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

S4. Model to inform the design of a Reef Integrated Monitoring and Reporting Program

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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.

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Executive Summary

This project developed a model to inform coral reef monitoring and management under the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) and the *Reef 2050 Long-Term Sustainability Plan* (Reef 2050 Plan). The model combines spatial statistical analyses with a mechanistic understanding of coral community dynamics. The purpose of the model is to analyse coral status and trend, and to guide the design of a coral monitoring program that most effectively captures these dynamics in space and time.

This model uses per cent cover of hard corals and benthic composition as key indicators of reef state. Input variables include environmental data (e.g. temperature, salinity, sediment covers) and disturbance history (e.g. tropical cyclones, bleaching, water quality and outbreaks of the crown-of-thorns starfish). The model is calibrated against 20 years of *in situ* coral monitoring data and remotely sensed observations (1996-2015). A dual classification of all Great Barrier Reef (Reef) reefs was established based on (*i*) their benthic community composition and (*ii*) their coral cover trajectory over the 1996-2015 period, as a potential tool to stratify the future reef monitoring design. Both classifications, along with model outputs of coral cover, are available as a set of spatial layers (0.01 degree resolution).

We used the coral model and the underlying data on environmental pressures and disturbance history to address two core aspects of the current monitoring design: **representation** and **complementarity**. Our analyses revealed three major results for existing monitoring efforts. Firstly, 40 per cent of all Reef habitats are currently represented by existing long-term monitoring programs (Australian Institute of Marine Science (AIMS) Reef Monitoring [RM] including the Long-Term Monitoring Program, Representative Areas Program [RAP] and Marine Monitoring Program [MMP]), increasing to 45 per cent of all Reef habitats when monitoring using manta tow is added. When Reef Health and Impact Surveys (RHIS) under the Authority's Eye on the Reef program and the Catlin Seaview surveys are included, existing monitoring programs cover a total of 60 per cent of all Reef habitats. Secondly, major hotspots of cyclone activity have remained unmonitored by the RM/RAP/MMP programs in the central Reef, but have been surveyed reactively by manta tow and Reef Health Impact Surveys (RHIS) to some extent. Thirdly, clusters of reefs with similar benthic community composition and similar past coral cover trajectories were identified to explore if these convey redundant ecological information. Results suggest that stratifying a lower number of survey reefs based on this clustering could potentially maximize their complementarity.

We also examined how the **accuracy** and **precision** of a monitoring program influences its ability to report on coral condition and to detect changes. Here, the design of spatial and temporal sampling affects precision while observer bias lowers accuracy. To illustrate the roles of accuracy and precision in monitoring design we examined these using simulation analyses in a modelled reef landscape and by comparing plot-based monitoring as examples representing Eye on the Reef technique. Analyses demonstrated that a high level of observer bias combined with the reactive design of RHIS prevents its direct integration with fixed-site long-term coral monitoring. However, because the main objective

of long-term monitoring programs is to report on changes and to evaluate management effectiveness, and the main objective of RHIS is to provide situational awareness in response to events, their spatial and temporal precision do not have to be consistent. Instead, their integration is via complementarity. We show that high accuracy RHIS data can better complement LTMP data where they are collected from similar habitats. We present a decision tree that can help guide what monitoring program can support what monitoring and management objective based on criteria around accuracy, precision, complementarity and representation. We illustrate the use of this decision tool in example scenarios where long-term surveys are coupled with post-disturbance reactive surveys.

Last, we developed a second, Bayesian version of the model to examine how the data used for model calibration affects model predictive ability and, in particular, whether including citizen science data (e.g. Reef Check images) influences model uncertainty through the QUT-led project: “Monitoring Through Many Eyes”. Based on this weighted Bayesian model, our analyses revealed an increase in model predictive ability with the amount of data used in model calibration from different data sources. High-resolution predictive maps of coral cover with associated uncertainty were generated and made available through an online interactive tool.

Contents

1.0 Introduction

Targeted monitoring is central to any adaptive management process. The Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) is charged with four key tasks: (1) to provide situational awareness or reef condition (e.g. in response to disturbances), (2) to report on status and trend (and attribute these to pressures and drivers), (3) to provide early warning, and (4) to evaluate management effectiveness (i.e. is Reef 2050 working?).[1] For RIMReP to be effective it has to deliver effectively on all four monitoring objectives.

Delivering on multiple objectives means a compromise between a desire to know as much about the system as possible and the reality of resource constraints (McDonald-Madden et al. 2010). For monitoring to be effective it needs to capture the behaviour sufficiently of things that matter to support objectives, and within budget (Field et al. 2005). This becomes a design challenge for monitoring programs and ultimately an exercise in prioritisation and trade-offs (Gerber et al. 2005, McDonald-Madden et al. 2008).

The purpose of this project is to advise on the design of coral monitoring for RIMReP. More specifically, it is to develop an operating model that can inform the monitoring design for coral reefs of the Great Barrier Reef (Reef). An operating model of system behaviour is required for any targeted monitoring program to explain how environmental drivers and biological processes lead to observed temporal and spatial patterns and trends (Nichols and Williams 2006). This can explain system dynamics relative to expectations, and supports management and policy decisions around actions required to sustain or improve essential elements of the system. Without a model, management based on monitoring will have no reference frame, and adaptive management decisions will be less informed (McCarthy and Possingham 2007).

We use a model to help inform design of a coral monitoring program using four core principles: (1) representation, (2) precision, (3) accuracy and (4) complementarity. We apply these principles to each of the three monitoring objectives. Further, we propose how information from different monitoring programs can be integrated using these principles.

For the Reef, the world's largest reef ecosystem, ***representation*** means capturing processes that play out over hundreds to thousands of kilometres and among myriad species groups influenced by dozens of environmental variables. Further, significant environmental variation driving biological and ecological change in the system may play out over the course of weeks (e.g. cyclones, flood events), months (e.g. bleaching events) or years (e.g. crown-of-thorns starfish outbreaks). Here, an effective monitoring design in terms of representation would be one that that captures the dynamics of key system variables sufficiently to support monitoring (and ultimately management) objectives. To achieve this, the "system" needs to be by described by a subset of indicators deemed

[1] http://www.gbrmpa.gov.au/managing-the-reef/reef-integrated-monitoring-and-reporting-program

representative of key species groups, processes and values. As an example of a key indicator of reef system state we use coral cover and a coarse categorisation of benthic community structure. Coral cover, and in particular structurally complex corals, can be regarded a key indicator as structural corals provide essential habitats for a rich fish fauna (Jones et al. 2004, Emslie et al. 2014).

Precision and ***accuracy*** of monitoring data and metrics are required to be able to conclude whether a change to the system has occurred or not. Observer error and scoring technique can affect accuracy while spatial and temporal variation can affect precision. Precision and accuracy in combination with system understanding (captured by the model) define uncertainty. Sampling design and replication can compensate for reduced precision and accuracy up to a point. We provide examples to illustrate how differences in precision and accuracy can affect the power to detect change, and how formal consideration of precision and accuracy can assist in data integration between programs. Importantly, different monitoring objectives have different requirements for precision and accuracy. While the evaluation of management effectiveness (objective 4) requires power to detect an effect size of, for example, 10 per cent, status and trend reporting (objective 2) can be of higher uncertainty and still support decision-making (Regan et al. 2005). Indeed, high precision is required to detect any changes in rates of key processes (such as recovery from disturbance) that can trigger a management action. Uncertainty associated with situational awareness following a disturbance event (objective 1) and early warning (objective 3) depends on the management time frame and the decision problem. For an integrated monitoring program that consists of different sub programs which operate at different spatial and temporal scales and using different techniques, finding ways for these to complement each other in an overall design would make RIMReP more effective and cost-efficient. We provide examples to illustrate this and a decision tool to support the assignment of monitoring techniques to different objectives so that their integration can be optimised.

In summary, the specific objectives of this project are to:

1. ***Guide sampling effort*** in space and time to adequately represent status and trend in coral cover and communities (assemblages) on the Reef;
2. Assist in the ***attribution of observed changes*** in coral cover and communities to key environmental drivers and pressures (e.g. cyclones, bleaching, crown-of-thorns starfish, disease, water quality), resolving cumulative impacts in space and time;
3. Guide the ***integration of data*** from different monitoring programs (LTMP, Eye on the Reef, Catlin) to assess and report on ecosystem condition, including its uncertainty in space and time. This will include discussion of how fixed long-term and adaptive/reactive monitoring sites can be integrated in status reporting;
4. ***Inform trade-offs in monitoring design*** and participant programs driven by RIMReP objectives.

2.0 Current status of the Reef monitoring programs

In this section we provide a synthetic overview of the objectives, survey design and sampling methods of each coral reef monitoring program considered in this report. Table 1 summarises the representation of the Great Barrier Reef Marine Park (the Marine Park) bioregions across the different monitoring programs. Table 2 provides a summary of the spatio-temporal scales considered and sampling procedures used by each monitoring program. Note that specific reports are available for each program that fully detail the scope and specific methodologies used (see references thereafter). Our aim here is to provide a comparative overview of their main objectives and procedures for the purpose of informing how they are best integrated – i.e. made complementary.

2.1 Reef Monitoring program

The Reef Monitoring (RM) program is part of the Australian Institute of Marine Science (AIMS) Long-Term Monitoring Program (LTMP) that is designed **to provide information on population trends in key groups of organisms (particularly crown-of-thorns starfish, corals and reef fishes) on appropriate spatial scales over the length and breadth of the Great Barrier Reef World Heritage Area (the World Heritage Area)** (Sweatman et al. 2008). The specific objectives of the RM program are:

- to monitor the status and changes in distribution and abundance of reef biota on a large scale, and
- to provide environmental managers with a context for assessing impacts of human activities within the Marine Park and with a basis for managing the Reef for ecologically sustainable use.

Reef communities of the Reef have been monitored yearly between 1993 and 2005, and then biennially thereafter. As part of the LTMP, a total of 46 reefs were monitored for transect-based benthic covers between 1996 and 2015 in six latitudinal sectors (Cooktown-Lizard Island, Cairns, Townsville, Whitsunday, Swain and Capricorn-Bunker) spanning 150,000km^2 of the Reef. In each sector (with the exception of the Swain and Capricorn-Bunker sectors) at least two reefs were sampled in each of three shelf positions (i.e. inner, mid- and outer).

Transect-based data on benthic assemblages are collected at three sites separated by > 50 m within a single habitat on the reef slope (the first stretch of continuous reef on the northeast flank of the reef, excluding vertical drop-offs) (Figure 1). Within each site, five permanently marked 50-m long transects were deployed parallel to the reef crest, each separated by 10 m along the 6-9 m depth contour. Images were taken at 1 m interval and per cent-age cover of benthic categories were estimated for each transect using point sampling based on a random selection of 40 images out of the 50 images available (photo point intercept [PPI] method) (Jonker et al. 2008). The benthic organisms under five points arranged in a quincunx pattern in each image were identified to the finest taxonomic resolution possible (n = 200 points per transect) and the data were converted to per cent cover. In this study we considered the combined cover of all hard corals, thereafter referred to as hard coral cover (HC; per cent). The final transect-based data was averaged at the reef level, consisting of 729 reef surveys from 46 different reefs across the Reef. The entire perimeter of each reef is surveyed using manta tows, providing a reef-wide context for the intensive surveys. Surveys are conducted by a team of expert benthic ecologists from AIMS.

2.2 Representative Area Program

The Representative Area Program (RAP), also part of the LTMP, was initiated in 2006 with the specific objective of **examining the effects of the Marine Park rezoning (in 2004) on reef biodiversity**. The pattern of LTMP surveys was changed in 2006, so that the original core monitoring reefs were surveyed every other year (odd years), while in the alternate even years, a different series of reefs was surveyed. This involved surveying matched pairs of reefs, one of which was rezoned as a no-take area in 2004 while the other remained open to fishing. Six pairs of mid-shelf or outer shelf reefs with the appropriate zoning history were selected in each of four localities close to centres of population: Cairns-Innisfail, Townsville, Mackay and the Swain Reefs, and four pairs of reefs were selected in the Capricorn-Bunker Group. Thus sites on 56 reefs were surveyed in 2006 and on 46 reefs in 2007. The RAP surveys use the same procedures as those used to survey benthic communities in the RM program.

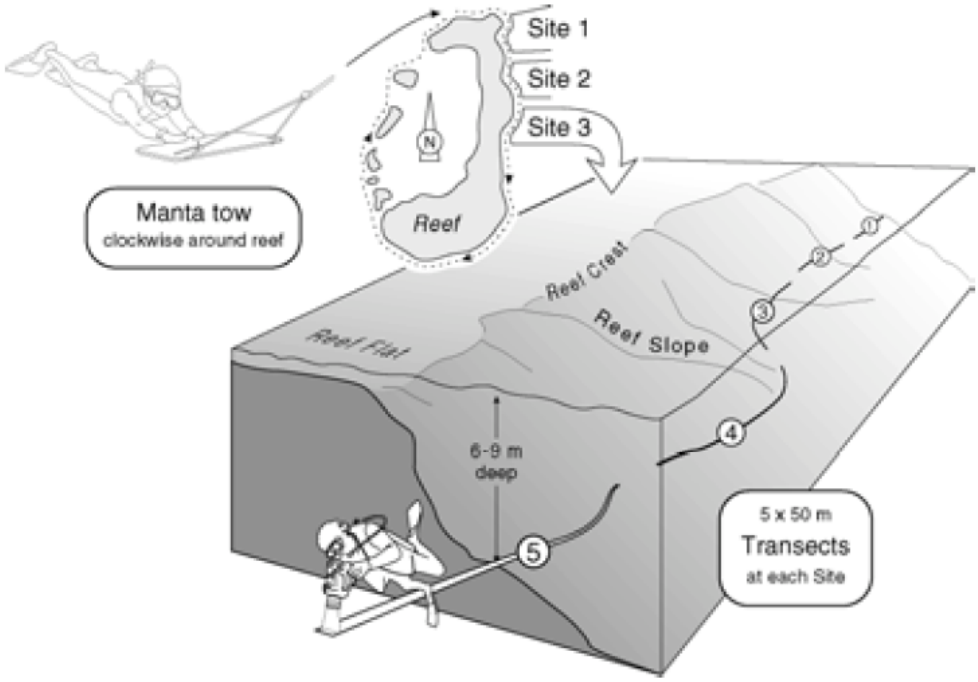

Figure 1. Schematic design of sampling efforts on a core survey reef from the LTMP (applies to both RM and RAP surveys) (Sweatman et al. 2008).

2.3 Marine Monitoring Program

The Marine Monitoring Program (MMP) was initiated in 2005 to assess trends in ecosystem health and resilience indicators for the Reef in relation to water quality and its linkages to end-of-catchment pollutant loads (Thompson et al. 2016). Specifically, the MMP aims to quantify temporal and spatial variation in the status of inshore coral reef communities in relation to local water quality changes. Reefs were designated as either 'core' reefs (N=14) or 'cycle' reefs (N=18), with a total of 32 reefs surveyed either annually (core) or biennially (cycle) from 2005 through to 2014. Since 2014 all reefs have been surveyed on a biennial basis. Throughout the time series, additional samples have been included to capture the effects of disturbances on reefs that where not scheduled for survey in a given year.

Two sites were selected at each survey reef to account for spatial heterogeneity of benthic communities within reefs. At each site, the structure and composition of benthic communities was quantified using the PPI method (Jonker et al. 2008), closely following the methods of the RM and RAP programs. At the same sites and as in the RM/RAP programs, scuba search transects were also conducted to document the incidence of disease and other agents of coral mortality and damage, and juvenile coral surveys were done to quantify coral recruitment and post-settlement survival (Thompson et al. 2016).

2.4 Reef Health and Impact Surveys

These surveys are conducted as part of the Authority's Eye on the Reef program. Reef Health and Impact Surveys (RHIS) are a means to provide a rapid snapshot of reef condition using a broad set of health and impact indicators (Beeden et al. 2014). The purpose is to provide synoptic data on reef health in places where, and at times when, long-term monitoring programs are not operating. RHIS surveys can complement long-term monitoring if designed and calibrated accordingly.

By 2016, a total of 4307 RHIS surveys were conducted across most of the Reef by a number of participants (Marine Park rangers, tourism operators, researchers and fishers). Importantly, because the design of RHIS surveys are situation-dependent, the spatial scope of the EotR program is growing. All participants in the Eye on the Reef program undertake a five-hour foundation training in addition to a full-day advanced in-water training. Later in this report we examine the role of observer bias in RIMReP's capacity to complement (and integrate with) long-term monitoring programs and its role in reporting and in providing decision support under RIMReP.

RHIS surveys consist of plots of 5-m radius (~78 m^2), typically conducted in triplicates. The plots are surveyed mostly by snorkelling in which observers estimate (by visual judgement) the relative abundance and health condition of a number of benthic groups (Figure 2) (Beeden et al. 2014). Specifically, observers collect a total of 178 data fields on reef health status, such as the total cover of live hard corals (split by growth forms), recently dead corals, soft corals, macroalgae, coral rubble and sand, in addition to the proportion of corals affected by coral bleaching, disease and crown-of-thorns starfish outbreaks and the type of habitat (e.g. reef flat, slope, crest, lagoon).

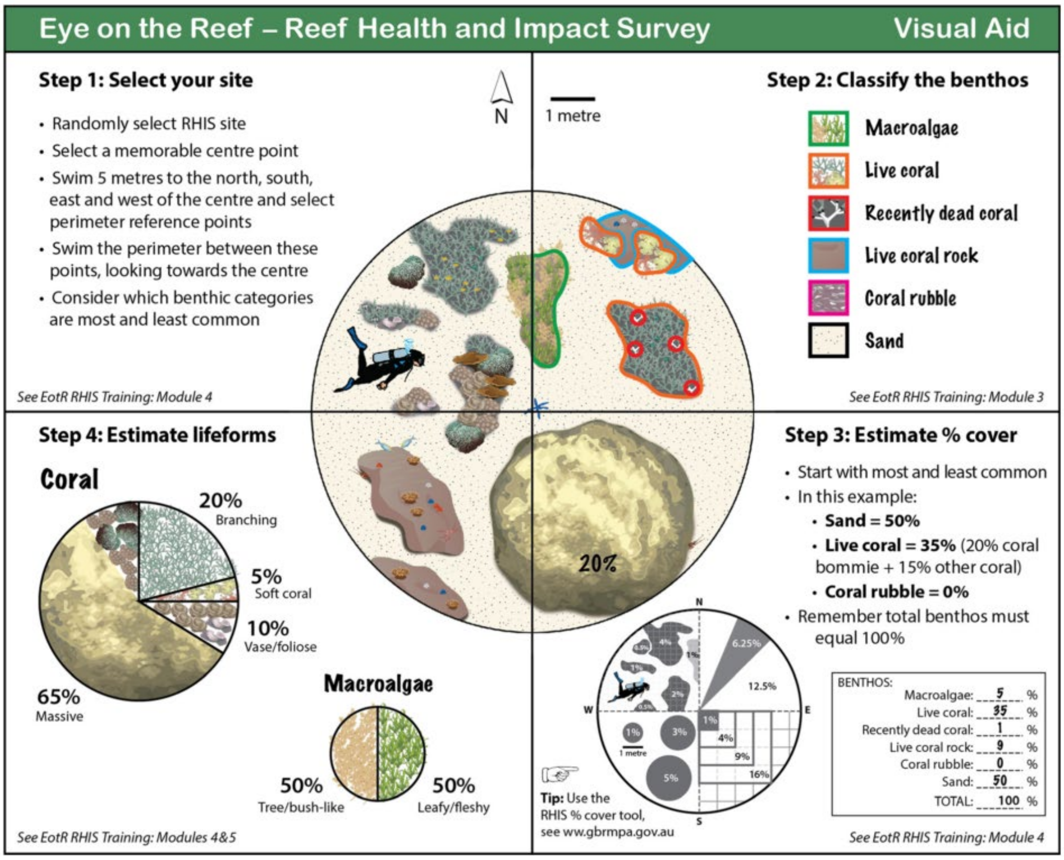

Figure 2. Synoptic overview of the Great Barrier Reef Marine Park Authority's Reef Health Impact Surveys

2.5 Catlin Seaview Surveys

The Catlin Seaview (CAT) surveys consist of large-scale monitoring of coral reefs using high-definition underwater imagery collected using customized underwater vehicles in combination with computer vision and machine learning (Gonzalez-Rivero et al. 2014). The CAT surveys started in 2012, surveying reefs of the Reef but also Coral Sea, Tropical Atlantic, Coral Triangle, Indian Ocean and Central Pacific.

CAT surveys are conducted across linear belt transects varying between 2 and 4m in width and 1.6 and 2 km in length. A customized diver propulsion vehicle holds three high-resolution and integrated digital cameras, offering a 360° view of the reef and covering about 2000m^2 per dive. The resulting imagery of the downward-pointing camera is analysed using an automated classification based on a Bayesian non-parametric approach (Coral Net, https://coralnet.ucsd.edu/) that estimates hard coral cover, the cover of different coral genera and functional groups with an accuracy ranging between 83-97 per cent.

Table 1. Distribution of the total number of survey sites in each monitoring program across the 28 bioregions within the Marine Park (see map in Appendix 1)

Bioregion	CAT	MMP	MANTA	RAP	RHIS	RM
Capricorn Bunker Mid Shelf Reefs			2	2	5	
Capricorn Bunker Outer Reefs	4		9	4	4	4
Central Open Lagoon Reefs		3			7	2
Coastal Central Reefs		4			17	
Coastal Far Northern Reefs				1	3	
Coastal Northern Reefs	3		1	17	119	9
Coastal Southern Fringing Reefs		4			28	4
Coastal Southern Reefs				1	7	
Coral Sea Swains-Northern Reefs		7	1		25	4
Exposed Mid Shelf Reefs	15		54		57	6
Far Northern Open Lagoon Reefs	2				24	2
Far Northern Protected Mid Shelf Reefs			3		62	4
Hard Line Reefs				6	29	
High Continental Island Reefs			5	2	7	2
High Tidal Fringing Reefs			3	3	55	3
Incipient Reefs			2		19	3
Northern Open Lagoon Reefs			12	7	53	3
Outer Barrier Reefs			28	2	17	2
Outer Shelf Reefs			15			
Sheltered Mid Shelf Reefs			33			
Strong Tidal Inner Mid Shelf Reefs			1			
Strong Tidal Mid Shelf Reefs (East)			4			
Strong Tidal Mid Shelf Reefs (West)			24		4	
Strong Tidal Outer Shelf Reefs			5		1	
Swains Mid Reefs			17		22	
Swains Outer Reefs			6			
Tidal Mud Flat Reefs						

Table 2. Summary of the current major reef monitoring programs on the Great Barrier Reef

Institute	Program	No survey locations	No survey reefs	Program start	Survey frequency	Survey objective	Main methods	Data collected	References
AIMS	RM	46	46	1993	1 year until 2005, 2 years thereafter	Document population trends in key groups of organisms (crown-of-thorns starfish, corals and reefs fishes)	Photo transects + expert-based classification	per cent cover of different benthic groups	Sweatman et al. (2008)
AIMS	RAP	45	44	2006	2 years	Assess the effect of Marine Park rezoning on reef biodiversity	Photo transects + expert-based classification	per cent cover of different benthic groups	Sweatman et al. (2008)
AIMS	MMP	32	23	2006	2 years	Assess trends in ecosystem health and resilience indicators with respect to water quality	Photo transects + expert-based classification	per cent cover of different benthic groups	Thompson et al. (2016)

AIMS	MANTA	-	270	1985	Variable	Document reef wide coral cover and crown-of-thorns starfish densities	Manta Tow surveys of reef perimeter	per cent coral cover, crown-of-thorns starfish densities, others	Miller et al.
The Authority	RHIS (Eye on the Reef	812	439	2009	Variable	Provide a snapshot of reef health at any time on any reef	Visual assessment within a 5-m radius circle by various participants	per cent cover of coral growth forms (live + recently dead) and per cent impacted by disturbances	[Great Barrier Marine Park Authority website]
UQ	Catlin Seaview Surveys	36	26	2012	2 years	Large-scale assessment of benthic community composition	Photo transects + automated image classification	per cent cover of hard corals, of different coral genera and functional groups	Gonzales-Rivero et al. 2014

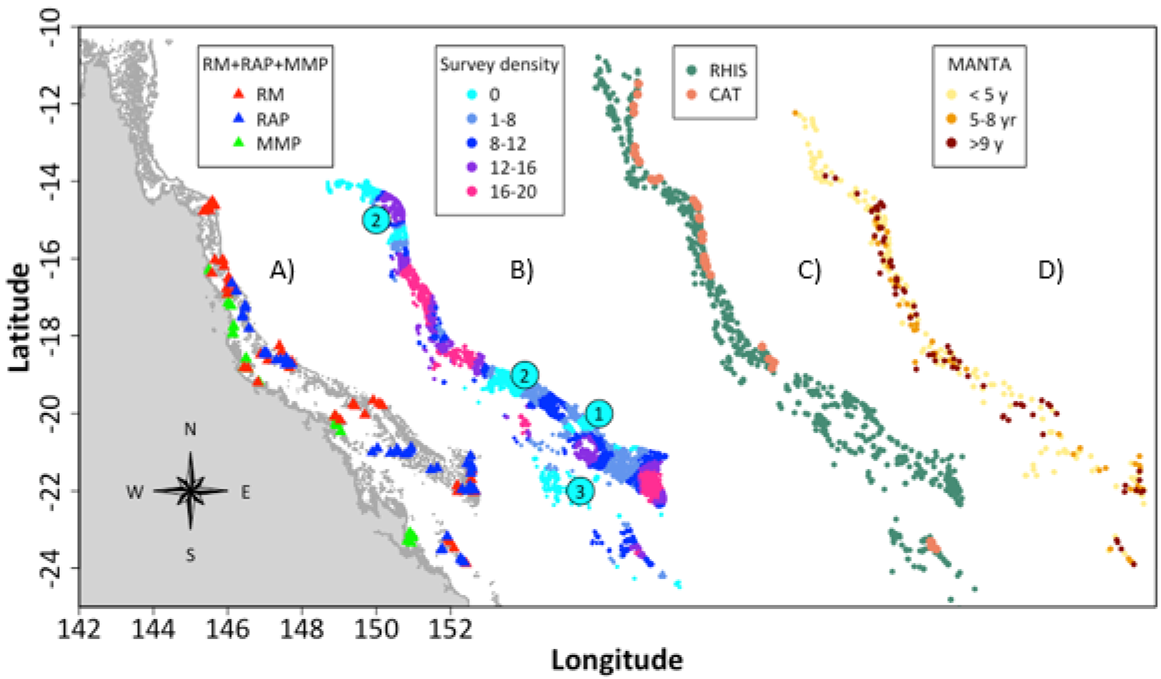

Figure 3 Survey locations for the current coral reef monitoring programs (A): location of the long-term monitoring program surveys, with RM: Reef Monitoring (AIMS), RAP: Representative Areas Program (AIMS), MMP: inner-shelf reef marine monitoring program (AIMS). (B): Survey density based on RM, RAP and MMP programs, calculated as the number of survey reefs within a 50-km radius. Low-density areas are represented in cyan and correspond to the following marine bioregions (based on the Authority bioregionalisation): (1) Coral Sea Swains Northern Reefs, strong tidal outer shelf reefs and hard line reefs; (2) outer barrier reefs, exposed mid shelf reefs and sheltered mid-shelf reefs and (3) incipient reefs. (C): Survey locations for the Catlin (CAT) and Reef Health and Impact Survey (RHIS). (D): Survey locations and number of years of data available for the manta tow monitoring program.

In summary, the LTMP documents long-term trends in the per cent cover of main taxonomic groups (RM), an assessment of management effectiveness (RAP) and of the effect of water quality on the biodiversity of inshore coral reef communities (MMP). Manta tow extends the coverage of the transect-based methods, providing synoptic long-term trends in reef-level cover and crown-of-thorns starfishpopulations. CAT surveys provide broad-scale assessments of benthic community composition and can directly complement LTMP if calibrated and if using fixed transects. RHIS surveys help provide situational awareness in areas, and during times, not captured by long-term monitoring programs and CAT.

Because RM/RAP/MMP surveys collect data at consistent spatiotemporal scales and levels of taxonomic description and are based on very similar methodologies, they are compatible (to some extent) for the purpose of modelling and statistical analysis. We thus used these data to calibrate the coral cover model, and manta tow as an independent validation dataset. The latter is justified because coral trends captured by fixed LTMP sites are closely reflected by manta tow data.

Although RHIS surveys do not explicitly quantify hard coral cover and do not use fixed-transect replicates over successive years, we illustrate how RHIS and RM/RAP/MMP can be made complementary in a RIMReP design as they address different monitoring (and management) objectives. For RHIS and CAT survey locations, we extracted model predictions for the entire study period (1996-2015) for each sampling location (Figure 3) and compared them with predicted trajectories of coral cover obtained for the RM/RAP/MMP survey reefs (Section 6).

3.0 Spatial model of hard coral cover

While data from a monitoring program can provide insights into patterns of change in an ecosystem, statistical models enable exploration of these patterns and allow inferences to be made about status and trends (Addison et al. 2015), and provide insight into how the system responds to management actions (Nichols and Williams 2006). Importantly, data from different monitoring programs can be difficult to compare because of different methodologies, spatial and temporal scales considered. Here, a unifying model of coral dynamics can help make the most of available data and assist in filling in the gaps where survey locations or years are missing. A system model is critical to provide a reference frame for a targeted monitoring program as it helps inform attribution of impacts (diagnostics), informs what replication and representation is required to detect changes, and to provide biological, ecological and environmental context for observed and predicted changes.

QUESTIONS AND OBJECTIVES

- We use a mechanistic model based on statistically derived parameters that integrates our current knowledge of coral-environment relationships, decline and recovery processes following multiple disturbances, and the influence of water quality on coral growth
- Derive high-resolution predictions of coral cover trajectories in response to disturbance between 1996 and 2015
- Quantify the relative influence of key environmental drivers and pressures on observed changes in coral cover and communities

MAIN RESULTS AND CONCLUSIONS

- The model predicted an average coral decline of -0.53 per cent y^{-1} across the Reef between 1996 and 2015, corroborating previous estimates and providing high-resolution maps of coral cover loss
- Cyclone severity was the main driver of coral loss, followed by crown-of-thorns starfish outbreak and bleaching. We note that recent bleaching events (2016-17) were not included in the analyses, so we likely underestimate bleaching impacts here
- Frequent river plume-like conditions had a negative effect on coral growth and recovery

PRODUCTS AND DELIVERABLES

- A high-resolution spatial model of hard coral cover using environmental layers as input variables
- A high-resolution map of benthic communities on the Reef (18 benthic clusters)
- An assessment and ranking of the main drivers of coral loss between 1996-2015

We used these model outputs as a framework to formulate recommendations on the design of a coral monitoring in the following sections of the report.

3.1 Overview of coral model

We developed a model of coral cover dynamics that accounts for the cumulative effects of multiple disturbances on the Reef and that allows us to reconstruct coral cover trajectories at a 0.01° resolution between 1996-2015 (Mellin et al. in review). This model explicitly accounts for the influence of habitat and environmental conditions on coral growth and recovery rates, benthic community composition and maximum coral cover at a given reef (i.e. carrying capacity). It does so by fitting species-environment relationships between coral characteristics derived from the LTMP transect-based observations and an extensive dataset of spatial features and environmental conditions on the Reef (Matthews et al. in review) using Boosted Regression Trees (Elith et al. 2008). A total of 33 spatial and environmental variables were compiled at 0.01° resolution and overlaid on the same spatial grid, and used as covariates in this model (Appendix 3).

The coral cover model incorporates the effect of past disturbances based on two components: (*i*) point-based records of coral damage collected concurrently with the LTMP surveys (Mellin et al. 2016) and (*ii*) spatial layers of disturbance history and associated severity across the Reef assembled from various data sources (Matthews et al. in review). Briefly, these layers included **bleaching** severity from aerial surveys after the 1998 and 2002 bleaching events (Berkelmans et al. 2004), **crown-of-thorns starfish** densities interpolated from the manta tow data collected by the AIMS in every year between 1996 and 2015 (Miller and Müller 1999, Miller et al. 2009). The potential for **cyclone** damage was estimated based on reconstructed sea state as per Puotinen et al. (2016). This model predicts the incidence of seas rough enough to severely damage corals (top one-third of wave heights >4m) caused by cyclones between 1996 and 2015. These layers are described in detail (Matthews et al. in review).

We also used exposure layers of river runoff, a proxy for the inundation of reefs with nutrients or sediment. Based on satellite observations during the 2005-2013 wet season, these layers represent the frequency (number of weeks), at approximately 1 km resolution, of primary, secondary and tertiary river plumes (Devlin et al. 2012, Alvarez-Romero et al. 2013). Primary water captures the turbid, sediment dominated parts of the plume, secondary water captures the chlorophyll-dominated parts of the plume and tertiary water captures the furthest extent of the relatively clearer parts of the plume. Here we pooled the three layers and captured the frequency of inundation of any plume water, expressed as a proportion of total wet season weeks. Current Status of [thematic area/value] Systems on the Reef.

3.2 High-resolution maps of benthic community composition

We identified a total of 18 benthic communities based on the habitat and environmental conditions they were associated with. These communities were defined based on multivariate regression trees (MRT) that form clusters of sites by repeated splitting of the data, with each split determined by habitat characteristics (De'ath 2002) and corresponding to a distinct species assemblage (i.e. ‘leaf’ of the tree) (Figure 4). Each community can be characterised by its indicator taxa, i.e. benthic groups that are significantly more represented in this community (Dufrêne and Legendre 1997) and by its average coral growth rate as predicted by the model. We then used the resulting MRT to predict community membership for every 0.01° grid cell on the Reef based on the spatial layers of spatial and environmental covariates (Figure 5).

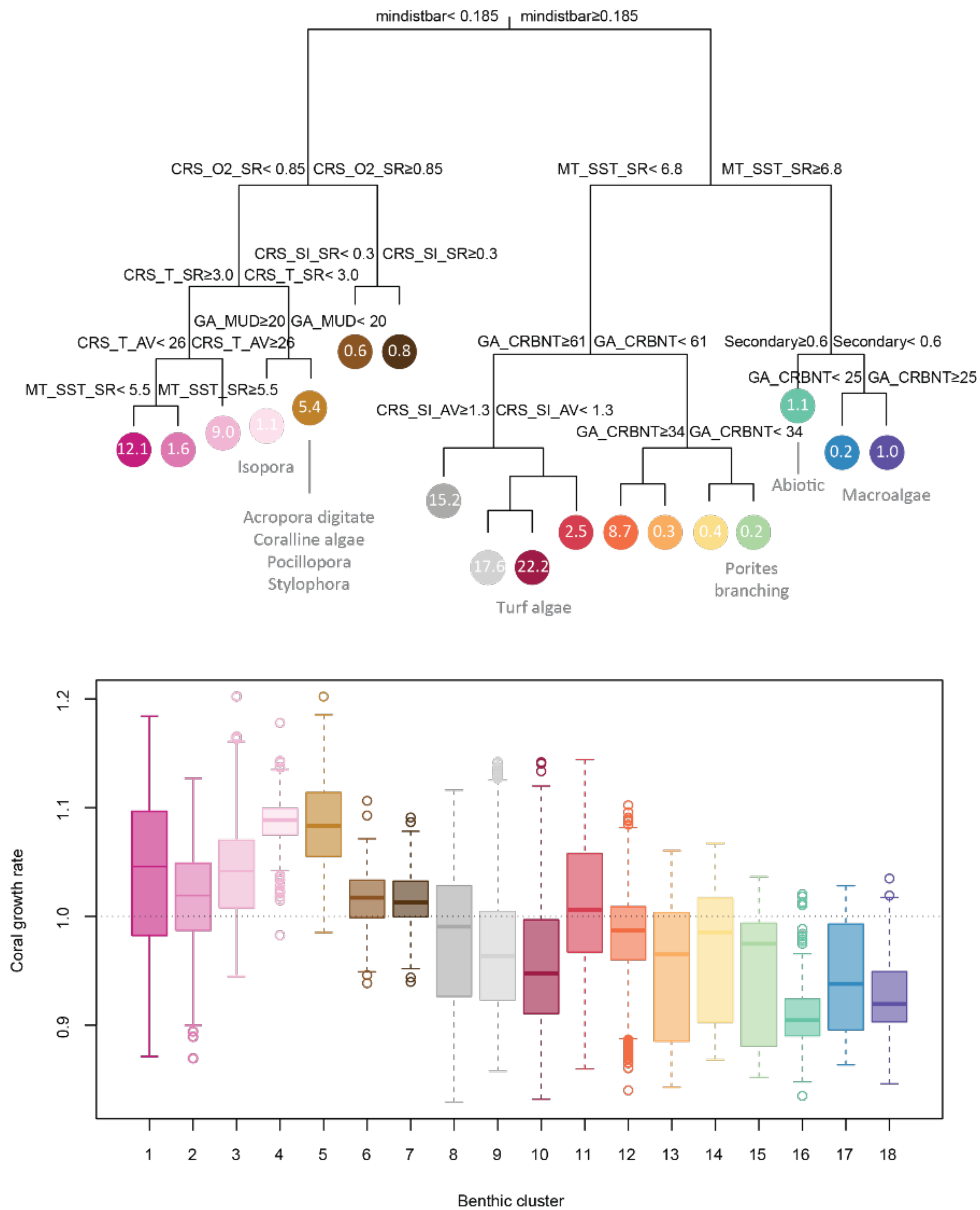

Figure 4. Benthic communities were defined across the Great Barrier Reef based on multivariate regression trees. Environmental covariates defining the splits of the tree are detailed in Appendix 3

The distance to the barrier reef edge (*mindistbar*) was the main determinant of benthic communities. Here, outer shelf communities with faster coral growth rates (communities 1-7) were distinct from inner and mid-shelf communities with slower growth rates (communities 8-18). Indicator taxa are indicated on Figure 4 where applicable.

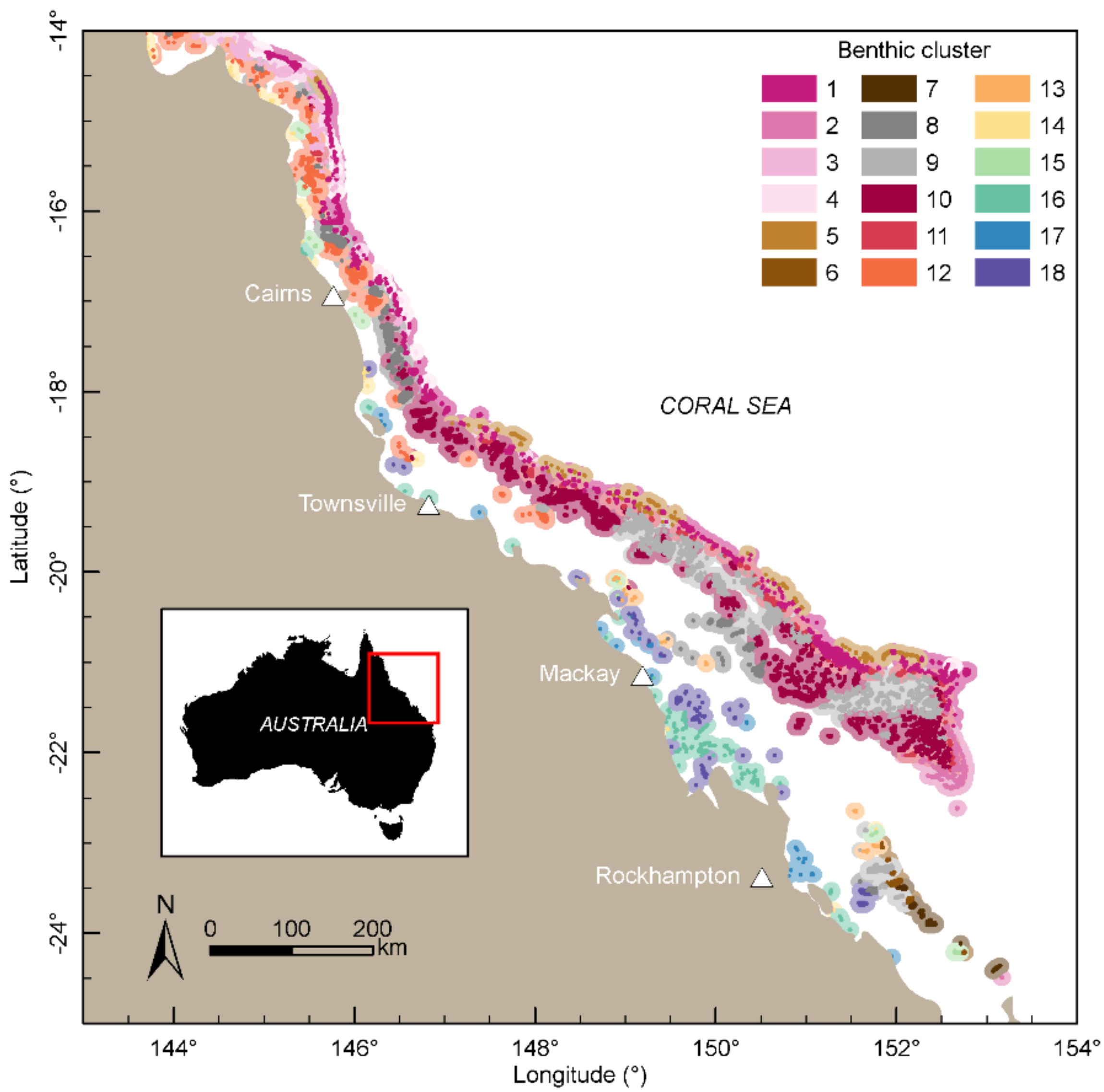

Figure 5. Benthic communities mapped at a 0.01° resolution across the Great Barrier Reef based on multivariate regression trees (Figure 4)

By combining high-resolution estimates of initial (1996) and maximum coral cover, coral growth rates, disturbance history and water quality, our model allowed us to reconstruct trajectories of coral cover between 1996 and 2015 and at a high resolution across the Reef (Mellin et al. in review). The resulting predictions also highlighted different degrees of coral cover decline and exposure to cumulative disturbance (Figure 6).

We calculated an index of model uncertainty based on the geographic distance between each pixel where predictions were derived, and the number of reefs and years for which we had *in situ* observations of hard coral cover. Model uncertainty is therefore the lowest for reefs located in the vicinity of clusters of survey reefs with >10 years of data (i.e. higher confidence in model predictions on Figure 6).

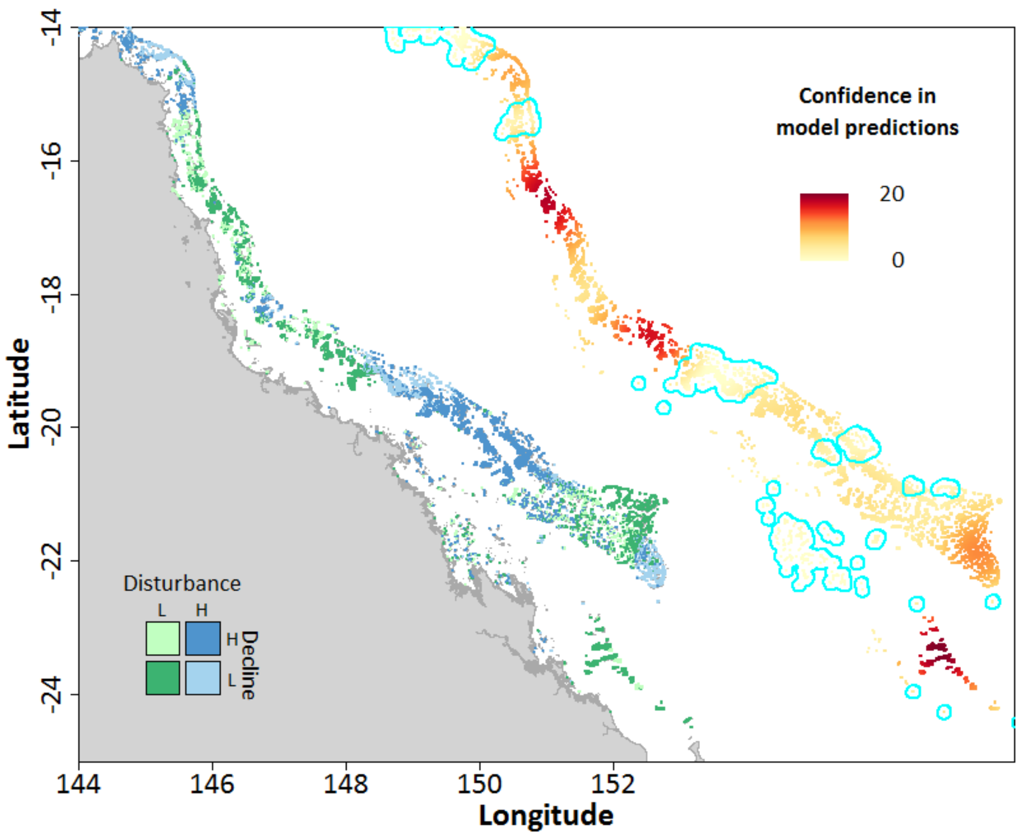

Figure 6. ***(Left)*** **Spatial patterns in coral cover decline as predicted by the model and the cumulative effect of multiple disturbances including crown-of-thorns starfish outbreaks, tropical cyclones and bleaching events on the Reef between 1996 and 2015.** For both decline and disturbance, low/high categories correspond to value below/above the median. (*Right)* index of confidence in model predictions. The index increases in the vicinity of multiple reefs surveyed for >15 years and where fewer reefs and/or years have been surveyed. The cyan envelopes show areas unmonitored by the RM, RAP and MMP monitoring programs (as per Figure 3).

3.3 Attribution of observed changes in coral cover and communities to key environmental drivers and pressures

We evaluated the relative effect of multiple disturbances and water quality on coral decline and recovery in two ways:

1. Effect sizes (posterior densities) for each disturbance and water quality level determined based on the Bayesian hierarchical model of coral growth and post-disturbance recovery, calibrated for the 46 reefs surveyed by the LTMP
2. Sensitivity analysis at the Reef -scale, quantifying the effect of disturbance frequency on the Reef-wide coral cover loss predicted by the model.

Table 3. Gompertz model parameters: source, description, mean and standard deviation across the calibration dataset. With BRT: boosted regression trees; HLM: hierarchical linear model.

Code	Variable	Mean	Standard deviation
$\boldsymbol{\beta_i}$	Disturbance effect sizes		
	• Bleaching	-0.19	0.01
	• *Crown-of-thorns starfish* outbreaks	-0.54	0.04
	• Cyclones	-0.64	0.01
	• Disease	-0.13	0.01
	• Unknown	-0.16	0.01
$\boldsymbol{\beta_{WQ}}$	Water quality effect size	-0.68	0.03

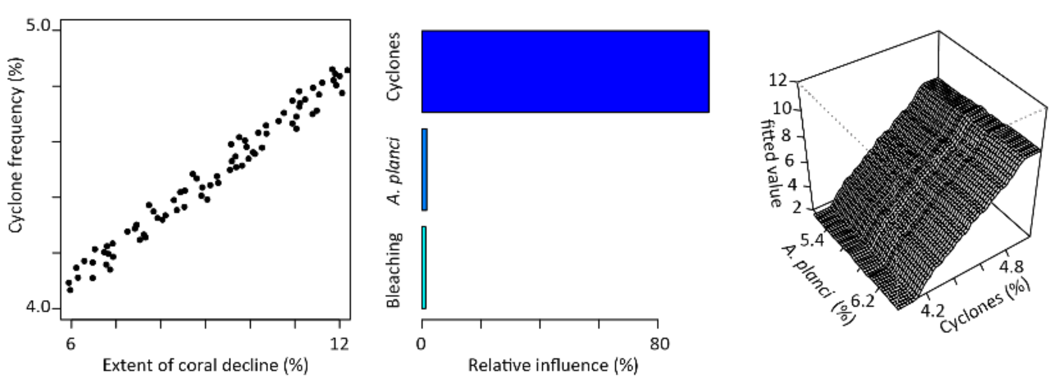

Figure 7. Sensitivity analysis quantifying the importance of disturbance frequency on predicted coral decline *(Left)* Scatter plot showing the mean extent of predicted coral decline across the Reef (per cent) as a function of cyclone frequency (per cent). *(Middle)* Relative influence (per cent) of the frequency of each disturbance on predicted coral decline across the Reef. *(Right)* Interaction between cyclones and crown-of-thorns starfish outbreak frequencies and its effect of the extent of predicted coral decline.

This analysis showed that:

- Cyclone severity (measured as the duration of destructive waves generated by cyclones) had the strongest effect on hard coral cover, followed by crown-of-thorns starfish outbreaks and bleaching (Table 3). Water quality (i.e. the frequency of river plume-like conditions) had a strong negative effect on hard coral growth.
- Our sensitivity analysis indicated that, when disturbance frequencies were altered by ± 10 per cent, the Reef-wide magnitude of coral decline varied from 9.6 per cent (at lower disturbance regimes) to 13.3 per cent (at higher disturbance regimes). Among all disturbances, cyclone severity had the largest relative influence on our predictions of coral cover (BRT relative importance = 98 per cent) (Figure 7). We also found a weak interactive effect of cyclone and crown-of-thorns starfish outbreak frequencies on overall patterns of predicted coral decline, with this effect being greatest at higher frequencies of both cyclones and crown-of-thorns starfish outbreaks (Figure 7).

It is important to bear in mind that these results are determined by the data used to calibrate the model, namely the long-term monitoring program between 1996-2015, for which the effects of bleaching were relatively minor compared to those measured in other datasets and in 2016-2017.

4.0 Environmental representativeness of the current reef monitoring

QUESTIONS AND OBJECTIVES

- Evaluate the extent to which the current reef monitoring programs represent the diversity of environmental conditions and reef habitats on the Reef
- Identify habitats that are under- (or over-) represented in the current reef monitoring design

MAIN RESULTS AND CONCLUSIONS

- 40 per cent of all reef habitats are currently represented by RM, RAP and MMP survey programs. Including the manta tow program extends coverage to 45 per cent, while the addition of RHIS and Catlin surveys gives a total coverage of 60 per cent of all reef habitats.
- Three main reef habitats ([1] Coral Sea Swains Northern Reefs, strong tidal outer shelf reefs and hard line reefs; [2] outer barrier reefs, exposed mid shelf reefs and sheltered mid-shelf reefs and [3] incipient reefs) are not currently surveyed and correspond to environmental conditions that are distinct from any other surveyed regions, suggesting that benthic communities could also be specific to these unsampled/unknown areas.

PRODUCTS AND DELIVERABLES

Map and list of unmonitored reefs corresponding to distinct environmental conditions from monitored ones.

We represented the diversity of reef habitats and environmental conditions on the Reef, and identified its main environmental correlates using a principal component analysis (PCA). We considered the grid cells of our study area as the individuals (N = 12,670) and a selection of all environmental correlates available (Appendix 1) as the explanatory variables. To this aim, we selected 10 environmental correlates that minimized multi-colinearity and maximized the variation explained by the first two axes of the PCA. We also represented benthic clusters and the different monitoring programs as illustrative factors, and colour-coded the individual plans based on these factors. Finally, we added grid cells corresponding to unmonitored habitats to assess how these differed from monitored habitats from an environmental perspective.

This analysis showed that temperature, salinity, primary productivity, depth and sediment cover explained 61.7 per cent of all environmental diversity based on the first two PCA axes (Figure 8). The individual plan basically splits offshore communities (benthic clusters 1-9) on the negative side of PCA2 (with strong tidal outer shelf reefs in light brown on the negative side of PCA1), and inshore communities on the positive side of PCA1 (with incipient reefs in green corresponding to the highest values) (top left panel of Figure 8).

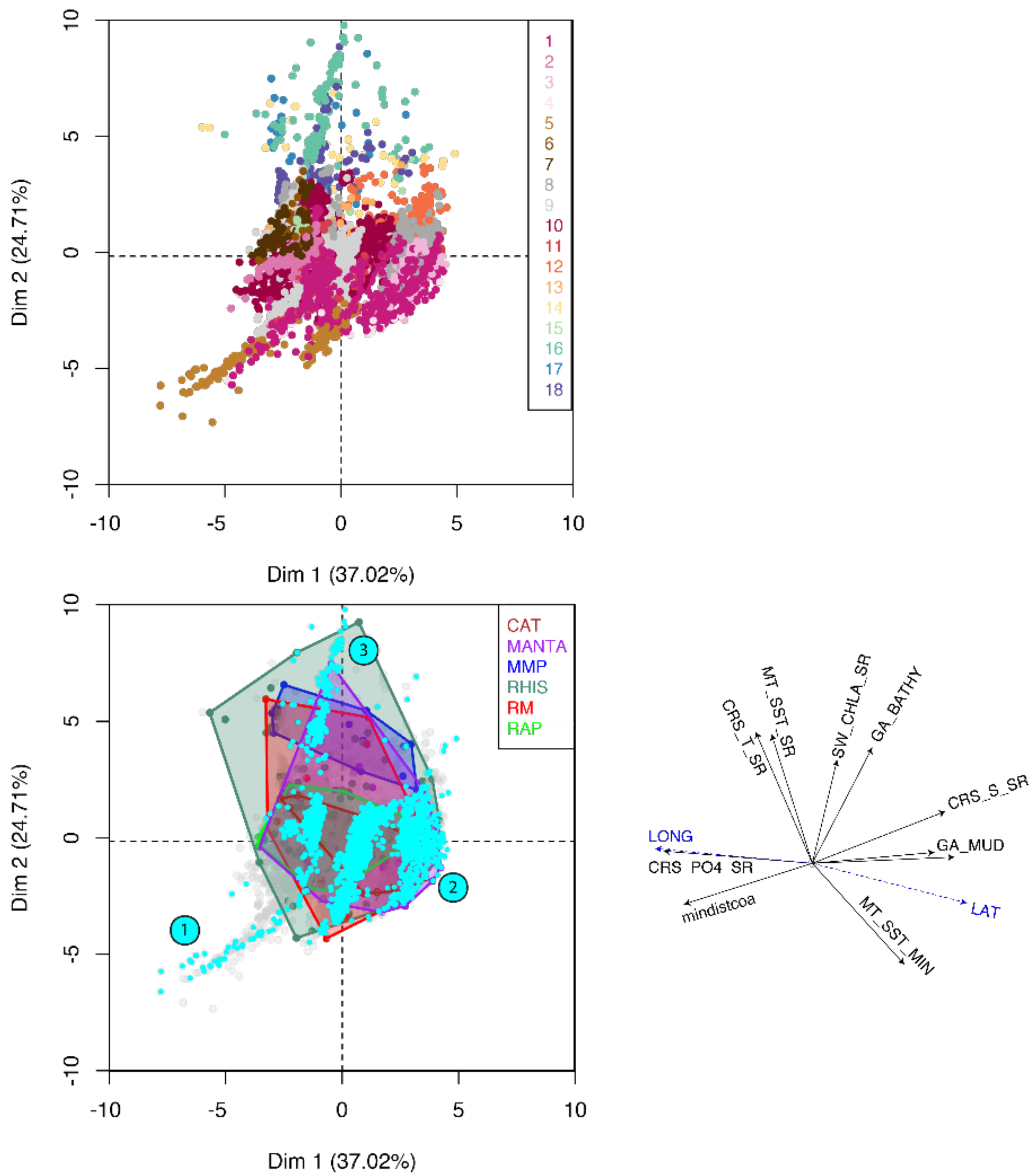

Figure 8. Principal component analysis of all Great Barrier Reef grid cells based on the main environmental covariates. Top left: individual factorial plan, with colour coding for the benthic cluster (as per Figure 4). Bottom left: individual factorial plan with colour and convex hulls coding for the survey program, and cyan dots showing grid cells characterised by low survey density (as per Figure 3). Bottom right: variable factorial showing environmental correlates mostly contributing to the overall variability and minimizing multicolinearity. Variable codes are indicated in Appendix 1 and spatial patterns are shown in Appendix 2.

Mapping the diversity of environmental conditions represented by the different monitoring programs (convex hulls on bottom left panel of Figure 8) indicated that 40.1 per cent of the environmental diversity of the Reef was represented by a combination of the RM, RAP and MMP programs. Areas under-represented by these monitoring programs included (1) Coral Sea Swains Northern Reefs, strong tidal outer shelf reefs and hard line reefs; (2) outer barrier reefs, exposed mid shelf reefs and sheltered mid-shelf reefs and (3) incipient reefs (refer to Figure 3 for their location). Manta tow, RHIS and Catlin monitoring programs represented 34.2, 60.1 and 9.2 per cent of all environmental diversity respectively, with a total of 60.4 per cent represented by all monitoring programs combined.

Areas that are currently not monitored by any programs and characterised by distinct environmental conditions include some of the strong tidal outer shelf reefs (area 1 on Figure 3).

5.0 Disturbance representativeness of the current reef monitoring

QUESTIONS AND OBJECTIVES

- Identify reefs that have been mostly exposed to coral bleaching, crown-of-thorns starfish outbreaks and cyclones, (i.e. disturbance hotpots) along with temporal trends in hotspot occurrence over the last 30 years (increasing/decreasing), and compare with distribution of survey reefs
- Among disturbance hotspots (especially those increasing over time), identify areas that have been under- or unmonitored

MAIN RESULTS AND CONCLUSIONS

- Major hotspots of cyclone activity have remained unmonitored by the RM/RAP/MMP programs in the central Reef, but have been surveyed by manta tow and RHIS to some extent

PRODUCTS AND DELIVERABLES

Map of disturbance hotspots and temporal trends over the last 30 years (1985-2015).

We identified hotspots of disturbance over the last 30 years based on an Emerging Hotspot analysis in ArcGIS. This analysis uses time series of disturbance severity in each 0.01° grid cell (as described in section 3.1) between 1985 and 2015 to quantify the per cent time a grid cell was considered a hot or cold spot. Other outputs of this analysis include a classification of the type of hotspots based on temporal trends relative to the present-day conditions (e.g. new/persistent/intensifying/diminishing hot or cold spot).

The disturbance hotspot analysis indicated that the northern section of the Reef, as well as the Capricorn Bunkers and the inshore reefs of Broad Sound (incipient reefs) were all major hotspots of coral bleaching between 1985-2015 based on Degree Heating Data (Figure 9). However, the central and southern sections of the Reef were major hotspots of crown-of-thorns starfish outbreaks (based on total crown-of-thorns starfish densities). The central section of the Reef was a hotspot of cyclone activity during this period (corresponding to the intersection between cyclones hitting the northern and southern parts of the Reef respectively) along with the southern section of the Swains reefs. When all disturbances were combined, the sector encompassing reefs between Cairns and Townsville recorded the highest disturbance severity (Figure 9).

Overlapping areas unmonitored by the RM, RAP and MMP programs (cyan outlines on Figure 9) revealed that **the major hotspot of cyclone activity in the central Reef has not been monitored by the RM/RAP/In programs**, and also corresponded to relatively high crown-of-thorns starfish densities on average (based on information collected during manta tow surveys). This area has been monitored by manta tow since the 1980s. Based on the map of cumulative disturbance hotpots, it appears that areas of highest disturbances between Cairns and Townsville were to some extent covered by the RM, RAP and MMP programs. Unmonitored areas in the northern, central and inshore section were nevertheless characterised by intermediate disturbance due to bleaching and cyclone activity.

If such spatial patterns are maintained over the next decades, this analysis suggests that **the new reef monitoring would benefit from additional sites in areas mostly exposed to disturbances** in order to capture the response of benthic communities to such disturbance. Manta tow and RHIS sites exist in these areas (Figure 3) that could help complement the current RM/RAP/MMP programs.

To further examine whether the current long-term monitoring sites adequately sample the full range of frequency of exposure of the reefs of the Reef to cyclones, we first reconstructed the extent to which sea conditions become energetic enough to damage reefs (significant wave heights (Hs) >= 4m). This was done for each cyclone that crossed the Reef from 1985 to 2017 (updated for 2016-2017 from Puotinen et al 2016). From this time series we mapped the return time (years) of damaging seas across the Reef (Figure 10). Short return times (>5 years: red bars; 5-10 years: orange bars) indicate reefs that may not be able to recover between cyclone events. Long return times (30+ years: blue bars) indicate reefs that would almost always be able to recover between cyclone events.

Further, we then calculated the per cent of the total area of reef across the Reef in each of eight classes of cyclone exposure frequency (top histogram of Fig. 10). The per cent of LTMP sites located in each of the same classes were then calculated (bottom histogram of Fig 10).

Results of this analysis showed that 3.4 per cent of the Reef's reef area is exposed to damaging seas very frequently (at least once every 5 years - red bar). However, no LTMP sites are currently located within these areas. More importantly, 19 per cent of the reefs in the Reef are very infrequently exposed to cyclones (return intervals >= 30 years – dark blue bar) with a further 5.5 per cent never having been exposed over the past 32 years (grey bars). However, only 2 per cent of the LTMP sites (n=19) sample within these areas, with none in the far north.

In conclusion, no LTMP sites are located within the damaging wave zone (as per Puotinen et al 2016) for 12 per cent (6 of 48) cyclones that crossed the Reef from 1985 to 2017. Based on this analysis, the current spatial design of LTMP sites can miss an entire cyclone.

We note, however, that while historical patterns of cyclone activity may provide some insight into regional cyclone behaviour, they do not predict future patterns and risks. Therefore, for the purpose of a spatial monitoring design, we recommend that the above analysis be complemented by the spatial cyclone risk maps developed by Wolff et al. 2018, which combines historical cyclone patterns with simulated paths forced by climate models.

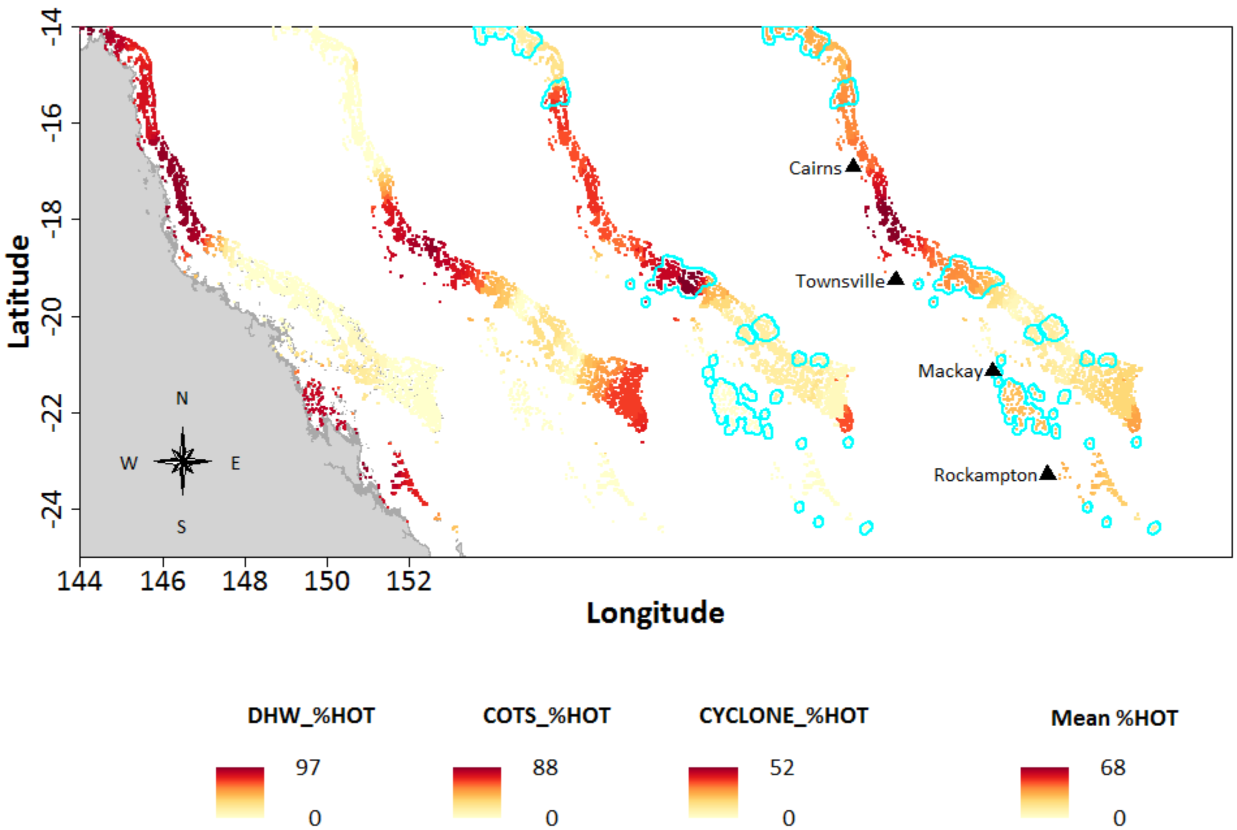

Figure 9. Disturbance hotspot analysis based on degree heating weeks (an index of coral bleaching risk), Crown-of-thorns starfish densities, cyclone severity and all three disturbances combined. For each map, the heat colour scale represents the per cent time a grid cell was classified as a hotspot over the study period (1996-2015). The cyan envelopes show areas characterised by a low survey density based on the RM, RAP and MMP monitoring programs (as per Figure 3).

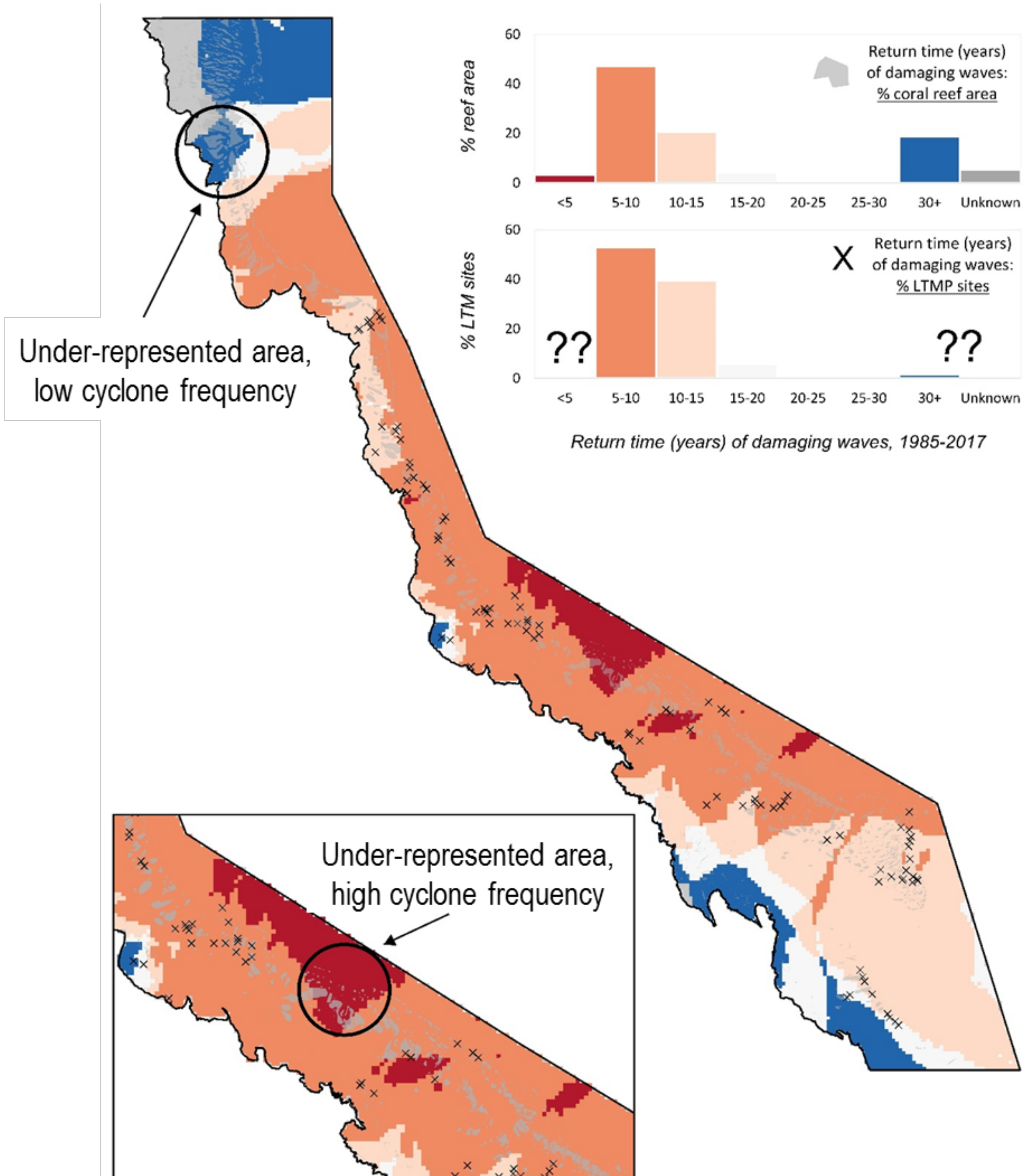

Figure 10. Assessment of how well the current spatial arrangement of LTMP sites captures the frequency of reef exposure to damaging waves from cyclones on the Great Barrier Reef based on the time series 1985-2017. Analysis by Marji Puotinien.

6.0 Ecological complementarity of current monitoring

QUESTIONS AND OBJECTIVES

- Among current survey sites, identify those that convey redundant information about reef environmental/ecological conditions
- In contrast, identify survey reefs that are unique/irreplaceable based on these criteria

MAIN RESULTS AND CONCLUSIONS

- A classification of all reefs was established based on their predicted coral cover trajectories, with reefs belonging to a same trajectory cluster (N=20 clusters) predicted to have similar trajectories
- There is potential redundancy between reefs of similar benthic community composition and similar coral cover trajectories over the last 20 years (identified by combining the two clustering methods)

PRODUCTS AND DELIVERABLES

A dual classification of all reefs on the Reef (including current survey reefs) based on their (i) benthic community composition and (ii) coral cover trajectory

We identified groups of reefs with similar coral cover trajectories between 1996 and 2015 across the Reef based on a functional principal component analysis (fPCA). Like a classic PCA, the fPCA identifies the main axes explaining variation among individuals, however here the individuals are the reef-level trajectories. Based on the scores of each reef on the first five axes of variation, it is then possible to conduct a hierarchical clustering of all reefs based on their coral cover trajectories.

We subsequently characterised each cluster of reefs with similar trajectories based on several statistics including the total number of reefs and reef area covered; minimum, maximum and mean coral cover between 1996 and 2015, as well as its inter-annual variation (standard deviation); average coral growth rate; predicted change in coral cover and cumulative index of disturbance over the study period; and an index of disturbance severity for bleaching, crown-of-thorns starfish outbreaks and cyclones.

Finally, we combined this clustering based on coral cover trajectories (N=20 clusters) with the previously defined benthic clustering (N=18 clusters) to identify similar reefs based on both coral cover trajectory and benthic composition.

Results indicate that reef clusters based on coral cover trajectories were strongly structured across the shelf and latitudinal sectors (Figure 11). With 15 per cent of all reefs, cluster 14 covered the northern and central sections of the Reef (N=239) and corresponded to average trends at the Reef scale (average decline: -10 per cent between 1996 and 2015) (Table 4). Reefs for which the strongest decline was predicted (cluster 7: -21 per cent coral cover between 1996 and 2015) corresponded to the area previously identified as a major hotspot of cyclone activity, which has remained unmonitored. The greatest inter-annual variation was observed for cluster 6 (Swains) and 13 (Capricorn Bunkers), characterised by severe disturbances from which reefs mostly recovered (Figure 11).

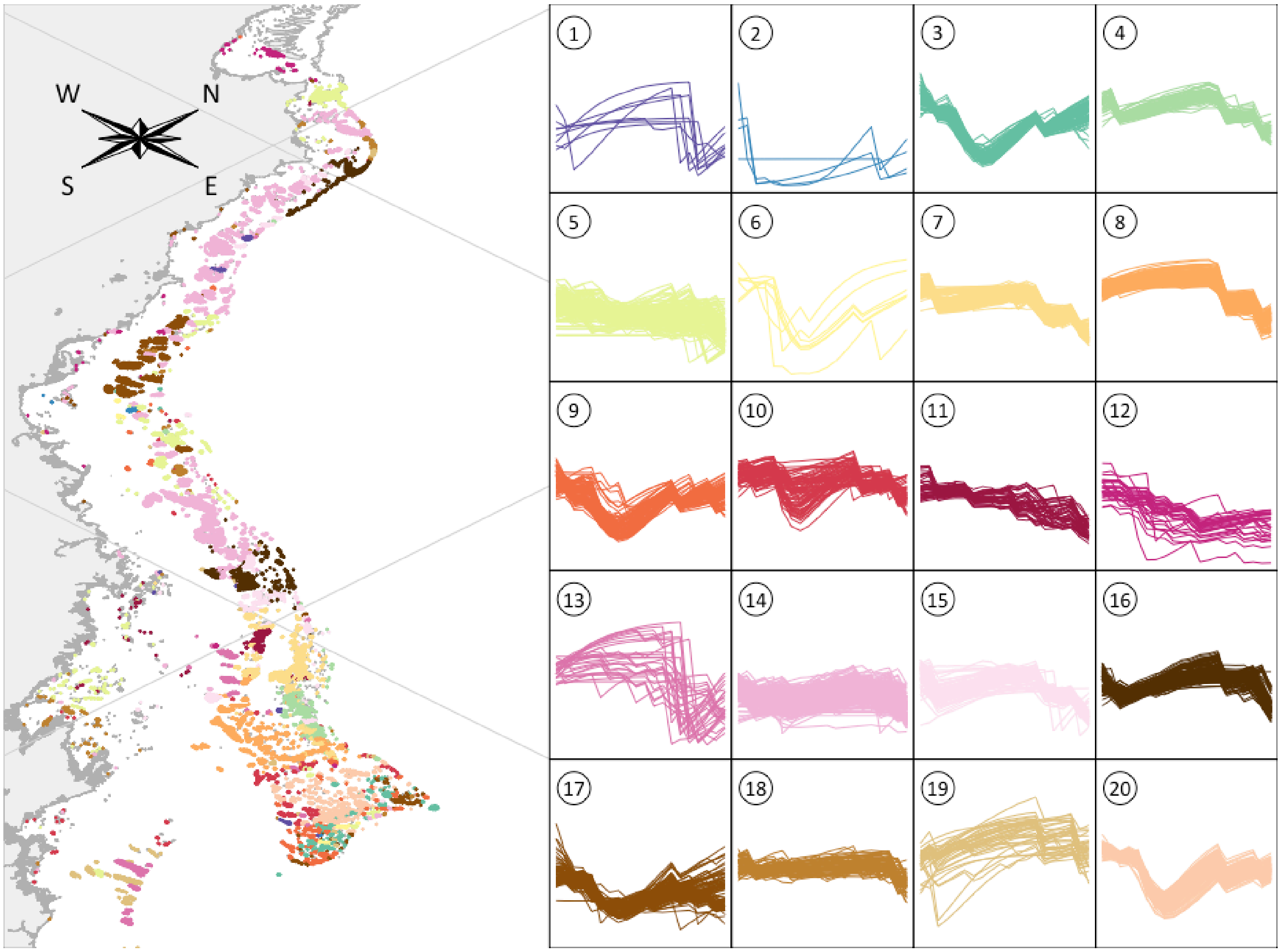

Figure 11. Clustering of all reefs on the Great Barrier Reef based on their coral cover trajectory predicted by the model over the study period (1996-2015) *LEFT*: spatial distribution of all clusters (N=20). *RIGHT*: coral cover trajectories predicted for the 20 clusters (x-axis: year from 1996 to 2015, y-axis: per centcoral cover from 0 to 80 per cent).

Reefs that belonged to the same cluster based on both benthic community composition and coral cover trajectory displayed very similar responses to disturbances, as observed *in situ* and predicted by the model (Figure 12). For example, several reefs from the Capricorn Bunkers currently surveyed by multiple monitoring programs (e.g. Fairfax Islands Reef, Lady Musgrave Reef, One Tree Reef etc) were characterised by the same initial increase in coral cover, which remained stable between 2003 and 2008 despite mild disturbances, and followed by a steep decrease corresponding to severe cyclones between 2009 and 2011.

Given such high level of similarity in the post-disturbance response of multiple reefs characterised by similar benthic community composition and coral cover trajectory, our analysis suggests that the survey reefs that compose these groups could convey redundant information, and that their number could potentially be reduced without a great loss of information. However, if benthic group clustering changes under climate change and/or local stressors, then this redundancy could ensure sufficient replication and representation in a future monitoring program. The number of reefs required to capture temporal trends in coral cover is currently being investigated using a power analysis (P Menendez, A Thompson). Cluster membership for all reefs surveyed by the RM, RAP and MMP monitoring programs is given in Appendix 4 and provides a basis for potentially stratifying and resampling the existing survey reefs to reduce their numbers in the new monitoring design.

Table 4. Characteristics of reef clusters based on their predicted coral trajectories (see Figure 11) Nreefs = total number of reefs, TArea_km2: total area (km2), HCmin: minimum coral cover, HCmax: maximum coral cover, HCmean: mean coral cover, HCsd: inter-annual standard deviation in coral cover, b0: average hard coral growth rate, delta: net change in coral cover between 1996-2015, disturb: combined index of disturbance severity between 1996-2015 including bleaching, crown-of-thorns starfish outbreaks, storms; B: index of bleaching severity, C: index of crown-of-thorns starfish outbreak severity; S: index of storm severity between 1996-2015.

Cluster	Nreefs	TArea_km2	HCmin	HCmax	HCmean	HCsd	b0	delta	disturb	B	C	S
1	8	94	8.55	36.92	27.07	9.03	0.95	-6.02	338.55	1	1	2
2	4	25	1.31	29.54	9.59	7.74	0.91	-16.31	795.24	5	4	1
3	78	300	9.11	41.44	27.30	9.74	1.02	-7.14	748.45	3	5	1
4	56	509	25.70	43.24	37.91	4.84	1.00	-13.24	858.72	2	2	4
5	141	967	18.42	35.22	29.51	4.72	0.98	-11.85	756.25	5	3	3
6	7	60	9.92	46.47	28.93	11.89	1.02	-4.20	682.42	1	5	1
7	121	1019	17.25	41.52	34.52	6.58	0.95	-21.27	1039.84	2	3	5
8	108	984	25.63	45.67	40.37	6.18	0.93	-13.51	715.02	2	2	4
9	82	361	13.33	40.14	28.41	8.13	1.00	-6.35	710.64	3	5	2
10	80	309	27.48	46.76	39.98	5.81	1.00	-8.68	591.30	4	4	3
11	40	232	11.27	37.90	29.79	7.65	0.90	-20.13	881.28	5	3	4
12	30	142	14.70	35.03	23.61	7.18	0.96	-16.95	844.04	4	4	4
13	29	421	11.29	45.75	35.29	11.49	0.96	-16.30	533.96	3	4	3
14	239	3399	18.50	31.90	26.88	3.70	1.01	-9.47	717.42	4	3	3
15	81	616	13.97	37.68	31.10	6.45	0.99	-18.00	1093.74	4	2	5
16	102	872	20.16	38.99	33.52	5.04	1.07	-11.72	992.22	4	2	5
17	90	1021	10.42	32.48	22.49	6.82	0.97	-8.01	645.43	4	5	2
18	63	275	29.66	40.54	36.92	3.00	0.98	-8.12	707.47	5	2	3
19	40	353	32.99	52.72	45.90	5.94	1.02	4.50	341.02	4	1	1
20	132	711	13.88	42.59	31.49	8.77	1.00	-9.19	616.55	2	5	2

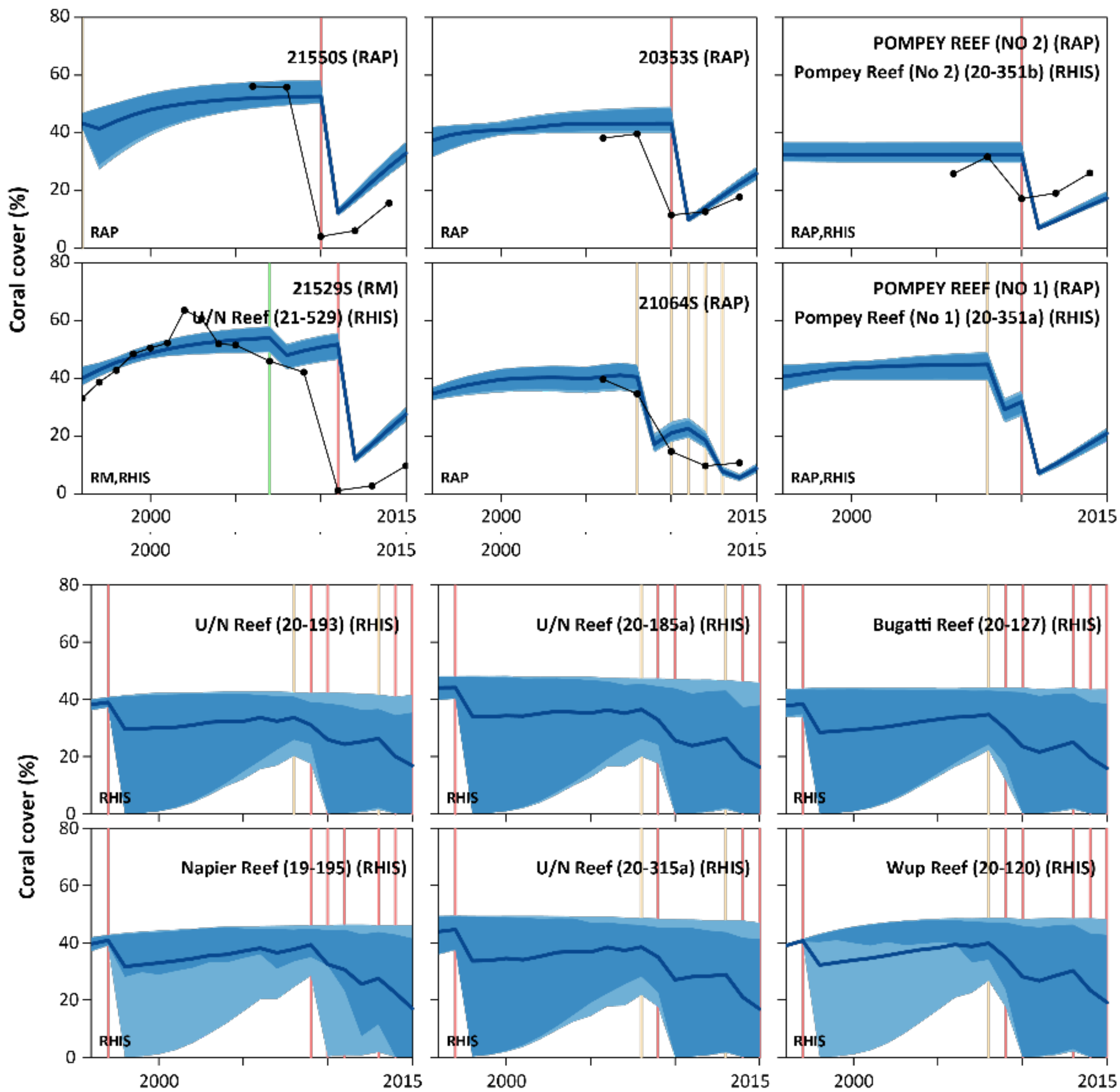

Figure 12. Predictions (blue envelopes) and observations (black dots) of coral cover for tree groups of reefs (top, middle and bottom) belonging to the same clusters based on both benthic community composition and coral cover trajectory.

7.0 Sampling design and accuracy of coral cover estimates

QUESTIONS AND OBJECTIVES

- How can RHIS surveys complement long-term monitoring programs such as LTMP?
- How can these programs be integrated under RIMReP?
- Simulations were conducted to illustrate the role of precision, accuracy and habitat consistency in the ability of RHIS surveys to assess reef condition (RIMReP objective 1 above) and thereby complement long-term monitoring such as AIMS LTMP.

MAIN RESULTS AND CONCLUSIONS

- Spatial heterogeneity of coral distribution across the sampled reef area drives down precision of coral cover estimates if using random sampling. This can be compensated for in part with additional replicates, but not to the extent that it obtains the precision of fixed sites.
- For RHIS, variation of up to 40 per cent among trained observers in a structured comparison indicated low capacity to estimate coral cover and hence reef state. The additional health indicators scored by RHIS, however, makes it a valuable tool for providing situational awareness between long-term monitoring surveys and can help LTMP better attribute impacts to causes.
- If *in situ* judgment of coral cover (and bleaching or other estimates of condition) can be replaced with photos and subsequent image analysis, then RHIS could have similar accuracy to AIMS LTMP and Catlin Seaview Surveys.

PRODUCTS AND DELIVERABLES

- We recommend that a branch of the Eye on the Reef program uses images rather than completing *in situ* score cards. This will greatly increase the accuracy of scores.
- This analysis led to the design of a decision tool to help evaluate and assign monitoring programs to their different objectives under RIMReP, which we present in the next section (Figure 15).

7.1 The scope for RHIS to assess coral cover under RIMReP

We used data from a joint Authority/AIMS monitoring campaign on Wheeler Reef in 2012 that sought to compare how three techniques performed when estimating the abundance of benthic groups including coral cover: RHIS scores, RHIS with photos and LTMP transects. These data used here focus only on the RHIS data.

To analyse the effect of observer error and spatial heterogeneity on coral cover estimates in more detail, we produced spatial simulations of coral cover in reef areas measuring 100 x 100 m (Figure 13). We generated two areas with high and low levels of coral-cover heterogeneity, respectively.

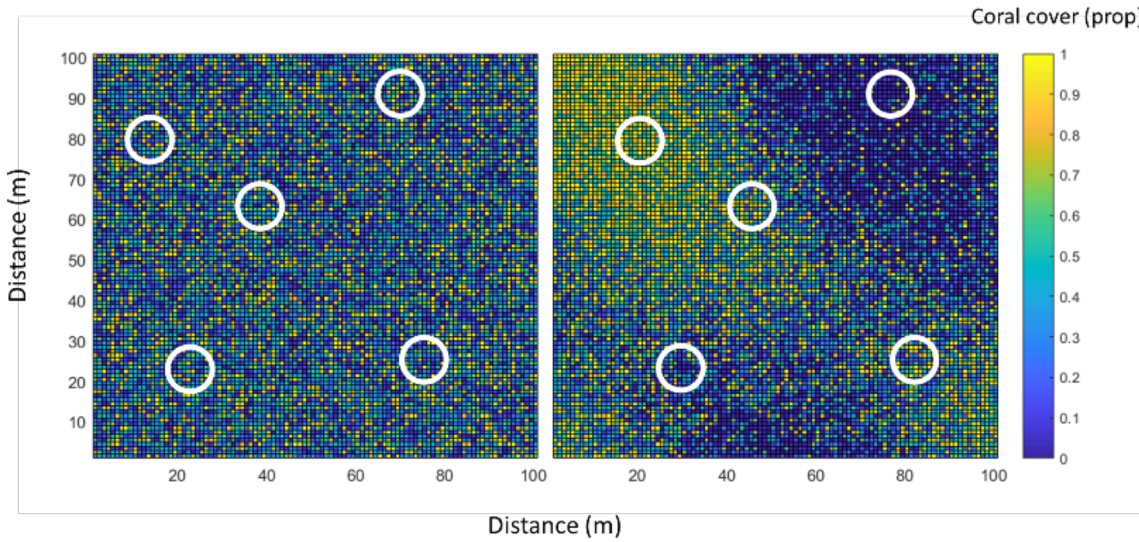

Figure 13. Examples of simulated spatial distributions of coral cover used to examine effects of observer error and sampling technique on the reporting of coral condition in homogeneous (left) and heterogeneous (right) reef habitats. These simulated environments were used to explore the relative importance of observer accuracy and habitat variability in enhancing precision. White circles illustrate one random placement of RHIS plots (5 m radius circles).

7.2 Effects of observer error and habitat

Table 5 presents the variation among six trained observers scoring coral cover estimates for RHIS plots on six reef sites on Wheeler Reef in 2012 (source: Great Barrier Reef Marine Park Authority). In summary, the mean estimate of coral cover within a site can vary from 12 per cent to 39 per cent among trained observers. We use these data in combination with the simulated reef terrains in Figure 13 to analyse the extent to which observer bias and coral patchiness affect the accuracy and precision of coral monitoring using RHIS in a random spatial design. For the purpose of illustration, we use the highest observer error (40 per cent) as a bookend, and then compare with simulations that use an observer error of 2 per cent, characteristic of photographic surveys. We run simulations 100 times for different levels of replications (1-10 plots).

Table 5. Summary results of RHIS surveys at Wheeler Reef in 2012 by joint Authority/AIMS monitoring team All observers where trained, but used visual assessments of coral cover.

Mean coral cover (per cent)	Sites						
Observers	1.1	1.2	1.3	1.4	2.1	2.2	Grand mean
Obs1	35	30	20		14	10	22
Obs2	20		35	24	15	10	21
Obs3	35		20	26	9	14	21
Obs4	45	15	15		8	6	18
Obs5	40	44	20	40	25	10	30
Obs6	45	45	20	40	18	19	31
Grand Total	37	33	22	32	15	11	24
Standard Dev	9	14	7	9	6	5	5
Coeff of var (per cent)	25	39	19	24	17	12	15

Under 40 per cent observer error, and in a reef terrain with high spatial heterogeneity, the variation around the mean was only marginally greater (Panel A) than under 2 per cent observer error (Panel B) (Figure 14). This demonstrates the high error associated with random sampling in spatially variable habitat (broad habitat representation compromises precision).

In the homogeneous reef terrain, the variation around the mean for simulations using the 40 per cent observer error (Panel C) was about 5 times greater than for simulations using 2 per cent observer error (Panel D). Here, precision is strongly driven by accuracy.

In both cases, additional samples can compensate for observer error in the low range of samples (2-5). For larger sample sizes, however, increasing replication provides diminishing returns as precision becomes set by the inaccuracy of observers, spatial variation, or both.

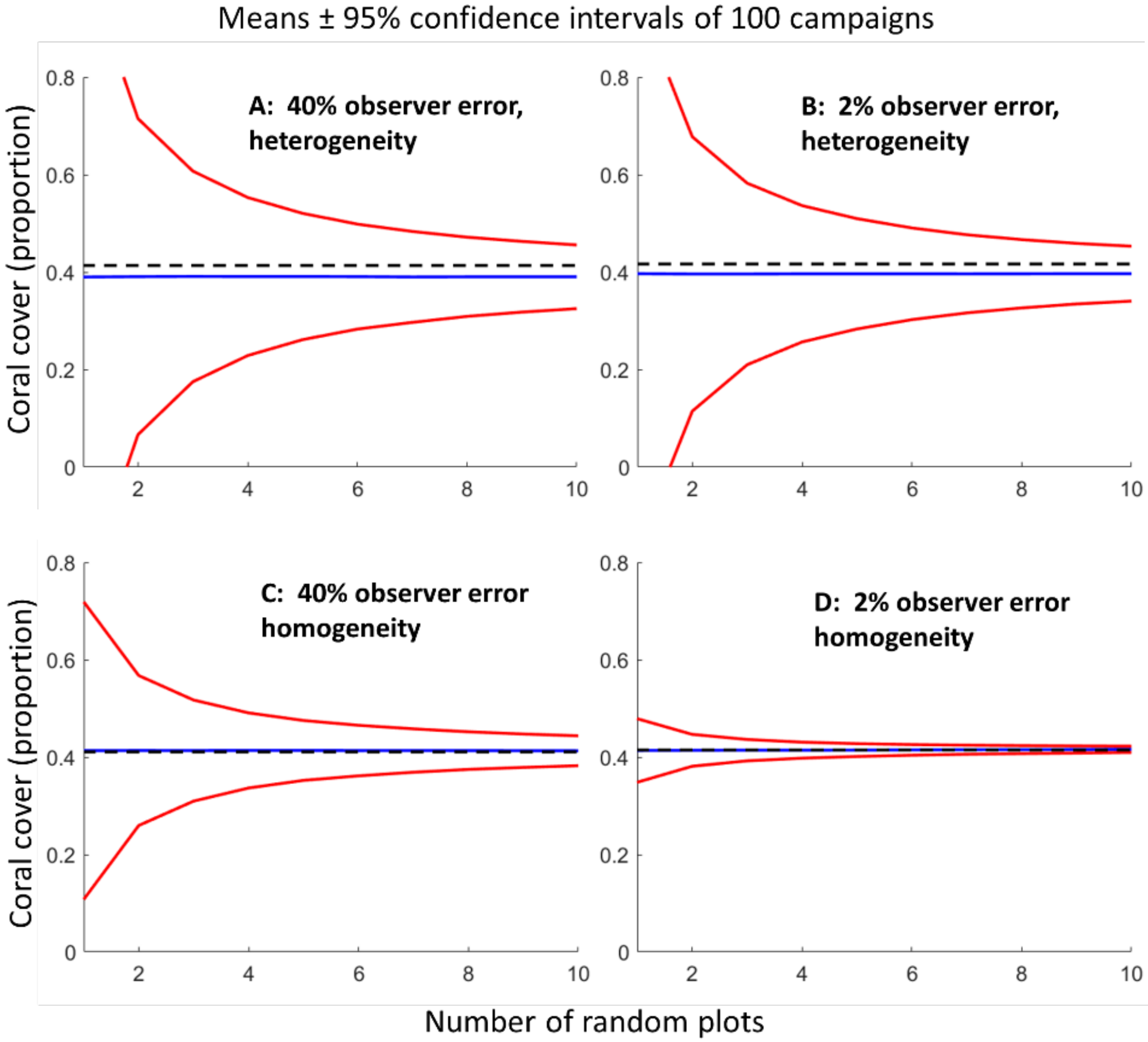

Figure 14. Precision analyses for RHIS plots using simulated terrains with contrasting spatial variation in the distribution of coral cover and contrasting levels of observer error Confidence bands are 1.96 x standard error of the mean of 100 simulations (campaigns) using varying number of plots in each campaign (x-axis). The dashed horizontal line is the true mean and the solid line is the estimated mean. Source: Anthony et al. in prep.

This section should describe the outcomes of the evaluation of the adequacy of existing monitoring activities/programs on the Reef. The adequacy of current monitoring and modelling will be determined by their ability to meet the objectives of RIMReP and information needs of Reef managers (see above).

The evaluation should consider the adequacy of the sampling methods, spatial and temporal resolution, and statistical power of existing monitoring programs that monitor the priority indicators to achieve the objectives and requirements of RIMReP (i.e. what can current monitoring programs tell us, and how confident are in what they say). If possible, this section should describe the level of accuracy required and the magnitude of changes that are relevant for managers and that RIMReP should be able to detect. This will inform the spatial and temporal sampling strategy and the methods used.

7.3 Gaps in current monitoring effort

This section should identify and discuss gaps and opportunities in current monitoring and modelling of priority indicators. Describe potential mechanisms to fill gaps and capitalise on opportunities.

8.0 Matching monitoring programs to monitoring objectives

A key challenge for RIMReP will be to reconcile the varying characteristics of different monitoring programs. Monitoring integration is more about assigning individual monitoring programs to tasks they are fit for (i.e. addressing different monitoring objectives), than about attempting to blend data streams. For example, RHIS surveys used in response to disturbances and fixed LTMP sites are opposite extremes in terms of accuracy, precision and representation, however they both perform well for what they were designed for: RHIS as a rapid means to provide situational awareness following disturbances; and LTMP as a means to assess long-term ecosystem changes and attribute changes to impacts and management actions.

Below we propose that the rules by which a monitoring program is assigned to a monitoring objective will be a combination of how well it meets criteria around accuracy, precision, representation and complementarity. We first propose how such a rule set can inform decisions about program allocation to specific monitoring objectives.

Based on the Authority's RIMReP Strategy[2], four operational monitoring objectives can be identified (see also introduction):

1. Provide situational awareness (e.g. following disturbances)
2. Detect changes and trends (and attribute to drivers and pressures)
3. Provide early warming, and
4. Evaluate management effectiveness (e.g. assess if Reef 2050 is working)

[2] https://issuu.com/gbrmpa/docs/rimrep_program_strategy_booklet

We approach this allocation problem using a decision tree in which accuracy, precision and representation form the basis for determining whether a monitoring program or technique can inform objectives (Figure 15). We contend that accuracy (e.g. observer bias) and precision determine whether a monitoring program is suited to only provide broad situational awareness following disturbances, or whether it can help detect change and attribute that change to a source.

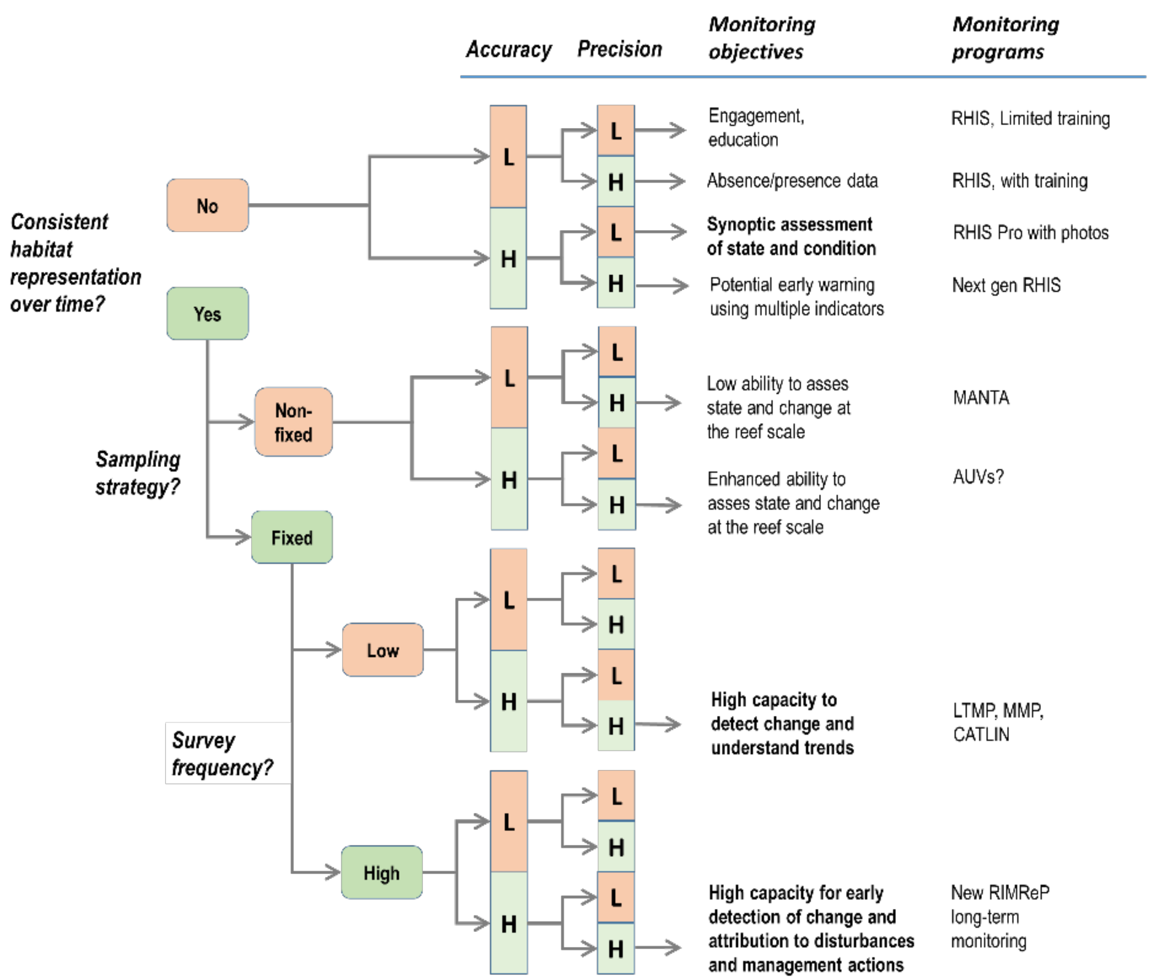

Figure 15. Decision tree to inform the allocation of monitoring programs to RIMReP objectives (bold) based on a hierarchy of attributes. L and H indicate low and high, respectively. Catlin surveys are here grouped with current LTMP and MMP under the low sampling frequency, but intervals between Catlin surveys are longer. Note also that early detection of change in coral cover (early warming) is only strictly possible in the most rigorous category (bottom branch of the tree). However, synoptic surveys using RHIS that estimate multiple resilience indicators with high accuracy and precision (suggested as a

next-generation RHIS under RIMReP), could complement information from the long-term monitoring. Source: Anthony, Logan, Thompson, Menendez, Gonzalez-Riviero and Ortiz (in prep).

In the previous simulation exercise, we illustrated that relatively small changes in how RHIS surveys are conducted and with what technique (observer vs photos) can shift these from being a coarse instrument to one that can provide detailed insight.

For the purpose of long-term monitoring, habitat consistency and the use of fixed as opposed to random sites (assuming high accuracy and precision and consistent habitat representation) determine whether change can be detected (objective 2) or not (again assuming high accuracy and precision). Lastly, because disturbances on the Reef are increasing in frequency and severity (e.g. Anthony 2016; Hughes et al. 2017, Wolff et al. 2018), recent LTMP analyses demonstrate that a high temporal frequency is now necessary to enable impact attribution from disturbances as well as management actions – that is, enable management effectiveness to be evaluated (objective 4).

Based on this decision tree and the attribution of different capacities to each monitoring programs, we suggest that RHIS and LTMP surveys could be coupled such that RHIS could provide broad-scale situational awareness to identify where and when more detailed LTMP surveys are required to document the impact on community state and recovery (Figure 16). In this scenario, a set of core reefs would continue to be monitored annually by the LTMP (e.g. Reef A; Figure 17). At other reefs (e.g. Reef B; Figure 17), the coral model could be used as an infill when no major disturbance occurs – when one does, RHIS could document the extent and severity before detailed LTMP surveys are conducted on that reef to document disturbance impact on benthic communities and their recovery.

It is, however, essential to bear in mind that RHIS can only complement, not substitute, fixed-transect and detailed benthic surveys.

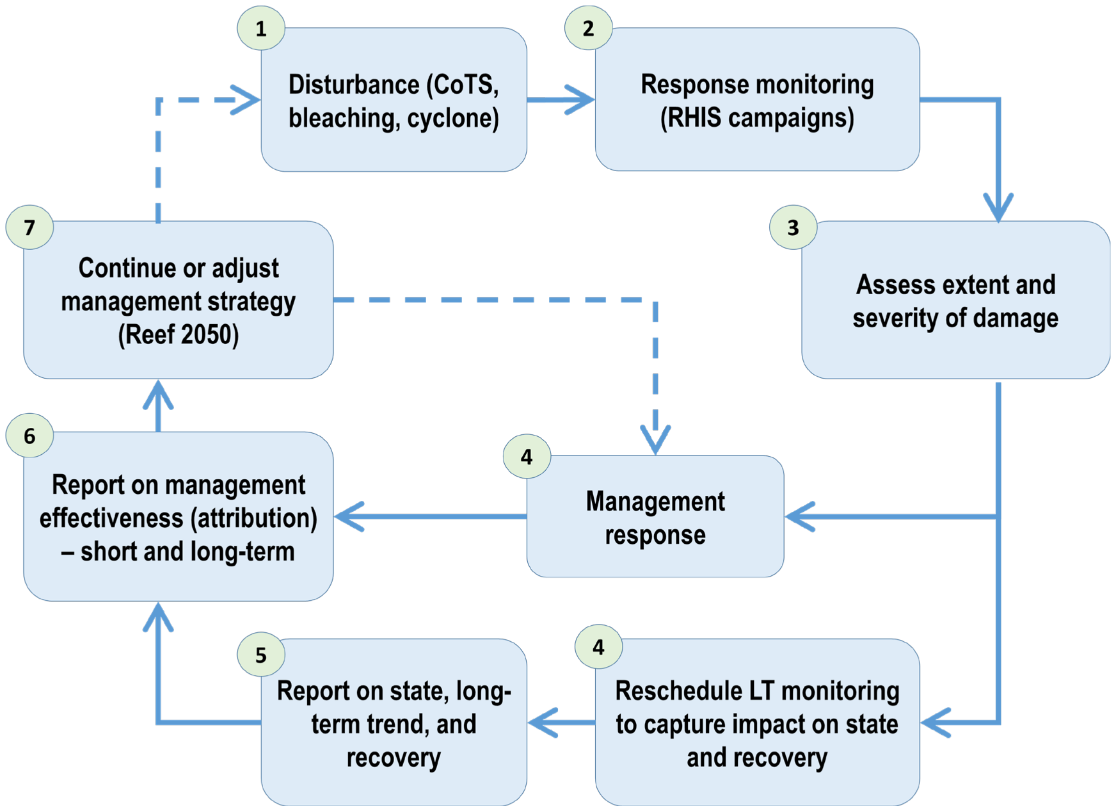

Figure 16. Proposed separation of tasks by response (RHIS) and long-term (LT) monitoring following a disturbance (time step 1) under RIMReP Here, RHIS provides key situational awareness (steps 2 and 3) and triggers two processes in step 4: a management response, and a rescheduling of long-term monitoring so the impacts of the disturbance are captured (e.g. start point for monitoring of recovery is reset). Results of LT monitoring and the management response are then reported (steps 5 and 6) and used to adjust and inform the management strategy (7). Consideration of chronic disturbances such as water quality are assumed implicit in management strategy and response.

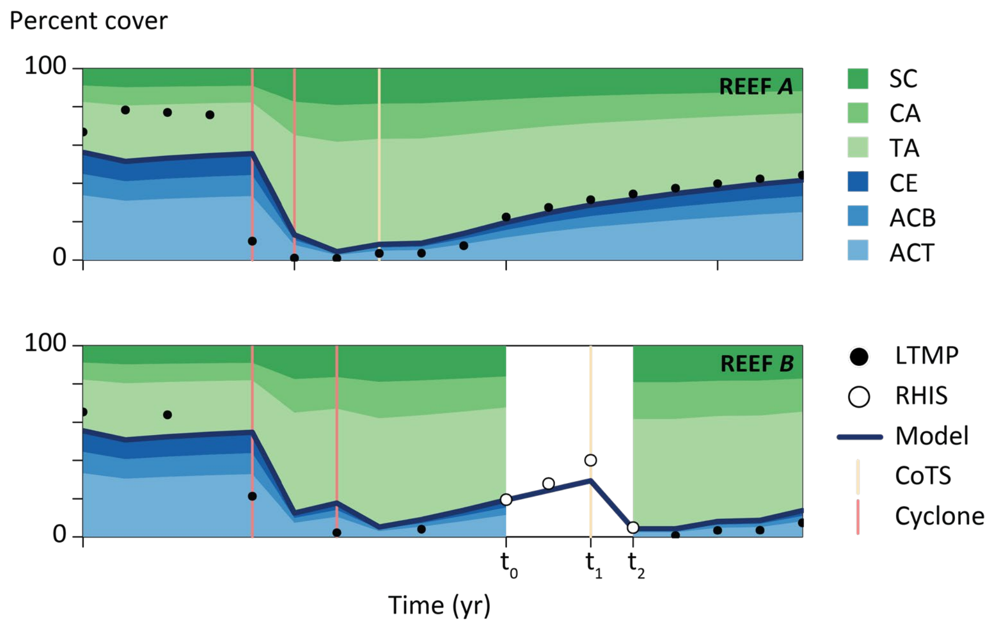

Figure 17. Simulated trajectories of coral cover and benthic community composition at two similar reefs Reef A, surveyed annually by LTMP, and Reef B, surveyed by RHIS from t_0. The coral model can inform coral cover trajectories until a new disturbance occurs in t_1. LTMP surveys then resume to capture detailed impact on state and recovery (as per Figure 16). With SC: soft corals, CA: coralline algae, TA: turf algae, CE: encrusting non-*Acropora*, ACB: branching *Acropora,* ACT: Tabular *Acropora*.

9.0 Integrating image-based data from multiple sources: the Monitoring Through Many Eyes project

QUESTIONS AND OBJECTIVES

- Develop a distinct spatial statistical model (thereafter the Bayesian coral model) that uses a mechanistic weighting scheme to integrate image-derived hard coral cover data (proportion) from multiple sources, including professional monitoring programs and citizen scientists, while accounting for the variable levels of uncertainty in those data;
- Compare the predictive ability of models fit to all data sources versus those fit to LTMP and MMP data only;
- Demonstrate how the effects of citizen-contributed data affect the model predictions and estimates of uncertainty as the number of citizens classifying hard coral within an image increases;
- Generate online interactive maps and spatial data products of predicted coral cover, with estimates of uncertainty, to facilitate management decisions, design monitoring programs, and expand public awareness and engagement.

MAIN RESULTS AND CONCLUSIONS

- The predictive ability of the Bayesian coral model fit to all data sources was significantly higher (98.6 per cent) than the model fit to LTMP and MMP data only. The 90 per cent prediction intervals (i.e. uncertainty estimates) for the model fit to all of the data sources captured the true value 90.3 per cent of the time, while intervals for the models fit to the LTMP and MMP data only included the true value 39.9 per cent of the time.
- Simulations showed that citizen-science data did not significantly influence model predictions unless large numbers of citizens were classifying hard coral cover within an image consistently. As the number of citizens classifying an image increased by 1000, 10000, and 100000, the prediction moved closer to the observed coral cover value and the uncertainty in the prediction steadily decreased.

PRODUCTS AND DELIVERABLES

- High-resolution prediction maps of coral cover based on the Bayesian coral model, with spatially explicit estimates of uncertainty, throughout the Reef based on spatially and temporally variable environmental and disturbance data; and
- An online, interactive reef decision-support system for government that also engages the general public in assisting scientists to monitor the Reef.

9.1 Proportion of hard coral cover data

Coral cover estimates are typically based on transects of individual images, which are then either manually annotated (i.e. classified) by marine scientists or automatically classified using software such as CoralNet (Beijbom et al. 2015). We used coral cover data from a number of different sources including the: XL Catlin Seaview Survey (Gonzalez-Rivero et al. 2014); AIMS

LTMP and the MMP, conducted by ; the Heron Island survey, by Roelfsema (2012); the Capricorn and Bunker group survey conducted by the Remote Sensing Research Centre (RSRC) at the University of Queensland (UQ). Each dataset provided multiple estimates of coral cover, but there were differences in the scale of the estimates and the estimation method (Table 6).

In addition to the professional data, we obtained 197 underwater images from Reef Check Australia (http://www.reefcheckaustralia.org). We developed an online classification tool to allow citizens to browse a map of the Reef and select images for annotation (www.virtualreef.org). For each image, a spatially balanced random sample of 20 elicitation points was generated, which the citizen classified as either water, (hard) coral, algae, sand, unknown, or other (Figure 18).

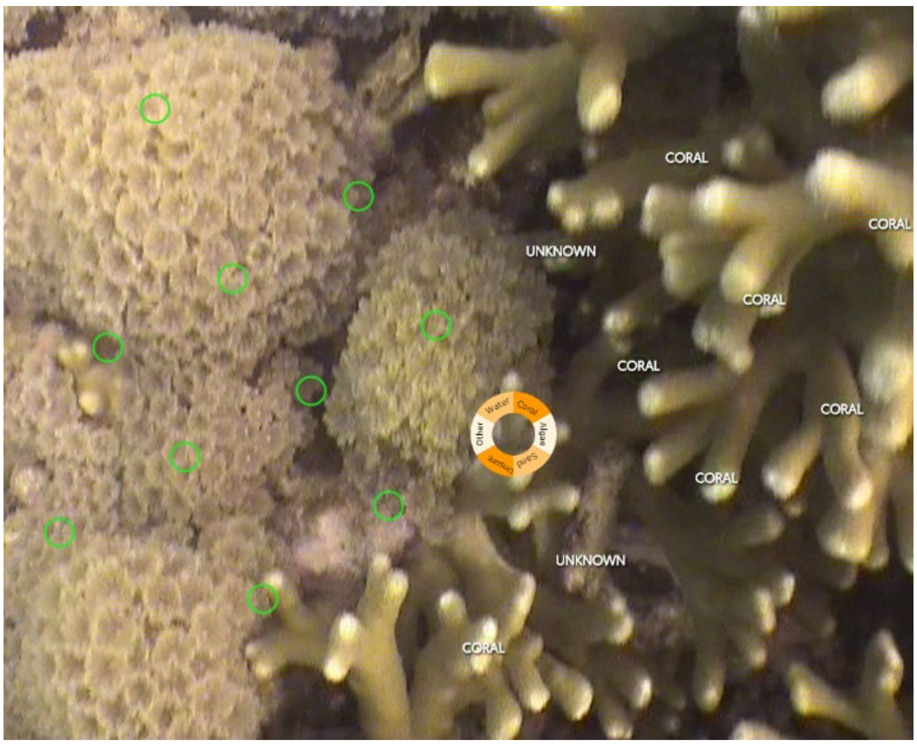

Figure 18. Partially annotated citizen-science image, derived from Reef Check Australia videos

Table 6. Differences in the coral-cover data sources included the number of images, scale of the coral cover estimate, the number of images the estimate was based on, the extent of each individual image, the number of annotations per image, and the number of estimates from each source used in the model.

Source	Scale	Number of images	Image extent (m^2)	Annotation points	Number of Estimates
Capricorn and Bunker group	Image	1	4.00	24	7276
Heron Island	Image	1	4.00	24	2222
XL Catlin[1]	Image	1	2.00	100	19819
LTMP[2]	5 × 50m transects	40	1.00	5	16851
MMP[3]	5 × 20m transects	32	1.00	5	950
Reef Check Australia	Image/person	1	0.12	20	197

[1] XL Catlin Seaview Survey, [2] AIMS Long-term Monitoring Program, [3] Marine Monitoring Program

9.2 Covariates

A number of physicochemical, topographic and disturbance variables were included in the model to account for direct and indirect sources of variation in coral cover (Table 7).

Table 7. Covariates that were included in the coral cover model. The original spatial resolution is given in decimal degrees.

Covariate	Description	Source	Spatial Resolution	Temporal Resolution
Bathymetry	Depth below sea level (metres)	(Beaman 2010)	0.001°	2010
Crown-of-thorns starfish	Interpolated crown-of-thorns starfish density	(Matthews et al. in review)	0.01°	2002-2015
Cyclone exposure	Damaging waves caused by cyclones (>4m):	(Puotinen et al. 2016)	0.01°	2002-2015

	0= No cyclone effects, 1 = Some cyclone effects			
Bleaching exposure	0= No bleaching, 1 = > 1 per cent bleached	(Matthews et al. in review)	0.01°	2002
Sea surface temperature anomaly	Difference between measured sea surface temperature (SST) and monthly long-term mean SST (°C)	(Bureau of Meteorology 2014)	0.02°	Annual means for 2002-2015
Shelf position	Position of reefs on the continental shelf; 1= inshore/inner shelf; 2 = middle shelf; 3 = outer shelf	(the Great Barrier Reef marine Park Authority 2014)	0.005°	Reef Zoning Plan 2003
No Take Zone	Protected areas where no fishing is allowed. 1 = no-take, 0 = otherwise	(the Great Barrier Reef marine Park Authority 2014)	0.005°	Reef Zoning Plan 2003

9.3 Model

The modelling framework we developed as part of the Cooperative Research Centre for Spatial Information Monitoring Through Many Eyes (MTME) project relies on a mechanistically based weighting scheme that accounts for the differences in the data source and survey design (e.g. individual images versus LTMP or MMP monitoring data aggregated over transects), the inherent quality (i.e. extent, orientation, and blur) of the images, and the expertise of the people annotating/classifying the images (e.g. professional marine scientists versus citizens) (Figure 19). The data are then aggregated to produce a weighted mean for each data source and year at a scale of 0.005 decimal degrees, along with an overall variance. Please see Peterson et al. (2017) for a detailed description of the weighting scheme.

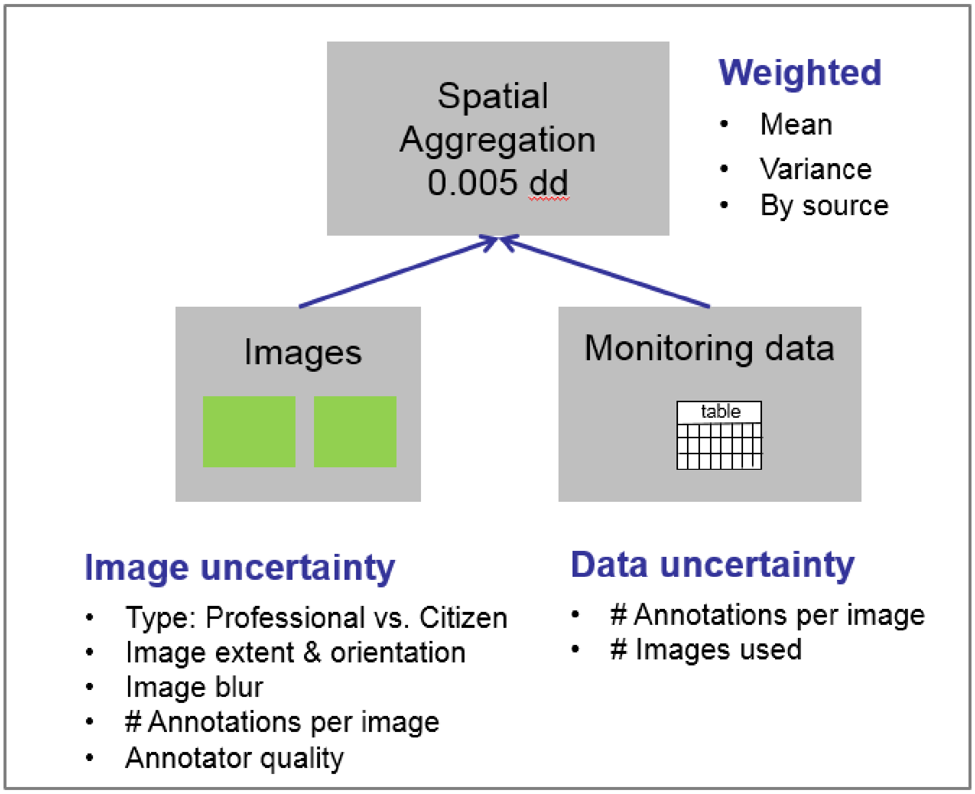

Figure 19. Numerous sources of uncertainty were accounted for in the model using a mechanistic weighting scheme before aggregating coral cover data to generate a weighted mean by source, for each 0.005 decimal degree (dd) cell within reefs, along with an overall variance estimate.

We chose to use a spatial statistical model because these models are specifically designed to model spatially dependent data. Spatial dependence, or autocorrelation, occurs when measurements at nearby locations tend to be similar or dissimilar, which is a common attribute of environmental datasets (Legendre 1993). The advantages of using a spatial statistical model are that they improve inference and predictive accuracy when data are spatially dependent (Hefley et al. 2017). For example, the estimated confidence intervals for the regression coefficients are often too narrow when spatial dependency is not accounted for, which leads to the conclusion that environmental or disturbance covariates have a significant influence on the response (e.g. coral cover), when they do not (Legendre 1993). Another advantage to a spatial statistical approach is that it can be used to make predictions within a probabilistic framework, with individual estimates of uncertainty, in areas where samples have not been collected (Peterson and Hoef 2010). As is the case with any regression model, predictions are based on the relationship between the response and the environmental and disturbance covariates. However, in a spatial statistical model, these predictions are also affected by their proximity and relationship to nearby observations. This is also true of the prediction uncertainty estimates, which are larger if the covariate values at unsampled locations are outside of the range of values found in the observed dataset, or if there are no observed values near the unsampled location.

There are many different types of spatial statistical models, but we chose to model weighted mean coral cover using a Bayesian basis function approach (Hefley et al. 2017) and a Beta distribution, which is appropriate for proportional data such as coral cover. More specifically, we implemented a stochastic partial differential equation (SPDE) model using the r-inla package (Martins et al. 2013) in R statistical software (R Development Core Team 2017). We selected this method because a basis function approach (*i*) is a well-established method (Hefley et al. 2017), (*ii*) is computationally efficient and will scale as the number of coral cover observations increases, and (*iii*) can be implemented using freely available software and no custom model-fitting code is required.

Models were fit to two datasets in order to assess the effects of integrating multiple sources of data on model outputs. First we fit the models to the LTMP and MMP data only, followed by a model fit to all of the data combined. The models were assessed using the mean square prediction error (MSPE), which provides an indication of how accurate the predictions are; noting that small MSPE values are more desirable. We also calculated the prediction coverage, which is simply the per cent of observed coral cover measurements that are captured within the prediction intervals; this statistic is important because it provides an indication about whether the model predictions and prediction intervals can be trusted. Note that a prediction interval should capture approximately the same per cent-age of observations (e.g. 90 per cent prediction interval should capture 90 per cent of observations).

Finally, we undertook a simulation study to assess the effects of the citizen science data on model outputs as the weights associated with them increased by 1000, 10000, and 100000 fold. The purpose of the exercise was to assess the effects of citizen science data on the accuracy of the predictions, and the prediction intervals.

9.4 Results and highlights

Highlight 1: Our results show that we can make use of all of the existing data, which increases the spatial and temporal distribution of the data in a cost-effective manner

The LTMP and MMP provide a valuable long-term record of coral cover data at a relatively small number of locations in the Reef, while the other datasets provide a wider spatial distribution of data in some cases, but only for individual years (Figure 20). Although each dataset provided image-based estimates of hard coral cover, there were differences in the scale of the estimates, the estimation method, and the quality of each data type (Table 6). The MTME model was designed to integrate these disparate sources of image-based coral cover data within a single statistical model, which significantly increases the spatial data coverage in the Reef. The ability to make use of all the available data is especially important given the need to (*i*) assess the effectiveness of the management actions; (*ii*) contribute to the outlook report every five years; (*iii*) provide situational awareness; and (*iv*) provide foresight and the opportunity for proactive, rather than reactive management of the Reef. In addition, the ability to make use of existing data, or data funded via alternative sources (e.g. philanthropy), is increasingly attractive as budgets for monitoring, conservation, and management continue to shrink. We note, however, that although this increased potential to assimilate data from multiple sources will increase replication and representation, there will be place-specific uncertainty. Again, this means an assessment will need to be made with respect to what monitoring (and management) objectives can be addressed when and where (see below).

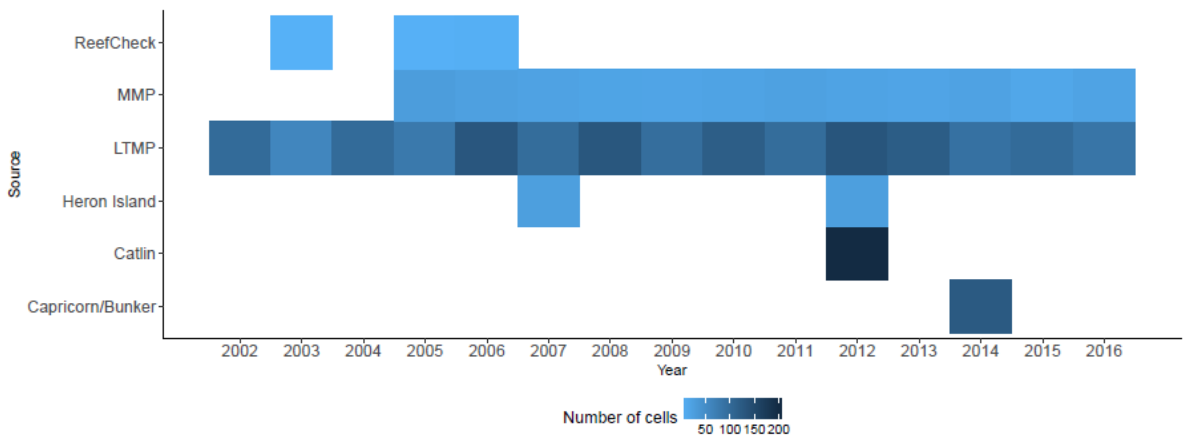

Figure 20. The number of raster cells containing at least one coral cover observation for each of the professional surveys and Reef Check citizen science data Professional surveys included the Marine Monitoring Program (MMP), Long-Term Monitoring Program (LTMP), the Heron Island and Capricorn and Bunker surveys, and the XL Catlin Seaview Survey.

Highlight 2: The model produces an individual uncertainty estimate for every prediction

The prediction maps with estimates of uncertainty produced by spatial statistical models are a valuable resource for managers (Figure 21, www.virtualreef.org.au). The predictions provide a holistic snapshot of coral cover proportions across the Reef based on all of the available data. However, the estimates of prediction uncertainty also provide a great deal of information for management. At the most basic level, differences in prediction uncertainty help managers understand where they can be most, or least confident in the predictions. This could be used to prioritise management actions, or identify areas where additional information is needed before management actions are implemented. The estimates of uncertainty can also be shared between organisations, so that sampling across the expanse of the Reef can be better coordinated to engage citizen scientists in the ongoing collection and annotation of images. Although we used coral cover as an example, this general approach is equally viable for other variables collected in the marine environment.

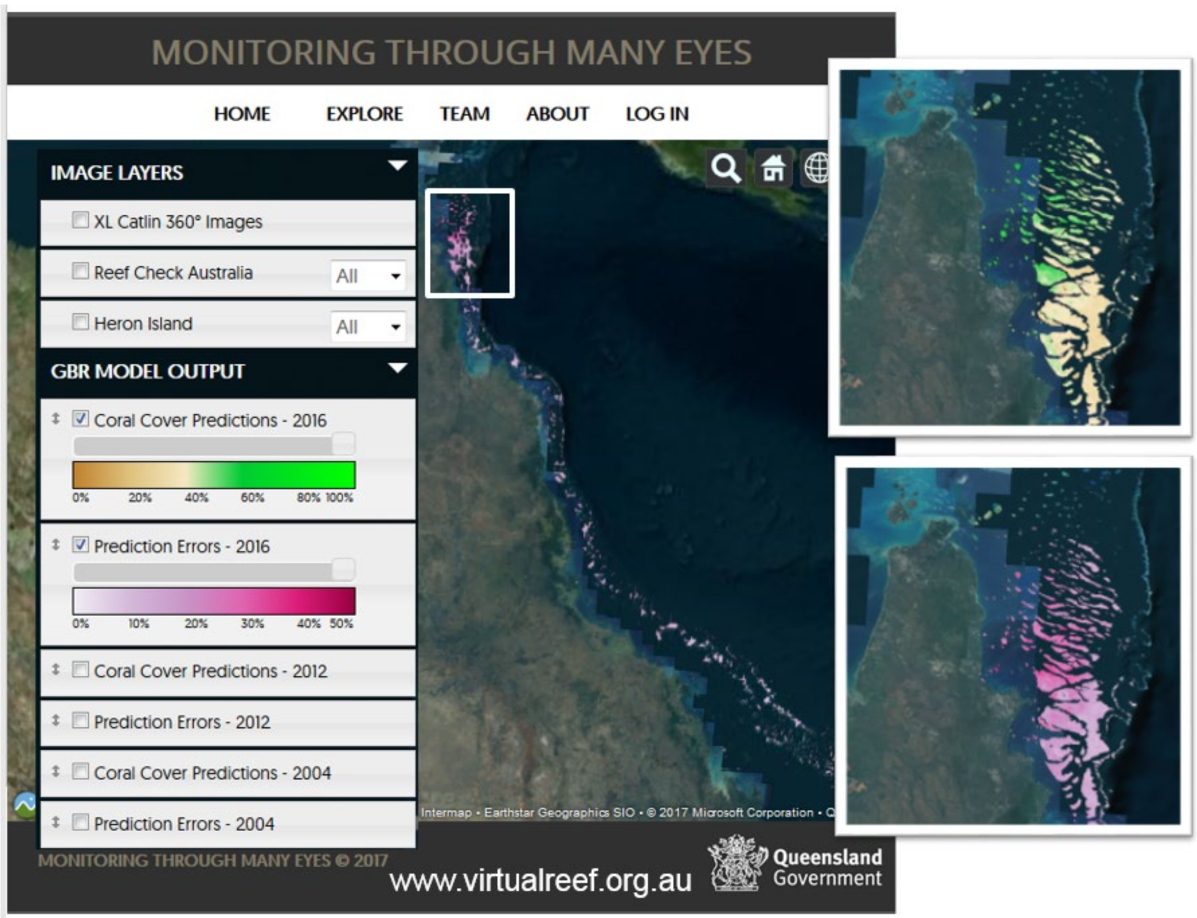

Figure 21. Maps of coral cover predictions and estimates of uncertainty are provided online so that managers can explore the data and download the spatial data products. Source: www.virtualreef.org.au

Highlight 3: The model predictions and uncertainty estimates significantly improve when additional data are included in the model

The MTME model includes a mechanistically based weighting scheme that accounts for the differences in survey design and coral-cover estimation method, as well as the inherent quality of the images and the people classifying the images (e.g. marine scientists versus citizens). Since all of the data sources originated from images, we were able to integrate coral cover estimates derived from citizen-contributed images and citizen annotations of images, while still accounting for differences in the quality of citizen science data compared to professional survey data. The approach is scientifically and statistically appealing because not all surveys are of equal quality. In addition, more data are available to fit the model and this results in an overall increase in information about coral cover throughout the Reef. In this particular case, the model results suggest that including additional data sources (e.g. Catlin, Heron Island, Reef Check and Capricorn Bunker), in addition to the LTMP and MMP, resulted in a 98.6 per cent increase in the predictive ability of the model based on mean square prediction error (Table 8). In addition, the 90 per cent prediction intervals (i.e. uncertainty estimates) for the model fit to all of the data sources captured the true value 90.3 per cent of the time, while intervals for models fit to the LTMP and MMP data only included the true value only 39.9 per cent of the time. Thus, the uncertainty estimates for the LTMP and MMP model predictions were overly confident (i.e. too narrow) to capture the observed coral cover value. However, the effect of incorporating additional data on the model's predictive accuracy is expected to vary spatially and temporally depending on the density of existing data nearby (in space and time), as well as the source and quality of the new data being integrated.

Table 8. Assessment of the predictive ability of models fit to the Long-term Monitoring Program (LTMP) and Marine Monitoring Program data only (LTMP/MMP) and to all of the data sources (All data), including the mean square prediction error (MSPE) and the 90 per cent prediction coverage.

Model	MSPE	90 per cent Coverage
LTMP/MMP	0.013	39.9
All Data	0.00018	90.3

Highlight 4: Citizen science data has little influence on the model until massive numbers of citizens annotate or contribute images.

The advantage of using image-based data is that it removes the subjective nature of visual estimates provided by a small number of citizens; thus, there is a 'hard' truth that can be revisited and assessed. For example, the citizen science data currently has little weight in the model compared to the professional survey data, due to the small pool of 'citizen scientists' and citizen-contributed images in this case study (top left panel, Figure 22). As a result, the predictions at those locations are clearly inaccurate and the large levels of uncertainty associated with them reflect that. However, the weights for citizen-contributed data will increase if there is a large increase in the number of images submitted or the number of people classifying an individual image. As an example, we assigned the Catlin data the weights normally associated with the citizen science data and then increased those weights by 1000, 10000 and 100000 fold (Figure 22). We found clear evidence that the accuracy of the predictions increased, as well as the relative level of certainty in those predictions as the number of citizens participating increases. However, this only occurred when large numbers of citizens were annotating the same image (>10000). Interestingly, increasing the weights for the citizen-contributed data did not significantly change the relationship between coral cover and the disturbance and environmental covariates (results not shown), which means that the inferences about influential factors affecting coral cover remained the same.

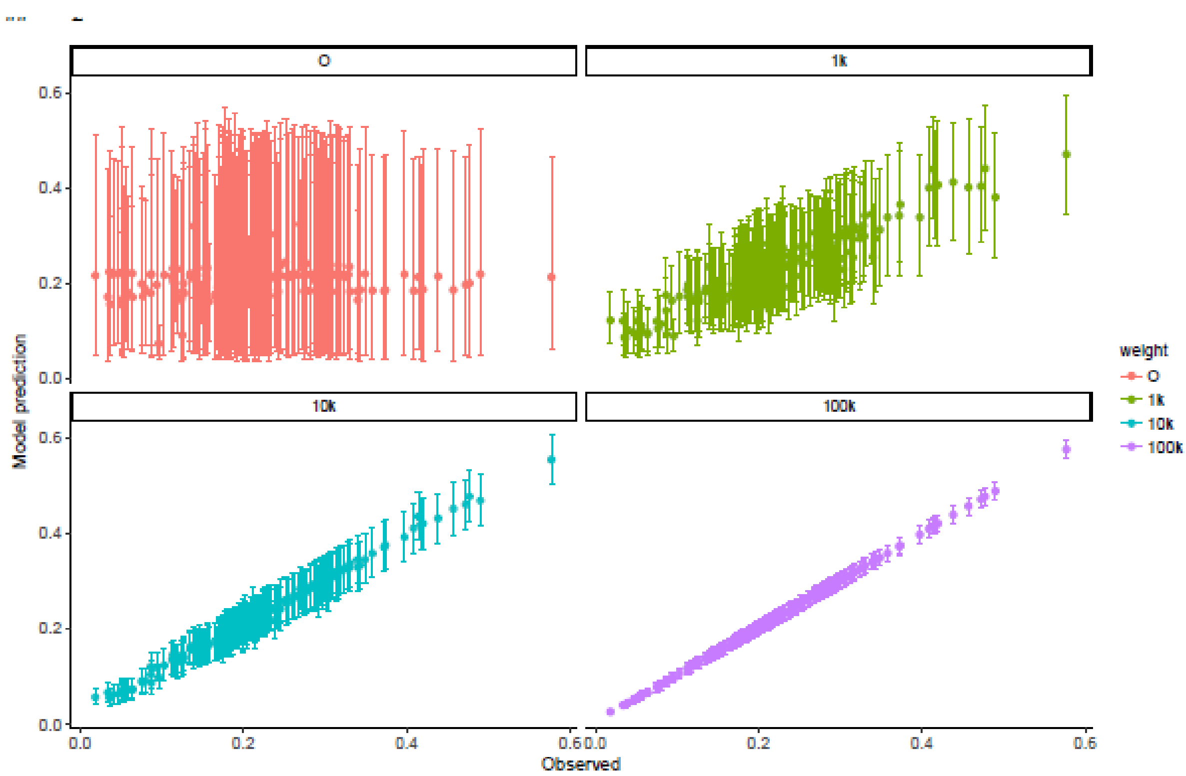

Figure 22. Results of the simulation exercise showed that as the original weights (O) for citizen-contributed data increase by 1000 (1k), 10000 (10k), and 100000 (100k), the accuracy of the predictions and the relative level of certainty increase Dots represent the mean predicted value (proportion of hard coral cover) and bars represent the 90 per cent prediction intervals.

10.0 Recommendations, expert feedback and future considerations

10.1 Recommendations based on the present analysis

A critical requirement of any sampling design is the careful consideration of the ecological question(s) being asked. If the future reef monitoring design is intended to capture most of the environmental diversity on the Reef, then our analyses suggest that the RM/RAP/In monitoring programs have encompassed about 33 per cent of all reef habitats (section 4). To increase spatial representation, additional sites could be added in distinct environments that have remained unmonitored. As we demonstrate above, RHIS monitoring can complement LTMP, MMP and Catlin surveys, but they cannot replace them because RHIS and LTMP address different objectives. Where the objective is to track long-term population dynamics and understand the response of reef communities to multiple disturbances, our results indicate that the RM/RAP/MMP surveys have successfully captured a range of disturbances, but that major hotspots of bleaching (northern and inshore Reef) and cyclone activity (central Reef) are under-represented or have remained unmonitored (section 5). Here, additional fixed, long-term monitoring sites will be critical to support management into the future. Further, a structured RHIS campaign strategy is needed to provide situational awareness on monitored and unmonitored reefs in and around disturbances. This will be critical to support LTMP analyses of impact timing, and to help reschedule LTMP after impacts so that state changes, recovery and management attribution can be sharpened.

It is critical to bear in mind that **long-term surveys with detailed biological information are the backbone of the Reef monitoring**. We thus strongly recommend that at least the core reefs of the RM/RAP/MMP remain in the new monitoring design. The alternative, if these time series were to be interrupted, would lead to the loss of years of data and effort and our inability to develop similar models in the future. Most importantly, the loss of a directly comparable baseline would severely delay the ability to identify any areas exhibiting a down turn in recovery, a process central to the ongoing ecosystem resilience.

Based on the last 20 years, our analysis suggests that not all reefs from the RM/RAP/MMP surveys might be necessary to successfully capture the temporal trends of coral cover in response to disturbance (section 6). Instead, a selection of survey sites among reefs with similar coral cover trajectory and benthic community composition might suffice to capture these temporal trends in the past and future, as long as they remain exposed to similar levels of disturbance. Further analyses are currently investigating the optimal number of reefs required to capture temporal trends in coral cover (P Menendez, A Thompson).

10.2 Expert feedback and considerations

In this section, we summarize our discussions with experts and benthic ecologists from AIMS (Kate Osborne [KO], Angus Thompson [AT], Hugh Sweatman [HS]) about the possibility and challenges associated with a redesign of the reef monitoring.

Survey design

- Transect-level monitoring (RM/RAP/MMP) provides estimates of coral growth rates and recovery potential, from which areas with low recovery potential or changes in coral growth rate over time can be identified. For RHIS the information should be focused and stratified based on the level of disturbance, including tropical cyclones, coral bleaching and crown-of-thorns starfish outbreaks to identify broad-scale pressures on reef communities. Importantly, RHIS cannot fill in gaps in the RM/RAP/MMP program, but can complement these by providing situational awareness and other health and impact data that supports attribution to impact and management. Also, RHIS can help pinpoint when a disturbance occurs, thus helping to schedule LTMP resurvey to provide both an accurate estimate of the impact of disturbance and the first data point in the recovery time series [AT]
- Point-based sampling might be inappropriate to survey crown-of-thorns starfish densities as their distribution is too patchy. Manta tow (or potentially CAT) surveys should be favoured if crown-of-thorns starfish outbreaks are of interest [AT], complemented by detailed crown-of-thorns starfish surveys where aggregations occur (i.e. the current practice for the Authority's field management team).
- The level of staff experience is critical, especially considering the number and type of data fields required to fill in the RHIS surveys [HS]. To maintain a core of suitably experienced staff is essential. In a reactive monitoring framework the frequency on number of intensive surveys may be informed by results of broad-scale assessments (Manta/CAT). Core staff would switch as between board-scale and intensive sampling as determined by disturbance and recovery cycles [AT].
- The estimation of the 5m radius circle is important: 5.5m vs 4.5 m makes ~50 per cent difference in area [HS]
- In RHIS surveys, it would seem essential to estimate hard coral cover (as opposed to the per cent cover of all corals) and clearly distinguish live corals from recently dead ones.

Sampling effort

- Skipping survey years means hard coral cover peaks and troughs are not as accurate and are likely to be misinterpreted over longer temporal series. It also makes it harder to determine what has caused the decline [KO]. It is essential that, if reefs are not listed for survey, reactive revisiting based on observed or estimated disturbance be built in to the sampling design [AT].
- Reducing number of reefs within habitats is risky and might increase uncertainty about patterns especially in coral composition. Reduce sampling within reef might be a better option if this can be done in a logistically sensible way [KO]. There is not much redundancy in the number of reefs surveyed in a location, other than in RAP (Thompson and Menendez power analysis). The current LTMP design of nominally 3 reefs in a sector shelf combination, largely akin to communities types identified in this report, appears appropriate [AT].

- Preliminary results of the power analysis suggest that relatively few reefs are required within a given latitudinal sector and cross-shelf region to capture temporal trends in hard coral cover, which reflects the consistency of recovery trajectories at this scale [AT]
- Allocation of sampling effort for the RHIS surveys in each year should be targeted towards filing gaps with other sampling programs in order to provide situational awareness [HS] and rapids assessment of the spatial extent and severity of events [AT].

Logistics

- If potentially redundant reefs are to be sub-sampled, selection criteria need to be considered and include distance to the coast (or nearest port) and to other survey reefs, ease of access, exposure to wind and major oceanographic currents.
- Surveying areas that have so far remained unmonitored (e.g. strong tidal outer shelf reefs) would potentially be valuable, however it poses some logistic challenges due to the strong currents that characterize these areas. In such situations alternative survey methods (e.g. automated underwater vehicles, automated diver propulsion vehicle as used in CAT surveys) could be of interest.

10.3 Future patterns of disturbance and adaptive sampling strategy

- Given that spatial patterns of disturbance vary over time (e.g. 2016-2017 mass bleaching events differed from the 1998-2002 ones; Hughes et al. 2017), it will become essential to understand and forecast the spatial patterns of future disturbance based on multiple climate change/management scenarios and need to re-orientate design accordingly (e.g. intensify sampling effort on inshore and northern reefs, include shallower sites on reef flats?)
- For cyclones and bleaching events it is risky to assume history will repeat. It would be more appropriate to design a spatially comprehensive project within which the frequency of sampling is responsive to disturbance and recovery cycles, or other, issues of periodic importance [AT]
- There is a need for value of individual data points to be considered. For example we know that cyclones damage reefs and, where disturbance is severe, recovery will be slow. Post cyclone surveys (RHIS) should be stratified to confirm expectations of extent. Revisitation of transect-based sites will be highly valuable within the year following an event to document extent of damage. Subsequent sampling value will depend on ongoing pressures and severity of disturbance, for example there will be little value in revisiting the next year as expected recovery will be slow initially, and any deviation from this expectation likely not detectible.

11.0 Conclusions

In this study, we used a spatial model of coral cover as a reference framework for comparing the effectiveness of different monitoring programs (using different survey methodologies and serving different purposes) in documenting patterns and trends of coral reef health based on three key criteria: *representation*, *complementarity* and *precision/accuracy*. Based on these results, we formulated a number of recommendations on how best to combine the different programs in an integrated monitoring design.

Our analyses revealed that:

- Across all monitoring programs, some of the survey reefs might convey redundant ecological information in terms of their coral cover trajectories and benthic community composition (section 6).
- If this is the case, a subset of all survey reefs could efficiently inform patterns of response to future disturbance, with the coral cover model used to fill in data gaps in space and time. The suggested scenario coupling long-term surveys at the selected reefs with reactive and broad scale surveys elsewhere would allow to document the extent and impact of future disturbances (section 9).
- This subset of survey reefs could be optimized to maintain the diversity of environmental conditions, benthic communities and disturbance footprint currently captured by the current monitoring programs (sections 4 and 5).
- Parallel ongoing studies (i.e., power analyses) will help define the optimal number of reefs required in each region to detect changes in coral cover in response to disturbance and subsequent recovery.
- At the reef scale, our simulation study showed that observer error and spatial variability interact in decreasing the precision in coral cover estimates, an effect that can be compensated for by larger sample size and the collection of benthic images (section 7).
- The collection of benthic images through citizen science data (e.g. Reef Check) can greatly improve model predictive ability and reduce the uncertainty in model prediction of coral cover, although simulations showed that citizen-science data did not significantly influence model predictions unless large numbers of citizens were classifying hard coral cover within an image consistently.

The assessment of the current coral reef monitoring based on their complementarity, representation and precision thus offers ways to combine the different sub programs operating at different spatiotemporal scales and using different techniques into an effective and cost efficient integrated monitoring program. We also demonstrated potential benefits of citizen science data as a cost-effective way to improve predictive ability of spatial models and to complement existing long-term monitoring programs. Optimising the design of RIMReP is indeed a multifaceted task that involves not only ecological but also budgetary, time and human constraints, which will need to be incorporated without compromising the integrity of existing long-term datasets.

12.0 References

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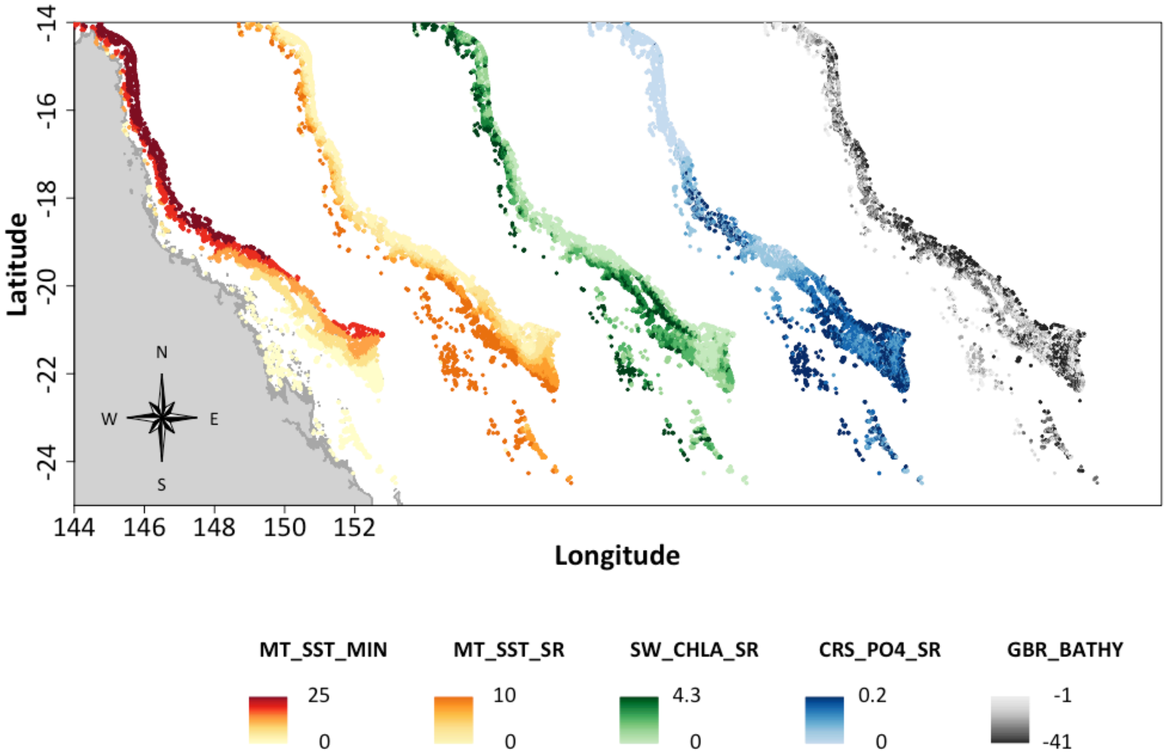
13.0 Appendices

Appendix 1. Marine bioregions of the Great Barrier Reef (source: the Authority)

Appendix 2. Spatial patterns of the main environmental covariates contributing to the principal component analysis.



Appendix 3. Environmental and spatial variables available at a 0.01º spatial resolution for the Great Barrier Reef, Australia mean = annual mean levels at the seabed, std dev = standard deviation in monthly mean levels at the seabed, as a measure of seasonal variability, CARS = CSIRO (Australian Commonwealth Scientific and Industrial Research Organisation) Atlas of Regional Seas (Condie & Dunn, 2006), GA = Geoscience Australia (see Webster & Petkovic, 2005 for original multibeam bathymetry dataset), MARS = MARine Sediment database (Mathews et al., 2007), GEOMACS = GEological and Oceanographic Model of Australia's Continental Shelf (Hemer, 2006), SeaWiFS = Sea-viewing Wide Field-of-view Sensor (NASA/Goddard Space Flight Center and Orbimage; e.g. Condie & Dunn, 2006). K490 is the diffuse attenuation coefficient at wavelength 490 nm.

Variable name	Source	Variable Definition	Type	Unit
CRS_NO3_AV	CARS	Nitrate	mean	µM
CRS_NO3_SR			std dev	
CRS_02_AV		Oxygen	mean	$mL.L^{-1}$
CRS_O2_SR			std dev	
CRS_PO4_AV		Phosphate	mean	µM
CRS_PO4_SR			std dev	
CRS_S_AV		Salinity	mean	PSU
CRS_S_SR			std dev	
CRS_SI_AV		Silicate	mean	µM
CRS_SI_SR			std dev	
CRS_T_AV		Temperature	mean	ºC
CRS_T_SR			std dev	
GA_BATHY	GA	Depth	mean	m
GA_SLOPE		Slope	Degree of slope of seabed	º
GA_ASPECT		Aspect	Degree aspect of slope	º
GBR_BATHY	MTSRF	Depth	mean	m
GA_CBRNT	GA/MARS	Carbonate sediments	mean	per cent
GA_GRAVEL		Gravel (Ø > 2 mm)	mean	per cent

GA_SAND		Sand (63 µm < ø < 2 mm)	mean	per cent
GA_MUD		Mud (ø < 63 µm)	mean	per cent
GMCS_STRESS_TMN	GA/GEOMACS	Bed shear stress	Trimmed mean	Pa
GMCS_STRESS_IQR			Interquartile range	Pa
SW_CHLA_AV	SeaWIFS	Chlorophyll a	mean	$mg.m^{-3}$
SW_CHLA_SR			std dev	
SW_K490_AV		K490 (Turbidity)	mean	m^{-1}
SW_K490_SR			std dev	
SW_BIR_AV		Benthic Irradiance	mean	
SW_BIR_SR			std dev	
MT_SST_AV	Modis Terra (NASA)	Sea surface temperature	mean	ºC
MT_SST_SR			std dev	
mindistbar	ArcGIS	Distance to the barrier reef edge (i.e. 100-m isobaths)	Minimum	°
mindistcoa		Distance to the coast	Minimum	°
Primary	(Devlin et al. 2012, Alvarez-Romero et al. 2013)	Primary flood plume frequency during wet season	Frequency	0-1
Secondary		Secondary flood plume	Frequency	0-1
Tertiary		Tertiary flood plume	Frequency	0-1

Appendix 4. List of survey reefs along with their corresponding benthic cluster (as per Figure 5) and trajectory cluster (as per Figure 11)

REEF_ID	SITE_NAME	P_CODE	bent_clust	traj_clust
1649	ST CRISPIN REEF	RM	1	1
2064	MICHAELMAS REEF	RM	1	1
2132	THETFORD REEF	RM	1	9
2469	SLATE REEF	RM	1	13
2663	REBE REEF	RM	1	13
735	21558S	RAP	1	14
870	21296S	RAP	1	14
900	EAST CAY REEF	RM	1	14
2122	MCCULLOCH	RAP	1	14
2431	HASTINGS REEF	RM	1	14
2638	ARLINGTON REEF	RAP	1	14
2638	ARLINGTON REEF	RM	1	14
3000	MOORE REEF	RAP	1	14
2587	MYRMIDON REEF	RM	1	15
911	HYDE REEF	RM	1	17
1770	21278S	RAP	1	18
710	TURNER REEF	RM	2	5
473	WADE REEF	RAP	2	16
641	21302S	RAP	2	18
431	CHINAMAN REEF(22102)	RM	2	19
2852	DIP REEF	RM	3	5
2968	HEDLEY REEF	RAP	3	5
1864	NORTH DIRECTION REEF	RM	3	14
2183	MACGILLIVRAY REEF	RM	3	14
2934	CHICKEN REEF	RM	3	17
1681	AGINCOURT REEFS (NO 1)	RM	4	13
2867	OPAL (2)	RM	4	15
2330	NO NAME REEF	RM	5	18
2109	CARTER REEF	RM	5	19
2477	YONGE REEF	RM	5	19
204	LADY MUSGRAVE REEF	RM	6	13
292	BROOMFIELD REEF	RM	6	13
320	ONE TREE REEF	RM	6	13
412	WRECK ISLAND REEF	RM	6	13

204	FAIRFAX ISLANDS REEF	RAP	7	13
225	BOULT REEF	RAP	7	13
418	NORTH REEF (NORTH)	RAP	7	13
455	HOSKYN ISLANDS REEF	RAP	7	13
2577	FEATHER REEF	RAP	8	12
1597	TERN REEF(20309)	RAP	8	13
1664	POMPEY REEF (NO 1)	RAP	8	13
1880	PENRITH REEF	RAP	8	14
1930	21591S	RAP	8	14
2652	PEART REEF	RAP	8	14
3200	LIZARD ISLAND	RM	8	15
2723	MACKAY REEF	RM	8	18
291	MAST HEAD REEF	RAP	9	5
688	21187S	RAP	9	13
55	ERSKINE REEF	RAP	9	19
740	21139S	RAP	9	19
1422	19131S	RM	9	19
1467	20104S	RM	9	19
359	22084S	RAP	10	1
514	19138S	RM	10	1
1640	20348S	RAP	10	1
179	GANNETT CAY REEF	RM	10	2
2490	FORE AND AFT REEF	RAP	10	2
2357	LITTLE KELSO REEF	RAP	10	5
2826	HELIX REEF	RAP	10	5
2831	ROXBURGH REEF	RAP	10	5
2921	FORK REEF	RAP	10	5
2935	GRUB REEF(18077)	RAP	10	5
2256	RIB REEF	RM	10	6
2912	JOHN BREWER REEF	RM	10	6
1340	21060S	RAP	10	10
1570	21062S	RAP	10	10
158	21550S	RAP	10	13
255	21529S	RM	10	13
1651	20353S	RAP	10	13
2021	21064S	RAP	10	13
2039	POMPEY REEF (NO 2)	RAP	10	13
2095	CENTIPEDE REEF	RAP	10	14
2105	KELSO REEF	RAP	10	14
2170	DAVIES REEF	RM	10	14

2613	GREEN ISLAND REEF	RM	10	14
2646	LYNCHS REEF	RAP	10	14
3425	TAYLOR REEF	RAP	10	14
483	21245S	RAP	10	15
252	SMALL LAGOON REEF	RAP	10	19
3068	SNAKE (22088)	RM	11	1
2921	KNIFE REEF	RAP	11	5
3423	HORSESHOE	RM	11	6
66	JENKINS REEF	RAP	11	19
2308	MARTIN REEF(14123)	RM	12	14
2355	FITZROY ISLAND REEF	RM	12	14
2589	Fitzroy West	MMP	12	14
2589	Fitzroy East	MMP	12	14
2898	Palms West	MMP	12	14
2898	Palms East	MMP	12	14
2286	LOW ISLANDS REEF	RM	12	17
2295	LINNET REEF	RM	12	18
1457	HAYMAN ISLAND REEF	RM	13	1
1396	Double Cone	MMP	13	14
1396	LANGFORD-BIRD REEF	RM	13	14
822	BORDER ISLAND REEF (NO 1)	RM	13	15
874	Dent	MMP	13	15
2691	Hook	MMP	14	5
2782	Bedarra	MMP	14	12
2782	Dunk South	MMP	14	12
2782	Dunk North	MMP	14	12
1175	Shute Harbour	MMP	15	11
1175	Daydream	MMP	15	11
2970	High West	MMP	15	12
2970	High East	MMP	15	12
2576	Franklands East	MMP	15	14
2576	Franklands West	MMP	15	14
2895	Snapper North	MMP	15	14
2895	Snapper South	MMP	15	14
1539	Seaforth	MMP	16	11
2849	Magnetic	MMP	16	12
2204	MIDDLE REEF(19011)	RM	16	19
385	Peak	MMP	17	5
78	Pelican	MMP	17	10
380	Middle	MMP	17	10

449	Keppels South	MMP	17	10
451	Barren	MMP	17	10
53	North Keppel	MMP	17	14
2877	HAVANNAH REEF	RM	18	2
2877	Havannah	MMP	18	2
2955	Pandora	MMP	18	2
2955	Lady Elliot	MMP	18	2
2955	PANDORA REEF	RM	18	2
1104	Pine	MMP	18	5
2647	Barnards	MMP	18	12
2229	King	MMP	18	14