grey literature and peer-reviewed publications were the most common forms of reporting. Existing programs used one or a combination of reporting forums.
- Quality control was generally well integrated into all existing programs, although the resolution of the data varied among programs.

Limitations of existing programs

Spatio-temporal design:

- Existing monitoring programs encompassed limited (one NRM region) to extensive spatial scales (six NRM regions).
- Monitoring is limited in the far north, particularly inshore.
- Monitoring frequency is highly variable among programs: regular (weekly to biennial) to haphazard.

Habitat/community:

- Deep water (greater than 30 metres) surveys are severely underrepresented (only one program has a deep-water component). Indeed, much of our knowledge from existing monitoring programs comes from depths of zero to 15 metres. The following dot points reflect such shallow reef monitoring only.

Indicators:

- Fish community indicators were least covered among programs; four programs covered most fish indicators in different ways, but eight had no fish component.
- Few programs monitored mobile invertebrate indicators aside from the coral feeding crown-of-thorns starfish and *Drupella* snail; key herbivores (i.e. urchins) and other charismatic invertebrates (for example, sea cucumbers and giant clams) were severely underrepresented.

- No program measured the size of crown-of-thorns starfish to the centimetre, but crown-of-thorns starfish were recorded in size classes by most.
- Soft coral indicators, excepting cover and bleaching status, were relatively poorly covered among programs.
- Cover of macroalgae was covered by most programs but only five routinely identify macroalgae to genus, and there is very little capacity among programs to estimate macroalgal biomass and growth.

A further desktop study (Mellin et al., 2018- Supplementary Report S4) developed a model to inform the design of a future RIMReP coral reef monitoring program to effectively capture benthic dynamics in space and time. The model was calibrated against 20 years of *in situ* coral monitoring data. Input variables also included environmental data and disturbance history.

The model was applied to assess two core aspects of the adequacy of selected[13] existing long-term monitoring programs: **representation** and **complementarity.** The analyses revealed that:

- 40 per cent of all reef habitats are currently represented by existing long-term monitoring programs (AIMS Reef Monitoring [LTMP-RM], Representative Areas Program [LTMP-RAP] and Marine Monitoring Program [MMP]), increasing to 45 per cent of all reef habitats when monitoring using manta tow (MANTA) is added. When Reef Health and Impact Surveys (RHIS) under the Authority's Eye on the Reef (EotR) program and the Catlin Seaview surveys are included, existing monitoring programs cover a total of 60 per cent of all reef habitats.

- Major hotspots of past cyclone activity were unmonitored by the RM/RAP/MMP programs in the central Reef but have been surveyed reactively by MANTA and RHIS to some extent.

- Clusters of reefs with similar benthic community composition and similar past coral cover trajectories were identified to explore if these convey redundant ecological information. Results suggest that stratifying of survey reefs based on this clustering could minimise redundancy and maximise complementarity.

Mellin et al. (2018) also examined how the **accuracy** (for example, observer bias) and **precision** (for example, spatio-temporal design) of a monitoring program influences its ability to report on coral condition and to detect changes. The analyses demonstrated that:

- Spatial heterogeneity of coral distribution across the sampled reef area reduces precision of coral cover estimates if using random sampling (such as most RHIS applications). This can be compensated for in part with additional replicates, but not to

[13] Note that the selection was largely based on data availability and resourcing for this desktop study. The desktop analysis focused on contrasting existing programs with accessible, sufficiently large datasets that represent structured programs (LTMP, MMP) and reactive survey programs (RHIS, EoTR).

the extent that it obtains the precision of fixed sites (such as the AIMS Long-Term Monitoring Program).

- For RHIS, variation of up to 40 per cent among trained observers in a structured comparison indicated low capacity to estimate coral cover and hence reef state. The additional health indicators scored by RHIS, however, makes it a valuable tool for providing situational awareness between long-term monitoring surveys and can help Long-Term Monitoring Program-type monitoring to better attribute impacts to pressures.

- If *in situ* visual assessment of benthos condition (coral cover, bleaching extent and severity) would be replaced with photographic sampling and subsequent standardised image analysis (see also Chapter on new technologies), RHIS could have similar accuracy to the Long-Term Monitoring Program and Catlin Seaview Surveys. (See also section on Integration and Reporting for further discussion).

A companion report (Thompson and Menendez, 2018- Supplementary Report S5) estimated the **statistical power to detect changes** in two of the recommended indicators in selected existing Reef monitoring programs: the rate of increase in coral cover during periods free from acute disturbance and species richness of herbivorous fishes. The data were existing time-series derived from AIMS long-term reef monitoring programs, which are the only time-series available for the Reef with sufficient spatial and temporal coverage for such analyses.

Using the methods and within-reef replication used by the LTMP-RAP and LTMP-RM programs there was reasonable power (greater than 0.8) to detect changes in coral cover within a 'region' of one per cent, per year over a five-year period. Detecting this level of change was reliant on annual sampling of four to five reefs within a region, where regions are defined as areas of similar location across the shelf with reefs separated by tens rather than hundreds of kilometres.

In general, the power to detect changes in the species richness of fishes was low compared to that to detect changes in trend of coral cover. Annual sampling of 3-4 reefs, over a ten-year period, was required to ensure reasonable power to detect a change in richness of three species of herbivorous fish. This lower power is to be expected given the added variability in fish census data as a result of the mobility of fishes.

In conclusion, the evaluation of the adequacy and gaps of existing coral reef monitoring programs showed that many programs measure the priority indicators, and a few have adequate sampling methods, spatial and temporal resolution, and statistical power to meet the objectives of RIMReP. The design of the future RIMReP coral reef monitoring component should be constructively building on these effective programs. Optimising the design will be a multifaceted task that involves not only ecological but also resource constraints, which will need to be integrated without compromising the integrity of existing, valuable long-term datasets. Recommendations and principles to support the design process, based on learnings from existing coral reef monitoring programs are summarised here:

- The assessment of the current coral reef monitoring based on their complementarity, representation and precision thus offers ways to combine different programs operating at different spatio-temporal scales and using different techniques into an effective and cost efficient integrated monitoring program. For example, a core feature of the recommended design will be the integration of structured long-term monitoring at fixed locations (to provide statistically robust assessments of trends) with reactive survey programs (to provide early warning/situational awareness between long-term monitoring surveys and to document the extent and impact of disturbances).
- Use modelling approaches for reporting to fill in observation gaps in space and time (see also section below on integration and reporting).
- Use a spatial model to optimise site selection. For example, determine across existing monitoring programs, which survey reefs might convey redundant ecological information. Available analyses suggest that a minimum of four reefs per spatial 'cluster' is required; a cluster should encompass reefs in broadly similar geomorphic and environmental settings (for example, based on Reef bioregions[14]) with similar community types to ensure regional trends of indicators are accurately estimated and to facilitate the spatial delineation of impacts from pressures.
- Fill spatial gaps in fixed sites in the far northern Reef, particularly inshore.
- Fill spatial gaps in monitoring deep reefs (great than 15 metres) in all regions.
- Return to an annual sampling frequency for fixed sites; this will reduce the period over which changes can be detected, reduce the magnitude of changes than can be detected and improve the attribution of changes to specific pressures.
- Survey at adequate intensity at fixed sites to maintain or improve within-reef precision of estimates of coral cover. At the reef scale, the simulation model showed that observer error and spatial variability interact in decreasing the precision in coral cover estimates, an effect that can be compensated for by larger sample size.
- Consider improvements to reactive survey programs by using standardised methods that are easier to standardise such as the collection of benthic images and automated image analyses (see also Chapter below on new technologies).

[14] http://www.gbrmpa.gov.au/__data/assets/pdf_file/0012/17301/reef-bioregions-in-the-gbrmp-and-gbrwh.pdf

7.0 New technologies for monitoring coral reef systems on the Great Barrier Reef

7.1 Data collection and processing technologies

A major challenge for the RIMReP coral reef monitoring component is to provide timely condition information for the entire Marine Park, encompassing very remote areas and reef in deep water (greater than 30 metres depth, also known as 'mesophotic' reefs). Advances in technology may be implemented within the RIMReP design as potential tools to accelerate, scale up and integrate assessments of coral reef condition.

In the current decade, the fast evolution of technology in engineering (from robotics to sensor design), molecular biology and genetic technology, computer vision and storage and processing capacity has empowered many aspects of modern society. Many technological advances are becoming more applicable and available to marine sciences; for example, underwater robotics are now widely used, and more accessible, artificial intelligence is proving very successful in data mining, satellites are increasing sensor resolution and frequency of data capture across the oceans; and molecular tools such as eDNA facilitate monitoring the presence of endangered or invasive species.

A commissioned desktop review (Gonzalez-Rivero et al., 2018- Supplementary Report S6) evaluated the potential of novel technologies to support coral reef monitoring within the RIMReP framework based on their performance, operational maturity and compatibility with traditional methods. The technologies considered in this review were grouped into:

- **Sensors**, passive (RGB = human visible spectrum, multi/hyperspectral), or active (laser, sonar)
- **Platforms** for image/data acquisition — for example, diver, underwater autonomous vehicle (AUV), underwater remote operated vehicle (ROV), airborne vehicles (UAV), and satellites.
- **Processing tools**, image classifiers, and three-dimensional reconstruction techniques.

The desktop review identified technological advances that offer solutions to maximise the spatial and temporal coverage of current monitoring and increase the speed of data analysis. The current readiness of new technologies means that traditional ecological monitoring methods will remain at the core of a future RIMReP because solutions offered by technology do not cover the entire spectrum of capabilities traditional methods can reliably achieve. For example, autonomous vehicles now offer the possibility of surveying reefs over scales of kilometres across multiple depths gradients, and in habitats that pose a risk to divers. However, assessments of fish communities as well as patterns of mortality and disease in corals, for example, cannot currently be measured accurately using any of the available technologies. The implementation of technological solutions should, therefore, integrate traditional and next-generation approaches (**Figure 7**). Importantly, such integration can only be achieved if data standardisation and compatibility among methods is assured.

Gonzalez-Rivero et al. (2018) recommend a staged implementation of new technologies. A suite of technological tools is sufficiently advanced to be immediately (one to two years) implemented in a RIMReP coral reef monitoring program (**Table 4**). Other technologies are evolving rapidly and are expected to be ready for implementation in coral reef monitoring in the near-future (two to five years). It will be important for continuous improvement of the RIMReP to review the readiness of these evolving technologies on a regular basis and to include a regular resource allocation for testing, validation and phasing-in of new technologies.

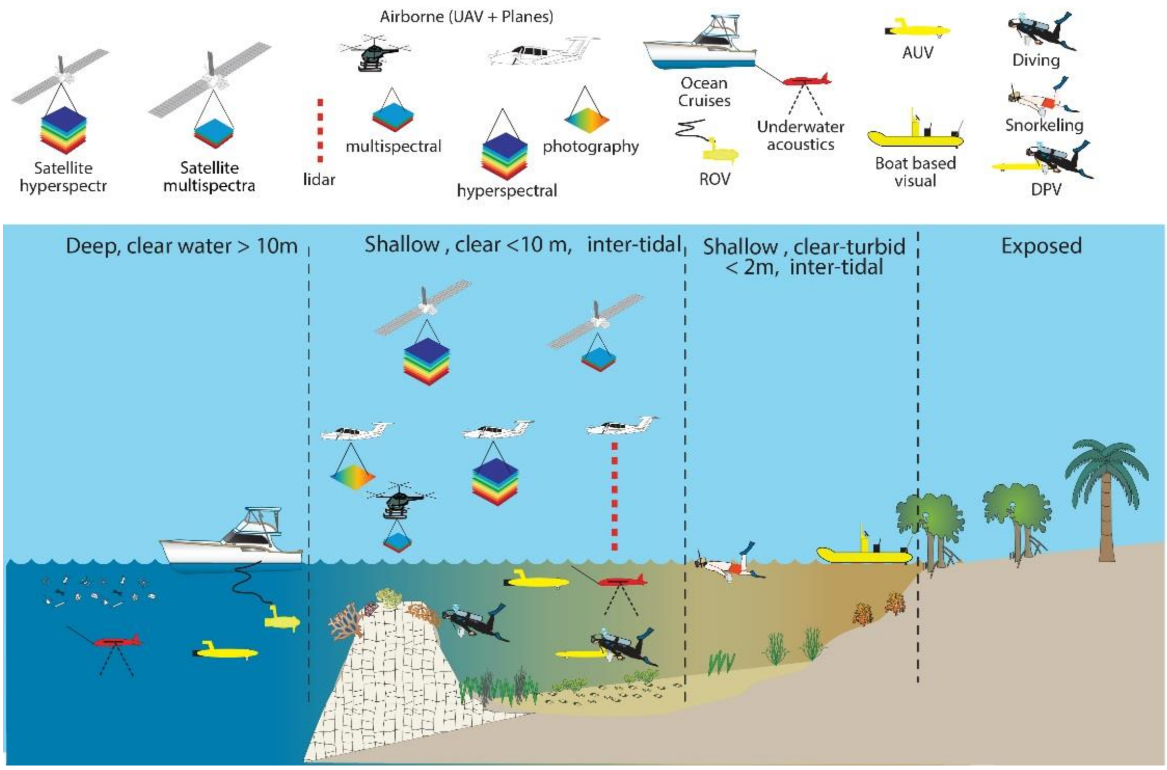


Figure 7: Conceptual diagram of integrated technologies, including variety of platforms and sensor types that could be combined and implemented for the RIMReP (adapted from Goodman et al., 2013)

Underwater and above-water vehicles or platforms are now operationally mature and sufficiently reliable to support observations of key ecological attributes at reef-wide scales. Autonomous platforms, such as underwater robots (AUV, ROV), are also available and would be offering access to habitats that pose risks to divers (e.g. reefs in coastal habitats inhabited by saltwater crocodiles) or represent keys gap in existing monitoring programs, such at depths that do not allow sufficient bottom time for effective monitoring activities (greater than 15 metres depth).

Analytical methods such as artificial intelligence and pattern recognition from images have evolved rapidly, to the point that measurements of key ecological attributes (for example, composition and abundance of benthos, structural complexity) can now be collected with high precision and several hundred times faster that manual expert analyses. As sensor (for example, underwater hyperspectral sensors) and software (for example, complex machine learning algorithms) technology develops over the next two to five years, the capabilities of automated image annotation and three-dimensional habitat reconstructions to contribute to coral reef monitoring are also growing rapidly.

Table 4: Summary recommendations of technological tools (sensors, platforms, processing tools) which currently are operationally available and capable of aiding coral reefs monitoring within three main spatial scale categories: a) in-depth (site within a reef), b) intermediate (reef scale) and c) broad-scale (whole of Reef)

Technology	In-Depth surveys	Intermediate surveys	Broad-scale surveys
Sensors	• RGB	• RGB + Multispectral	• Multispectral
Platforms	• Divers / Snorkelers • Digital Cameras • Autonomous vehicles (e.g. drones for reef flat and crest; AUV/ROV for reef areas >15 m depth)	• Underwater vehicles (DPV, AUV) • Airborne drones	• Airborne drones • Satellites
Processing tools	• Automated image annotation • 3D reconstructions • Manual analyses	• Automated Image Annotation • 3D reconstructions	• Automated Image Annotation
Outputs	• Detailed community composition (fish and benthos) • Agents of Mortality • Demographic attributes (e.g. growth rates, size classes)	• Functional community composition (benthos) • Structural complexity	• Habitat mapping at various information scales • Bleaching maps (if imagery available at the right time)

Remote sensing is reaching a maturity to be implemented for monitoring of shallow coral reef systems. Accessibility of satellite-based sensors with higher temporal repetition (daily instead of weeks) and coverage (for example, Reef-wide) is now allowing the evaluation of status and trends of reef systems at intermediate and broad scales (for example, area and cover of dominant habitats and substrate types, extent of coral bleaching; see Roelfsema et al., 2018 for a case study in the Capricorn Bunker Group). In the medium term, access to easy-to-operate drones, high-quality sensors (increased in radiometric quality and high resolution) and a development of advanced processing techniques (online processing of large data sets, object-based analysis or machine learning routines) will allow extracting higher level of detail at reef scales.

7.2 Molecular, genetic, genomic and physiological monitoring approaches

Molecular and genetic monitoring tools were not considered in the desktop review (Gonzalez-Rivero et al., 2018- Supplementary Report S6). However, information is available in a growing body of published research.

Many studies show that techniques such as analysis of environmental DNA (eDNA) have substantial potential to become a core tool for environmental monitoring (Kelly et al. 2014) (Herder et al., 2014; Robson et al., 2016). Some jurisdictions have already implemented eDNA methods. For example, the Ontario Ministry of Natural Resources uses eDNA for detection of endangered aquatic species and for surveillance programs aimed at detecting aquatic invasive species such as carp (Wilson et al., 2014). Most of these examples are from freshwater environments, but there are recent marine studies on using meta-barcoding or specific primer approaches for species detection, (for example, for fish, sharks, octopus and *Symbiodinium*) (Mauvisseau, 2017; Boussarie et al., 2018; Thomsen et al. 2012, 2016; Shinzato et al., 2018).

In the Marine Park, the application of eDNA has been developed to detect and quantify the presence of crown-of-thorns starfish larvae (Uthicke et al., 2015, 2018; Doyle et al., 2017) as well as for post-settlement detection (Uthicke et al., 2018). Herder et al. (2014) suggest that biodiversity assessments of rare species will involve eDNA techniques but that in the short term conventional methods will remain more cost-effective. Similar to the above recommendation for the engineering-type monitoring approaches, the authors suggest that eDNA and other molecular techniques will complement rather than replace conventional monitoring methods, as essential information on growth, fecundity and health will continue to rely on in situ observations, and taxonomic and ecological expertise. As more and more information about applications of eDNA become available, the scope for inclusion of this method in a future RIMReP is rapidly increasing.

Bio-indicators based on physiological changes within the coral reef organisms have been widely studied, with a focus on being able to measure early stress responses in the coral holobiont. These indicators include measurements of symbiont photophysiology, tissue content of chlorophyll a and lipids and skeletal elemental and isotopic composition (reviewed in Cooper et al., 2009). A recent study of environmental metabolomics (which describes the physiological state of an organism by measuring changes to specific metabolites) showed potential for this technique to be included in coral reef monitoring (Great Barrier Reef Foundation, 2017). However, detailed results do not appear to be published at the time of writing and so it is difficult to assess the readiness of this technique. Metabolomics may be able to quantify the amount of stress an organism has been exposed to, and to differentiate between specific pressures, for example, water quality versus temperature. Indicators for the physiological status of coral reef organisms were identified as being most applicable to short-term monitoring programmers to assess the effects of acute, and mostly sublethal disturbances on coral communities (Cooper et al., 2009). A further approach to develop diagnostic tools for identifying and quantifying sublethal stress is the use of gene expression biomarkers. While these have been studied for more than a decade (especially to find specific markers for heat stress), many knowledge gaps remain that make this approach plausible but not yet ready for application in routine monitoring, for example lack of reproducibility across species and life stages, limited stress-specificity, and poorly understood temporal variation (Louis et al., 2017). As bio-indicators and biomarkers have a rapid response time, frequent sampling is required. When selecting these indicators it also needs to be considered that sampling involves destructive methods.

A detailed review (Webster and Gorsuch, 2018) discusses the potential and readiness of using microbes as early warning indicators in coral reef monitoring. Environmental disturbances and chronic pressures can change the composition and function of microbial communities, including those in the water column and those associated with sediment or benthic organisms. Microbial partnerships are critical to the health and resilience of coral reefs (Wegley Kelly et al., 2018). As responses of microbes to pressures may affect the functioning of entire coral ecosystems, monitoring of microbial indicators may provide a rapid and sensitive technique for identifying early signs of declining ecosystem health (Glasl et al., 2017; 2018). The first step towards identification of microbial indicators for coral reef health is the establishment of microbial baselines for Australia's coral reefs, including the analysis of temporal and spatial variability of microbial communities (taxa and functions) associated with certain habitats and along environmental gradients. Microbial collections at three inshore sites monitored by the Marine Monitoring Program will produce valuable baseline information that will progress the development of microbial markers for operational application in future Reef monitoring (Glasl et al., 2019). Initial results of this research show that pelagic microbes would be better environmental indicators than host-associated microbes which tend to be less affected by changing environmental condition and hence have limited indicator value. Sampling of pelagic microbes would also be logistically simpler, more cost-effective (the standard technique is the sampling and filtering of 2L of seawater) and would be conducive to automated, high throughput sampling and applications like in-line flow cytometry on vessels and real-time DNA/RNA sequencing for community characterisation.

8.0 Recommendations for integrated monitoring of coral reef ecosystems on the Great Barrier Reef

The recommendations were based on discussion during two formal workshops of the RIMReP Coral Reef Expert Group, additional desktop studies (see Supplementary Reports) and further out-of-session work. The design recommendations are underpinned by the following principles:

- Learning from existing long-term programs (qualitative and quantitative assessments of adequacy and gaps, see above);
- Utility of monitoring information to deliver against identified management information needs and reporting requirements;
- Consideration of a tiered, hierarchical sampling approach as most appropriate for the size and remoteness of the marine park;
- Selection of widely used indicators with demonstrated value for condition and trend assessments, process studies and development of ecological models, supported by decision criteria and expert input;
- Selection of an initial set of monitoring sites, based on a spatial multi-criteria analysis tool; and
- Phased implementation of new sites and new technologies.

Recent national and international initiatives have started discussions and formed specific working groups to standardise monitoring approaches, including the selection of 'essential indicators' or 'essential variables' (Hayes et al., 2015; Constable et al., 2016) and to work towards integration of disparate monitoring datasets and approaches. These initiatives have had representation by members of the Coral Reef Working Group and/or the Authority and the recommendations made in this report were developed in context of these wider discussions about the integration and standardisation of ecosystem monitoring. The key initiatives, relevant to the RIMReP design process, include:

- The Global Coral Reef Monitoring Network (GCRMN). Its most recent regional summary report for the Caribbean Reef (Jackson et al., 2014) highlighted the "urgent need to develop simple, standardized monitoring protocols".
- The Global Ocean Observing System (GOOS), which focuses on coordination of observations "to avoid duplication of efforts, (…) and to adopt common standards for data collection and dissemination to maximize the utility of data" and "to approach ocean observations with a focus on Essential Ocean Variables" (Miloslavich et al., 2018).
- The Working Group for development of Essential Environmental Measures, hosted by the Department of the Environment and Energy, to identify measures which are essential for tracking change in the state of the environment and improve the discovery, access and reuse of data and information.
- The Baselines and Monitoring Working Group of the National Marine Science Committee (NMSC), which agreed at its inaugural meeting in 2017 that "Systems for collecting, evaluating, and reporting on data should, were possible (…) be consistent, comparable and additive."

The RIMReP design process strove to anticipate future changes (for example, change of needs, advancements in technology) but the Coral Reef Expert Group clearly acknowledged that the current design process will be for RIMReP version 1.0, which will evolve over the Reef 2050 time period.

8.1 Hierarchical spatial sampling design

The recommended hierarchical design (**Figure** with three spatial scales incorporates the following monitoring approaches:

Broad-scale, whole-of reef monitoring

- Broad scale (satellite-based) mapping of geomorphic zonation and dominant benthic cover, reef-wide assessments of bleaching extent (blue shaded area in **Figure 8**).

Medium-scale monitoring

- Structured monitoring, regular sampling at fixed, ‘backbone’ sites (red transect symbols in **Figure 8**);
- Reactive surveys at local to regional scale which, for example, provide information on changes to pressures or reef condition (early warning), assessment of extent and severity of disturbances, context-specific monitoring of management effectiveness (red shaded area in **Figure 8**);
- Manta tow-style sampling, for coral cover and crown-of-thorns starfish detection (blue dotted reef perimeters in **Figure 8**);
- Sites for monitoring of currently under-represented habitats due to safety constraints for diving (for example, deep reefs or shoals greater than 15 metres, far northern inshore reefs) by Autonomous Underwater Vehicles or Remotely Operated Vehicle surveys (yellow star symbols in **Figure 8**).

Small-scale monitoring

- Site specific-monitoring: ‘sentinel’ or ‘reference’ sites (green shaded area in **Figure 8**), for example, for sampling additional indicators, testing and validation of new technology, process studies (see further discussion below);
- Other site-specific monitoring, e.g. Eye-on-the-Reef (EotR) observations at fixed sites (e.g. EotR Tourism Weekly) (green circles in **Figure 8**).

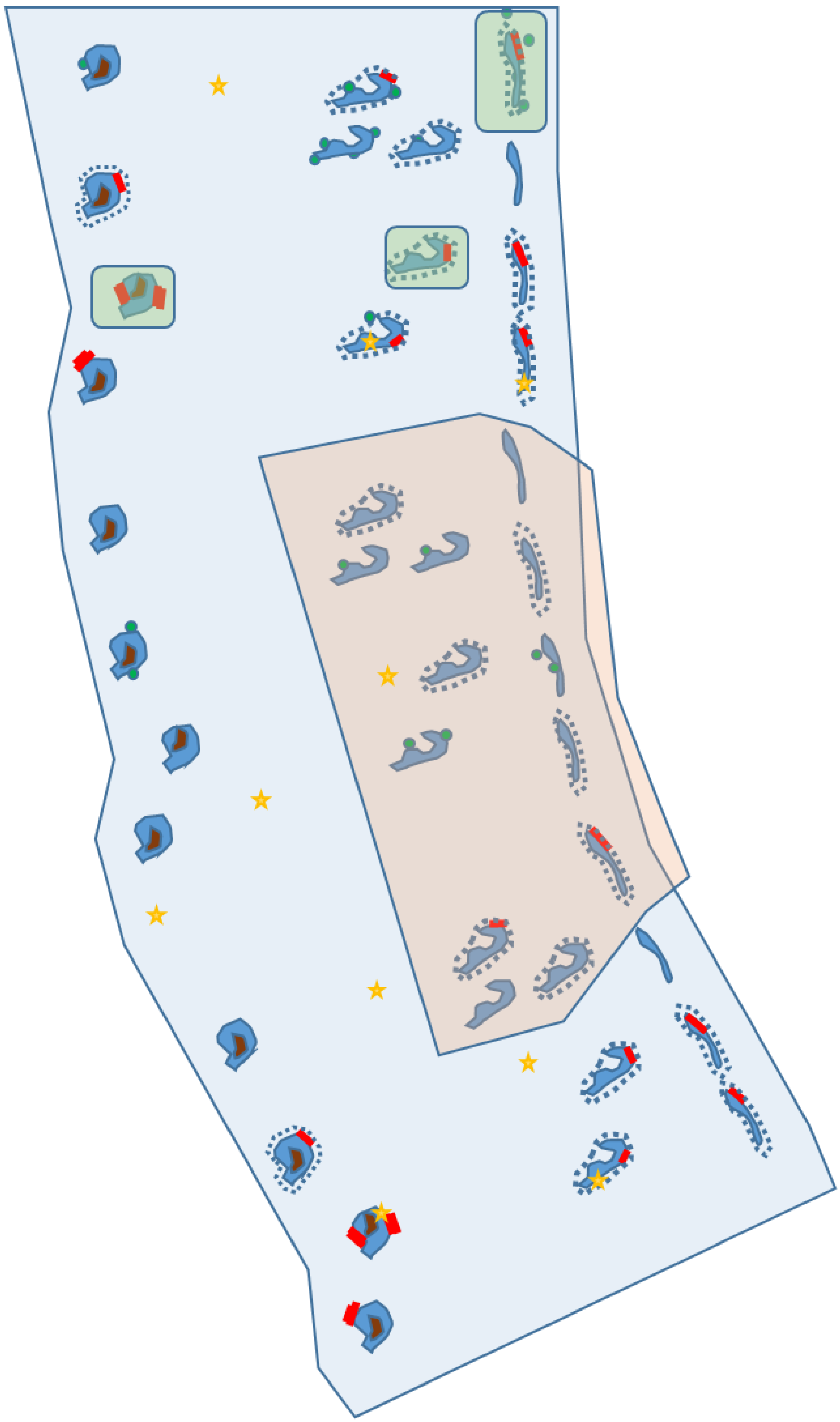


Figure 8. Illustration of the recommended hierarchical sampling design (see text above for further explanation).

8.2 Matching recommended indicators with spatio-temporal scales of monitoring

The next step is the matching of indicators with the three spatio-temporal scales of coral reef monitoring and an initial identification of recommended methods for immediate implementation (**Table 5**). All indicators can be monitored to some extent by existing approaches.

It needs to be noted that for the purpose of structured long-term monitoring, habitat consistency and the use of fixed sites are essential to detect ecologically relevant changes (Mellin et al., 2018; Thompson and Menendez, 2018; see Supplementary Reports S4, S5).

Additionally, because disturbances on the Reef are increasing in frequency and severity (e.g. Anthony 2016; Hughes et al. 2017a, b, Hughes et al. 2018), annual monitoring frequency is necessary to enable attribution of change to pressures and disturbances as well as management.

Table 5. Recommended coral reef monitoring methods for collection of identified priority indicators at broad and medium spatial scale. Shaded cells represent priority indicators that are recommended to be collected, at least initially, only at the small (reference/sentinel site)-scale (see text for further discussion). Note that only high-level information on recommended, immediately operational methods is included and further refined later in the report. Information in brackets describes the measure obtained for the indicator

Indicator	Broad-scale methods	Medium-scale methods
Hard and soft corals		
Abundance, cover	Satellite remote sensing, analyses repeated ~every 5-10 years (live coral reef cover, broad functional groups).	1. Manta tow, annual at fixed sites, as-needed at reactive sites (per cent cover of hard and soft corals) 2. Photo transects, annual at fixed sites and as-needed at reactive sites (per cent cover of genera and/or growth form) 3. RHIS for spatial in-fill (per cent cover of hard and soft corals)
Number of juveniles	n/a	Visual in situ assessment along transects, annual at fixed sites (counts and size classes of juvenile corals)
Number of coral recruits (by settlement tiles)	n/a	n/a
Rugosity/3D structure	n/a	Analyses of stereo camera photo transects, annual at fixed sites (living 3D structure)
Reef size and extent	Satellite remote sensing, analyses repeated ~every 5-10 years (live coral reef cover, no distinction between taxa).	n/a
Accretion vs erosion assessment (e.g. NOAA erosion blocks)	n/a	n/a
Coral bleaching	Aerial surveys, as required, perhaps guided/augmented by satellite remote sensing (area of bleached shallow reef)	1. Manta tow, as-needed at fixed or reactive sites (Proportion of per cent live coral cover that is bleached) 2. Photo transects, as-needed at fixed or reactive sites (ditto)
Coral disease	n/a	Visual *in situ* assessment along transects, annual at fixed sites, as-needed at reactive sites (disease prevalence)[1]
Particle-feeding	n/a	Data analyses (cover and community composition of particle-feeding benthos derived from per cent benthic cover data)
Macroalgae		

Abundance, cover	n/a	Photo transects, annual at fixed sites and as-needed at reactive sites (per cent cover, combination of genus-level for key genera and functional form for all others)
Cover and community composition of benthic primary producers	n/a	Data analyses (cover and community composition of benthic primary producers derived from per cent macroalgal cover data)
Turf heights/canopy heights	n/a	*in situ* assessment using a ruler along transects (height in mm)
Ratio CCA vs turf vs fleshy	n/a	Data analyses (ration derived from per cent macroalgal cover data)
Fish		
Counts and size of reef fish	n/a	Visual underwater census, annual (counts and size of reef fish)
Counts and size of reef-associated pelagic fish	n/a	n/a
Biomass of herbivorous fish	n/a	Data analyses (biomass data derived from counts and size of reef fish species data)
Mobile Invertebrates		
Counts of crown-of-thorns starfish, size of crown-of-thorns starfish, feeding scars on corals, eDNA	n/a	1. eDNA analysis in water samples (perhaps also in fish guts), sampling site selection to be informed by eReefs model to identify conducive conditions for outbreaks; early warning surveys in the crown-of-thorns starfish 'initiation box'; Lizard Island Research Station crown-of-thorns starfish observations (presence/absence during non-outbreak conditions) 2. Manta tow & visual in situ assessment along transects, annual at fixed sites, as-needed at reactive sites (counts of crown-of-thorns starfish, feeding scars) 3. Visual *in situ* assessment along transects, annual at fixed sites, as-needed at reactive sites (size of crown-of-thorns starfish)
Counts of key herbivores (e.g. sea urchins)	n/a	n/a

[1] More detailed assessments of disease (e.g. incidence, disease progression) may be required at specific site-level as an additional adaptive, reactive monitoring if coarser indictors identify a problem

8.3 Matching recommended RIMReP monitoring approaches to management needs

A key consideration for RIMReP is that the recommended monitoring approaches and spatial scales address the identified management uses and information needs and RIMReP's overarching goal of 'enabling the early detection of trends and changes in the Reef's environment, informing the assessment of threats and risks, and driving resilience-based management'.

As a step to develop the recommendation for the RIMReP coral reef monitoring design, the information delivered by the recommended three hierarchical spatial scales are matched with the five identified key management uses (**Table**). This clearly shows the importance of the medium-scale monitoring (at reef or sub-reef level), especially the structured sampling at the fixed, 'backbone' sites, for delivering the required management information. Monitoring at the broad and site-specific sampling scale complement this 'backbone' for a comprehensive monitoring of the Marine Park.

Monitoring integration is about conducting fit-for-purpose monitoring approaches/programs to the different management needs as well as about integrating data streams from different sources and for different indicators.

For example, the analysis in Mellin et al. (2018, Supplementary Report S4) showed that reactive survey programs (for example, the Reef Health and Impact Surveys) had high 'representativeness', which was estimated as how much the surveyed locations represent the diversity of reef habitats and environmental gradients on the Reef; in the case of RHIS this was 60 per cent. These reactive programs are able to detect large changes, for example after a significant disturbance event relevant to inform management. However, these programs had low accuracy and precision in their assessments and limited ability to assess trends in reef condition. In contrast, the structured programs (for example, the AIMS Long-Term Monitoring Program) have high accuracy, precision, and power for detecting ecologically-relevant changes (see also Thompson and Menendez, 2018, Supplementary Report S5); the trade-off is lower representativeness (45 per cent). High precision is required to detect any changes in rates of key processes (such as recovery from disturbance).

In a scenario of a regional-scale disturbance, the integration of the two monitoring approaches means that:

i) they both perform well for what they were designed for: RHIS as a rapid means to provide regional-scale situational awareness following disturbances; and AIMS' Long-Term Monitoring Program to document the impact on community state, assess long-term trends in recovery, and attribute changes to pressures;

ii) they deliver information to support the management uses: informing tactical responses, measuring effectiveness of management actions, reporting condition and trend, informing planning and policy (Mellin et al. 2018, Supplementary Report S4 and **Figure 9**).

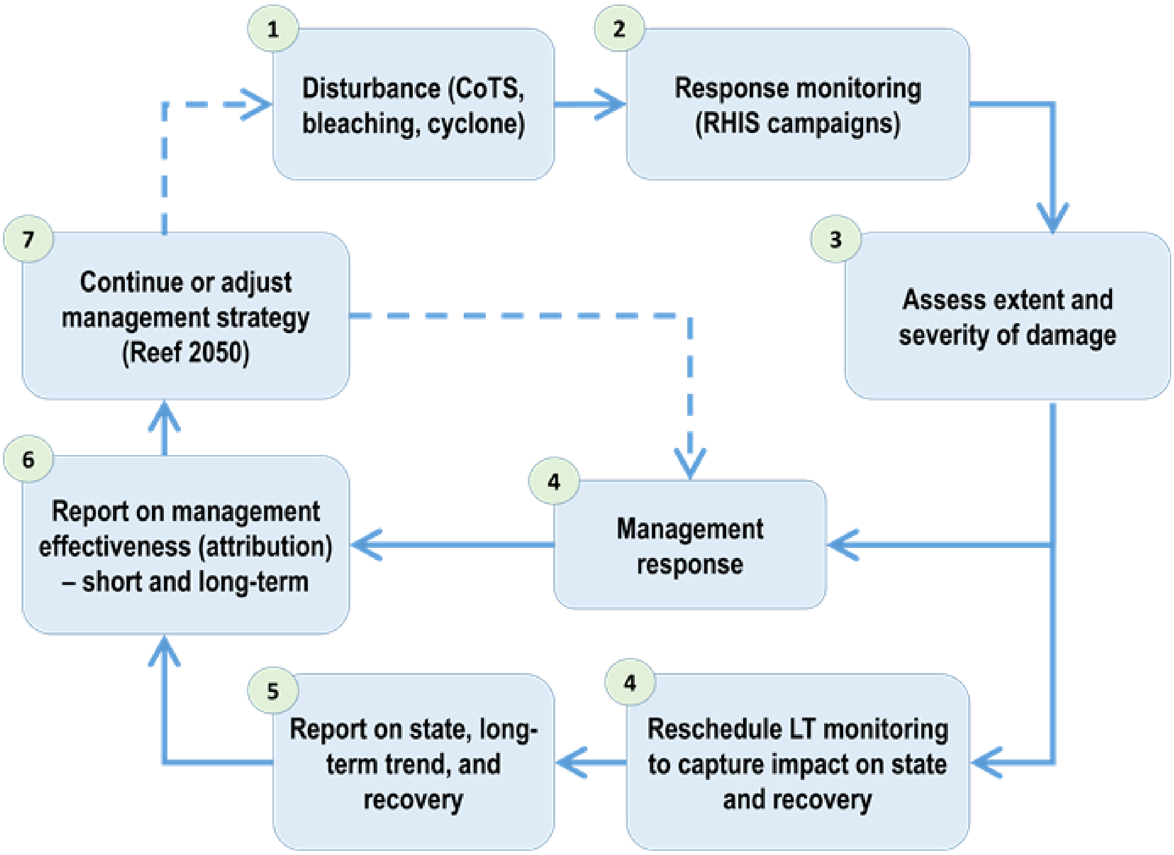


Figure 9. Illustration of the potential integration of reactive survey programs (such as RHIS) and structured long-term (LT) monitoring programs Following a disturbance (time step 1) that is either directly documented (e.g. cyclone track map) or informed by early warning monitoring (e.g. coral disease incidence, higher abundance of crown-of-thorns starfish larvae), RHIS provides key situational awareness (steps 2 and 3). This triggers two processes in step 4: a management response, and long-term monitoring so the impacts of the disturbance are captured (e.g. start point for monitoring of recovery is reset). Results of LT monitoring and the management responses are then reported (steps 5 and 6) and used to adjust and inform the management strategy (7). Consideration of chronic disturbances such as water quality are assumed implicit in management strategy and response.

Table 6. Examples of information provided to key management uses from spatially tiered coral reef monitoring

Management use	Broad-scale	Medium-scale[1]	Site-specific sampling[1]
1. Tactical – responding to an event or incident (e.g. vessel grounding, flood, cyclone, coral bleaching, crown-of-thorns)	• Bleaching severity and extent assessments by remote sensing (aerial, satellite)	• Timely availability of local to regional-scale information on the extent and severity of disturbance events; sampling site selection guided by decision trees (tbd; immediately available for decision support are e.g. AIMS cyclone impact model, freshwater/plume extents from eReefs). • Early detection of crown-of-thorns starfish; guidance of control effort (ongoing development by NESP project – already operationally applied by AMPTO and FMP).	• Case-specific targeted sampling delivers detailed information of impacts at individual reefs or locations (e.g. ship grounding).
2. Operational (prioritisation of compliance effort, moorings, permit assessments)	• n/a	• Status and trend information from repeatedly sampled 'backbone' sites provides context and baselines for risk and impact assessments[2,3].	• Case-specific targeted sampling.
3. Strategic planning (e.g. zoning, policy development)	• Baseline of living reef area (repeated every 5-10 years)	• Status and trend information from repeatedly sampled 'backbone' sites provides context and baselines for spatial planning[2,3].	• Reference/sentinel sites, e.g. for process studies and to better enable attribution of changes to pressures.
4. Effectiveness of management actions	• n/a	• Status and trend information from repeatedly sampled 'backbone' sites provides context for management effectiveness assessments[2,3]; • Zoning monitoring (blue-green) as key criterion in selection of repeatedly sampled 'backbone' sites; • Monitoring of effectiveness of crown-of-thorns starfish control (tbd, this needs to be specifically designed as addition to 'backbone' monitoring).	• Case-specific targeted sampling.
5. Condition and trend reporting to community and stakeholders (e.g. report cards, Outlook reports, web and social media)	• Baseline of living reef area (repeated every 5-10 years)	• Status and trend information from repeatedly sampled 'backbone' sites provides key input into regional report cards and Outlook Report; • Reactive surveys to reefs/sites provide 'in-fill' data to complement 'backbone' sites.	• Reference/sentinel sites, e.g. for process studies, improved attribution of changes to pressures, development of forecasting models.

[1] Medium-scale and site-specific sampling is recommended to use standard techniques that allow data integration, e.g. image-based techniques and Manta tow.
[2] May require specific data analyses (e.g. attribution to pressures, forecast modelling).
[3] Inclusion of data from e.g. Ports or AMPTO monitoring sites into integrated reporting or assessments may require specific permit conditions for data availability.

8.4 Initial selection of 'backbone' monitoring sites

The final step in developing the recommendation is the selection of fixed sites for the medium-scale 'backbone' coral reef monitoring. The assessment of adequacy of existing programs (above) has identified important geographical gaps, as well as developed a spatial model to assist the site selection on the basis of (i) benthic community composition and (ii) coral cover trajectory (Mellin et al., 2018, Supplementary Report S4).

The (re)design of a monitoring program is complex as it involves trading off a range of criteria against a large number of potential monitoring site combinations, while retaining sites that have historical data to allow for continued reporting of long-term trends. A popular method for selection of sites for biological and environmental monitoring programs is to use spatially balanced sampling (Brown et al., 2015; Foster et al., 2017; Foster et al., 2018). This approach aims to ensure that coverage of survey effort is spread evenly over the survey region to ensure that the survey method is representative of measured variables of interest, without requiring prior knowledge of its distribution. It is often difficult to assess the trade-off between the number (= cost) of surveyed sites and the level of performance of the monitoring program. Environmental variables, which influence the type and condition of ecological communities and ecosystems, may have smooth gradients (for example water quality variables changing across the shelf, or temperature decreasing from north to south) and thus only a few sample sites are required to understand each parameter over the regions of interest. However, the combination of various variables of interest with different gradients and with other spatial criteria that are of relevance to the monitoring program generally require much denser sampling.

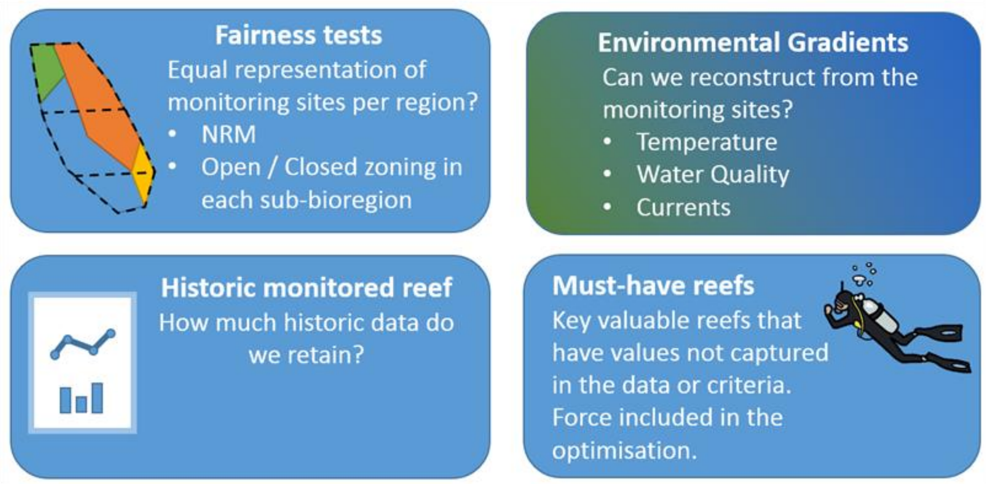
A multi-criteria analysis tool (Monitoring Site Planner) was developed to evaluate different spatial designs for the RIMReP coral reef monitoring against three types of performance criteria (Lawrey et al., 2019, Supplementary Report S8). These assess how fairly distributed the monitoring sites are within desired, fixed spatial attributes (representativeness), the ability of the data from the monitoring sites to reconstruct environmental gradient data, and whether the selected sites have historic data (**Figure 10**). The Monitoring Site Planner tool also includes an optimisation algorithm that develops a survey design that trades off the specified set of criteria. For this recommendation report the Monitoring Site Planner was applied using a set of initial criteria, with the view of refining these for the ultimate site selection once the funding envelope for RIMReP is known and providing the opportunity for additional selection criteria or identification of 'must-have' by managers and other stakeholders.

The three performance criteria groups for the initial runs of the Monitoring Site Planner (**Table 7**) included (see Lawrey et al., 2019 for more details on the methods and input data sources):

- Spatial attributes (Natural Resource Management regions which could be used, for example, as reporting regions for the RIMReP, Marine Park zoning, reef Bioregions of the Reef);

- Environmental gradient data (summer and winter temperature climatology, annual mean Secchi depth, annual mean non-algal particulates, annual mean chlorophyll, maximum annual current flow);
- The amount of historic data available (in years) at each of the reefs that have been monitored. This included data from existing programs with the widest spatial and temporal cover [Effects of management zoning on inshore reefs of the Marine Park (JCU), Long-Term Monitoring Program: Reef monitoring (AIMS Marine Monitoring Program: inshore (AIMS), Gladstone Harbour monitoring (AIMS), North Queensland Bulk Ports Corporation monitoring (AIMS and private consultants); see report section "Synopsis of existing monitoring programs" for more details of these programs].

Figure 10. Each survey design is optimised against three evaluation methods. In addition, 'Must-have' reefs can be included during the optimisation to force inclusion of these sites.



The overall performance and further specifics of selected runs is presented in **Table 8**. Maps of the sites selected in two highest performing options ('Expert site selection' and 'Optimisation for environmental gradients, spatial fairness and historic data criteria') are in **Figures 11 and 12**. Both designs had almost the same performance based on the selected criteria and had almost the same overall number of sites. The difference between the designs was in the retention of existing sites (slightly higher in the expert sites selection).

For a final site selection, the Monitoring Site Planner can be refined, for example by determining different weightings between the selected criteria, adding additional criteria, and adding 'must have' sites. These decisions would best be made in close consultation between key RIMReP stakeholders and the Coral Reef Expert Group. The advantage of using the interactive Monitoring Site Planner for future design refinement is that trade-offs between various criteria can be easily evaluated and visualised.

Table 5. Example survey designs evaluated by the Monitoring Site Planner

Survey design evaluated	Description
Random site allocation	Randomly allocating monitoring sites with no consideration of other criteria. The runs were for preselected number of sites (n=100 and n=200)
Existing design	This corresponds to the existing fixed site monitoring sites (n=167*)
Expert site selection (*see **Figure 11***)	This design was developed by a CREG subgroup using the following criteria: 1. Two Blue/Green zoning pairs per bioregion (4 reefs). Preference for pink zone sites. 2. Big/long bioregions have more pairs. 3. Very strong preference for existing sites, retains all existing inshore reefs as they represent management needs and are required for current reporting (e.g. Regional report Cards). 4. Bioregions with excessive existing pairs had reefs removed. 5. Bioregions without enough reefs had pairs added. 6. Reef structure, existing data from other surveys (e.g. Catlin Seaview Surveys) and known logistical constraints used to choose additional reefs.
Optimised for temperature gradient along the Reef	Site selection was optimised to best reconstruct the summer and winter temperature environmental gradients, to illustrate a design that would be suitable if responses of coral reefs to average temperatures were the main information need.
Optimised for water quality gradient (concentration of non-algal particles) across the shelf	Site selection was optimised to best reconstruct the annual mean concentration of non-algal particles (NAP, an estimate of the suspended solids in the water) to illustrate a design that would be suitable if responses of coral reefs to water quality were the main information need.
Optimised for water quality gradient (Secchi depth)	As above
Optimised for spatial attributes and historic data retention	Site selection was optimised to perform best against the selected spatial criteria (see above) and retention of historical sites
Optimised for both environmental gradients, spatial fairness and historic data criteria (*see **Figure 12***)	Site selection was optimised on the various environmental gradient variables, spatial attributes and historical data criteria.

** LTMP and MMP sites were represented in the database at the reef level, whereas the JCU RAP site entries correspond to individual sites. To make these comparable, JCU RAP sites were aggregated to match a reef-level scale.*

Table 6. Weighted average of the performance scores for selected monitoring designs (the lower the score the better the performance). Shaded cells highlight the two highest performing designs, which are also presented as maps below.

	Random site allocation		**Existing design**	**Expert site selection**	**Optimised for all criteria**	
Number of monitoring sites	100	200	159	169	156	82
Overall performance score	0.64	0.57	0.48	0.40	0.39	0.52
Retained historic data (fraction of all monitoring years that the selected sites correspond to)	0.05	0.12	0.73	0.67	0.61	0.22

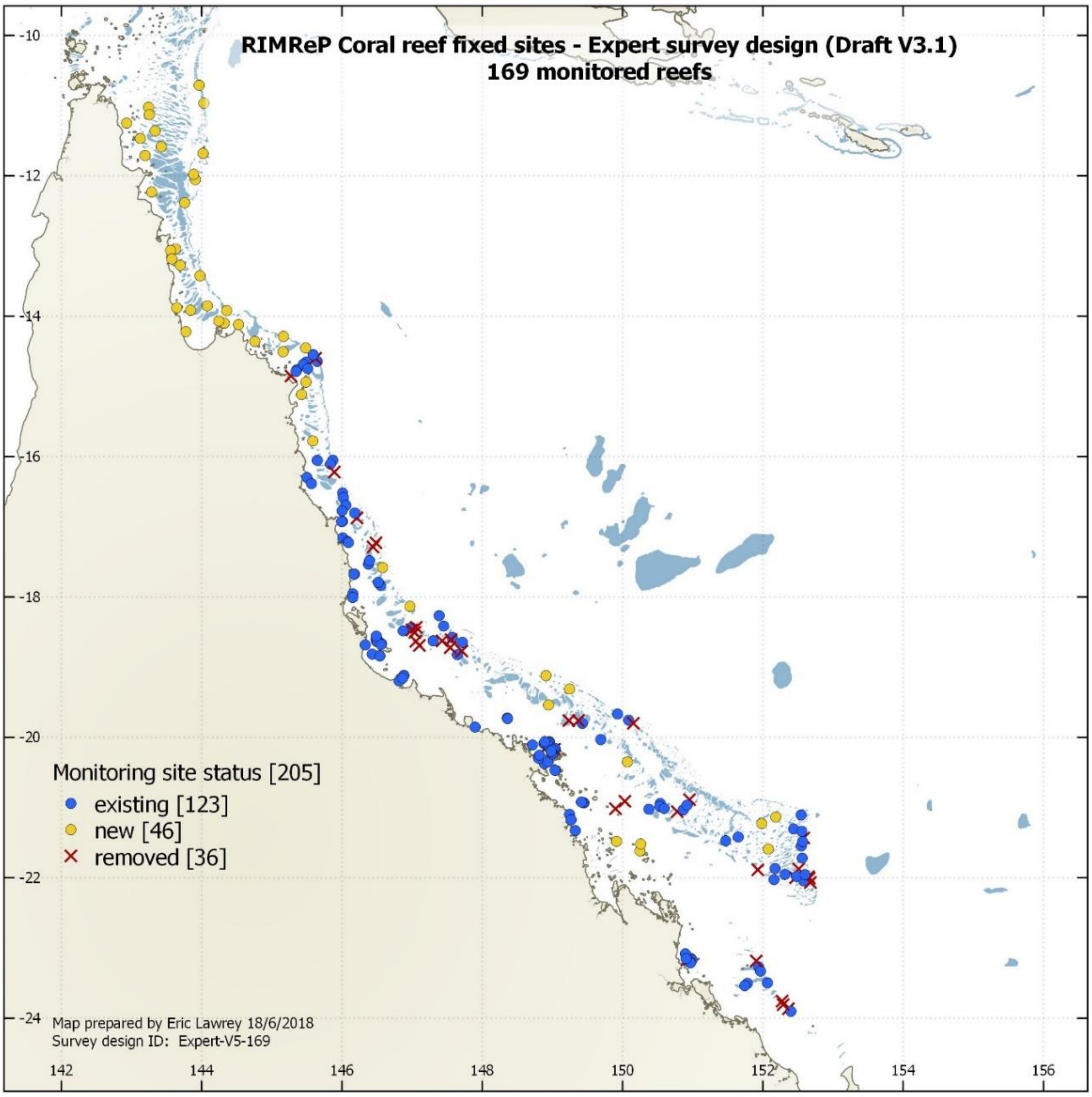


Figure 11. Monitoring design based on expert site selection (see **Table 7** for further details). This was developed by modifying the existing survey design to remove some existing redundant sites and reallocating them to fill spatial gaps.

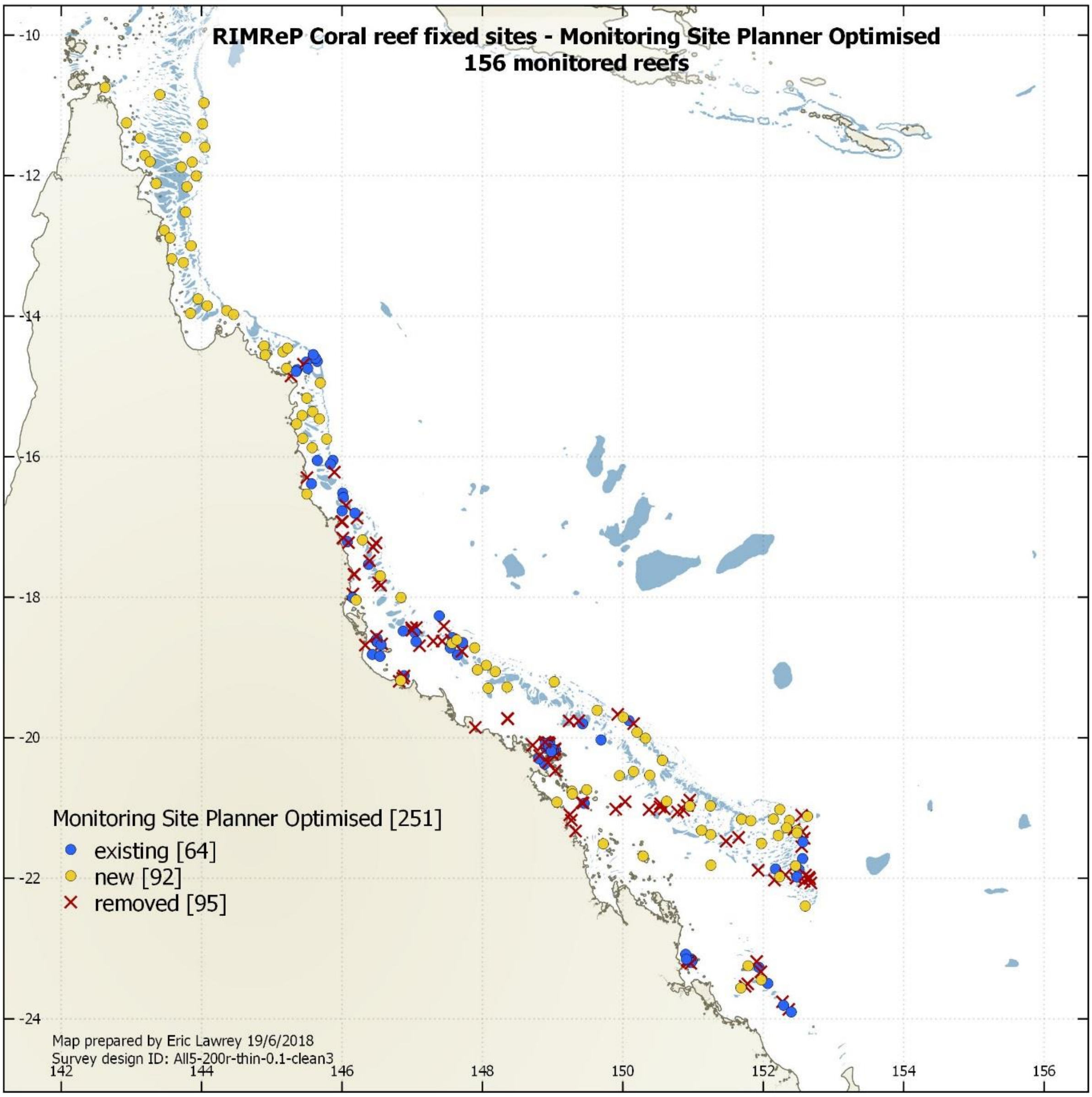


Figure 12. Example of an optimised monitoring design with 156 reefs developed with the Monitoring Site Planner (see **Table 7** for further details). Note that this sampling design was developed by requesting that the optimiser develop a survey design with 200 reefs. Once this was complete a second stage of optimisation was performed that thins out the survey design by removing reefs that don't significantly degrade the performance of the monitoring program. In this case a threshold of 0.5 per cent degradation in performance was used, resulting in 50 reefs being removed from the initial design.

8.5 Outline of the recommended, immediately operational coral reef monitoring program

Based on the design steps in the previous chapter, a description of the coral reef monitoring program that is expected to be operational within the first year of RIMReP is summarised in **Table 7**.

Table 7. Immediately operational coral reef monitoring activities

RIMReP coral reef monitoring activity	Reporting products/outputs
Broad scale monitoring	
1. Acquisition and analysis of Reef-scale satellite imagery for mapping of geomorphic zonation (every 5-10 years).	• Seamless Sentinel 2 satellite image mosaic • Maps of geomorphic zonation, water depth, slope, wave climate
Medium-scale monitoring	
2. Annual monitoring at recommended 'backbone' sites (Figure 11) for all priority indicators, see Table 6) using the following methods: • photo transects (stereo camera) for benthos assessment • Automated image analysis[1] with manual QAQC • Manta tow around reef perimeter • Visual census of reef fish • Continuation of annual monitoring of Ports monitoring sites, using standard methods, data lodged in RIMReP data system • Data integration and analyses	• Annual reporting of reef condition and resilience index by spatial reporting unit[2] • Annual reporting of coral cover based on Manta tow (continuation of historical reporting) • Immediate reporting of crown-of-thorns starfish abundance, based on Manta tow • Annual reporting of fish community condition (initial focus on zoning comparison) • Data/indices supplied to regional report cards • Data for development of Reef-wide condition and forecast model and guidance system
Disturbance monitoring: early warning, extent and scale	
3. Early warning of disturbances • Eye on the Reef observations[3] • Crown-of-thorns starfish (eDNA sampling, informed by eReef model; observations from EotR), 4. Post-disturbance assessments • Case specific targeted sampling to document disturbance events by FMP staff, tourism staff/volunteers (site selection guided by e.g. using cyclone model, freshwater/plume extents from eReefs), • photo transects (normal camera) for benthos assessment, automated image analysis as part of 2, • Manta tow for crown-of-thorns starfish detection by FMP staff, tourism staff/volunteers (data combined with 2.)	• Early warning alert/reporting system (tbd)

[1] Photographic images will be the ‘common currency’ to facilitate data integration, with standardised automated image analysis providing efficiency and quality assurance. Note: this requires a shared image database
[2] Spatial reporting units (e.g. NRM region, Great Barrier Reef Marine Park Authority management area) need to be advised by the Great Barrier Reef Marine Park Authority.
[3] Recommendation for discussions about modification to EotR methods (e.g. inclusion of photographic sampling) to improve compatibility between monitoring types. Initial focus perhaps on ~20-30 EotR Tourism Weekly sites.

8.6 Development and continuous improvement over the following two to five years

8.6.1 Community and citizen monitoring

The recommended design is largely based on monitoring by trained experts. However, some aspects are expected to be delivered by citizen scientists, for example by the Authority’s Eye on the Reef Program. A useful integration of expert-collected and citizen science data will require further development and implementation of fit-for-purpose standard methods (Edgar et al., 2016). New technologies such as automated image analysis will also open up new opportunities to involve a broader range of data and information collectors, once suitable storage and processing platforms are developed and tested to integrate ecological information from multiple sources of underwater imagery. A key component of the recommended design is the use of images as the ‘common currency’ for monitoring of coral reef benthos.

An important opportunity will also be the engagement of Traditional Owners in monitoring activities. This will be particularly important for monitoring in the Cape York region of the Marine Park. Recognising that RIMReP will almost certainly be a multi-institutional partnership, we expect further discussion about suitable arrangements to support Traditional Owner engagement for the entire RIMReP program. Engagement relevant to the recommended coral reef monitoring may include:

- notifying and providing information to the appropriate Traditional Owner groups, prior to conducting research, to allow Traditional Owners to either dedicate ranger staff or elders/members to participate in monitoring;
- resourcing and valuing Traditional Owner participation, time, and expertise where possible;
- supporting capacity-building of Traditional Owners such as providing a 1–2-day introductory training session to cover workplace health and safety, purpose and rationale of the monitoring, data collection and methodology, and discussing mutual expectations from the activity;
- supporting Traditional Owners to obtain marine accredited training including sea time towards coxswains licences, diving certifications and others; and
- providing Traditional Owners a summary of research outcomes, outputs, and/or findings to inform Traditional Owners of reef health in their traditional sea country.

8.6.2 Reference, sentinel or testing sites, monitoring technology development

An important addition to the recommended coral reef monitoring program will be the addition of site-specific monitoring activities. These will have three main purposes, which are discussed further below:

1. Testing and validation of new monitoring technologies (for example, remote platforms);
2. Collection of data for additional indicators to report on condition of broader reef-associated biodiversity and processes;
3. Improved attribution of pressures to state (condition of the values, as relevant to coral reef ecosystems).

The routine testing and validation of new monitoring technologies is recommended to be a core aspect of RIMReP. We additionally recommended that priority development activities be identified and included in a regularly updated RIMReP and Reef 2050 Research, Development and Innovation Strategy. For coral reefs the immediate priorities are activities such as:

- the operationalising of new platforms that will enable monitoring of deeper reefs and sites too dangerous for divers (for example, autonomous underwater vehicles, AUV), and of reef flats and crests (for example, drones). This could be coordinated with the planned expansion of the benthic AUV facility of the Integrated Marine Observing System (IMOS).
- cross-validation of existing methods to allow selection of the most suitable and cost-efficient approach for the application in the Reef, for example a comparison of traditional manta tow surveys, camera-based manta tows and AUV-collected benthic imagery; and comparisons of the two widely used standard fish survey methods, underwater visual census (Underwater Visual Census; Emslie et al., 2018) and baited remote underwater video (Baited Remote Underwater Video; Langlois et al., 2018). The cross validations also need to consider data continuity.
- further development of the semi-automated method tested by Roelfsema et al. (2018) to provide maps for the whole Reef of reef geomorphic zonation, dominant benthic cover type and predicted dominant coral type, based on the integration of satellite data, field data and modelling.

The recommended ‘backbone’ monitoring sites have been identified as capable of providing high capacity to detect change. It is, however, not cost-effective to monitor all candidate indicators (which represent the Reef’s values) at this spatial scale. Selection of specific sites for more intense monitoring would enable the inclusion of additional indicators (see **Table 5**; **Appendix 1** for additional indicators). These sites may also be visited more frequently and could serve to apply monitoring techniques for indicators that respond on shorter time scales and have early warning potential for sublethal stress (for example, physiological, genetic and – omics indicators – see section on New Technologies for monitoring earlier in the report).

Due to the nature of the information collected at the recommended ‘backbone’ monitoring sites (focus on abundance of different organisms), it will not always be possible to precisely attribute the pressures responsible for observed trends and, more importantly, the ecological mechanisms driving these changes.

Observed reductions in reef state, reef recovery rate etc. can occur as a consequence of reductions of one or multiple demographic process (recruitment, natural mortality, colony growth rate etc.) The identification of these mechanisms is important because it can help evaluate the potential effectiveness of different management alternatives in different regions. However, collecting the information required to inform these processes is logistically challenging at the medium spatial scale.

Sampling at a relatively small number of strategically selected sites will provide deeper insight into environmental drivers and pressures and processes underpinning reef functioning (reef dynamics) at and around long-term (fixed) sites, and/or following disturbances. At these sites, more detailed, or more frequent sampling of several indicators across RIMReP themes (for example coral reef condition and physico-chemical indicators) would be undertaken to complement the 'backbone' monitoring across broad exposure gradient. The insights from these 'reference' sites would assist with:

- development, validation and calibration of ecological response and forecasting models;
- increased capacity to attribute reefs dynamics to multiple stressors and management actions;
- improved understanding of resilience – why some reefs are 'bright spots' or 'dark spots' and what reef managers can do to shift dark to bright. This will support, for example the identification of resilient reefs currently underway by the Authority ('resilience network');
- improved ability to evaluate potential effectiveness of different management strategies;
- improved ability to tailor region-specific actions that can target specific demographic processes (for example, early detection of crown-of-thorns starfish outbreaks).

Specific selection criteria for these reference sites and indicators will need to be developed, based around specific questions and could include, for example, pressure gradients, overlap with physicochemical monitoring, a subset of medium-level sites, sites in the crown-of-thorns starfish initiation zone to assist in the development of an early warning system for primary crown-of-thorns starfish outbreaks (for example, eDNA monitoring stations, sensor networks).

8.6.3 Integration and reporting

The usefulness of the information derived from observational data from RIMReP will largely depend on the integration, analyses and reporting methods and products. While this will be addressed by the later RIMReP integration stages and the Synthesis and Reporting Working Group, we make a few recommendations here which stem from discussions during the Coral Reef Expert Group meetings and from the supplementary desktop studies.

A key component of the reporting of RIMReP observational data will be the integration of indicator data into meaningful metrics and indices, which can, for example, be reported in form of report cards. Good examples for the Reef region are available in the Reef Water

Quality Protection Plan Report Card, and regional report cards[15]. The science behind indicator aggregation is well developed (for example, Browne et al., 2007; Dobbie and Clifford, 2015; Dobbie and Dail, 2013; Kuhnert et al., 2007; Thompson et al., 2016; Gladstone Healthy Harbour Partnership, 2017) and being continuously improved (Logan et al., in prep). A core principle of a reporting index is an assessment against meaningful thresholds. While thresholds for biophysical indicators are available in in the Great Barrier Reef Water Quality Guidelines (Great Barrier Reef Marine Park Authority, 2010), comparable thresholds are still being developed for coral reef attributes. Operationally applied indices that combine various attributes of coral reef benthos are currently used for reporting as part of the Marine Monitoring Program (Thompson et al., 2016) and in the Mackay Whitsunday regional report card (Logan and Thompson, unpubl.).

Continuous improvement of existing thresholds and development of thresholds for more indicators will be essential for future RIMReP reporting. The RIMReP Coral Reef Expert Group recommended this as an important, accompanying research activity.

Another key component for the assessment and reporting of RIMReP observational data will be the use of modelling approaches.

Models will be essential to:

- guide the spatial extent and resolution of reactive monitoring (for example, to assess the footprint of disturbances);
- integrate data from various sources (depends on standardised, or at least comparable, methods and integrated data management systems) for reporting (see below);
- complement observational data in areas where there are no samples sites (see also Mellin et al. 2018, Supplementary Report S4);
- report against thresholds (for example, assessment of expected versus observed growth or recovery rates, (Thompson and Dolman, 2010; Osborne et al., 2017);
- to predict future ecosystem state/condition to inform decision-making, for example:
  - climate change predictions: to project scenarios of future bleaching events;
  - water quality: to simulate spatial scenarios of changing concentrations of sediments, nutrients, chlorophyll, pesticides on corals, algae and/or crown-of-thorns starfish;
  - Crown-of-thorns starfish control: to simulate realistic control scenarios;
  - reef restoration: to explore scenarios to assess the feasibility of novel techniques to assist coral recovery or adaption to future thermal stress; and
  - spatial prioritisation of management strategies.

Bozec and Mumby (2018, see Supplementary Report S7) reviewed existing models of temporal/spatial dynamics of coral communities available for the Reef, with the specific aim

[15] http://www.reefplan.qld.gov.au/measuring-success/report-cards/; http://healthyriverstoreef.org.au/report-card-results/; http://riverhealth.org.au/report_card/ehi/; http://ghhp.org.au/report-cards/2016; http://wettropicswaterways.org.au/report-card-2017/

of evaluating their strengths and weaknesses for the assessment and reporting of coral reef health for use within the RIMReP.

The desktop study of Mellin et al. (2018) also presented a specific example using a Bayesian model to integrate image-derived hard coral cover data (proportion) from multiple sources, including professional monitoring programs and citizen scientists and to assess how well the model predicts actual observations. The model is visualised via prediction maps with estimates of uncertainty produced by spatial statistical models (see www.virtualreef.org.au) – this is an example of a model-based decision resource for managers and a useful basis for the desired future RIMReP 'guidance system' (see **Figure 1**).

The Coral Reef Expert Group (CREG) also suggested that a suite of models, rather than reliance on one or few, will be more useful to support decision-making based on the data that are recommended to be collected under a future RIMReP. A multi-model approach, ranging from statistical to ecological response models, is more likely to capture different properties of the modelled system and a broader range of responses to disturbances.

While a number of models are available and fit for specific purposes (Bozec and Mumby, 2018), much more work needs to be done to produce a modelling suite for RIMReP. Specific requirements and priorities should be articulated during the RIMReP implementation phase, including the identification of potential funding sources for this essential development.

9.0 Estimate of the resources required to implement the recommended design

The resource estimate (**Table 10**) is based on known resources requirements of existing monitoring programs and has been scaled to reflect the scope and spatio-temporal design recommended by the Coral Reef Expert Group that is assumed to be immediately operational (as per Table 9).

The template captures effort from the planning to the reporting of a project to capture the complete costs of an activity. It is very important to note that these resource estimates are for each individual activity conducted independently; a combination of activities would lead to significant savings.

Resource estimates could not be fully provided for some components, such as those that rely on in-kind or data contributions from, for example, the Joint Field Management Program, the tourism industry or citizen scientists, or those that are event-driven. Costing these aspects will require more planning and discussions of scope and integration processes.

Table 10 provides a resource estimate (same principles as above) for the recommended coral reef monitoring activities to be developed or implemented of the next two to five years.

The provided resource estimates will also inform the trade-off analysis that is occurring as part of the RIMReP design process (final report not yet available at the time of writing).

As future research and development is likely to lead to further efficiencies in the recommended monitoring methods, the resourcing of regular reviews and continuous improvement activities should be explicit aspects of a future RIMReP. Such activities are not included in the provided resource estimates.

Table 8. Estimate of resources required for the recommended, immediately operational, coral reef monitoring activities

Note that estimates are for each individual activity conducted independently; a combination of activities would lead to significant savings

Monitoring activity	Indicators	Method	Frequency	Spatial scale:	Annual effort (person days)	Annual effort ship (days)	Annual operational costs ($)	Details, capital items required, etc
Broad-scale monitoring – whole-of-Reef								
Geomorphic zonation mapping	Reef size and extent of benthic habitat zones	Satellite remote sensing, and physical attributes	5-10 years	Broad scale / reef-wide	400	0	310,000	High performance computing
Medium-scale monitoring								
Manta tow surveys	Cover (corals), coral bleaching, counts and size of crown-of-thorns starfish, feeding scars on corals	Manta tow	Annual	100 reefs, additional reactive surveys by the Great Barrier Reef Marine Park Authority Field Management Program and the crown-of-thorns starfish control program	735	100 large vessel	20,000	5 trips on large vessel *6 pax, 20d reporting
Photo transects surveys: shallow reef slope	Cover (benthic groups to appropriate taxonomic resolution), rugosity/3d structure, coral bleaching	Fixed photo transects (automated image analysis with manual QAQC)	Annual	140 reefs	1792	180 large vessel, 50 medium vessel, 40 small vessel	86,000	9 trips on large vessel *4 pax, 5 trips on medium vessel *3 pax, 8 trips on small vessel *3 pax

Visual in situ assessment along transects, shallow reef slope	Number and composition of juvenile corals, coral disease prevalence, counts and size of crown-of-thorns starfish, feeding scars on coral, canopy height of algae	Visual in-situ assessment along fixed transects, direct measurements	Annual	140 reefs	1339	110 large vessel, 50 medium vessel, 40 small vessel	74,000	6 trips on large vessel *6 pax, 5 trips on medium vessel *3 pax, 8 trips on small vessel *3 pax
Visual census of reef fish, shallow reef slope	Counts and size of reef fish	Underwater visual census	Annual	120 reefs	1241	180 large vessel, 50 medium vessel	66,000	9 trips on large vessel *4 pax, 6 trips on medium vessel *4 pax
Disturbance monitoring: early warning, extent and scale								
Early warning observations by Eye on the Reef, crown-of-thorns starfish control program, the Agency Field Management Program, citizen science programs[16]	Occurrence of coral disease, crown-of-thorns starfish, other unusual observations	Various	Various	Various	40			Only costed for analysis and reporting time (20d + 20 d) as it assumes access to data collected outside the RIMReP
Coral bleaching aerial survey	Coral bleaching	Aerial survey	As required	As dictated by extent of temperature anomalies	48	12 - light aircraft	5,000	
eDNA detection of crown-of-thorns starfish	crown-of-thorns starfish DNA	eDNA analysis in water samples	Annual	Sites informed by modelling and early warning observations of population increases	145	15 - large vessel	45,000	Genetics lab or field-going analytical equipment

[16] note: these are not under direct control of RIMReP

Post-disturbance sampling	Depends on nature of disturbance, i.e. crown-of-thorns starfish outbreak, cyclone, tourism impact	Various as appropriate and ideally compatible with medium-scale data	As required depending on disturbance.	As required depending on disturbance	334	30 - large vessel	12,000	Assume annual contingency of 30d in field, 3 trips *6 pax, 20 sites; vessel size dependent on type and location of disturbance

Table 9. Estimate of resources required for the recommended coral reef monitoring activities to be developed or implemented of the next two to five years

Monitoring activity	Indicators	Method	Frequency	Spatial scale:	Annual effort (person days)	Annual effort ship (days)	Annual operational costs ($):	Details, capital items required, etc
Medium-scale monitoring								
Baseline fine scale benthic habitat mapping, shallow reef slope, crest and flat	Cover[17], rugosity/3D structure, shallow reef slope, crest and flat	Satellite remote sensing, photo transects, automated vehicle surveys, physical attributes	Initial baseline, then on a needs basis (after major changes) - assume repeat every 4 years	100 reefs	2430	200 large vessel	60,000	10 trips on large vessel (1.5d per site, 5 day steaming) *6 pax, m need access to AUV(s)
Automated vehicle surveys: deep reef slope	Cover, rugosity/3D structure, coral bleaching,	Fixed photo transects[18]	Annual	100 reefs	1590	200 large vessel	60,000	10 trips on large vessel (1.5d per site, 5 day steaming) *4 pax, need access to AUV(s)

[17] Benthic groups to appropriate taxonomic resolution
[18] Automated image analysis with manual QAQC

Automated vehicle surveys, all relevant depth on reefs with crocodile hazards	As above for deep reef slope	As above for deep reef slope	Annual	10 reefs	194	25 large vessel	60,000	1 trip on large vessel (2 d per site, 5 day steaming) *4 pax, need access to AUV(s)
Census of reef fish, deep reef slope	Counts and size of reef fish and reef-associated pelagic fish on deep reef slopes	BRUVS surveys	Annual	100 reefs	982	130 large vessel	37,000	6 trips on large vessel *3 pax, 10 BRUVS per reef, need access to Stereo BRUVS
Census of reef fish, shallow reef slope	QAs above for deep reef slope	BRUVS surveys	Annual	100 reefs	1408	130 large vessel	37,000	6 trips on large vessel *6 pax, 10 BRUVS per reef, need access to Stereo BRUVS
Reference, sentinel or testing sites[19]								
Coral demographics/physiology	Colony growth, colony survival, coral fecundity, visible recruits, biochemical or physiological responses to environmental or anthropogenic pressures	Various, dependent on indicator	Intra-annual, frequency dependent on indicator, costing assumption: 2x pa		196	40 large vessel	28,000	2 trips pa on large vessel (1 d per site, 4 d steaming) *3 pax, various laboratory analyses or field-going analytical equipment
Coral settlement assays	Number and composition of coral settlers (larval supply)	settlement tiles	Annual after spawning		196	40 large vessel	8,000	2 trips on large vessel (1 d per site, 4 d steaming) *3 pax,
Assessment of calcification	Net accretion or erosion	Calcification blocks	Biennial		70	10 large vessel pa	2,000	1 trip every 2 years, 3 pax (20 d)

[19]Number and location of sites to be determined, should include a subset of photo transect sites representative of latitudinal and cross shelf gradients. Assumption for costing: 16 sites.

Visual census of key invertebrates	Number and composition	Underwater visual census	Biennial		70	10 large vessel pa	2,000	1 trip every 2 years 3 pax (20 d)

10.0 References

Addison, P., Walshe, T., Sweatman, H., Jonker, M., MacNeil, A., Thompson, A., Logan, M. 2015, Towards an integrated monitoring program: Identifying indicators and existing monitoring programs to effectively evaluate the Long-Term Sustainability Plan, Report to the National Environmental Science Programme. Reef and Rainforest Research Centre Limited, Cairns, p. 118pp.

Althaus, F., Hill, N., Ferrari, R., Edwards, L., Przeslawski, R., Schönberg, C.H.L. 2015, A Standardised Vocabulary for Identifying Benthic Biota and Substrata from Underwater Imagery: The CATAMI Classification Scheme. PLoS ONE 10(10): e0141039.

Anthony, K.R.N. 2016, Coral Reefs Under Climate Change and Ocean Acidification: Challenges and Opportunities for Management and Policy, *Annual Review of Environment and Resources*, 41: 59-81.

Anthony, K., Dambacher, J.M., Walsh, T., Beeden, R. 2013, A framework for understanding cumulative impacts, supporting environmental decisions and informing resilience-based management of the Great Barrier Reef World Heritage Area. Great Barrier Reef Marine Park Authority, Canberra.

Anthony, K.R.N., Marshall, P.A., Abdulla, A., Beeden, R., Bergh, C., Black, R., Eakin, C.M., Game, E.T., Gooch, M., Graham, N.A.J., Green, A., Heron, S.F., van Hooidonk, R., Knowland, C., Mangubhai, S., Marshall, N., Maynard, J.A., McGinnity, P., McLeod, E., Mumby, P.J., Nyström, M., Obura, D., Oliver, J., Possingham, H.P., Pressey, R.L., Rowlands, G.P., Tamelander, J., Wachenfeld, D., Wear, S. 2015, Operationalizing resilience for adaptive coral reef management under global environmental change, *Global Change Biol.*, 21: 48-61.

Babcock, R., Bridge, T. 2018, Practical taxonomy for coral reef monitoring under the Reef 2050 Integrated Monitoring and Reporting Program. Supplementary Report S1 to Final Report of the Coral Reef Expert Group. Report provided to GBRMPA.

Berkelmans, R., Jones, A.M., Schaffelke, B. 2012, Salinity thresholds of Acropora spp. on the Great Barrier Reef, *Coral Reefs*, 31: 1103-1110.

Bongaerts P, Ridgway T, Sampayo EM, Hoegh-Guldberg O. 2010, Assessing the deep reef refugia hypothesis: Focus on Caribbean reefs, *Coral Reefs*, 29: 309-327.

Bongaerts, P., Riginos, C., Brunner, R., Englebert, N., Smith, S.R., Hoegh-Guldberg, O. 2017, Deep reefs are not universal refuges: Reseeding potential varies among coral species, *Science Advances*, 3.

Boussarie, G., Bakker, J., Wangensteen, O.S., Mariani, S., Bonnin, L., Juhel, J.-B., Kiszka, J.J., Kulbicki, M., Manel, S., Robbins, W.D., Vigliola, L., Mouillot, D. 2018, Environmental DNA illuminates the dark diversity of sharks, *Science Advances*, 4.

Bozec, Y-M., P J. Mumby. 2018, Coral reef models as assessment and reporting tools for RIMReP: a review. Supplementary Report S7 to Final Report of the Coral Reef Expert Group. Report provided to GBRMPA.Brodnicke, O.B., Bourne, D.G., Heron, S.F., Pears, R.J., Stella, J.S., Smith, H.A., Willis, B.L. 2019, Unravelling the links between heat stress, bleaching and disease: fate of tabular corals following a combined disease and bleaching event. Coral Reefs

Brown, J.A., Robertson, B.L., McDonald, T. 2015, Spatially Balanced Sampling: Application to Environmental Surveys, *Procedia Environmental Sciences*, 27: 6-9.

Browne, M., Kuhnert, P., Petersen, E., Bartley, R., Steven, A., Harch, B. 2007, Review of existing approaches used to develop integrated report card frameworks (IRCF) and their relevance to catchments draining to the Great Barrier Reef, in: (CSIRO), C.S.a.I.R.O. (Ed.). MTSRF Milestone Report Project 3.7.7, p. 62.

Burge, C.A., Eakin, C.M., Friedman, C.S., Froelich, B., Hershberger, P.K., Hofmann, E.E., Petes, L.E., Prager, K.C., Weil, E., Willis, B.L., Ford, S.E., Harvell, C.D. 2014, Climate Change Influences on Marine Infectious Diseases: Implications for Management and Society, *Annual Review of Marine Science*, 6: 249-277.

Carleton, J.H., Done, T.J. 1995, Quantitative video sampling of coral reef benthos: large-scale application, *Coral Reefs,* 14: 35-46.

Cheal, A. J., M. J. Emslie. 2018, Synopsis of current coral reef monitoring on the Great Barrier Reef. Supplementary Report S3 to Final Report of the Coral Reef Expert Group. Report provided to GBRMPA.

Cheal, A., Emslie, M., Miller, I., Sweatman, H. 2012, The distribution of herbivorous fishes on the Great Barrier Reef, *Marine Biology*, 159: 1143-1154.

Cheal, A.J., MacNeil, M.A., Emslie, M.J., Sweatman, H. 2017, The threat to coral reefs from more intense cyclones under climate change, *Global Change Biol.*, 23: 1511-1524.

Cheal, A.J., Wilson, S.K., Emslie, M.J., Dolman, A.M., Sweatman, H. 2008, Responses of reef fish communities to coral declines on the Great Barrier Reef, *Marine Ecology Progress Series*, 372: 211-223.

Commonwealth of Australia. 2015, *Reef 2050 Long-Term Sustainability Plan*. Australian Government, Canberra, Australia.

Constable, A.J., Costa, D.P., Schofield, O., Newman, L., Urban, E.R., Fulton, E.A., Melbourne-Thomas, J., Ballerini, T., Boyd, P.W., Brandt, A., de la Mare, W.K., Edwards, M., Eléaume, M., Emmerson, L., Fennel, K., Fielding, S., Griffiths, H., Gutt, J., Hindell, M.A., Hofmann, E.E., Jennings, S., La, H.S., McCurdy, A., Mitchell, B.G., Moltmann, T., Muelbert, M., Murphy, E., Press, A.J., Raymond, B., Reid, K., Reiss, C., Rice, J., Salter, I., Smith, D.C., Song, S., Southwell, C., Swadling, K.M., Van de Putte, A., Willis, Z. 2016, Developing priority variables (“ecosystem Essential Ocean Variables” — eEOVs) for observing dynamics and change in Southern Ocean ecosystems, *Journal of Marine Systems*, 161: 26-41.

Cooper, T., Gilmour, J., Fabricius, K. 2009, Bioindicators of changes in water quality on coral reefs: review and recommendations for monitoring programmes, *Coral Reefs*, 28: 589-606.

Dambacher, J.M., Hodge, K.B., Babcock, R.C., Fulton, E.A., Apte, S.C., Plagányi, É.E., Warne, M.S.J., Marshall, N.A. 2013, Models and Indicators of Key Ecological Assets in Gladstone Harbour. A report prepared for the Gladstone Healthy Harbour Partnership. CSIRO Wealth from Oceans Flagship, Hobart.

De'ath, G., Fabricius, K.E., Sweatman, H., Puotinen, M. 2012, The 27–year decline of coral cover on the Great Barrier Reef and its causes, *Proceedings of the National Academy of Sciences*, 190: 17995-17999.

Diaz-Pulido, G. 2018, Practical Taxonomy for monitoring of coral reef macroalgae under the Reef 2050 Integrated Monitoring and Reporting Program. Supplementary Report S2 to Final Report of the Coral Reef Expert Group. Report provided to GBRMPA.

Dobbie, M.J., Clifford, D. 2015, Quantifying uncertainty in environmental indices: an application to an estuarine health index, *Marine and Freshwater Research*, 66: 95-105.

Dobbie, M.J., Dail, D. 2013, Robustness and sensitivity of weighting and aggregation in constructing composite indices, *Ecological Indicators*, 29: 270-277.

Doyle, J.R., McKinnon, A.D., Uthicke, S. 2017, Quantifying larvae of the corallivorous seastar Acanthaster cf. solaris on the Great Barrier Reef using qPCR, *Marine Biology*, 164:176.

Edgar, G.J., Bates, A.E., Bird, T.J., Jones, A.H., Kininmonth, S., Stuart-Smith, R.D., Webb, T.J. 2016, New Approaches to Marine Conservation Through the Scaling Up of Ecological Data, *Annual Review of Marine Science*, 8: 435-461.

Emslie, M.J., Cheal, A.J., Johns, K.A. 2014, Retention of Habitat Complexity Minimizes Disassembly of Reef Fish Communities following Disturbance: A Large-Scale Natural Experiment, *PLoS ONE*, 9: e105384.

Emslie, M.J., Cheal, A.J., Logan, M. 2017, The distribution and abundance of reef-associated predatory fishes on the Great Barrier Reef, *Coral Reefs*, 36: 829-846.

Emslie, M.J., Cheal, A.J., MacNeil, M.A., Miller, I.R., Sweatman, H.P.A. 2018, Reef fish communities are spooked by scuba surveys and may take hours to recover, *PeerJ*, 6: e4886.

Emslie, M.J., Cheal, A.J., Sweatman, H., Delean, S. 2008, Recovery from disturbance of coral and reef fish communities on the Great Barrier Reef, Australia, *Marine Ecology Progress Series*, 371: 177-190.

Emslie, M.J., Logan, M., Ceccarelli, D.M., Cheal, A.J., Hoey, A., Miller, I., Sweatman, H. 2012, Regional-scale variation in the distribution and abundance of farming damselfishes on Australia's Great Barrier Reef, *Marine Biology*, 159: 1293-1304.

Emslie, M.J., Pratchett, M.S., Cheal, A.J., Osborne, K. 2010, Great Barrier Reef butterflyfish community structure: the role of shelf position and benthic community type, *Coral Reefs*, 29: 705-715.

Emslie, Michael J., Logan, M., Williamson, David H., Ayling, Anthony M., MacNeil, M.A., Ceccarelli, D., Cheal, Alistair J., Evans, Richard D., Johns, Kerryn A., Jonker, Michelle J., Miller, Ian R., Osborne, K., Russ, Garry R., Sweatman, Hugh P.A. 2015, Expectations and Outcomes of Reserve Network Performance following Re-zoning of the Great Barrier Reef Marine Park, *Current Biology*, 25: 983-992.

Englebert, N., Bongaerts, P., Muir, P.R., Hay, K.B., Pichon, M., Hoegh-Guldberg, O. 2017, Lower Mesophotic Coral Communities (60-125 m Depth) of the Northern Great Barrier Reef and Coral Sea, *PLoS ONE*, 12: e0170336.

Fabricius, K.E. 2011,Factors determining the resilience of coral reefs to eutrophication: a review and conceptual model., in: Dubinsky, Z., Stambler, N. (Eds.), Coral Reefs: An Ecosystem in Transition, Springer Press, pp. 493-506.

Flower, J., Ortiz, J.C., Chollett, I., Abdullah, S., Castro-Sanguino, C., Hock, K., Lam, V., Mumby, P.J. 2017, Interpreting coral reef monitoring data: A guide for improved management decisions, *Ecological Indicators*, 72: 848-869.

Foster, S.D., Hosack, G.R., Lawrence, E., Przeslawski, R., Hedge, P., Caley, M.J., Barrett, N.S., Williams, A., Li, J., Lynch, T., Dambacher, J.M., Sweatman, H.P.A., Hayes, K.R. 2017, Spatially balanced designs that incorporate legacy sites, *Methods in Ecology and Evolution*, 8: 1433-1442.

Foster, S.D., Monk, J., Lawrence, E., Hayes, K.R., Hosack, G.R., Przeslawski, R. 2018, Statistical considerations for monitoring and sampling, in: Przeslawski, R., Foster, S.E. (Eds.), Field Manuals for Marine Sampling to Monitor Australian Waters. National Environmental Science Programme (NESP), pp. pp 23-41.

Gladstone Healthy Harbour Partnership. 2017, Technical Report, Gladstone Harbour Report Card 2017, GHHP Technical Report No.4.

Glasl, B., Bourne, D.G., Frade, P.R., Webster, N.S. 2018, Establishing microbial baselines to identify indicators of coral reef health, *Microbiology Australia,* March 2018: 42-46.

Glasl, B., Bourne, D.G., Frade, P.R., Thomas, T., Schaffelke, B., Webster, N.S.J.M. 2019, Microbial indicators of environmental perturbations in coral reef ecosystems, Microbiome, 7: 94.

Glasl, B., Webster, N.S., Bourne, D.G. 2017, Microbial indicators as a diagnostic tool for assessing water quality and climate stress in coral reef ecosystems, *Marine Biology*, 164: 91.

Gonzalez-Rivero, M., C. Roelfsema, S. Lopez-Marcano, C. Castro-Sanguino, T. Bridge, R. Babcock. 2018, Novel technologies in coral reef monitoring. Supplementary Report S6 to Final Report of the Coral Reef Expert Group. Report provided to GBRMPA.

Goodman, J., Purkis, S., Phinn, S.R. 2013, *Coral Reef Remote Sensing: A Guide for Multi-level Sensing Mapping and Assessment.* Elsevier.

Graham, N.A.J., Jennings, S., MacNeil, M.A., Mouillot, D., Wilson, S.K. 2015, Predicting climate-driven regime shifts versus rebound potential in coral reefs, *Nature*, 518: 94.

Great Barrier Reef Foundation. 2017, Resilient Reefs Successfully Adapting to Climate Change. Final report December 2017. Available at https://www.barrierreef.org/uploads/Final%20report%20Resilient%20Reefs%20Successfully%20Adapting%20to%20Climate%20Change%20program.pdf

Great Barrier Reef Marine Park Authority. 2010, Water Quality Guidelines for the Great Barrier Reef Marine Park. Revised Edition 2010. Great Barrier Reef Marine Park Authority, Townsville, p. 100 p.

Great Barrier Reef Marine Park Authority. 2019, Great Barrier Reef Outlook Report 2019. Commonwealth of Australia, Townsville.

Great Barrier Reef Marine Park Authority. 2014, Great Barrier Reef Region Strategic Assessment. Commonwealth of Australia, Townsville.

Great Barrier Reef Marine Park Authority. 2017, Final report: 2016 coral bleaching event on the Great Barrier Reef. Great Barrier Reef Marine Park Authority, Townsville.

Gust, N., Choat, J.H., McCormick, M.I. 2001, Spatial variability in reef fish distribution, abundance, size and biomass-a multi-scale analysis, *Marine Ecology Progress Series*, 214: 237-251.

Hayes, K.R., Dambacher, J.M., Hosack, G.R., Bax, N.J., Dunstan, P.K., Fulton, E.A., Thompson, P.A., Hartog, J.R., Hobday, A.J., Bradford, R., Foster, S.D., Hedge, P., Smith, D.C., Marshall, C.J. 2015, Identifying indicators and essential variables for marine ecosystems, *Ecological Indicators*, 57: 409-419.

Hedge, P., Molloy, F., Sweatman, H., Hayes, K., Dambacher, J., Chandler, J., Gooch, M., Chinn, A., Bax, N., Walshe, T. 2013, An integrated monitoring framework for the Great Barrier Reef World Heritage Area. Department of the Environment, Canberra.

Herder, J.E., Valentini, A., Bellemain, E., Dejean, T., van Delft, J.J.C.W., Thomsen, P.F., Taberlet, P. 2014, Environmental DNA - a review of the possible applications for the detection of (invasive) species. Stichting RAVON, Nijmegen. Report 2013-104.

Hock, K., Wolff, N.H., Beeden, R., Hoey, J., Condie, S.A., Anthony, K.R.N., Possingham, H.P., Mumby, P.J. 2016, Controlling range expansion in habitat networks by adaptively targeting source populations, *Conservation Biology*, 30: 856-866.

Hock, K., Wolff, N.H., Condie, S.A., Anthony, K.R.N., Mumby, P.J. 2014, Connectivity networks reveal the risks of crown-of-thorns starfish outbreaks on the Great Barrier Reef, *Journal of Applied Ecology*, 51: 1188-1196.

Hoey, A.S., Bellwood, D.R. 2008, Cross-shelf variation in the role of parrotfishes on the Great Barrier Reef, *Coral Reefs*, 27: 37-47.

Hughes, T.P., Anderson, K.D., Connolly, S.R., Heron, S.F., Kerry, J.T., Lough, J.M., Baird, A.H., Baum, J.K., Berumen, M.L., Bridge, T.C., Claar, D.C., Eakin, C.M., Gilmour, J.P., Graham, N.A.J., Harrison, H., Hobbs, J.-P.A., Hoey, A.S., Hoogenboom, M., Lowe, R.J., McCulloch, M.T., Pandolfi, J.M., Pratchett, M., Schoepf, V., Torda, G., Wilson, S.K. 2018, Spatial and temporal patterns of mass bleaching of corals in the Anthropocene, *Science*, 359: 80-83.

Hughes, T.P., Barnes, M.L., Bellwood, D.R., Cinner, J.E., Cumming, G.S., Jackson, J.B.C., Kleypas, J., van de Leemput, I.A., Lough, J.M., Morrison, T.H., Palumbi, S.R., van Nes, E.H., Scheffer, M. 2017b, Coral reefs in the Anthropocene, *Nature*, 546: 82-90.

Hughes, T.P., Kerry, J.T., Álvarez-Noriega, M., Álvarez-Romero, J.G., Anderson, K.D., Baird, A.H., Babcock, R.C., Beger, M., Bellwood, D.R., Berkelmans, R., Bridge, T.C., Butler, I.R., Byrne, M., Cantin, N.E., Comeau, S., Connolly, S.R., Cumming, G.S., Dalton, S.J., Diaz-Pulido, G., Eakin, C.M., Figueira, W.F., Gilmour, J.P., Harrison, H.B., Heron, S.F., Hoey, A.S., Hobbs, J.-P.A., Hoogenboom, M.O., Kennedy, E.V., Kuo, C.-y., Lough, J.M., Lowe, R.J., Liu, G., McCulloch, M.T., Malcolm, H.A., McWilliam, M.J., Pandolfi, J.M., Pears, R.J., Pratchett, M.S., Schoepf, V., Simpson, T., Skirving, W.J., Sommer, B., Torda, G., Wachenfeld, D.R., Willis, B.L., Wilson, S.K. 2017a, Global warming and recurrent mass bleaching of corals, *Nature*, 543: 373-377.

Jackson, J.B.C., Donovan, M.K., Cramer, K.L., Lam, V.V., (editors). 2014, Status and Trends of Caribbean Coral Reefs: 1970-2012, Global Coral Reef Monitoring Network. IUCN, Gland, Switzerland.

Johns, K.A., Osborne, K.O., Logan, M. 2014, Contrasting rates of coral recovery and reassembly in coral communities on the Great Barrier Reef, *Coral Reefs*, 33: 553-563.

Kelly, R.P., Port, J.A., Yamahara, K.M., Crowder, L.B. 2014, Using Environmental DNA to Census Marine Fishes in a Large Mesocosm, *PLoS ONE*, 9: e86175.

Kennedy, E.V., Ordoñez, A., Diaz-Pulido, G. 2018, Coral bleaching in the southern inshore Great Barrier Reef: a case study from the Keppel Islands, *Marine and Freshwater Research*, 69: 191-197.

Kuhnert, P., Bartley, R., Petersen, E., Browne, M., Harch, B., Steven, A., Gibbs, M., Henderson, A., Brando, V. 2007, Conceptual and statistical framework for a water quality component of an integrated report card for the Great Barrier Reef catchments, in: CSIRO (Ed.). MTSRF Milestone Report Project 3.7.7, p. 114.

Kuhnert, P.M., Liu, Y., Henderson, B., Dambacher, J., Lawrence, E., Kroon, F. 2014, Review of the Marine Monitoring Program (MMP), Final Report for the Great Barrier Reef Marine Park Authority (GBRMPA). CSIRO, Australia.

Lamb, J.B., Wenger, A.S., Devlin, M.J., Ceccarelli, D.M., Williamson, D.H., Willis, B.L. 2016, Reserves as tools for alleviating impacts of marine disease, *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 371.

Langlois, T., Williams, J., Monk ,J., Bouchet, P., Currey, L., Goetze, J., Harasti, D., Huveneers, C., Ierodiaconou, D., Malcolm, H., Whitmore, S. 2018, Marine sampling field manual for benthic stereo BRUVS (Baited Remote Underwater Videos). In *Field Manuals for Marine Sampling to Monitor Australian Waters*, Przeslawski, R., Foster, S. (Eds). National Environmental Science Programme (NESP). pp. 82-104.

Lawrey, E., Smith, A., Lafond, G., Hammerton, M. 2019, Monitoring Site Planner - Choosing where to monitor coral reefs on the Great Barrier Reef. Supplementary Report S8 to Final Report of the Coral Reef Expert Group. Report provided to GBRMPA.

Louis, Y.D., Bhagooli, R., Kenkel, C.D., Baker, A.C., Dyall, S.D. 2017, Gene expression biomarkers of heat stress in scleractinian corals: Promises and limitations, *Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology*, 191: 63-77.

MacNeil, M.A., Mellin, C., Pratchett, M.S., Hoey, J., Anthony, K.R.N., Cheal, A.J., Miller, I., Sweatman, H., Cowan, Z.L., Taylor, S., Moon, S., Fonnesbeck, C.J. 2016, Joint estimation of crown of thorns (Acanthaster planci) densities on the Great Barrier Reef, *PeerJ*, 4: e2310.

Madin, J.S., Hoogenboom, M.O., Connolly, S.R., Darling, E.S., Falster, D.S., Huang, D., Keith, S.A., Mizerek, T., Pandolfi, J.M., Putnam, H.M, Baird, A.H. 2016, A Trait-Based Approach to Advance Coral Reef Science, *Trends in Ecology & Evolution*, 31:419-428

Mauvisseau, Q. 2017, On the way for detecting and quantifying elusive species in the sea: The Octopus vulgaris case study. *Fisheries research,* 191:41-48.

Maynard, J., van Hooidonk, R., Eakin, C.M., Puotinen, M., Garren, M., Williams, G., Heron, S.F., Lamb, J., Weil, E., Willis, B., Harvell, C.D. 2015, Projections of climate conditions that increase coral disease susceptibility and pathogen abundance and virulence, *Nature Clim. Change*, 5: 688-694.

McClanahan, T.R., Donner, S.D., Maynard, J.A., MacNeil, M.A., Graham, N.A.J., Maina, J., Baker, A.C., Alemu I, J.B., Beger, M., Campbell, S.J., Darling, E.S., Eakin, C.M., Heron, S.F., Jupiter, S.D., Lundquist, C.J., McLeod, E., Mumby, P.J., Paddack, M.J., Selig, E.R., van Woesik, R. 2012, Prioritizing Key Resilience Indicators to Support Coral Reef Management in a Changing Climate, *PLoS ONE*, 7: e42884.

Mellin, C., K.R.N. Anthony, E. Peterson, C. Ewels, M. Puotinen. 2018, Model to Inform the Design of a Reef Integrated Monitoring and Reporting Program (RIMReP). Supplementary Report S4 to Final Report of the Coral Reef Expert Group. Report provided to GBRMPA.

Mellin, C., Lurgi, M., Matthews, S., MacNeil, M.A., Caley, M.J., Bax, N., Przeslawski, R., Fordham, D.A. 2016a, Forecasting marine invasions under climate change: Biotic interactions and demographic processes matter, *Biol. Conserv.*, 204: 459-467.

Mellin, C., MacNeil, M.A., Cheal, A.J., Emslie, M.J., Caley, M.J. 2016b, Marine protected areas increase resilience among coral reef communities, *Ecology Letters*, 19: 629-637.

Miller, J., Muller, E., Rogers, C., Waara, R., Atkinson, A., Whelan, K.R.T., Patterson, M., Witcher, B. 2009, Coral disease following massive bleaching in 2005 causes 60% decline in coral cover on reefs in the US Virgin Islands, *Coral Reefs*, 28: 925.

Miloslavich, P., Bax, N.J., Simmons, S.E., Klein, E., Appeltans, W., Aburto-Oropeza, O., Andersen, G.M., Batten, S.D., Benedetti-Cecchi, L., Checkley, D.M., Chiba, S., Duffy, J.E., Dunn, D.C., Fischer, A., Gunn, J., Kudela, R., Marsac, F., Muller-Karger, F.E., Obura, D., Shin, Y.J. 2018, Essential ocean variables for global sustained observations of biodiversity and ecosystem changes, *Global Change Biol.*, 24: 2416-2433.

Mouillot, D., Graham, N.A.J., Villeger, S., Mason, N.W.H., Bellwood, D.R. 2013, A functional approach reveals community responses to disturbances, *Trends in Ecology & Evolution* 28:167-177

Muir, P., Wallace, C., Bridge, T.C.L., Bongaerts, P. 2015, Diverse Staghorn Coral Fauna on the Mesophotic Reefs of North-East Australia, *PLoS ONE*, 10: e0117933.

Mydlarz, L.D., Couch, C.S., Weil, E., Smith, G., Harvell, C.D. 2009, Immune defenses of healthy, bleached and diseased Montastraea faveolata during a natural bleaching event, *Diseases of Aquatic Organisms*, 87: 67-78.

Ortiz, J.C., Bozec, Y.-M., Wolff, N.H., Doropoulos, C., Mumby, P.J. 2014, Global disparity in the ecological benefits of reducing carbon emissions for coral reefs, *Nature Clim. Change*, 4: 1090-1094.

Osborne, K., Dolman, A.M., Burgess, S.C., Johns, K.A. 2011, Disturbance and the Dynamics of Coral Cover on the Great Barrier Reef (1995–2009), *PLoS ONE*, 6: e17516.

Osborne, K., Thompson, A.A., Cheal, A.J., Emslie, M.J., Johns, K.A., Jonker, M.J., Logan, M., Miller, I.R., Sweatman, H.P.A. 2017, Delayed coral recovery in a warming ocean, *Global Change Biol.*, 23: 3869-3881.

Pratchett, M.S., Caballes, C.F., Rivera-Posada, J.A., Sweatman, H.P.A. 2014, Limits to understanding and managing outbreaks of crown-of-thorns starfish (Acanthaster spp.), *Oceanography and Marine Biology: An Annual Review*, 52: 133-200.

Puotinen, M., Maynard, J.A., Beeden, R., Radford, B., Williams, G.J. 2016, A robust operational model for predicting where tropical cyclone waves damage coral reefs, *Scientific Reports*, 6: 26009.

Richardson, L.E., Graham, N.A.J., Pratchett, M.S., Hoey, A.S. 2017, Structural complexity mediates functional structure of reef fish assemblages among coral habitats, *Environmental Biology of Fishes* 100: 193–207.

Robson, H.L.A., Noble, T.H., Saunders, R.J., Robson, S.K.A., Burrows, D.W., Jerry, D.R. 2016, Fine-tuning for the tropics: application of eDNA technology for invasive fish detection in tropical freshwater ecosystems, *Molecular Ecology Resources*, 16: 922-932.

Roelfsema, C., Kovacs, E., Ortiz, J.C., Wolff, N.H., Callaghan, D., Wettle, M., Ronan, M., Hamylton, S.M., Mumby, P.J., Phinn, S. 2018, Coral reef habitat mapping: A combination of object-based image analysis and ecological modelling, Remote Sens. Environ., 208: 27-41.

Roth, C., Addison, J., Anthony, K., Dale, A., Eberhard, R., Hobday, A., Horner, N., Jarvis, D., Kroon, K., Stone-Jovicich, S., Walshe, T. 2017, Reef 2050 Plan Review Options, Final Report submitted to the Department of the Environment and Energy. CSIRO, Australia.

Russ, G.R. 1984, Distribution and abundance of herbivorous fishes in the central Great Barrier Reef. I. Levels of variability across the entire continental shelf, *Mar. Ecol. Progr. Ser.*, 20: 23-34.

Russ, G.R., Cheal, A.J., Dolman, A.M., Emslie, M.J., Evans, R.D., Miller, I., Sweatman, H., Williamson, D.H. 2008, Rapid increase in fish numbers follows creation of world's largest marine reserve network, *Current Biology*, 18: R514-R515.

Schaffelke, B., Collier, C., Kroon, F., Lough, J., McKenzie, L., Ronan, M., Uthicke, S., Brodie, J. 2017, Scientific Consensus Statement 2017: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef, Chapter 1: The condition of coastal and marine ecosystems of the Great Barrier Reef and their responses to water quality and disturbances. State of Queensland, Brisbane.

Shinzato, C., Y. Zayasu, M. Kanda, M. Kawamitsu, N. Satoh, H. Yamashita, Suzuki, G. 2018, Using Seawater to Document Coral-Zoothanthella Diversity: A New Approach to Coral Reef Monitoring Using Environmental DNA. *Frontiers in Marine Science,* 5:28.

Thompson, A., Costello, P., Davidson, J., Logan, M., Coleman, G., Gunn, K. 2018, Marine Monitoring Program. Annual Report for coral reef monitoring: 2016 to 2017. Report for the Great Barrier Reef Marine Park Authority. Australian Institute of Marine Science, Townsville, 148 pp.

Thompson, A., Costello, P., Davidson, J., Logan, M., Gunn, K., Schaffelke, B. 2016, Marine Monitoring Program. Annual Report for coral reef monitoring: 2014 to 2015, Report for the Great Barrier Reef Marine Park Authority. Australian Institute of Marine Science, Townsville, 133 p.

Thompson, A., Dolman, A. 2010, Coral bleaching: one disturbance too many for near-shore reefs of the Great Barrier Reef, *Coral Reefs*, 29: 637-648.

Thompson, A., P. Menendez. 2018, Statistical power of existing AIMS long-term reef monitoring programs. Supplementary Report S5 to Final Report of the Coral Reef Expert Group. Report provided to GBRMPA.

Thomsen, P. F., J. Kielgast, L. L. Iversen, P. R. Møller, M. Rasmussen, Willerslev, E.. 2012, Detection of a Diverse Marine Fish Fauna Using Environmental DNA from Seawater Samples. *PLoS ONE*, 7:e41732.

Thomsen, P. F., P. R. Møller, E. E. Sigsgaard, S. W. Knudsen, O. A. Jørgensen, E. Willerslev, E.. 2016, Environmental DNA from seawater samples correlate with trawl catches of subarctic, deepwater fishes. *PLoS ONE,* 11:e0165252.

Udy, J. 2017, Identifying management needs: Informing the program design of the Reef 2050 Integrated Monitoring and Reporting Program. Final report prepared for GBRMPA, Townsville.

Uthicke, S., Doyle, J., Duggan, S., Yasuda, N., McKinnon, A.D. 2015, Outbreak of coral-eating Crown-of-Thorns creates continuous cloud of larvae over 320 km of the Great Barrier Reef, *Scientific Reports*, 5: 16885.

Uthicke, S., Lamare, M., Doyle, J.R. 2018, eDNA detection of corallivorous seastar (*Acanthaster* cf. *solaris*) outbreaks on the Great Barrier Reef using digital droplet PCR, *Coral Reefs*, 37: 1229–1239.

Vanhatalo, J., Hosack, G.R., Sweatman, H. 2017, Spatiotemporal modelling of crown-of-thorns starfish outbreaks on the Great Barrier Reef to inform control strategies, *Journal of Applied Ecology*, 54: 188-197.

Vercelloni, J., Clifford, S., Caley, M.J., Pearse, A.R., Brown, R., James, A., Christensen, B., Bednarz, T., Anthony, K., González-Rivero, M., Mengersen, K., Peterson, E.E. 2018, Using virtual reality to estimate aesthetic values of coral reefs, *Royal Society Open Science*, 5.

Webster, N. and Gorsuch, H. 2018, RIMReP Additional Values Report: Monitoring Microbes. Report provided to GBRMPA.

Wegley Kelly, L., Haas, A.F., Nelson, C.E. 2018, Ecosystem Microbiology of Coral Reefs: Linking Genomic, Metabolomic, and Biogeochemical Dynamics from Animal Symbioses to Reefscape Processes, *mSystems*, 3.

Williams, D.M., Hatcher, A.I. 1983, Structure of Fish Communities on Outer Slopes of Inshore, Mid-Shelf and Outer Shelf Reefs of the Great Barrier Reef, *Marine Ecology Progress Series*, 10: 239-250.

Williamson, D.H., Ceccarelli, D.M., Rossetti, G., Russ, G.R., Jones, G.P. 2016, Assessing the cumulative impacts of climatic disturbances on coral reefs in the Keppel Islands, Great

Barrier Reef Marine Park, Report to the National Environmental Science Programme, Reef and Rainforest Research Centre Limited, Cairns, p. 65pp.

Willis, B.L., Page, C.A., Dinsdale, E.A. 2004,Coral Disease on the Great Barrier Reef, in: Rosenberg, E., Loya, Y. (Eds.), Coral Health and Disease. Springer, Berlin, Heidelberg.

Wilson, C., Bronnenhuber, J., Boothroyd, M., Smith, C., Wozney, K. 2014, Environmental DNA (eDNA) monitoring and surveillance: field and laboratory standard operating procedures. Ontario Ministry of Natural Resources and Forestry Aquatic Research Series 2014-05.

Wilson, S.K., Dolman, A.M., Cheal, A.J., Emslie, M.J., Pratchett, M.S., Sweatman, H.P.A. 2009, Maintenance of fish diversity on disturbed coral reefs, *Coral Reefs*, 28: 3-14.

Wolff, N.H., Mumby, P.J., Devlin, M., Anthony, K.R.N. 2018, Vulnerability of the Great Barrier Reef to climate change and local pressures, *Global Change Biol.*, 24: 1978-1991.

11.0 Appendix 1

Full table of indicators discussed and prioritized (red= high priority, blue= lower priority) during the 2nd workshop of the RIMReP Coral Reef Expert Group.

Selection criteria are related to a candidate indicator's capability to: 1. Provide tactical information for management, 2. Provide operational information for management, 3. Contribute to policy development and strategic planning, 4. Evaluate the effectiveness of management actions/responses, 5. Describe condition, trend, potential resilience and status of key processes, 6. Attribute causes of change in condition (state), 7. Contribute information across themes, 8. Ensure continuity of historical data sets and build on existing programs.

Value/Pressure/ Process	Candidate Indicator	measured ?	1	2	3	4	5	6	7	8
Hard and soft corals	Abundance/cover by genus/growth form	y								
	Number of juveniles genera	y								
	Recruitment tiles	y								
	Community growth - derived from cover	derived								
	Colony size	y								
	colony growth- sentinel colonies									
	Rugosity/3D structure	y								
	initial baseline of whole of reef size and extent	y								
	Consider ratio of tabulate Acropora vs other taxa	derived								
	Incidence of coral disease	y								
	Incidence and severity of bleaching	y								
	other mortality - part of demographic	y								
	Physiological and molecular responses	y								
Fish	Counts and size of all reef fish by species	y								
	reef associated pelagic fish	y								
	cryptic reef fish	y								
Mobile invertebrates	Counts and size of crown-of-thorns starfish, feeding scars on corals	y								
	Count of *Drupella*	y								
	Counts of key herbivores (e.g. sea urchins)	y								
	Counts of other "charismatic invertebrates" (e.g. trochus, triton, some holothurians as commercially harvested species, giant clams)	y								
	painted crays									
	population dynamics/growth, perhaps for functional groups	derived								

Macroalgae	Abundance/cover by genus/functional group	y
	Biomass	y
	Community growth rates, perhaps for functional groups	derived
	Turf heights/canopy heights	y
	Ratio CCA vs turf vs fleshy	derived
	Incidence of CLOD (coralline lethal orange disease)	y
Microbial processes	Coral disease	y
	Physiological health indicators of corals	y
Particle feeding	Community composition of particle-feeding benthos	as above
Primary production	Community composition of benthic primary producers	as above
Herbivory	Fish biomass & community composition	as above
Predation	crown-of-thorns starfish numbers, predatory fish biomass & community composition,	as above
Symbiosis	Community composition of symbiotic benthos, bleaching prevalence	as above
Competition	Benthic community composition	as above
Connectivity	Hydrodynamic connectivity models as covariate	Env mon
Recruitment	Settlement tiles	as above
	Counts of Juvenile corals	as above
Reef building	Community composition	as above
	Accretion vs erosion assessment	y
	DIC and alkalinity measurements	Env mon