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Supplementary Report to the Final Report of the Coral Reef Expert Group:

S3. Synopsis of current coral reef monitoring on the Great Barrier Reef

Cheal, A. J., Emslie, M. J.

Australian Institute of Marine Science

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 9780648589273

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

This publication should be cited as:

Cheal, A., Emslie, M.J. 2020, *Supplementary report to the final report of the coral reef expert group: S3. Synopsis of current coral reef monitoring on the Great Barrier Reef,* Great Barrier Reef Marine Park Authority, Townsville.

Front cover image: Reefscape, Shallow Reefs. © Commonwealth of Australia (GBRMPA), photographer: Chris Jones.

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

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1.0 Executive Summary

The intent of the future Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) is not to duplicate existing arrangements but to coordinate and integrate existing monitoring, modelling and reporting programs. This report presents the results of a desktop review of 15 current coral reef monitoring programs on the Great Barrier Reef (the Reef) to guide the recommendations for the design of the RIMReP coral reef monitoring. The review had three main objectives:

- Collate detailed information about the spatio-temporal design, methods, data quality and reporting processes of existing programs;
- Identify which of the candidate indicators, as identified by the RIMReP Coral Reef Expert Group, are covered in existing programs;
- Discuss potential limitations of the current programs.

Coral reef monitoring on the Reef can be broadly grouped into two approaches:

1. Structured programs carried out by university-trained scientists to gather high quality, high resolution, temporally-consistent and mostly quantitative data at fixed locations.
2. Rapid assessment programs using large numbers of observers of varying levels of training and experience, surveying larger numbers of reefs, reef zones and habitats, but often un-repeated and using quasi-quantitative (subjective estimation by an observer) rather than quantitative (counted or measured by an observer) assessments.

The logistical requirements of structured programs can limit their spatial extent (both within and among reefs). Nonetheless, current structured programs have revealed statistically valid trends of indicators of population and community structure at local, regional and Reef-wide scales due to their rigorous design and execution.

The spatially more extensive sampling of rapid assessment programs provides assessment of status at a wider variety of locations and of early warning of the impacts associated with disturbances (i.e. bleaching, and outbreaks of crown-of-thorns starfish, etc.). However, the resulting data is often of coarse taxonomic resolution and so has limited capacity to support indicators of population and community structure, unlike the higher taxonomic resolution data gathered from the structured monitoring. The robustness of temporal trend information from rapid assessment programs is limited due to haphazard sampling regimes and sampling error between multiple observers, which has not been quantified for the majority of these programs.

Ultimately, the two broadly different approaches of monitoring on the Reef should be seen as complementary, taking into consideration the limitations of each. Having both styles in an integrated Reef monitoring program should prove effective to inform management strategies in the future.

The following dot-points (in no particular order of importance) summarise further findings of the review to inform the development of the design of RIMReP:

- Deep water (>30m) surveys are notably underrepresented (only one of the 15 programs has a deep water component). Indeed, most of our knowledge from

existing monitoring programs comes from 0 to 15m depths. The following dot points reflect such shallow reef monitoring only.

- Existing monitoring programs encompassed limited (1 Natural Resource Management region) to extensive spatial scales (6 Natural Resource Management regions).
- Monitoring is limited in the Far Northern Management Area, particularly inshore.
- Monitoring frequency is highly variable among programs: regular (weekly - biennial) to haphazard.
- Most proposed candidate indicators of target organisms for RIMReP are covered to some extent by at least one existing program, but often at relatively coarse taxonomic levels.
- Most fish community indicators were measured in four out of the 15 programs, but eight had no fish component.
- Few programs monitored candidate mobile invertebrate indicators aside from the coral feeding crown-of-thorns starfish and *Drupella* snail; key herbivores (i.e. urchins) and other charismatic invertebrates (i.e. sea cucumbers, giant clams etc.) were severely underrepresented.
- No program measured the size of crown-of-thorns starfish to the cm, but crown-of-thorns starfish were recorded in size classes by most.
- 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 (i.e. genus) or provide robust indicators of their population/community structure (i.e. juvenile counts, size structure, diversity/composition etc.).
- Soft coral indicators, excepting cover and bleaching status, were relatively poorly covered among programs.
- Cover of macroalgae was measured by most programs but only five routinely identify macroalgae to genus, and none of the programs estimate macroalgal biomass and growth.
- 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.
- 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 taxonomic and spatial resolution of the data varied among programs.

2.0 Introduction

The Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) is intended to integrate existing programs, fill critical information gaps and align reporting and modelling to provide the most comprehensive and up-to-date understanding of the Great Barrier Reef, its values, the processes that support it and the pressures that affect it.

The process of designing the coral reef component of the RIMReP began with the establishment of a Coral Reef Expert Group who met for the first time in January 2017. At this scoping workshop a list of candidate indicators to monitor the condition of Reef coral reef habitats was agreed. As part of the prescribed design process, several desktop studies were carried out to guide the overall design recommendations.

This report presents the results of a desk top study commissioned to provide a synopsis of current coral reef monitoring on the Reef, addressing three main objectives:

- Collate detailed information about the spatio-temporal design, methods, data quality and reporting processes of existing programs;
- Identify which of the candidate indicators, as identified by the RIMReP Coral Reef Expert Group, are covered in existing programs;
- Discuss potential limitations of the current programs.

3.0 Methods

3.1 Selection of existing coral reef monitoring programs to review

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 also meet the following criteria:

- "Location: Monitoring occurs in the Reef World Heritage Area or neighbouring catchments.
- Current: At least one monitoring event has occurred in the last 5 years, with some indication that the monitoring will continue in the future (dependent on funding).
- Relevant to the Reef 2050 Long-Term Sustainability Plan (LTSP): The values monitored address at least one of the environmental or socio-economic values and attributes (e.g., coral reef condition), or threats identified through the LTSP.
- Publicly available: Monitoring results are publicly accessible through scientific publications, government/institutional reports, online databases, or are available upon request from data custodians."

The Addison et al. (2015) study collated information about broad design parameters (organisation, regional coverage, duration and sampling frequency), and additionally assessed whether the monitoring programs addressed the targets, objectives and threatening processes identified in the Reef 2050 Long-Term Sustainability Plan. Addison et al. (2015) identified 16 programs that specifically monitor coral reef habitats.

For the present synopsis we provide a more detailed evaluation of the design characteristics of these 16 programs, building on a more detailed inventory provided to the RIMReP Program Design working group (Addison, unpublished), containing information on, for example, temporal and spatial coverage, type of monitoring, targets monitored. For additional information we used web-based resources (program web sites, online reports and methodologies, etc.) and sought clarification directly from program representatives.

Note that the "Effects of management zoning on inshore reefs of the Great Barrier Reef Marine Park" program was divided into two separate programs by Addison et al. (2015): "Benthic condition and fish" and "Derelict fishing line on fringing reefs". Given that the derelict fishing line project is very small and specific, and that the fishing line is documented during the benthic and fish surveys (as advised by project leader David Williamson), we have merged these two programs in this synopsis.

This resulted in a total of 15 Reef coral reef monitoring programs which are listed below along with the coordinating organisation and the observer category:

1. Effects of management zoning on inshore reefs of the Great Barrier Reef Marine Park (James Cook University (JCU), university trained scientists).
2. Long-Term Monitoring Program: historical program (Australian Institute of Marine Science (AIMS), university trained scientists).
3. Long-Term Monitoring Program: effects of management zoning (AIMS, university trained scientists).
4. Eye on the Reef: rapid monitoring (Great Barrier Reef Marine Park Authority (the Authority), online trained reef visitors and traditional owners).
5. Eye on the Reef: reef health and impact surveys (the Authority, online/in-water trained individuals from varied groups that may include university trained scientists).
6. Eye on the Reef: tourism weekly monitoring surveys (the Authority and tourism industry, online/in-water trained tourism operators).
7. Reef Check (Reef Check Australia, classroom/field trained volunteers that may include university trained scientists).
8. Marine Monitoring Program: inshore (AIMS, university trained scientists).
9. Gladstone Harbour monitoring (AIMS, university trained scientists).
10. North Queensland Bulk Ports Corporation monitoring: Abbot Point, Mackay and Hay Point (AIMS and private consultants, university trained scientists).
11. Reef Life Survey (Reef Life Survey, trained recreational divers and university trained scientists).
12. Coral Watch (University of Queensland, citizen scientists).
13. Crown-of-thorns Starfish Outbreak Management Program (Reef and Rainforest Research Centre and the Authority, Association of Marine Park Tourism Operators).
14. Catlin Seaview Survey (University of Queensland (UQ), university trained scientists).
15. Recovery of theGreat Barrier Reef (Earthwatch and AIMS, university trained scientists and trained citizen scientists).

3.2 Assessment of design characteristics

3.2.1 Monitoring methods

Monitoring methods were classified as quantitative if data were obtained via counts or measurements and quasi-quantitative if estimated by an observer. We also detail the methods used to collect data and what types of data are collected.

3.2.2 Spatio-temporal extent and quality control

We assessed the spatial extent of each program in terms of their geographical spread (the number of National Resource Management regions in which surveys were conducted), the number of reef habitats surveyed and level of replication of reefs, sites and sampling units (e.g. transects or quadrats). We also estimated the aerial extent of each program in terms of the amount of reef area surveyed (m2). The temporal scope of each program was defined as both the duration and the frequency of sampling. We documented the quality control measures employed by each program in terms of training, inter-observer calibration, data entry and data checking.

3.3 Coverage of candidate indicators

Our initial approach here was to create a matrix with candidate indicators identified in the Coral Reef Expert Group workshop along the top and the 15 existing programs down the side, and populate the boxes with text describing how each indicator is currently measured. However, the candidate indicators (as tabulated in the report from the January 2017 Coral Reef Expert Group workshop and reproduced here as Table 1) first needed to be modified appropriately for our "candidate vs currently monitored matrix", as follows:

- While shallow and deep coral reef communities were both listed as necessary candidates in Table 1, data presented here is for shallow habitats only as deep habitats were only included in one of the existing 15 programs (Catlin Seaview Surveys; see Discussion for more detail on their deep-water surveys).
- To make the matrix less cumbersome we used separate Excel sheets for each of the Monitoring Objectives in Table 1 (i.e. taxonomic and functional etc.), but with one exception; candidate indicators in the objectives "Population and community dynamics" were moved into the "Population and community structure" objective for streamlining because there was some overlap and the "dynamics" (interpreted as change) of most candidate indicators (including counts/cover of organisms in the Taxonomic and functional objective groups etc.) could in theory be assessed.
- When different candidate indicators were listed within a sentence in Table 1, they were separated and listed in individual columns in the matrix. For example, "Counts of crown-of-thorns starfish and *Drupella*, size of crown-of-thorns starfish, feeding scars on coral", listed as a dot point in Table 1, is presented as four columns in the matrix (labelled: counts of crown-of-thorns starfish, counts of *Drupella* etc.)
- To retain links with Table 1, candidate indicators in the matrix are presented in order of fish communities then mobile invertebrates, hard and soft corals, and macroalgae.
- Table 1 did not identify any candidate indicators for "population and community structure" of fish communities and mobile invertebrates and the "population and

community dynamics” indicators for these organisms were vague (i.e. “derived from count and size data, e.g. to estimate growth, perhaps for functional groups”). As such, we have attempted to interpret the intent and refine this area with more specific indicators, resulting in seven fish indicators and one crown-of-thorns starfish indicator in one streamlined “Population/community structure” objective in the new matrix.

- Table 1 included giant clams as “charismatic invertebrates” in the “mobile invertebrates” objective. While this is incorrect we retained this classification in our matrix for continuity with Table 1.
- Fish length as an indicator of size was separated into two groups, “multiple spp.” and “coral trout” as coral trout were prioritised among fishes in some programs.
- We added to the assessment eight indicators that were measured in existing programs for completeness (see Table 2a)

Any indicators currently measured in existing programs, but not identified as candidates by the Coral Reef Expert Group, were also included in the matrix and identified as such. Note also that the crown-of-thorns starfish outbreak management program, while primarily focussed on starfish removal also incorporates surveys as done by the separate Eye on the Reef: Reef Health and Impact Surveys program (RHIS). So, all indicators measured by the RHIS also appear under the starfish outbreak management program in our matrix. It should also be noted that not all “environmental pressures” (one of the objectives for monitoring in Table 1) were expected to be covered by coral reef monitoring programs as many are generic to all Reef habitats (i.e. cyclone activity) and data could be sourced from other existing observation programs. However, the Coral Reef Expert Group agreed that environmental pressures will need to be considered in the design of the RIMReP, so they established different priority levels for monitoring indicators of environmental pressure: high priority (14 candidates from RIMReP or elsewhere), additional high priority (seven candidates for measurement or data provision) and non-essential (15 candidates useful for narrative and interpretation).

The initially constructed “candidate vs currently monitored matrix” identified how each program addressed candidate indicators, so providing a detailed reference source (the detailed results of this assessment have been provided to the Authority as an Excel file). To provide a more user-friendly summary of these data we colour coded each of the text-filled boxes in the original matrix into one of three categories that reflected whether monitoring of each indicator is covered, partially covered or not covered at all in each program; this summary being displayed in two tables for ease of interpretation, one for specific target groups of organisms (Table 2a) and the other for the target environmental pressures (Table 2b). The assessment of “covered” or “partially covered” was necessarily subjective but was based around specific criteria (Table 2c). In some cases, the candidate indicator would need to be calculated after processing and checking of field data (i.e. community structure/composition, fish biomass, fish community functional diversity, etc.). For these types of indicators, we rate them as covered by a program if data is currently gathered that allows their calculation, either at higher (covered) or lower (partially covered) levels, even if the measure in question is not currently used/calculated by that program. Some programs use imagery to characterise the benthos (i.e. from quadrats, transects etc.) so reinterrogation of those images could allow categorization of more/different benthic variables of better taxonomic resolution. But this possibility was not incorporated into our final summary tables; we stuck with what is currently recorded by each program and how those data could be applied to inform more advanced indicators (i.e. fish length and count data can be used to calculate a biomass indicator) to avoid getting drawn into speculation on the level of further interrogation possible in each program, particularly given that the quality of images may vary among programs.

Overall, the colour coded summary tables provide a convenient guide to who is monitoring what, how comprehensively each indicator is covered in simple terms and to key knowledge gaps.

3.4 Reporting

For each program we tabulated how its findings are reported and what is reported.

3.5 Feedback from representatives of Great Barrier Reef monitoring programs

Once we had populated all tables summarising the monitoring methods, spatio-temporal extent, quality control and indicators used by each Reef coral reef monitoring program we forwarded these tables to relevant staff from each program, requesting feedback to ensure that we had not inadvertently misrepresented their program. Staff from all programs have responded and their comments have been incorporated in our results.

4.0 Results

4.1 Assessment of design characteristics

Comments in this section all relate to Table 3. Five programs conducted monitoring in all six National Resource Management regions (Eye on the Reef Rapid Monitoring, Eye on the Reef RHIS, AIMS Long-Term Monitoring Program: historical, Reef Life Survey and Coral Watch).

The Eye on the Reef Rapid Monitoring program, while represented in all six Natural Resource Management regions, surveys a variable number of reefs each year in three positions across the continental shelf, and multiple zones and habitats within individual reefs. It uses quasi-quantitative point count estimates of benthic cover and timed swims to record the abundance of some iconic fish species. It doesn't use permanent sites and relies on large numbers of trained volunteers but has few quality control measures in place.

Similarly, the Eye on the Reef Reef Health Impact Survey (RHIS) program has good spatial coverage, and although the sampling intensity varies annually, it visited more than 200 reefs spread across all shelf positions in 2016. It has been running since 2009 and while surveys are conducted annually, it was designed as a rapid response to assess reef condition in the wake of acute disturbance events, meaning that surveys tend to be haphazard and sites may or may not be revisited each year. Historically, sites were not permanently marked although a GPS mark was taken. There is now a subset of sites that are associated with the crown-of-thorns starfish control program that are permanently marked. Quasi-quantitative estimates of per cent cover of broad benthic categories and quantitative counts of mobile invertebrates and agents of coral mortality are collected by large numbers of observers from government agencies and the tourism industry, who undergo brief online and in-water training. There is limited quality control with few observer comparisons, circle radius calibration, and some checking of databases against original hard copies.

The AIMS Long-Term Monitoring Program: historical program monitors reef condition and how it changes through time, in a systematic way on fixed survey sites in a standard reef slope habitat on 46 reefs, and is the longest running monitoring program, spanning two and a half decades. The use of fixed sites in a standard habitat allows valid spatial and temporal comparisons to be made. Until 2004, surveys were conducted annually and then biennially thereafter. It collects quantitative data on the abundance, diversity, length and biomass of fishes and per cent cover of benthic assemblages at high taxonomic resolution (species for fish and genus for corals). It also quantifies several important agents of coral mortality such as disease and bleaching, crown-of-thorns starfish and *Drupella*. The manta tow component of the program collects quasi-quantitative data on per cent cover of hard and soft corals as well as the extent of bleaching, and quantitative counts of crown-of-thorns starfish, coral trout and sharks. The manta tow component is the longest running monitoring program on the Reef, commencing in 1985 and in 2017 covered the largest area. The Long-Term Monitoring Program utilises very few highly experienced observers who all received tertiary training in marine ecology, and employs stringent quality control measures including permanently marked sites, standard operating procedures, annual training, observer comparisons and calibration (fish lengths, transect widths, image, taxonomic), and database error checking.

Reef Life Survey has been running since 2007 and in 2016 visited 153 inshore, mid-shelf and outer-shelf reefs throughout the Reef. Surveys are conducted in all Reef zones and multiple habitats and collect quantitative data on the abundance, length and biomass of all fish species (including cryptic and pelagic species), as well as per cent cover of hard coral growth forms and abundance of mobile invertebrates. Surveys are conducted haphazardly on sites marked by GPS and rely on trained volunteers that may or may not have tertiary training. There is no systematic sampling design and the number of sites visited varies annually. Instead, the program relies on surveys being conducted in locations where ever volunteers happen to visit, which may or may not have been surveyed previously. Reef Life Surveys rely on a multitude of volunteers who undergo two weeks training before being allowed to participate. The program has rigorous quality control measures including GPS marked sites, training of volunteers by university staff, data entry error checking algorithm and observer comparisons.

The final program that surveys all six Natural Resource Management regions is Coral Watch, which relies on untrained volunteers to quantify bleaching levels in corals. The project surveys variable numbers of reefs and sites each year, and in 2016 received reports from 81 reefs from the inshore, mid-shelf and outer-shelf of the Reef. Surveys are conducted in a variety of Reef zones and habitats and collect qualitative data on coral health of four broad growth forms measured by comparison to a colour chart. We were unable to verify the project's quality control measures at the time of writing.

The AIMS Long-Term Monitoring Program: effects of management zoning program surveys reefs in five Natural Resource Management regions, with no surveys being conducted in the remote far north of the Reef. Surveys are conducted on paired reefs, one open to fishing and the other closed to fishing, to examine the effectiveness of the 2004 re-zoning of the Great Barrier Reef Marine Park (the Marine Park). It collects quantitative data on the abundance, diversity, length and biomass of fishes and per cent cover of benthic assemblages at high taxonomic resolution (species for fish and genus for corals). It also quantifies several important agents of coral mortality such as disease and bleaching, crown-of-thorns starfish and *Drupella*. The manta tow component of the program collects quasi-quantitative data on per cent cover of hard and soft corals as well as the extent of bleaching, and quantitative counts of crown-of-thorns starfish, coral trout and sharks. The Long-Term Monitoring Program utilises very few, highly experienced observers who all received tertiary training in marine ecology and employs stringent quality controls measures including permanently marked sites, standard operating procedures, annual training, observer comparisons and calibration (fish lengths, transect widths, image, taxonomic), and database error checking.

Five other programs are more limited in spatial extent, monitoring reefs in three or four Natural Resource Management regions, and include the Inshore Zoning Effects program, Eye on the Reef: tourism weekly, Reef Check, Marine Monitoring Program, and the Catlin Seaview Survey program. Programs such as the Inshore Zoning Effects program run by JCU and the Marine Monitoring Program run by AIMS, fill a valuable niche detailing reef health on inshore reefs from the Wet Tropics to the Fitzroy Natural Resource Management. The Inshore Zoning Effects program has been running since 1999 and documents the status and trends in fish and benthic assemblages on the fringing reefs of three inshore island groups. It collects quantitative data on the abundance, diversity, length and biomass of fish species and the per cent cover of coral growth forms plus the incidence of coral disease and abundance of derelict fishing line. The inshore program has stringent quality control measures in place including using few very experienced observers who have all had university training, GPS marked permanent sites, regular observer comparisons, regular fish length calibration and checking computer-entered data against original data sheets.

The AIMS Marine Monitoring Program samples inshore reefs in four Natural Resource Management regions and has been running since 2005. It collects no information on reef fishes, instead focusing on the impacts of water quality on benthic communities on reefs close to the coast. The program collects quantitative data on the per cent cover of coral genera, coral disease incidence, coral recruit and juvenile abundance, and water quality. The program uses permanent transects marked with metal stakes and fixed with a GPS mark, and very few highly experienced, tertiary educated observers. The program employs stringent quality control measures including observer image comparisons, taxonomic comparisons, use of an SQL database and comparing databased records against original datasheets.

Reef Check relies on volunteers who are trained in its methods before being allowed to undertake surveys. Volunteers may or may not have university training, and they undergo moderate levels of classroom and in-water training in identification and methodology. Reef Check has been running since 1998 and in 2016 conducted surveys on 17 inshore, mid-shelf and outer-shelf reefs in four Natural Resource Management regions. Surveys were conducted at 44 GPS-marked sites, across multiple habitats and zones within individual reefs. Reef Check collects quantitative data on the abundance of some fish families and iconic species (e.g. Maori Wrasse), as well as the per cent cover of hard coral growth forms, incidence of coral disease, numbers of crown-of-thorns starfish, per cent of corals bleached and the presence of rubbish and derelict fishing line. They employ fairly rigorous quality control measures including standardised site selection, grouping similar species to avoid misidentification, field data verification and raw data revision.

Catlin Seaview Survey is part of a unique global study to monitor change on coral reefs, but also communicates its findings to the general public through innovative use of technology. Biennial surveys began in 2012 and in 2016, the program visited 27 outer-shelf reefs from four Natural Resource Management regions. Video footage is taken along a two kilometre transect on the reef slope at each site in numerous reef zones, with a subset of images covering $1800m^2$ per site analysed to produce quantitative estimates of the cover of coral families and growth forms. The program uses automatic image analysis based on deep neural networks, which can process images three orders of magnitude faster than manual analysis. The program also produces presence/absence of mobile invertebrates, such as crown-of-thorns starfish, but is presently unable to provide any information on reef fishes. Additionally, the footage can be stitched together to provide three-dimensional virtual dives in which the observer can be immersed, and is invaluable to raising awareness of the threats to coral reefs. The program uses rigorous quality control methods including the use of few university-trained observers, GPS-marked sites and extensive validation of automated analysis against human observers.

The most temporally frequent monitoring program on the Reef is the Eye on the Reef: tourism weekly program which, as the name suggests, uses staff from tourism operators to monitor reef health on their patch every week. The program was initiated in 2007 and in 2016 received surveys from 30 tourism sites on 24 inner, mid, and outer-shelf reefs spread across three Natural Resource Management regions. Surveys are conducted in numerous zones and habitats within individual reefs. They are performed by tourism staff that have undergone moderate training (nine online modules), four two-hour workshops per year, and a day’s in-water training. Observers use timed swims to count some iconic animals such as turtles, sea snakes, some fishes (e.g. coral trout, maori wrasse, sharks, herbivores) and invertebrates. They also get quasi-quantitative estimates of macroalgae (canopy height and abundance categories), plus the amount of different coral growth forms affected by disease, bleaching, physical damage, crown-of-thorns starfish and *Drupella*.

The remaining four programs, Gladstone Harbour, North Queensland Bulk Ports, crown-of-thorns starfish outbreak management and Earthwatch Recovery of the Great Barrier Reef, are all limited in spatial extent and very much focused on specific issues, rather than the monitoring of general status and trends of Reef coral reefs. The Gladstone Harbour and North Queensland Bulk Ports programs use the same or similar techniques and collect the same data as the AIMS Marine Monitoring Program and are conducted by university trained scientists but are limited to very specific areas of the Reef associated with ports and harbours. The crown-of-thorns starfish outbreak management program is not a monitoring program *per se*, but looks to reduce number of crown-of-thorns starfish on mainly mid-shelf reefs in two Natural Resource Management regions, the tourism hotspot between Port Douglas and Townsville. While much of their effort is focused on starfish removal, they also conduct RHIS surveys on permanently marked sites, thereby providing quasi-quantitative assessments of per cent cover of broad hard and soft coral growth forms, and algae. The program also uses manta tow, but more as a tool to identify areas of high crown-of-thorns starfish density for targeted removal, rather than systematically attempting to estimate hard coral cover around the entire reef perimeter. Earthwatch Recovery of the Great Barrier Reef is limited to two inshore fringing reefs in one Natural Resource Management region and has conducted biannual surveys since 2012. The program uses university trained staff to train volunteers and collects information on per cent cover, colony density and size of hard coral growth forms in four size classes, plus quantifies the abundance of juvenile corals.

With the exception of the Inshore Zoning Effects, AIMS Marine Monitoring Program and both Long-Term Monitoring Program programs, it is worth noting that very few programs systematically return to the same sites on an annual basis. The replication of sampling units within a given site is highly variable among programs; ranging from one to two 50 x 5m transect (Reef Life Survey fishes) to 5x50m transects (Long-Term Monitoring Program) and one 2km transect (Catlin Seaview Survey). The reef habitats in which surveys are conducted are also highly variable, from a standardised reef slope habitat on the north-east flank (Long-Term Monitoring Program) to any reef habitat dependent on conditions (RHIS). Few programs estimate reef-wide metrics, apart from the manta tow component of the Long-Term Monitoring Program.

4.2 Coverage of candidate indicators

Below we highlight key findings relating to coverage of RIMReP candidate indicators among the 15 Reef coral reef monitoring programs. In this section all comments on organisms relate to Table 2a, on environmental pressures relate to Table 2b, and Table 2c aids interpretation of both.

4.2.1 Organisms

We assessed the existing 15 monitoring programs against 71 indicators for monitoring of coral reef organisms. All but seven of these indicators are covered or partially covered by at least one existing monitoring program. The seven exceptions are: agents of health and disease for fish and for mobile invertebrates, count and size of adult soft coral colonies, coral recruitment to settlement tiles, incidences of physiological/molecular response by hard corals and by soft corals and direct collections of macroalgae (vs estimates of cover/height).

Of the four groups of target organisms identified by the Coral Reef Expert Group, fish communities were least comprehensively monitored among the 15 programs, with over half having no fish component. The Reef Life Survey Program covered all candidate indicators (except for agents of fish health and disease, but that was not monitored by any program). The two Long-Term Monitoring Program programs covered the majority of indicators except for counts of cryptic and pelagic fish species, and rays, while the Inshore Zoning Effects Program covered over half the indicators and partially covered the rest.

Counts of two mobile invertebrates of particular interest due to their role as coral predators, crown-of-thorns starfish and *Drupella* snails, were covered by the majority of programs, with most also covering counts of their feeding scars. While the size of crown-of-thorns starfish was partially covered by many programs through estimates of diameter binned into size classes, crown-of-thorns starfish were not recorded to the centimetre in any program, meaning that these programs only provide a basic assessment of crown-of-thorns starfish population size structure. Counts of mobile invertebrates other than crown-of-thorns starfish and *Drupella* were not well represented among the 15 programs. Counts of key invertebrate herbivores, particularly urchins, were only covered by two programs, Reef Check and Reef Life Survey. Similarly, “other charismatic invertebrates” were only covered by these two programs and one other (Eye on the Reef: tourism weekly) and partially covered by two others.

The cover of hard and soft corals was monitored by most programs as was the growth form category of hard corals. Identification of corals to higher taxonomic resolution was limited among programs. Only five programs (those coordinated by the AIMS Long-Term Monitoring Program and Marine Monitoring Program teams) identified all hard corals to genus level (when possible) and four other programs routinely identified a few select genera (i.e. they partially covered this indicator). Only three programs (all coordinated by the AIMS Marine Monitoring Program) identified all soft corals to genus level (when possible) but two others (run by the AIMS Long-Term Monitoring Program) also did this for a select subset of soft corals. Soft coral growth forms were only monitored (partially) by one program. Only one program (Eye on the Reef: Rapid Monitoring) did not differentiate between hard and soft coral cover, instead estimating the cover of “live coral”. Indicators of hard and soft coral population/community structure were more sparsely distributed among programs, with the ability to calculate an indicator of hard coral community diversity/composition being most common; the five AIMS-led programs cover this indicator at the genus level (and were also the only programs to cover or partially cover soft coral community diversity/composition) while others only partially cover it (at the growth form level only). Only six programs, the same five AIMS programs and the Recovery of the Great Barrier Reef program (at Orpheus Island) specifically count juvenile hard corals and their sizes are either not recorded, binned into a few size categories or, in the Recovery of the Great Barrier Reef program, are actually measured in mapped quadrats. This mapping also allows counts and sizes of individual adult hard coral colonies to be measured: no other program specifically measures the size of adult hard coral colonies or allows this indicator to be easily post-processed. The three AIMS Marine Monitoring Program programs are the only ones that count and size juvenile soft corals. Only four programs currently monitor habitat complexity (the Inshore Zoning Effects program, the two AIMS Long-Term Monitoring Program programs and the Catlin Seaview Survey program). Incidences of disease, bleaching (along with a severity assessment) and recent death/partial mortality of hard corals are currently covered by the majority of monitoring programs. The same three indicators are not covered so comprehensively among programs for soft corals; while their bleaching is covered relatively well, their disease and mortality is covered by less than half the programs.

The per cent cover of macroalgae was estimated in most programs but one (Eye on the Reef: Tourism Weekly) used subjective categories instead (i.e. “bits and pieces”, “large patches” etc.). Five programs, all coordinated by the AIMS Long-Term Monitoring Program or Marine Monitoring Program, identified all macroalgae to genus level (when possible), allowing them to provide the most refined estimates of macroalgal community composition; other programs are more limited to estimates of composition at lower levels (i.e. family or growth form). Only in two programs (Eye on the Reef: RHIS and the RHIS component of the Crown-of-thorns starfish Outbreak Management Program) is there some potential for basic measurements of biomass and community growth rates of macroalgae based on their height (estimated in length classes by the RHIS). More than 50per cent of the programs could provide ratios of CCA (crustose coralline algae) vs Turf vs Fleshy macroalgae. Four programs monitor macroalgal functional groups (as noted from literature or as advised by program staff), although some other programs measure the same variables (or record data that could be adapted) but do not specifically ascribe them as functional groups (i.e. the Marine Monitoring Program, Gladstone Harbour program and the North Queensland Bulk Ports program). The five AIMS-coordinated programs were the only ones to record Coralline Lethal Orange Disease.

Other indicators, not identified as candidates in Table 1, included the cover of other benthic organisms (sponges, ascidians etc.), even though this indicator is currently covered by >50per cent of the programs. The proportion of coral cover affected by crown-of-thorns starfish and *Drupella* was also covered by five programs. Other indicators not initially identified as candidates were counts of turtles, records of spawning/mating of any organism, and of maturity phases of parrotfishes or wrasse, incidences of clam disease, occurrences of sponge overgrowth or sediment smothering and core samples for microbial analyses. Most of these were sparsely covered among the programs, although six programs did cover an indicator of sponge overgrowth or sediment smothering.

4.2.2 Environmental pressures

There were 36 indicators of environmental pressures identified by the Coral Reef Expert Group and we added one extra, “discarded fishing line”, that was specifically targeted by a number of programs (so we were reluctant to lump it into the “marine debris” pressure), resulting in a total of 37 pressures (Table 2b). Only 13 of these pressures were covered or partially covered by existing Reef coral reef monitoring programs. Two high priority indicators, “Outbreaks of crown-of-thorns starfish” and “outbreaks of disease”, were best covered, with most programs monitoring these pressures. Numerous programs could also catch an “outbreak or bloom of species other than crown-of-thorns starfish” because a range of species with potential to outbreak or bloom are routinely monitored (e.g. *Drupella*, sponges, macroalgae, etc.). Similarly, most programs could also catch obvious invasions of “exotic species and diseases” at some level. Accumulation of marine debris, and discarded fishing line in particular, were monitored by six programs. Sea temperature is measured by many programs, so contributing to the high priority monitoring of “sea temperature increase”, but only those five AIMS-led programs that deploy electronic temperature loggers monitor this pressure continuously. “Damage to reef” structure, another high priority indicator, was partially covered by most programs through records of coral damage and/or habitat complexity. We interpreted an "Extraction" pressure to mean that any associated indicator must specifically involve quantification of removal by human harvesting (i.e. by spearfishing, general fishing etc.). Programs that measured changes in abundance of harvested species, but did not quantify actual extraction rates were not included. Under these criteria, no programs covered any of the seven “extraction” pressures.

4.3 Reporting

All monitoring programs report at some level (Table 4), utilising at least one online website or data repository, piece of grey literature (reports to funding bodies, government agencies) and scientific peer-reviewed journal, although the quality and quantity varies. The two AIMS Long-Term Monitoring Program programs have a strong online presence and report at numerous spatial scales (e.g. reef, sector, regional and Reef-wide). Additionally, the Long-Term Monitoring Program provides survey updates to the Authority usually within two weeks of the completion of a survey cruise, with more detailed information posted to the website upon completion of image analysis and data checking. The Long-Term Monitoring Program also provides annual reports to funding bodies (National Environmental Science Program, NESP) and to date there have been over 100 peer-reviewed manuscripts arising from these data. Similarly, the Reef Life Survey reports via a web portal where data are freely available, as well as annual reports, and has produced 25 peer-reviewed manuscripts to date. Eye on the Reef and Reef Check programs have an online reporting process, produce annual reports, and some data (e.g. RHIS and Reef Check benthic) has been published in peer-reviewed journals. Other programs like the Marine Monitoring Program have limited online reporting, where annual reports can be accessed and non-interactive data summaries reside. The Marine Monitoring Program and North Queensland Bulk Ports programs report mainly through annual reports and their data feeds into the Reef Report Cards for each Catchment Area of the Great Barrier Reef. Additionally, Marine Monitoring Program data has been used in a few peer-reviewed journals. The JCU Inshore Monitoring Program has no online reporting, and instead produces reports for funding bodies (e.g. National Environmental Science Program, the Authority) and the data has contributed to 28 peer-reviewed publications since 2004. Catlin Seaview Surveys report via an online portal where benthic data are available in an interactive format, although at the time of writing it was not apparent how long it takes for the images to be processed and data uploaded to the website. The program also provides imagery in the form of virtual transects, where users can 'swim' the transect using a computer. Such tools are excellent in terms of outreach to the general public, managers and politicians and are excellent at raising awareness of coral reefs. The program has also produced a handful of peer-reviewed manuscripts. Reef Check utilises online reporting where data summaries are publically available, as well as annual reports and to date has used in a handful of peer-reviewed manuscripts. Coral Watch has produced a handful of peer-reviewed manuscripts and has an online reporting process where data can be viewed and downloaded. The Recovery of the Great Barrier Reef – Earthwatch program has limited reporting available through the Earthwatch website and to date has one published peer-reviewed manuscript.

5.0 Discussion

Our main objective in this report was to provide an informed assessment of the utility of existing Reef coral reef monitoring programs for the RIMReP in relation to generally desirable features of monitoring programs that best inform status and trend (i.e. spatially and temporally extensive, high quality data etc.) and in relation to the candidate indicators identified by the Coral Reef Expert Group. It is important to note here that while monitoring of an indicator may be "covered" by a number of programs, this does not necessarily reflect an equal utility for management or scientific purposes among those programs. Assessment of the true utility of current programs for RIMReP requires careful consideration of a range of other factors, including the program's methodology, spatio-temporal extent and data quality (related to sampling methodology, skill level of data collectors, quality control procedures, etc.). Here, we use all such information (collated during this study) to assess the limitations of current Reef coral reef monitoring programs for the RIMReP, identifying key gaps. Gaps might be spatial (i.e. where an indicator is not measured), temporal (i.e. when indicators are not measured with sufficient frequency to maintain adequate knowledge of condition) or, in some cases, indicators might not be measured at all.

5.1 Assessment of design characteristics

In assessing these aspects of each monitoring program, it was apparent that some programs have extensive spatial coverage, but their objective was not necessarily to monitor the status and trends in health of the Reef in a systematic way. For example, the Eye on the Reef Reef Health Impact Surveys (RHIS) covers a large part of the Reef with over 5000 surveys conducted since its inception. However, it was designed as a rapid response to provide a snapshot of reef health with a haphazard/opportunistic sampling design where reefs are not necessarily revisited on a regular basis. Coupled with a large number of observers and the use of quasi-quantitative estimates of per cent cover, this means that any examination of temporal changes using the current methodology should be viewed with caution and must consider how large the observer and spatial errors are compared to estimates of change through time. The use of large numbers of observers with various levels of experience also means that inter-observer calibration should form an integral part of any quality control procedures to gauge the level of variability on estimates gained by multiple observers. Ideally, estimates of per cent cover produced by RHIS observers should be compared against quantitative estimates of cover produced by Photo Point Intercept (PPI) or Line Intercept Transects (LIT). RHIS surveys only focus on the status of the benthic assemblages and will provide a reasonable snapshot of broad taxonomic groupings of corals, algae and agents of mortality, however they do not provide any information on fishes. The results of the RHIS program are disseminated through departmental and government reports and some online portals. To date, the program has produced some peer-reviewed manuscripts (e.g. Beeden et al 2014; Beeden et al 2015). The other Eye on the Reef program with extensive spatial coverage is the Rapid Monitoring program, which also collects survey data from all Natural Resource Management regions. While observers in this program undergo online and in-water training, the number of observers is high with experience varying greatly. There appears to be limited inter-observer calibration and this, coupled with the use of quasi-quantitative estimates, means any spatio-temporal trends must be treated with caution.

Reef Life Survey has extensive spatial coverage and collects quantitative data on both reef fish and benthic assemblages. The use of citizen science means information is not collected in any systematic way as surveys are conducted wherever the observer happens to be. Resolving temporal trends means coalescing information from multiple observers with differing levels of experience, and from a collection of sites that are visited haphazardly. It is questionable whether all observers can accurately identify fishes to species, especially cryptic species which are notoriously difficult to identify by even very experienced observers. The program appears to have very limited within site replication, mostly using one to two 50m transects at each site, and so the level of spatial resolution of inference is necessarily broad, and any attempt to look at finer-scale trends (e.g. within a reef) must be treated with caution. On the positive side of things, RLS has very broad spatial coverage, rigorous training and quality control measures and should produce good estimates of the status and trends of fish and benthic assemblages at coarse spatial scales.

The AIMS Long-Term Monitoring Program: historical and Long-Term Monitoring Program: zoning effects programs also have extensive spatial coverage. The Long-Term Monitoring Program historical is one of the few programs that had monitoring the status and trends of Reef coral reef communities as a stated objective, and the design reflects this. The zoning effects program was specifically designed to examine the effects of management zoning on fish and benthic assemblages, but as it used the same methodology and similar sampling design, can dovetail easily with the historical program to examine status and trends more broadly. In both programs, reefs are surveyed systematically on fixed, permanent sites using standard operating procedures and produces quantitative data of high taxonomic resolution for both fishes and the benthos, although the programmes survey a restricted pool of diurnally active, large mobile fishes. Very few, highly experienced observers have been used, meaning temporal trends are unlikely to be conflated with observer error. There are limitations to the program; aside from manta tow, surveys are restricted to one standard habitat on the north east flank of each reef, meaning inferences about trends can only be made about that habitat. However, this design means that the program can make valid spatio-temporal comparisons among reefs in different areas of the Reef. Aside from quasi-quantitative manta tow surveys, the program has little information from the far northern Reef, as permanent sites do not extend north of the reefs around Lizard Island (~15oS). While manta tow surveys produce quasi-quantitative estimates of hard coral cover, it uses very few highly experienced observers who undergo regular inter-observer calibration. These data match well with trends produced by quantitative techniques from the permanent sites, and have been used in a number of high impact publications detailing the status and trends in hard coral cover across the Reef. The Long-Term Monitoring Program also has a very strong online presence with information updated shortly after the completion of each survey trip, meaning relevant information on any changes in reef health is disseminated rapidly to managers.

The final program with extensive spatial coverage, Coral Watch, has a defined purpose examining the occurrence and severity of coral bleaching. It does not collect quantitative data on per cent cover of benthic taxa, or abundance and diversity of fishes, but uses untrained volunteers to assess the level of bleaching in coral colonies against a standard colour chart. While this information is no doubt very useful for checking the health of coral colonies across a large area of the Reef, its utility as a monitoring program *per se* appears limited. However, the information gained from this program is valuable as an early warning tool and likely to be useful from an integrated monitoring perspective.

Over half of the existing coral reef monitoring programs are much more limited in the spatial extent and have been designed for specific purposes. For example, the North Queensland Bulk Ports and Gladstone Harbour monitoring programs were designed specifically to examine the status and trends in coral reef heath of inshore reefs in close proximity to specific harbours. While these programs are necessarily limited spatially, they have robust methods that produce quantitative information on the status of benthic communities at fine taxonomic resolution at these locations. However, they include no information on fish assemblages and have only been running since 2015, so any inferences on changes through time is necessarily limited. Similarly, the Earthwatch Recovery of the Great Barrier Reef program monitors adult, and juvenile assemblages of hard corals and algae at one island group in the central Reef. Again, while they utilise robust methods, the biannual and spatially limited sampling design means that inferences on broad scale spatio-temporal patterns would be very restricted, although the demographic information of corals produced by this program is very useful and could possibly be incorporated under RIMReP. Reef Check relies on trained volunteers but does not utilise a systematic sampling design except in very few core locations. The data produced quickly becomes publicly available through their online reporting facility, however a robust assessment of the data in terms of the amount of noise versus trend and consistency in use of variables across sites and through time is needed. Similarly, extensive inter-observer comparisons and calibrations are needed to quantify the level of observer error in the data, due to the large numbers of observers used by the program.

The Marine Monitoring Program and JCU Inshore Zoning Effects programs have a moderate spatial extent, but fill a much needed niche in that they are dedicated to monitoring status and trends of inshore reef communities, which is a much underrepresented area of the Reef. The Marine Monitoring Program has utilised robust methods on permanently marked sites since 2005 to quantify the per cent cover of the benthos at fine taxonomic resolution. Additionally, it also captures useful information on the distribution and abundance of juvenile corals and water quality parameters, in a bid to assess the status of the health of inshore reefs along a water quality gradient. The coupling of biological and physical information can be particularly useful for linking water quality to coral reef health, and few other monitoring programs on the Reef capture this information. However, the Marine Monitoring Program does not collect information on fishes, although this knowledge gap is partially filled by the JCU Inshore Zoning Program, which overlaps with the Marine Monitoring Program in a number of island groups. The JCU Inshore program has collected quantitative information on reef fishes and broad benthic categories on GPS marked sites since 1999, representing the longest running monitoring program on inshore fringing reefs of the Reef. Both programs use robust methods and few, highly experienced observers with university training, and employs rigorous quality control measures, meaning the information provided by these programs is of high quality and disseminates reliable estimates of the status and trends of the health of inshore reefs through a large number of unpublished reports and peer-reviewed articles. However, without a strong online reporting process, the circulation of this information necessarily takes some time.

The Catlin Seaview Surveys differs from most contemporary monitoring programs by its use of technology, especially image recognition algorithms, by which it quantifies the per cent cover of hard coral. This enables estimates of coral cover to be produced much more rapidly than manual analysis currently employed by programs using PPI. However, it is an emerging technology and while the taxonomic resolution remains coarse today, rapid improvements are expected in the coming years. There are a lot of positive aspects to this program. It is spatially extensive at a number of scales, it captures three-dimensional digital footage providing a permanent record of reef status, it provides quantitative data on benthic coverage in the remote far northern Reef, which is underrepresented in contemporary monitoring programs. However, the program also has a number of limitations including logistical difficulties involved with launching and retrieving the cumbersome hardware, the coarse taxonomic resolution in estimates of per cent cover of the benthic community, no fish data, and is currently spatially restricted to mid-and-outer-shelf reefs. One of the benefits of this program was its ability to raise awareness of coral reefs with the general public, by creating 'virtual dives' through its web portal. Here, users can immerse themselves on a reef without getting wet, as the program captures imagery which can be stitched together into three-dimensional footage, which users can interact with on their computers using virtual reality goggles. The use of such imagery for creating public awareness of coral reefs cannot be understated.

Eye on the Reef: tourism weekly provides fine temporal resolution of reef health at a number of tourism locations, however it uses coarse taxonomic metrics. As such, this program should provide early warnings of any impacts and degradation to the local patches around regularly visited tourism locations. If consistency in observer error could be ascertained it would also offer the ability to detect rapid or subtle change at the tourism sites, which may signify risks for other reef areas. The real utility of this program, however, is the engagement of enthusiastic citizen scientists who visit the sites regularly and undertake these observations on top of the normal duties conducted whilst on site. The tourism staff who conduct these surveys are in a unique position to educate the multitude of tourists who flock to the Reef every year as to the importance of coral reefs and the threats they face.

5.2 Coverage of candidate indicators

5.2.1 Missing indicators

There are some possible reasons why seven candidate indicators are not monitored by existing Reef programs. Practical field monitoring techniques for four of these – agents of health and disease for fish and mobile invertebrates, and incidences of physiological/molecular response by hard corals and by soft corals – are maybe yet to be developed or proven, and are logistically difficult or costly to collect. However, innovative and practical indicators developed in these areas could be of great value if they prove logistically feasible to implement in a monitoring program (see Kroon et al. (2017) for a recent review of biomarkers to assess fish health). Counts and sizing of soft coral colonies were not addressed and only one program did the same for hard corals. These indicators have likely been given low priority because most programs record a range of variables within limited field time; taking measurements of individual coral colonies is particularly time consuming. Settlement tiles are also not currently used by any of the 15 Reef coral reef monitoring programs because the deployment/retrieval/recruit counting process is time consuming, logistically difficult and variability in coral recruitment to tiles is typically high, making it difficult to interpret settlement patterns. The last of the unmonitored indicators, direct collections of macroalgae (vs estimates of cover/height), requires suitable storage/preservation capacity that is maybe not practical for many programs or the benefit to monitoring programs, with typically limited funds and field time, of collecting and processing macroalgae is not obvious at present.

5.2.2 Fish communities

The total lack of fish monitoring in over half of the reviewed programs was noteworthy; most, apart from the very specific Coral Watch and Recovery of the Reef programs, incorporated monitoring of other target groups. While four programs covered or partially covered most of the fish indicators, there are differences among them worth considering. On the face of it the Reef Life Survey program stands out as most comprehensively monitoring reef fishes of the Reef, covering all the candidate indicators and having broad spatial coverage. Their volunteers even count all fish species compared to the other three major Reef fish monitoring programs (the two AIMS Long-Term Monitoring Programs and the Inshore Zoning Effects program) in which trained scientists count a subset of around 215 fish species that they felt could be reliably identified and accurately quantified, and that well represented fishes of known ecological and social (to humans) importance. Identifications and counts of many other fishes that inhabit coral reefs were felt to be less reliable (particularly of small and cryptic species) and logistically too time consuming. However, Reef Life Survey cite work showing that their volunteer divers, trained for two weeks by professional biologists, produce data from counts of all fishes that are not statistically different from those gathered by the professionals (Edgar & Stuart-Smith 2009). Nonetheless, it should be noted that these comparisons were based largely on temperate reefs, and the comparison of trainee versus professional scientist remains to be validated in high diversity tropical reefs. That notwithstanding, Reef Life Survey fish data has been published in a range of peer reviewed articles. Currently, sampling by Reef Life Survey on the Reef is spatially and temporally haphazard compared to that of the two AIMS Long-Term Monitoring Programs and the Inshore Zoning Effects program in which fixed sites are sampled consistently. This means that Reef Life Survey data provides instantaneous assessments of fish communities in more Reef locations, while data from the latter three programs allows more accurate quantification of trends in fish communities in specific locations, either inshore only (Inshore Zoning Effects program) or across the Reef shelf (the two AIMS Long-Term Monitoring Programs) in a range of Natural Resource Management regions. It should be noted though that due to the hierarchical spatial design of the two Long-Term Monitoring Program programs and the fact that identical techniques are used in both, status and trends at broad (i.e. regional) spatial levels are still statistically valid despite fewer reefs being surveyed annually than by Reef Life Survey. Some information on fish communities is also provided by Reef Check and two Eye on the Reef programs (tourism weekly and rapid monitoring), but many of their indicators are only partially covered, compared to the greater coverage in the four other highlighted programs.

5.2.3 Mobile invertebrates

The mobile invertebrates most responsible for coral mortality, the crown-of-thorns starfish and *Drupella*, were counted by most programs, the major differentiation among these programs being the spatial scale of survey, both within and among reefs, sampling frequency/consistency and data quality (see earlier section of the Discussion). The fact that no program accurately measured the size of crown-of-thorns starfish (size classes were used by most) likely reflects that the survey method precludes it (i.e. not possible on manta tow), that measuring on scuba is logistically too time consuming or that size-classing is perceived to be sufficient. Whether more accurate measurements of the size structure of crown-of-thorns starfish populations would contribute to a better understanding of their dynamics or better inform management could be considered. Surprisingly, only two programs (Reef Check and Reef Life Survey) counted urchins (key mobile invertebrate herbivores). Given the increasing importance given to urchins for their functional roles on coral reefs (as bio-eroders and algal feeders) and a greater impetus to understand functional aspects of coral reef community dynamics, the under-representation of urchin monitoring among Reef programs needs consideration. Counts of other charismatic invertebrates (giant tritons, lobsters, giant clams etc.) were also under-represented, so consideration could be given to whether more comprehensive monitoring of this group, and which species or taxa in particular, would improve our ecological understanding and better inform management.

5.2.4 Hard and soft corals

Hard corals are perceived by many as the most essential indicator group for reef monitoring because of their fundamental importance for reef growth and general reef biodiversity (i.e. their structures support a huge range of other reef inhabitants). Not surprisingly then, cover of hard corals was monitored by most of the 15 Reef coral reef programs, with the major differences relating to the monitoring methodology and spatial scale of investigation (see earlier section in Discussion). While it is very difficult to identify many hard corals to species level without microscopic appraisal of specimens, only five programs (those coordinated by the AIMS Long-Term Monitoring Program and Marine Monitoring Program) identified all hard corals to genus level (when possible). This highlights a gap in many programs because the higher the taxonomic resolution, the deeper the understanding of population and community dynamics – a bonus for managers and ecologists alike. It was positive that most programs covered an indicator of hard coral growth form as the abundance and diversity of many other organisms are positively associated with specific coral structures.

Indictors of hard coral population/community structure were far less well represented across programs than were taxonomic and functional indicators. Counts of juvenile hard corals provide a good indication of recovery and potential community growth but only six programs covered this indicator. Of these, only four addressed size of those juveniles and the size structure of adult hard corals is largely undocumented on the Reef (only being possible from mapped quadrats at Orpheus Island by the Recovery of the Great Barrier Reef program). Overall the size structure of hard corals populations/communities on the Reef is currently not well monitored, likely because it is deemed logistically too time consuming. While an indicator of hard coral community diversity/composition was possible from data gathered by most programs, the majority could only address it a basic level (growth form); only the five AIMS coordinated programs allowed an assessment at the genus level. This means that most programs have limited capacity to assess the subtleties of hard coral community changes following disturbances, even though the higher taxonomic level of investigation (i.e. genus) may provide greater insights into the winners and losers under current disturbance regimes and as climate change exacerbates certain pressures. The fact that only two programs could partially cover an indicator of hard coral extent within a reef, likely reflects logistical difficulties in providing such spatially extensive information. Better technology may allow this information to be more easily gathered, because reliable assessments of hard coral extent could help inform where hard coral communities are shrinking or expanding, and where deep-water refuges exist. Indicators of habitat complexity were also poorly represented among programs, despite the fundamental importance of habitat complexity (particularly that provided by hard corals) for a wide range of reef organisms.

Agents of health and disease for hard corals relating to disease, bleaching and mortality were covered by most programs, reflecting intense interest in the causes of general coral decline on the Reef. The major differentiation among these programs in the potential utility of these indicators being the spatial scale of survey, both within and among reefs, sampling frequency/consistency and data quality (see earlier section in discussion)

Soft coral indicators were far less extensively monitored compared to hard coral indicators. Most programs monitored cover of soft corals and an indicator of their bleaching, but aside from these, other soft coral indicators were sparsely covered among programs. However, genus level identifications, count/size of juvenile soft corals and community diversity/composition were best covered by the three AIMS-coordinated inshore programs and, for soft coral disease and mortality, by the Eye on the Reef: RHIS program, Reef Check and Coral Watch. The relatively limited focus among programs on soft versus hard corals likely reflects perceptions that soft corals are not the most functionally important organisms for general reef condition or for the survival of other organisms. However, their ecological importance is not well understood, and some believe it is under-valued. Whether soft coral indicators, aside from their cover and bleaching status, should be a higher priority in monitoring programs could be considered further.

5.2.5 Macroalgae

The perceived ecological importance of macroalgae was reflected by indicators of macroalgal cover being covered by most programs. However, only five programs (all coordinated by AIMS) recorded macroalgae at the genus level, meaning that their indicators of community diversity/composition would be the most advanced and informative among programs. At least, >50per cent of the programs can differentiate between CCA, turf and fleshy algae, so providing a very basic assessment of algal community structure. Some programs consider different groupings of algae to be functional groups, although their actual functional attributes are not clearly defined, suggesting a more refined consideration/understanding (i.e. what function do we believe this species/group performs?) of this indicator is warranted. Only two programs (Eye on the Reef: RHIS and the RHIS component of the crown-of-thorns starfish outbreak management program) measured turf/canopy height of macroalgae sufficiently to allow very limited calculations of biomass and growth. This very limited capacity among current Reef monitoring programs to understand the dynamics of macroalgal growth deserves further consideration given that undesirable coral-macroalgal phase shifts may become more of a threat (particularly to inshore reefs) as climatic disturbances escalate and coastal pressure increase.

5.2.6 Deep water

Only one program, Catlin Seaview Survey, monitored deep water (>30m) coral reefs. They used specialist deep sea divers and remotely operated vehicles with high definition cameras that allowed assessment of the benthos and collection of coral samples to determine genetic connections with shallow reef corals (over 3000 samples were collected from the Great Barrier Reef and Coral Sea in 2012). The Catlin Seaview Survey team also are deploying unique deep-water pulsed amplitude modulated stress detection devices that remotely monitor stress events (i.e. bleaching) at mesophotic depths. The absence of deep water coral reef monitoring in the other 14 Reef programs was identified in the earlier assessment by Addison et al. (2015). Deep water precludes standard scuba monitoring methodologies, commonly employed in shallow waters, due to very restricted dive times at depths. Methodologies to allow greater flexibility for scuba divers when working at depth (i.e. mixed gases, long decompressions etc.) are not commonly condoned by employers due to workplace safety concerns. This means that monitoring deep water coral reefs usually involves use of electronic survey equipment deployed from vessels that either record or stream data. While some remote methodologies are currently used to survey deep water coral reef communities (i.e. Catlin Seaview Surveys), this field is still developing and currently the logistics of setting up deep water monitoring programs are challenging and expensive.

5.2.7 Environmental pressures

Although candidate indicators of most environmental pressures were not expected to be sourced from specific coral reef monitoring programs, a number of high priority or additional high priority environmental pressures were covered or partially covered by at least two of those programs. Not surprisingly, outbreaks of crown-of-thorns starfish and disease were best covered, but a wide range of programs incorporated a measure that could inform sea temperature increase. However, only five of these (all AIMS-led) deployed continuous-monitoring electronic temperature loggers, suggesting that use of these small, but most informative, temperature monitoring devices are under-utilised among programs on the Reef. Other types of continuous-monitoring equipment, deployed by monitoring programs, could help increase knowledge of environmental pressures. For example, only one program (the Marine Monitoring Program) deployed equipment that could monitor increased freshwater inflow. Another four programs only covered this indicator very basically by recording presence/absence of flood plumes. Marine debris was recorded by only six programs, despite being an additional high priority pressure and not difficult to assess. Maybe, other programs could consider incorporating assessments of marine debris if it would not affect the quality of routine data collection.

5.3 Reporting

There is a distinction in the type of information reported by monitoring programs in terms of their utility for management decisions and the advancement of scientific knowledge of the ecology of the system. While the Authority has highlighted that the quick dissemination of information is very important, there also needs to be some consideration given to the quality of the information provided, especially if management and political decisions are to be based on this information. All monitoring programs reported their results to some degree, although the depth of detail and the methods varied. Some programs (e.g. Long-Term Monitoring Program, Reef Check and Catlin Sea View Survey) had extensive online reporting displaying status and trends of key indicators at a number of spatial scales, while other programs simply reported summaries online at broad spatial scales (e.g. Reef Life Survey). It was unclear at the time of writing how long it took for the information to be analysed and reported online for the majority of programs, but there is likely substantial variation among programs in the time between data collection and reporting. Programs using online reporting were likely to get the information out relatively quickly, compared to programs which rely on reports to funding bodies or peer-reviewed manuscripts. Programs which utilise all methods of reporting will certainly distribute the information to a much wider audience than those using a single source. Ideally for RIMReP, summary information should be forwarded to management as soon as possible after returning from the field, with more detailed follow-up reporting once detailed analysis has been completed.

6.0 Summary and implications for the design of RIMReP

Here we apply sound principles of monitoring and the findings of this report to conceptualise what a good RIMReP sampling design could look like, using existing programs as they are currently structured or after some modification.

Firstly, any monitoring design must be guided by clear objectives. While there are many desirable higher-level outcomes from RIMReP, such as tracking progress towards targets and objectives of the Reef 2050 Long-Term Sustainability Plan, measures of status and change must underpin the whole program. We define the fundamental RIMReP objective as “to gather the most accurate measurements of status of target indicators in ways that allow the most sensitive assessment of change over as much Reef coral reef habitat as possible”. We assume that the target indicators of RIMReP will be those defined by the Coral Reef Expert Group (Table 1) and are relevant to management.

There are fundamental aspects of any monitoring design that are particularly desirable to obtain the most accurate measures of status and trend. At any specific Reef location, it is best that surveys are appropriately replicated and conducted on fixed sites using standardised methods to allow detection of the smallest possible changes in indicators with statistical confidence. It is also best if: surveys are spatially extensive and representative of coral reefs across the whole Reef, surveys are temporally consistent, data is quantitative where possible, trained scientists are used to provide the highest level of expertise and hence data quality, and all sources of error in measurements and data processing are minimised through strict quality control protocols. Seven of the Reef programs fit many of these criteria: Inshore Zoning Effects, the two AIMS Long-Term Monitoring Programs, the three AIMS-led inshore programs and Catlin Seaview Survey, noting that only the first three programs have a fish component and two of the AIMS inshore programs are very localised. We believe that any management or political decisions concerning the Reef should be grounded in rigorous science and it is these rigorous styles of programs that should form the backbone of the RIMReP sampling, ideally with expanded coverage in sparsely surveyed areas (e.g. the Far Northern Management Area), as their data is the most defensible and therefore can be applied with confidence. These types of programs are particularly suited to two of the three types of necessary monitoring identified in the *Reef 2050 Long-Term Sustainability Plan*: compliance monitoring (already incorporated into the design of the Inshore Zoning Effects program and the AIMS Long-Term Monitoring Program: Zoning Effects program) and Long-Term Monitoring. Some aspects of these programs could also be proactively applied to the third type of monitoring in the Reef 2050 Plan, short to medium term - issue specific monitoring (i.e. manta tow surveys by the AIMS Long-Term Monitoring Program have been used in this way to assess developing bleaching events and crown-of-thorns starfish outbreaks).

However, programs using these rigorous approaches are necessarily time consuming, meaning that while specific reef locations are very well monitored and assessments of their status and trends are likely to be extremely sound, there are limits to the number of habitats, reef-zones, reefs and regions that can be logistically surveyed each year. Therefore, to monitor areas of the Reef that the rigorous style programs do not cover due to resource and time limitations, rapid assessment programs will need to be incorporated into the RIMReP design. Short to medium-term, or issue-specific monitoring will also not necessarily be captured by the rigorous style programs, and this is where the rapid survey protocols could be successfully applied (i.e. Eye on the Reef: RHIS has been used to assess impacts of Cyclone Yasi).

Rapid assessment monitoring is carried out by six Reef programs: Eye on the Reef: rapid monitoring and RHIS (including that done within the crown-of-thorns starfish Management program), Reef Check, Reef Life Survey and Coral Watch. These programs do not necessarily revisit the same sites on a regular basis. they often (but not always) use “citizen scientists” instead of university trained scientists and tend to collect more quasi-quantitative than quantitative data (with the exception of Reef Life Survey). However, they do opportunistically survey more sites, reefs and reef zones throughout the Reef than those programs which only survey fixed sites. Therefore, for the RIMReP we recommend that these programs would best be used to fill existing knowledge gaps by providing some indication of status in locations/habitats not visited by core survey teams, to provide early warning of recent/developing disturbances and to extend known distributions of disturbances or organisms (although there is scope for misidentification of species from “citizen scientists”). Importantly, the flexibility of these programs and speed of sampling of some, makes them suited for a quick response to assess specific issues (i.e. disturbances to benthic communities from cyclones, bleaching, ship groundings etc.), but only if the sampling is carried out under a well-conceived and replicated design (ideally pre-conceived as a response template of sorts, able to be easily and quickly adapted for different issues/locations). Conversely, data from rapid assessment programs will be of limited use in assessing trends in target indicators (except at very broad scales) compared to rigorous style programs because of one or more of the following: inconsistent spatial and temporal sampling, greater observer numbers and as yet undefined observer error, and less rigorous quality controls, as discussed earlier.

Two Reef programs, Eye on the Reef: tourism weekly and Recovery of the Great Barrier Reef have monitoring styles unusual among Reef programs. Both revisit the same sites but do not necessarily use trained scientists. The tourism weekly program collects data more frequently than any other program (weekly, as suggested by the program name), allowing a unique ability to capture local short-term changes in their limited set of indicators (compared to many other programs). The Recovery of the Great Barrier Reef program is unusual in that is it is based solely at one island location (Orpheus Island) and uses detailed mapping of quadrats, a technique used by no other program. Both programs thus cover unique aspects of monitoring on the Reef despite their limited spatial scope and should be incorporated in the RIMReP design.

Overall, incorporating a variety of the styles of current Reef monitoring into the RIMReP should prove a sound basis for management. However, a key early step will be to instigate discussions among all programs with the goals of RIMReP in mind, to help refine and synergise sampling methodologies and locations (within existing constraints, given that certain programs operate independent of government agencies) for best comparability of data among programs and best spatial coverage on the Reef. Discussions will need to address aspects such as further prioritising indicators, filling current gaps in sampling of those indicators whether those gaps be spatial, temporal, too coarse data resolution or other, and the clear benefits of streamlining approaches under the umbrella of RIMReP to obtain the greatest understanding of Reef-wide status. Within a new RIMReP sampling design, rapid assessment programs should be encouraged to fill spatial gaps in core sampling and to deliver early warning information. The value of these programs within RIMReP could also be improved by looking at ways to reduce sources of error in measurements and data processing, or at least provide some better assessment of that error. Consideration should also be given to incorporating monitoring of deep-water coral reefs and embracing innovative/cost effective monitoring technology (i.e. robots, drones or equivalent etc.) to boost the efficiency and scope of Reef sampling. It should also be noted that, while “citizen science” has its place in RIMReP, it is those scientifically more rigorous programs that, as well as informing management, have traditionally furthered most our understanding of Reef ecology. The importance of the latter should not be under-valued as greater knowledge of how the Reef functions ecologically is necessary to support better, more refined management strategies in the future.

7.0 Acknowledgements

We thank Britta Schaffelke, Ken Anthony and Angus Thompson for stimulating discussions about the RIMReP and some of their ideas are reflected in this report. We also thank representatives of each monitoring program for feedback and information provided during the writing of this report.

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9.0 Tables

Table 1. Candidate indicators as defined by the Coral Reef Expert Group in January 2017.

Monitoring objective	Fish communities (shallow & deep reefs)	Mobile invertebrates[1] (shallow & deep reefs)	Hard and soft corals (shallow & deep reefs)	Macroalgae[2] (shallow & deep reefs)
Taxonomic and functional	• Counts and size of all reef fish by species, including reef associated pelagic fish and cryptic fish	• Counts of crown-of-thorns starfish[3] and *Drupella*, size of CoTS, feeding scars on corals • Counts of key herbivores[4] (e.g., sea urchins) • Counts of other “charismatic invertebrates” (e.g., trochus, some holothurians as commercially harvested species, giant clams)	• Abundance/cover by genus/growth form[4]	• Abundance/cover by genus/growth form/functional group[4]
Population and community dynamics	• Derived from count and size data, e.g. to estimate growth, perhaps for functional groups	• Derived from count and size data, e.g. to estimate growth, perhaps for functional groups[11]	• Number of juveniles by genera (in size classes, e.g. <2cm, 2-5cm) • Recruitment tiles[5] • Community growth - derived from cover • Colony size - growth	• Biomass[6] • Community growth rates[6], derived from biomass or size and abundance size data, perhaps for functional groups
Population and community structure	tbd	tbd	• Rugosity/3D structure • An initial baseline of whole of reef size and extent was recommended (to be repeated at perhaps decadal intervals) • Consider ratio of tabulate *Acropora* vs other taxa	• Turf heights/canopy heights • Direct collection vs cover/height • Ratio CCA vs turf vs fleshy
Agents of health and disease	*No practical indicators identified*	*No practical indicators identified*	• Incidence of coral disease • Incidence and severity of bleaching • Recently dead colonies/partial mortality • Physiological and molecular responses (especially response or compliance monitoring)	• Incidence of CLOD (coralline lethal orange disease)

[1] Potential for logistical constraints as mobile invertebrates are often nocturnal
[2] Seasonal fluctuations of macroalgal communities need to be considered in the design (sampling timing and frequency)
[3] Targeted surveys on deeper reefs for R&D question about the importance of crown-of-thorns starfish on deeper reefs for influencing or sustaining outbreaks on shallow reefs.
[4] Desktop study on “practical taxonomy” to recommend appropriate taxonomic/functional resolution
[5] Limited utility for Long-Term Monitoring due to large inter-annual variability
[6] Usefulness of biomass, community growth rates, and ratios of groups as condition indicators would need to be confirmed by R&D

Table 2a. Coverage of candidate indicators for specific target groups of organisms by existing monitoring programs: covered (dark grey), partially covered (light grey) and not-covered (white). The criteria for coverage allocation is in Table 2c.

			Monitoring Programs														
		Acronyms: LTMP = Long-term Monitoring Program, RHIS = Reef Health and Impact Surveys, MMP = Marine Monitoring Program (inshore), NQBP = North Queensland Bulk Ports Corporation, COTS = Crown-of-thorns Starfish, GBR = Great Barrier Reef	INSHORE ZONING EFFECTS	LTMP: HISTORICAL	LTMP: ZONING EFFECTS	EYE ON THE REEF: RAPID MONITORING	EYE ON THE REEF: RHIS	EYE ON THE REEF: TOURISM WEEKLY	REEF CHECK	MMP	GLADSTONE HARBOUR	NQBP: ABBOT PT, MACKAY & HAY PT	REEF LIFE SURVEY	CORAL WATCH	COTS OUTBREAK MANAGEMENT	CATLIN SEAVIEW SURVEY	RECOVERY OF THE GBR
Target group	**Monotoring objective**	**Candidate indicator**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Fish communities	Taxonomic & functional	Counts: obvious reef spp.															
		Counts: cryptic reef spp.															
		Counts: pelagic spp.															
		Counts: sharks															
		Counts: rays															
		Lengths: multiple spp.															
		Lengths: coral trout															
	Population/community structure	Population: size structure of multiple spp.															
		Population: size structure of coral trout															
		Population: biomass															
		Community: spp. richness/composition															
		Community: biomass															
		Community: functional diversity															
		Community: functional redundancy															
	Agents of health and disease	*No practical indicators identified*															
Mobile invertebrates	Taxonomic & functional	Counts: COTS															
		Counts: COTS feeding scars															
		Size: COTS															
		Counts: *Drupella* snails															
		Counts: *Drupella* feeding scars															
		Counts: key herbivores (e.g. urchins)															
		Counts: other charismatic invertebrates															
	Population/community structure	Population: COTS size structure															
	Agents of health and disease	*No practical indicators identified*															
Hard and soft corals	Taxonomic & functional	Cover: hard coral															
		Genus level ID: hard coral															
		Growth form ID: hard coral															
		Cover: soft coral															
		Genus level ID: soft coral															
		Growth form ID: soft coral															
		Cover: hard and soft coral combined															

Table 2a. continued

	Population/community structure	Count and size of adult colonies: hard coral
		Count of juvenile colonies: hard coral
		Size of juvenile colonies: hard coral
		Community diversity/composition: hard coral
		Baseline reef size/extent: hard coral
		Ratio of tabulate *Acropora* cover to cover of other corals
		Habitat complexity: substrate and hard coral combined
		Substrate complexity: substrate only (hard corals excluded)
		Count and size of adult colonies: soft coral
		Count and size of juvenile colonies: soft coral
		Community diversity/composition: soft coral
		Baseline reef extent: soft coral
		Recruitment to settlement tiles: hard and soft corals
	Agents of health and disease	Incidence of coral disease: hard coral
		Incidence & severity of bleaching: hard coral
		Incidences of recent death/partial mortality: hard coral
		Incidences of physiological/molecular response: hard coral
		Incidence of coral disease: soft coral
		Incidence & severity of bleaching: soft coral
		Incidences of recent death/partial mortality: soft coral
		Incidences of physiological/molecular response: soft coral
Macroalgae	Taxonomic & functional	Cover: macroalgae
		Genus level ID: macroalgae
		Growth form ID: macroalgae
		Functional group: macroalgae
	Population/community structure	Biomass: macroalgae
		Community diversity/composition: macroalgae
		Turf/canopy height: macroalage
		Direct collection (vs cover/height): macroalgae
		Ratio of CCA vs turf vs fleshy: macroalgae
		Community growth rates: macroalgae
	Agents of health and disease	Incidence of CLOD: macroalgae
Other (not original candidates)	Taxonomic & functional	Cover: other benthic organisms (i.e sponges, ascidians etc.)
		Count: turtles
	Population/community structure	Record of spawning/mating: any species
		Record of maturity colour phases: parrotfish or wrasse
	Agents of health and disease	Incidences of bleaching: clams
		Record of sponge overgrowth or sediment smothering
		Core samples for microbial analyses
		Proportion of coral cover affected by COTS and *Drupella*

Table 2b. Coverage of candidate indicators for target environmental pressures by existing monitoring programs: covered (dark grey), partially covered (light grey) and not-covered (white). The criteria for coverage allocation is in Table 2c.

			Monitoring Programs														
		Acronyms: LTMP = Long-term Monitoring Program, RHIS = Reef Health and Impact Surveys, MMP = Marine Monitoring Program (inshore), NQBP = North Queensland Bulk Ports Corporation, COTS = Crown-of-thorns Starfish, GBR = Great Barrier Reef	INSHORE ZONING EFFECTS	LTMP: HISTORICAL	LTMP: ZONING EFFECTS	EYE ON THE REEF: RAPID MONITORING	EYE ON THE REEF: RHIS	EYE ON THE REEF: TOURISM WEEKLY	REEF CHECK	MMP	GLADSTONE HARBOUR	NQBP: ABBOT PT, MACKAY & HAY PT	REEF LIFE SURVEY	CORAL WATCH	COTS OUTBREAK MANAGEMENT	CATLIN SEAVIEW SURVEY	RECOVERY OF THE GBR
Target group	**Monotoring objective**	**Candidate indicator**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Environmental pressures	Cyclone activity	High priority indicators															
	Damage to reef structure (includes hard coral)	High priority indicators															
	Disposal and resuspension of dredge material	High priority indicators															
	Extraction - fishing in spawning aggregations	High priority indicators															
	Extraction - lower order predators	High priority indicators															
	Extraction - top order predators	High priority indicators															
	Grounding large vessel	High priority indicators															
	Grounding small vessel	High priority indicators															
	Increased freshwater inflow	High priority indicators															
	Outbreak of COTS	High priority indicators															
	Outbreak of disease	High priority indicators															
	Pesticides from catchment runoff	High priority indicators															
	Sea temperature increase	High priority indicators															
	Sediments from catchment run-off	High priority indicators															
	Altered ocean currents	Additional high priority indicators															
	Dredging	Additional high priority indicators															
	Marine debris	Additional high priority indicators															
	Modifying supporting terrestrial habitats	Additional high priority indicators															
	Nutrients from catchment run-off	Additional high priority indicators															
	Ocean acidification	Additional high priority indicators															
	Outbreak or bloom of species other than COTS	Additional high priority indicators															
	Atmospheric pollution	Non-essential indicators															
	Artificial barriers to flow	Non-essential indicators															
	Damage to seafloor	Non-essential indicators															
	Exotic species and diseases	Non-essential indicators															
	Extraction – Discarded catch	Non-essential indicators															
	Extraction – herbivores	Non-essential indicators															
	Extraction – Incidental catch, spp. of concern	Non-essential indicators															
	Extraction — lower trophic orders	Non-essential indicators															
	Noise pollution	Non-essential indicators															
	Rising sea level	Non-essential indicators															
	Spill — large chemical	Non-essential indicators															
	Spill — large oil	Non-essential indicators															
	Spill — small chemical and oil	Non-essential indicators															
	Urban and industrial discharge	Non-essential indicators															
	Waste discharge from a vessel	Non-essential indicators															
	Discarded fishing line	Extra indicator															

Table 2c. Criteria for coverage allocation of each candidate indicator: covered (dark grey) or partially covered (light grey). Only those indicators which were at least partially covered by one monitoring program are shown.

Target themes	Monitoring objective	Candidate indicator	Covered	Partially covered
Fish communities	Taxonomic & functional	Counts: obvious reef spp.	>100 spp.	Some spp.
		Counts: cryptic reef spp.	All spp.	Cryptic serranids or moray eels only
		Counts: pelagic spp.	All spp.	Some spp.
		Counts: sharks	All spp.	*Not covered by any program*
		Counts: rays	All spp.	*Not covered by any program*
		Lengths: multiple spp.	>100 spp.	Some spp.
		Lengths: coral trout	Estimated accurately or in > 3 size classes	Estimated in 3 or fewer size classes
	Population/community structure	Population: size structure of multiple spp.	Lengths for >100 spp.	Lengths for some spp.
		Population: size structure of coral trout	Length estimated accurately or in > 3 size classes	Length estimated in 3 or fewer size classes
		Population: biomass	Lengths for >100 spp.	Lengths for some spp.
		Community: spp. richness/composition	>100 spp.	*Not covered by any program*
		Community: biomass	Lengths for >100 spp. from many families	Lengths for some spp. from a few families
		Community: functional diversity	Spp. from multiple functional groups counted	*Not covered by any program*
		Community: functional redundancy	Spp. from multiple functional groups counted	*Not covered by any program*
Mobile invertebrates	Taxonomic & functional	Counts: crown-of-thorns starfish (COTS)	All individuals	Qualitative measure
		Counts: COTS feeding scars	All scars recorded	*Not covered by any program*
		Size: COTS	*No programs measure COTS to the cm*	Size classes
		Counts: *Drupella* snails	All individuals	*Not covered by any program*
		Counts: *Drupella* feeding scars	All scars recorded	*Not covered by any program*
		Counts: key herbivores (e.g. urchins)	All/multiple spp. of urchins at least	*Not covered by any program*
		Counts: other charismatic invertebrates	>3 spp.	1 or 2 spp.
	Population/community structure	Population: COTS size structure	*No programs measure COTS to the cm*	Size classes or qualitative measure
Hard and soft corals	Taxonomic & functional	Cover: hard coral	Estimated	*Not covered by any program*
		Genus level ID: hard coral	All corals when possible	Only for certain genera
		Growth form ID: hard coral	A range of growth forms	*Not covered by any program*
		Cover: soft coral	Estimated	*Not covered by any program*
		Genus level ID: soft coral	All corals when possible	Some genera
		Growth form ID: soft coral	*Not covered by any program*	3 basic categories
		Cover: hard and soft coral combined	Estimated/possible	*Not covered by any program*
	Population/community structure	Count and size of adult colonies: hard coral	Possible from quadrat mapping	*Not covered by any program*
		Count of juvenile colonies: hard coral	All corals	*Not covered by any program*
		Size of juvenile colonies: hard coral	Possible from quadrat mapping	3 size classes
		Community diversity/composition: hard coral	Genus and growth form level	Possible for growth forms
		Baseline reef size/extent: hard coral	*Not covered by any program*	Possible using CATLIN hardware or GIS mapping
		Ratio of tabulate *Acropora* cover to cover of other corals	Possible	*Not covered by any program*
		Habitat complexity: substrate and hard coral combined	Estimated	*Not covered by any program*
		Substrate complexity: substrate only (hard corals excluded)	Estimated	*Not covered by any program*
		Count and size of juvenile colonies: soft coral	*Not covered by any program*	3 size classes
		Community diversity/composition: soft coral	Genus level	Family level
		Baseline reef extent: soft coral	*Not covered by any program*	Possible using CATLIN hardware or GIS mapping
	Agents of health and disease	Incidence of coral disease: hard coral	Quantified for a variety of diseases	Qualitative measure
		Incidence & severity of bleaching: hard coral	Incidences/cover affected	Qualititative measure, minor/severe
		Incidences of recent death/partial mortality: hard coral	Quantified in various ways	*Not covered by any program*
		Incidence of coral disease: soft coral	Quantified if present	Qualitative measure
		Incidence & severity of bleaching: soft coral	Incidences/cover affected	*Not covered by any program*
		Incidences of recent death/partial mortality: soft coral	Quantified in various ways	*Not covered by any program*

Table 2c continued

Macroalgae	Taxonomic & functional	Cover: macroalgae	Estimated	Subjective categories
		Genus level ID: macroalgae	All macroalgae when possible	A few genera
		Growth form ID: macroalgae	A range of growth forms	*Not covered by any program*
		Functional group: macroalgae	Three or more groups	*Not covered by any program*
	Population/community structure	Biomass: macroalgae	*Not covered by any program*	Possible using growth form/average height
		Community diversity/composition: macroalgae	Genus level	Possible with growth forms/family/a few genera
		Turf/canopy height: macroalage	4 height classes	*Not covered by any program*
		Ratio of CCA vs turf vs fleshy: macroalgae	Possible	*Not covered by any program*
		Community growth rates: macroalgae	*Not covered by any program*	Possible using growth form/average height
	Agents of health and disease	Incidence of CLOD: macroalgae	Quantified	*Not covered by any program*
Other (not original candidates)	Taxonomic & functional	Cover: other benthic organisms (i.e sponges, ascidians etc.)	A range of organisms	Grouped into "other"
		Count: turtles	All, identified to species if possible	*Not covered by any program*
	Population/community structure	Record of spawning/mating: any species	Number of incidences from a range of taxa	Anecdotal
		Record of maturity colour phases: parrotfish or wrasse	Recorded for all parrotfishes	Recorded for Maori Wrasse only
	Agents of health and disease	Incidences of bleaching: clams	Quantified	Qualitative measure
		Incidences of sponge overgrowth or sediment smothering	Quantified or estimated	*Not covered by any program*
		Core samples for microbial analyses	*Not covered by any program*	Extracted
		Proportion of coral cover affected by COTS and *Drupella*	Estimated	*Not covered by any program*
Environmental pressures	Damage to reef structure (including hard coral)	High priority indicators	*Not covered by any program*	Estimates of habitat complexity/coral damage
	Increased freshwater inflow	High priority indicators	Salinty measusured/flood plumes monitored	Prescence/absence of flood plume
	Outbreak of crown-of-thorns starfish	High priority indicators	Counts of all individuals	Qualitative measure
	Outbreak of disease	High priority indicators	Incidences of various diseases	Qualitative measure
	Sea temperature increase	High priority indicators	Temperature loggers deployed	Temperature recorded during dsurveys
	Sediments from catchment run-off	High priority indicators	*Not covered by any program*	Turbidity sensors at some locations
	Dredging	Additional high priority indicators	*Not covered by any program*	Turbidity sensors at some locations
	Marine debris	Additional high priority indicators	Counts of a range of debris	Counts of fishing debris only
	Nutrients from catchment run-off	Additional high priority indicators	Water quality sampling	*Not covered by any program*
	Ocean acidification	Additional high priority indicators	*Not covered by any program*	pH recorded during water quality surveys
	Outbreak or bloom of species other than COTS	Additional high priority indicators	Counts/cover of a wide range of taxa	Counts/cover of *Drupella* /macroalgae
	Exotic species and diseases	Non-essential indicators	*Not covered by any program*	Some may be picked up during surveys
	Discarded fishing line	Extra indicator	Pieces counted	*Not covered by any program*

Table 3: Spatio-temporal extent and methodological details of the 17 Great Barrier Reef coral reef monitoring programs.

Frequency of sampling is broadly defined as Biannual (twice per year), Annual (once per year), Biennial (once every two years), Haphazard (no set temporal resolution, can be in response to an event). Spatial coverage examines the number of broad Natural Resource Management (NRM) regions (Cape York, Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy, Burnett Mary), the number of individual reefs visit per year, the number of sites surveyed, (which can vary among and within programs), the area of each survey site (based on the method with the largest spatial footprint, e.g. belt transect), and Great Barrier Reef -wide total area of the covered. Zone = broad zones within individual reefs surveyed in relation to the prevailing trade winds. Surveys on fringing reefs and entire reef perimeters are also identified. Habitat – habitats defined by a reef cross section (slope, crest, flat, and lagoon). The methods include the type of surveys undertaken (UVS – underwater visual surveys (belt transects, quadrats), PPI – photo point intercept, TS - timed swims, PS – point surveys, CPUE – catch per unit effort, MT – manta tow, OB – observation, LIT – line intercept transects) and whether surveys are conducted on permanently marked sites (GPS – deploy to GPS mark but no metal stakes mark the site, stakes - deploy to GPS mark with metal stakes, no – use neither stakes or GPS). The data section categorises each monitoring program by whether it collects measurements and counts (Quant), or whether it uses observer estimates or categorical data (Quasi). It further examines the range of metrics for fish, sessile benthos (hard coral, soft coral, algae etc) and mobile inverts (echinoderms, crustaceans, molluscs) and the best taxonomic resolution possible. The last section of the table examines Quality Control measures, including who conducts the surveys and what level of training they have received, then what procedures are employed to provide assurances of data quality and usefulness in terms of monitoring coral reef communities through space and time. COTS= crown-of-thorns starfish, LTMP= AIMS Long-Term Monitoring Program, NQPB= North Queensland Bulk Ports monitoring.

	INSHORE ZONING EFFECTS	LTMP: HISTORICAL	LTMP: ZONING EFFECTS	EYE ON THE REEF: RAPID MONITORING	EYE ON THE REEF: RHIS	EYE ON THE REEF: TOURISM WEEKLY	REEF CHECK	Marine Monitoring Program	GLADSTONE HARBOUR	NQBP: ABBOT PT, MACKAY & HAY PT.	REEF LIFE SURVEYS	CORAL WATCH	COTS OUTBREAK MANAGEMENT	CATLIN SEAVIEW SURVEYS	RECOVERY OF THE Great Barrier Reef
Temporal coverage															
Duration	1999 to present	1985 to present (transects from 1992)	2006 to present	2011 to present	2009 to present	2007 to present	1998 to present	2005 to present	2015 to present	2015 to present[+]	2007 to present	2003 to present	2012 to present	2012 to present	2012 to present
Frequency	Annual to 2003, biennial thereafter	Annual to 2005, biennial thereafter	Biennial	Haphazard	Haphazard	Weekly	Haphazard	Annual	Annual	Biannual	Haphazard	Haphazard	Haphazard	Biennial	Biannual
Spatial coverage															
NRM regions yr^{-1} (max 6)	3	6	5	6	6	3	4	4	1	2	6	6	2	4	1
# Reefs yr^{-1}	20	46 Manta 83	56 Manta 53	41*	238[€]	24[¥]	17[#]	31	6	6	153[^]	81[β]	76	27[Ω]	2[&]
#Sites yr^{-1}	108	138 Manta 3,836[@]	168 Manta 2,565[@]	290*	5,341[€]	30[¥]	44[#]	62	6	32	313[^]	245[β]	2,980[π]	81[Ω]	6

Area site^{-1} (m^2)	1,500	1,250[@] Manta 2,000[@]	1,250[@] Manta 2,000[@]	78.5	78.5	N/A[¥]	400[#]	400	200	200[+]	500	N/A[β]	2,000[π]	1,800[Ω]	300
Great Barrier Reef Area yr^{-1} (m^2)	162,000	172,500 [@] Manta 7,672,000[a]	210,000 [@] Manta 5,130,000[a]	22,765*	419,268.5[€]	N/A[¥]	17,600[#]	24,800	1,200	6,240	157,000[^]	N/A[β]	5,960,000[π]	145,800[Ω]	1,800
Shelf	Inshore	Inshore, mid-shelf, outer-shelf	Inshore, mid-shelf, outer-shelf	Inshore, mid-shelf, outer-shelf	Inshore, mid-shelf, outer-shelf	Inshore, mid-shelf, outer-shelf	Inshore, mid-shelf, outer-shelf	Inshore	Inshore	Inshore	Inshore, mid-shelf, outer-shelf	Inshore, mid-shelf, outer-shelf	Mid-shelf	Outer-shelf	Inshore
Zone	Fringing, front, back, oblique	Fringing, oblique, reef perimeter	Fringing, oblique, reef perimeter	Front, back, oblique	Front, back, oblique	Back	Back, oblique, fringing	Front, back	Front, back	Fringing, front, back, oblique.	Front, back, oblique	Fringing, front, back, oblique	Front, back, oblique	Front, back, oblique	Fringing, front, back, oblique
Habitat	Slope	Slope	Slope	Slope, flat, lagoon	Slope	Slope, flat	Slope, flat, crest, lagoon	Slope	Slope	Slope	Slope, crest, flat, lagoon	Slope, crest, flat, lagoon	Slope, lagoon	Slope	Slope
Methods															
Surveys	UVS, LIT	UVS, PPI, MT	UVS, PPI, MT	TS, PS	PS	TS	UVS, LIT	PPI	PPI	PPI, LIT, UVS	UVS, PPI	OB	CPUE, PS , MT	PPI	UVS, LIT
Permanent sites	GPS	GPS, stakes	GPS, stakes	No	GPS, stakes[€]	GPS	GPS	GPS, stakes	GPS, stakes	GPS, stakes	GPS	Some[β]	No	GPS	GPS, stakes
Data	<u>Quant.</u> *Fish:* abundance, diversity, length, biomass,	<u>Quant.</u> *Fish:* abundance, diversity, length, biomass, trophic,	<u>Quant.</u> *Fish:* abundance, diversity, length, biomass, trophic,	<u>Quant.</u> *Fish:* abundance	<u>Quant.</u> *Fish:* none	<u>Quant.</u> *Fish:* abundance	<u>Quant.</u> *Fish:* abundance	<u>Quant.</u> *Fish:* none	<u>Quant.</u> *Fish:* none	<u>Quant.</u> *Fish:* none	<u>Quant.</u> *Fish:* abundance, diversity, length, biomass, trophic,	<u>Quant.</u> *Fish:* none	<u>Quant.</u> *Fish:* none	<u>Quant.</u> *Fish:* none	<u>Quant.</u> *Fish:* none

	trophic, community metrics, fishing line. *Sessile benthos:* per cent cover, disease incidence. *Mobile inverts:* none	community metrics. *Sessile benthos:* per cent cover, diversity, disease incidence, temperature, depth *Mobile inverts:* abundance <u>Qual.</u>	community metrics. *Sessile benthos:* per cent cover, diversity, disease incidence, temperature *Mobile inverts:* abundance <u>Qual.</u>	*Sessile benthos:* per cent cover *Mobile inverts:* abundance <u>Qual.</u>	*Sessile benthos:* none *Mobile inverts:* abundance *Other:* count <u>Qual.</u>	*Sessile benthos:* Impact category *Mobile inverts:* abundance <u>Qual.</u> *Fish*	*Sessile benthos:* per cent cover disease incidence. *Mobile inverts:* abundance size, # feeding scars *Other:* count <u>Qual.</u> *Fish* none	*Sessile benthos:* per cent cover, disease incidence, juveniles, coral settlement, water quality. *Mobile inverts:* none <u>Qual.</u> *Fish*	*Sessile benthos:* per cent cover, juvenile abundance and size class, disease incidence. *Mobile inverts:* none <u>Qual.</u>	*Sessile benthos:* per cent cover, juvenile abundance and size class, disease incidence. *Mobile inverts:* none <u>Qual.</u>	community metrics. *Sessile benthos:* per cent cover, debris count *Mobile inverts:* abundance, diversity, length. <u>Qual.</u> *Fish*	*Sessile benthos:* Hard and soft coral health (6-point colour scale) *Mobile inverts:* none <u>Qual.</u> *Fish* none	*Sessile benthos:* none *Mobile inverts:* none <u>Qual.</u>	*Sessile benthos:* per cent cover *Mobile inverts:* Presence/ absence <u>Qual.</u>	*Sessile benthos:* per cent cover, colony density, colony size, juvenile abundance, *Mobile inverts:* none

	Qual. *Fish* none *Sessile benthos:* none *Mobile inverts:* none *Other:* none	*Fish* none *Sessile benthos:* per cent cover hard, soft, complexi ty, *Mobile inverts:* abundan ce *Other:* reef aesthetic s,	*Fish* none *Sessile benthos:* per cent cover hard, soft, complexi ty, *Mobile inverts:* abundan ce *Other:* reef aesthetic s,	*Fish* none *Sessile benthos:* per cent cover rubbish p/a *Mobile inverts:* none *Other:* none	*Fish* none *Sessile benthos:* per cent cover, per cent bleaching , per cent cover disease, abundan ce, Drupella abundan ce, # colonies damaged *Mobile inverts:* COTS, Drupella *Other:* rubbish	Size class abundan ce. *Sessile benthos:* macroal gae, bleachin g, disease, coral damage *Mobile inverts:* none *Other:* none	*Sessile benthos:* per cent bleaching *Mobile inverts:* none *Other:* none	none *Sessile benthos:* none *Mobile inverts:* none *Other:* none	*Fish* none *Sessile benthos:* none *Mobile inverts:* none *Other:* none	*Fish* none *Sessile benthos:* none *Mobile inverts:* none *Other:* none	none *Sessile benthos:* none *Mobile inverts:* none *Other:* none	*Sessile benthos :* none *Mobile inverts:* none *Other:* none	*Fish* none *Sessile benthos :* per cent cover, per cent bleachin g, per cent cover disease, abunda nce, Drupella abunda nce, # colonies damage d *Mobile inverts:* COTS, Drupella *Other:* Rubbish	*Fish* none *Sessile benthos:* none *Mobile inverts:* presenc e *Other:* Disease, bleachin g presenc e	Qual. *Fish* none *Sessile benthos :* none *Mobile inverts:* none *Other:* none

		temperature, depth, sea state, tide, cloud cover, wind	temperature, depth, sea state, tide, cloud cover, wind													
Taxonomic resolution	Fish species Sessile benthos growth forms Mobile inverts: none	Fish species Sessile benthos genera, growth form, juveniles, Mobile inverts: genera	Fish species Sessile benthos genera, growth form, juveniles, Mobile inverts: genera	Fish Some iconic species, functional groups and families. Sessile benthos Coral, algae, rubble Mobile inverts: COTS, Drupella, other inverts	Fish none Sessile benthos growth forms, Mobile inverts: COTS Other	Fish Herbivores, Iconic species, Shark species Sessile benthos growth forms, Mobile inverts: COTS, Drupella, other inverts.	Fish Family, some iconic species. Sessile benthos growth forms Mobile inverts: genera, species Other	Fish none Sessile benthos genera, growth form Mobile inverts: none	Fish none Sessile benthos genera, growth form Mobile inverts: none	Fish none Sessile benthos genera, growth form Mobile inverts: none	Fish Species Sessile benthos growth form, debris categories, macro-invert species Mobile inverts: none	Fish none Sessile benthos Four coral forms Mobile inverts: none	Fish none Sessile benthos Coral and algal growth forms Mobile inverts: COTS, Drupella	Fish none Sessile benthos Coral and algal family and growth forms Mobile inverts: Macro-inverts (COTS, Sea cucumber etc	Fish none Sessile benthos Coral and algal growth forms, four size classes Mobile inverts: none

		<u>Manta</u> hard and soft cover, COTS, Shark species, Coral trout	<u>Manta</u> hard and soft cover, COTS, Shark species, Coral trout		rubbish, disease		Debris categories, Fishing line, megafauna							grouped)	
Quality control															
Staff	JCU	AIMS	AIMS	Tourism, Visitor, Fisher, Traditional owner	QPWS, the Authority, tourism	Tourism	Reef Check, Volunteers	AIMS	AIMS	AIMS, Sea Research	U TAS, IMAS, Tas PWS, SA DOE, WADDI, WA DPW	UQ	AMPTO	UQ	AIMS, JCU, Earthwatch
QC Measures	University trained, few observers, Observer comparison, length calibration, database v originals	University trained, few observers, observer comparison, annual training, alternate observers, length calibration, Transect width calibration,	University trained, few observers, observer comparison, annual training, alternate observers, length calibration, Transect width calibration,	Trained volunteers – online, many observers, few observer comparisons, circle radius calibration,	Trained volunteers – online modules, 1 day in-water, Many observers, few observer comparisons, circle radius calibration, Some database v originals	Trained volunteers – online modules, 1 day in-water, quarterly workshops, visual assessment of data.	Trained volunteers – classroom and in-water, all surveys led by Team Scientist/ Leader, standardised site selection and transect deployment, grouping of similar spp	University trained, few observers, observer comparison, image comparison, taxonomic comparison,	University trained, few observers, observer comparison, image comparison, taxonomic comparison, SQL database,	University trained, few observers, observer comparison, image comparison, taxonomic comparison, SQL database,	Trained volunteers (2 weeks), most university graduates, volunteers trained by university staff, many observers, data entry by 'certified'	Untrained volunteers	Trained volunteers	University trained, Few observers, Comparison machine learned and observer id.	University trained, trained volunteers, few observers,

		database v originals	database v originals				to avoid misidentification, field data verification, database entry procedures, raw data revision	SQL database, database v originals	database v originals	database v originals	volunteers, trainee/ trainer comparisons, images of unidentified species checked by taxonomic advisors, SQL database with pre-determined error checking capacity, correction of errors identified and updated to database, data publicly available through online portal.				

[a] number of reefs surveyed using manta tow varies each year. The value for historical LTMP is from 2017 while the zoning effects LTMP is from 2016. Calculation of manta tow area is based on one tow = 200m.

[@] LTMP - area estimates are based on the largest fish transect (5m wide). The area of benthos sampled would be much less. Manta tow estimates of #Sites yr-1 are number of 200m x 10m tows conducted

*Eye on the Reef: rapid monitoring - Variable numbers of surveys are undertaken each year and the data presented is for 2016.

€ Eye on the Reef: RHIS – Variable numbers of surveys are undertaken each year and the data presented is for 2016. The number of reefs and sites visited each year has varied from 123 reefs in 2010 and 347 sites in 2009 to the highest levels reported for 2016. Reefs are re-visited but may not be necessarily the same sites each year, although a subset of RHIS sites are now permanently marked with GPS and metal stakes.
¥ Eye on the Reef: tourism weekly monitoring –Variable numbers of surveys are undertaken each year and the data presented is for 2016. surveys are done using 30 timed swim – no area estimated.
+ NQBP – monitoring began at Hay Pt/Mackay in 2006, and was conducted by another contractor Advisian. Sites at Abbott Pt cover 200m^2 (five 20x2m belt transects), while those at Hay Pt/Mackay where there are only four 20 x 2m transects. There are also differences in methodology: Abbot Pt. is surveyed using PPI and UVS while Hay Pt/Mackay uses LIT and UVS.
Ω Catlin Seaview Survey - values for 2017. The number of sites, defined in this report as what Gonzalez-Rivero et al 2016 refer to as transects, has varied from 108 in 2012 to 60 in 2014. Site area is the area sampled for benthic classification, not the total area surveyed by the camera.
Reef Check – Numbers of reefs surveyed varies each year. The figures presented are for 2016 and are estimates of area of fish surveys.
π Crown-of-thorns starfish Control Program – Numbers of reefs surveyed varies each year. The figures presented are for the 2016-17 financial year, and the total area estimate of the Great Barrier Reef is based on manta tow surveys (2000m^2).
^ Reef life Surveys – numbers of sites and reefs vary each year. Data presented are from surveys at Great Barrier Reef sites conducted in 2016.
β Coral watch – numbers of sites and reefs vary each year, data presented are for the period 1 August 2016 to 31 July 2017. The area of a given site is not estimated, but a minimum of 20 colonies are surveyed each dive/snorkel. 10,947 colonies were surveyed in the reported period. Site are mostly random, however there are 2 permanent sites at Heron Island and one at Lady Elliot Island.
& Earthwatch Great Barrier Reef recovery – area estimates based on adult surveys only with three 10x10 quadrats at each site. Juveniles are also surveyed but in three 3x3m quadrats in each of six sites = 162m^2.

Table 4. Reporting mechanisms of the 15 reviewed coral reef monitoring programs.

	Program and organisation	How are findings reported?	What is reported?
1	Effects of management zoning on inshore reefs of the Great Barrier Reef Marine Park.	In refereed papers (28 since 2004) and in reports to National Environmental Science Program, the Authority and others (full details of papers and reports can be provided upon request).	Varied outputs but many relate to effects of marine park zoning on fish communities and the influences of changes in benthic communities. The accumulation of fishing line on reefs as a proxy for illegal fishing in protected zones has also been reported.
2	Long-Term Monitoring Program: historical program.	Online, in reef pages (for each survey reef), in regular survey reports at the sector level and in annual Great Barrier Reef summary reports, and offline in many scientific papers (>100 dating back to the early 1990's).	Online: current status of and long-term trends in measures of key benthic and fish community variables, and of agents of coral mortality. Papers: highly varied outputs from different areas i.e. methodological, pure ecology, applied (i.e. efficacy of protected areas) etc.
3	Long-Term Monitoring Program: effects of management zoning.	Online, in reef pages (for each survey reef), in regular survey reports at the sector level and in annual Great Barrier Reef summary reports. Offline in scientific papers.	Online: current status of and long-term trends in measures of key benthic and fish community variables, and of agents of coral mortality. Papers: two seminal scientific papers on the efficacy of marine protected areas on the Great Barrier Reef.
4	Eye on the Reef: rapid monitoring.	Currently in papers and in internal reports to the Authority and Department of the Environment. An online Eye on the Reef Survey Activity Map is freely available. Annual summary reports of Eye on the Reef monitoring for the public. Public portal for Rapid Monitoring participating groups such as schools is being developed and will include Google Earth maps with reef health data compared to regional summaries (C Jones pers comm).	Internal reports within the Eye on the Reef system inform the suite of Response Plans and trigger further action under the Incident Response Framework. Sightings of various organisms can be queried using the website and provide users with the ability to search for a particular species and receive a map of existing sightings. Major sightings and survey information summarised in simple annual report.

5	Eye on the Reef: reef health and impact surveys.	Currently in papers and in internal reports to the Authority and Department of the Environment. An online Eye on the Reef Survey Activity Map is freely available. Annual summary reports of Eye on the Reef monitoring for the public.	Papers have included such topics as cyclone damage, coral damage in no anchoring areas and rapid monitoring protocols for reef management. The online Eye on the Reef Survey Activity Map provides a summary of recent survey activity throughout the Great Barrier Reef.
6	Eye on the Reef: tourism weekly monitoring surveys.	Currently in papers and in internal reports to the Authority and Department of the Environment. Annual summary reports of Eye on the Reef monitoring for the public. Tourism industry receives electronic nature diaries and can query their data collected in the Weekly program.	Internal reports within the Eye on the Reef system inform the suite of Response Plans and trigger further action under the Incident Response Framework. Sightings of various organisms can be queried using the website and provide users with the ability to search for a particular species and receive a map of existing sightings. Major sightings and survey information summarised in simple annual report.
7	Reef Check	Online "Reef Health Database" with sites searchable from map interface. Monitoring reports prepared every 1 – 2 years for different regions/locations (i.e. 2015 Heron Reef Health Report) and reports sharing long-term results (i.e. Great Barrier Reef 10 year report); all accessible online.	The online "Reef Health Database" provides summary graphs of trends in various variables grouped into four report sections: Benthic, Invertebrate, Impact and Fish. The monitoring reports cover similar variables but in more detail with textual background and interpretation.
8	Marine Monitoring Program: inshore.	In an annual report, available online after internal reviews. Peer reviewed journal	Current status of and temporal trends in measures of a coral community condition index, coral cover, coral composition, proportion of macroalgae, pressures and disturbances, density of juvenile corals, turbidity and chlorophyll concentrations.
9	Gladstone Harbour monitoring.	In an annual report/report card but not for general dissemination due to contractual restrictions.	Current status of and temporal trends in measures of coral community condition assessment, coral cover, proportion of macroalgae, pressures and disturbances, and density of juvenile corals.
10	North Queensland Bulk Ports Corporation monitoring: Abbot	Findings are reported in annual reports/report cards but not for general dissemination due to contractual restrictions. Data also included in regional report cards.	Current status of and temporal trends in measures of coral community condition assessment, coral cover, proportion of macroalgae, pressures and disturbances, and density of juvenile corals.

	Point, Mackay and Hay Point.		
11	Reef Life Survey.	Data is freely available and searchable from an online map interface. Data is reported in scientific papers and management reports (including government reports and annual Reef Life Survey summary reports) that are accessible online.	Depends on the publication, but may include status of measures of key benthic and fish community variables, and of mobile macro-invertebrates and large organisms (i.e. turtles, sea snakes etc.).
12	Coral Watch.	Data is freely available and searchable from an online interface. Data is reported in scientific papers and in occasional reports that are accessible online.	Reef condition based on use of the Coral Health Chart (based on different colour shades).
13	Crown-of-thorns Starfish Outbreak Management Program.	Data is available in eAtlas via online interactive map and in the Atlas of Living Australia online Monitoring, Evaluation, Reporting and Improvement Tool (MERIT) which has been developed for the project and programme reporting requirements of Australian Government Natural Resource Management programmes. Data contributed to government reports.	Reported data includes number of crown-of-thorns starfish removed, catch per unit effort etc. RHIS component feeds into publications (see earlier Eye on the Reef RHIS section).
14	Catlin Seaview Survey	Online through the Catlin Global Reef Record and in scientific papers.	Cover of attached benthic organisms such as hard and soft corals and algae, and "other" (i.e. sand).
15	Recovery of the Great Barrier Reef	Annual (internal) reports are produced for Earthwatch. Scientific papers have also incorporated the data.	Aspects of coral disease from field surveys and onshore experiments. Coral demography and recovery has also been reported.