Great Barrier Reef Foundation

Research for a resilient Reef

Final Report

Supporting Resilience-Based Management in the Cairns Section of the Great Barrier Reef

Unit 1, 9 Longland St, Newstead, QLD
Postal: PO Box 2725,
Fortitude Valley BC, QLD 4006
P +61 7 3252 7555
F +61 7 3252 7666
W barrierreef.org

ABN 82 090 616 443

Project collaborators (in alphabetical order)

Name	Organisation
Dr Ken Anthony	Australian Institute of Marine Science
Dr Mark Baird	CSIRO
Dr. Yves Marie Bozec	Marine Spatial Ecology Lab (MSEL), School of Biological Sciences, UQ
Dr Scott Condie	CSIRO
Dr. Karlo Hock	Marine Spatial Ecology Lab (MSEL), School of Biological Sciences, UQ
Dr Eric Lawrey	Australian Institute of Marine Science
Prof. Peter Mumby	Marine Spatial Ecology Lab (MSEL), School of Biological Sciences, UQ
Dr. Juan Ortiz	Marine Spatial Ecology Lab (MSEL), School of Biological Sciences, UQ / AIMS
Dr Chris Roelfsema	Remote Sensing Research Centre (RSRC), School of Geography Planning and Environmental Management (GPEM), University of Queensland (UQ)
Mr Aaron Smith	Australian Institute of Marine Science
Dr. Nicholas Wolff	The Nature Conservancy

Project collaborators are grateful for contributions from and discussions with the following colleagues:

Name	Organisation
Dr Petra Lundgren	Great Barrier Reef Foundation
Dr Rachel Pears	Great Barrier Reef Marine Park Authority
Dr David Wachenfeld	Great Barrier Reef Marine Park Authority
Dr Britta Schaffelke	Australian Institute of Marine Science
Dr Katharina Fabricius	Australian Institute of Marine Science
Prof Stuart Phinn	Remote Sensing Research Centre (RSRC), School of Geography Planning and Environmental Management (GPEM), University of Queensland (UQ)

Executive Summary

This project is a prototype of an online, spatial toolbox to inform resilience-based management of coral reefs in the Cairns Management Areas (CMA) of the Great Barrier Reef (GBR). The purpose of this toolbox is to help reef managers explore the effectiveness of different control strategies for Crown-of-Thorns Starfish (CoTS) in protecting coral cover under different climate change and water quality scenarios.

To achieve this, the project has brought together a number of key resources. Firstly, the project has developed a state-of-the art, spatial and dynamic model of coral and CoTS meta-populations in the region. The model captures biological, population-level and ecosystem-level processes including the connectivity of both corals and CoTS among reefs. Secondly, the model uses dynamic layers of environmental pressures (exposures) as inputs to inform projections of coral cover over time in both hindcast and forecast mode. To deliver such projections, the project has produced new spatial projections of reef exposures to cyclones and thermal stress.

The strength of the resilience-based management (RBM) toolbox is predominantly to guide decision-making based on near- to medium term coral forecasting (decades). Subsequent versions will develop its capacity as a diagnostic toolset to inform management detective work and help attribute observed impacts to causes in areas of specific interest. Comparisons of predicted and observed coral trajectories in this prototype indicate high model skill and a strong basis for developing such diagnostic capacity. Lastly, the project has made these new resources available in a web-integrated portal to place these resources at the fingertips of managers in an interactive and user-friendly environment.

Our structured comparisons of model projections revealed a set of key findings. Firstly, implementing an effective CoTS strategy could become increasingly critical under climate change as reefs that escape climate impacts will become increasingly susceptible to CoTS. Further, highly effective CoTS control would mean higher coral survival and recovery to around 25% cover by around 2035. This can maximise coral stocks and potentially coral resilience before bleaching events become annual or semi-annual events. Secondly, even if global warming can be kept within 1.5°C above preindustrial levels, the average coral cover on the GBR could decline regionally as we approach mid-century despite perfect CoTS control and a water quality representative of pre-industrial levels. However, some reefs are predicted to sustain high coral cover through time, potentially representing resilient reefs or refuges. The spatial variation in reef resilience and/or susceptibility to exposures provides scope for sustained reef values locally and potentially in resilient networks, but also caution a trend of regional decline if global warming continues unabated. Under such a scenario, new additional interventions will be needed in addition to intensified conventional management.

The resilience-based management toolbox, which is an operational prototype that represents the first stage in a series of developments, is the product of focused collaboration between five institutions: AIMS, UQ, CSIRO, GBRMPA and the GBRF. Specifically, each institution has put forward elements of their flagship products to make this project happen: eReefs (CSIRO), regional coral and CoTS model (MSEL, UQ with contributions from AIMS and CSIRO), eAtlas (AIMS) and Live Habitats Maps (RSRC, UQ).

Table of Contents

1. Why a resilience-based management toolbox?

The Great Barrier Reef (GBR) needs resilience support now more than ever. Four mass bleaching events, a Crown of Thorns Starfish outbreak in full progress and a decade of stronger-than-usual cyclones are testing the Reef's resilience. In addition, water quality remains an issue in the GBR lagoon, and adds to the cumulative pressures on the system.

Understanding how we provide resilience support now and in the future will be critical for management strategies and policies, in particular the Reef 2050 Plan, that attempts to sustain reef functions, services and values. Climate change is here to stay, but the gravity of its impacts will be contingent on the carbon emission path that the world follows now and in years to come. This project provides a new way for GBR managers to explore how some of the conventional management interventions already in play can help provide that much-needed resilience support.

The project focuses on CoTS control as a key GBR management lever. Between 1984 and 2011, CoTS were responsible for approximately half of the GBR-wide decline. Now, in a time of climate change where reef resilience is being compromised on a regional scale, understanding to what extent effective CoTS control can help protect coral cover will be critical for shifting the balance from net coral loss to net coral gain.

A key strength of the toolbox is its capacity to help managers ask questions such as: "*What benefits am I likely to see for reefs X-Y if I employ a CoTS control strategy from 4 boats as opposed to 2 boats*?" Another question could be: "*What benefits do I gain if such a control program is informed by an understanding of CoTS connectivity as opposed to one that goes where CoTS have highest density*?" The toolbox also includes projections of coral cover for options of *No CoTS Control* and *Perfect CoTS control* (effective suppression of outbreak densities below outbreak thresholds). These can be used as benchmarks for other control strategies. Importantly, the RBM toolbox is intended to inform strategic management decisions around CoTS control under different environmental scenarios in the regional area– it is not meant to be a tactical management tool for individual reefs.

For the moment, however, the toolbox is still at prototype stage. While the toolbox can compare outcomes of scenarios and CoTS strategies in terms of their likelihood of preserving coral cover, it cannot yet provide advice on where CoTS should ideally be managed. Nor can it provide quantitative assessments of the level of return on investment in a given strategy or the numbers of CoTS that need to be culled to achieve a desired effect. Over time, and with further improvements, however, we expect the *RBM Toolbox* will be able to inform such lines of enquiry.

The toolbox includes two contrasting climate change and two contrasting water quality scenarios. These allow the manager to place the five CoTS control strategies in the context of both regional and global environmental change. Specifically, it allows the user to ask the critical question: "*What will be the benefit of effective CoTS control and water quality management under climate change*?" This could spark the question: "*Would other interventions be needed to sustain GBR coral cover under intensified climate change (RCP 8.5), or perhaps also under the best-case climate scenario (RCP 2.6)*?

Beyond informing CoTS strategies in a changing environment, the toolbox can also help managers identify reefs that are more or less susceptible to decline. These are the reefs often referred to as either strong or weak, implying differences in biological or ecological resilience, or lucky or unlucky, implying consequences of past disturbance environments, or the possibility that they are refuges. By allowing the user to complement model projections with new live habitat maps and base layers such as Marine Park zoning, the *RBM Toolbox* can help inform the user about the extent to which some reefs are indeed strong or lucky, or are the consequence of effective management. Forward coral projections under climate change can then help inform the user about whether some reef areas are likely to sustain their status over time, thereby helping to inform spatial planning and prioritisation.

2. How to use this report?

This report is structured as a tour of the *RBM Toolbox*. A later planned output of the project will be a users' guide to the *RBM Toolbox* and we here illustrate some of those elements.

In the first section of the report we provide an overview of the toolbox architecture. Here we start by explaining how the overall project design is tailored to answering questions about CoTS strategy effectiveness under different climate and water quality scenarios. We then present worked examples of how such scenarios can be explored and how resources, e.g. environmental exposure layers, can be pulled in to help the user understand drivers of change in space and time.

In this section we also explain some of the limitations of the toolbox stemming from the fact that this was only a 1-year project. For the technically-minded user we provide a full appendix of model details, assumptions and caveats.

We have attempted to make this report easily accessible to end-users with a range of backgrounds. Therefore, we explain or define technical concepts in boxes or refer to technical chapters as appendices. These are not complete in this report, but will be in the next version.

Lastly, decision support forms a thread throughout the report. Therefore, we introduce the concepts of structured decision analyses and how we see the project informing management decision-making under the Reef 2050 Plan via the Reef Integrated Monitoring and reporting Program (RIMReP).

3. Why a focus on CoTS control, water quality and climate change?

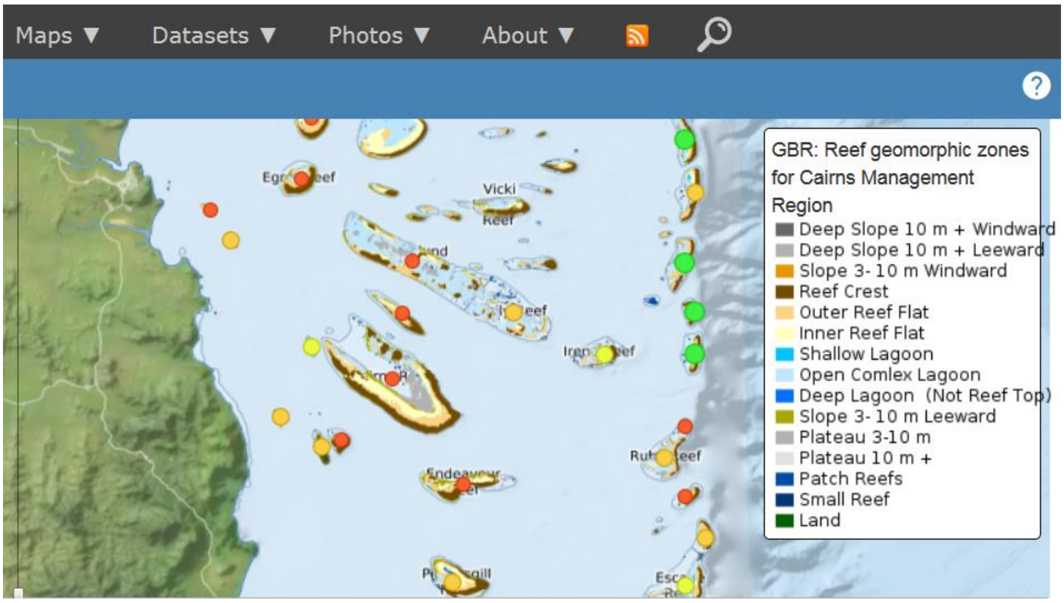
CoTS outbreaks are a major disturbance on the GBR that is also potentially amenable to local, targeted control efforts (GBRMPA 2016). Outbreaks are assumed to be at least partially driven by pulses in nutrients (chlorophyll *a*) following flood events. We want to understand how different strategies of CoTS control are helping, and can help further, to improve coral cover on the GBR. One question we are asking for example is to what extent the current CoTS control strategy performs compared to a no-control strategy or to perfect control (i.e. no CoTS outbreaks).

In light of recent mass bleaching episodes on the central and northers GBR, and projected continued warming, CoTS management strategies will be working alongside growing pressures and impacts from climate change – in particular increased coral bleaching risks and continued risks of storm damage. To account for climate change we use two contrasting projections for global warming by the Intergovernmental Panel on Climate Change. These are Representative Carbon Pathways (RCP) 2.6 and 8.5. The RCP 2.6 represents a strongly mitigated carbon future and is the scenario aspired to by the Paris Climate agreement (Schleussner et al. 2016, UNFCCC 2016) as it can potentially limit global warming to within 1.5°C above preindustrial levels. In contrast, RCP 8.5 represents a future of less or no carbon mitigation and could see the world warming by more than 2°C already by 2050 (Pachauri and Meyer 2014). As GBR surface waters warm at around 70% the rate of the globe (Lough 2012), RCP 2.6 predicts another 0.2 - 0.4°C warming in coming decades and RCP 8.5 could see GBR waters warm by another 1°C by 2050.

4. Study domain – the Cairns section of the GBR

The rationale for a focus on the Cairns Management Area (CMA) of the GBR is several-fold. Firstly, the CMA is a key area of focus for a large part of GBR tourism, with around one million visitors per year (http://www.gbrmpa.gov.au/visit-the-reef/visitor-contributions/gbr_visitation/numbers/tourist-visits-to-the-cairns-planning-area). Secondly, the reef area between Cairns and Cooktown is often referred to as the CoTS initiation box (Fabricius et al. 2010). One reason is that the GBR shelf is relatively narrow here and thereby influenced to a greater extent by land-use run-off. Episodic blooms of water-column chlorophyll coinciding with CoTS spawning is assumed to be a driver implicated in the environmental triggering of primary CoTS outbreaks (Wooldridge and Brodie 2015). Thirdly, the central to northern section has historically seen more cyclones than other GBR regions (Wolff et al. 2016). Lastly the CMA was impacted by back-to-back mas coral bleaching in 2016 and 2017 (Hughes et al. 2017), leaving the area in a state of vulnerable recovery.

We model reef dynamics on 156 reefs identified by habitat mapping. The criterion for including a particular reefs was based on how much reef habitat (i.e., hard substratum for a given depth range) was observable from satellite imagery and therefore available to construct habitat maps (see figure below). Since our ecosystem model was parameterised with coral demographic rates representative of a reef slope habitat (3-10m depth), we only considered the reef slope for this project. As a result, only the 156 reefs that exhibit a total reef slope area > 0.17 km^2 were considered in the metapopulation models.



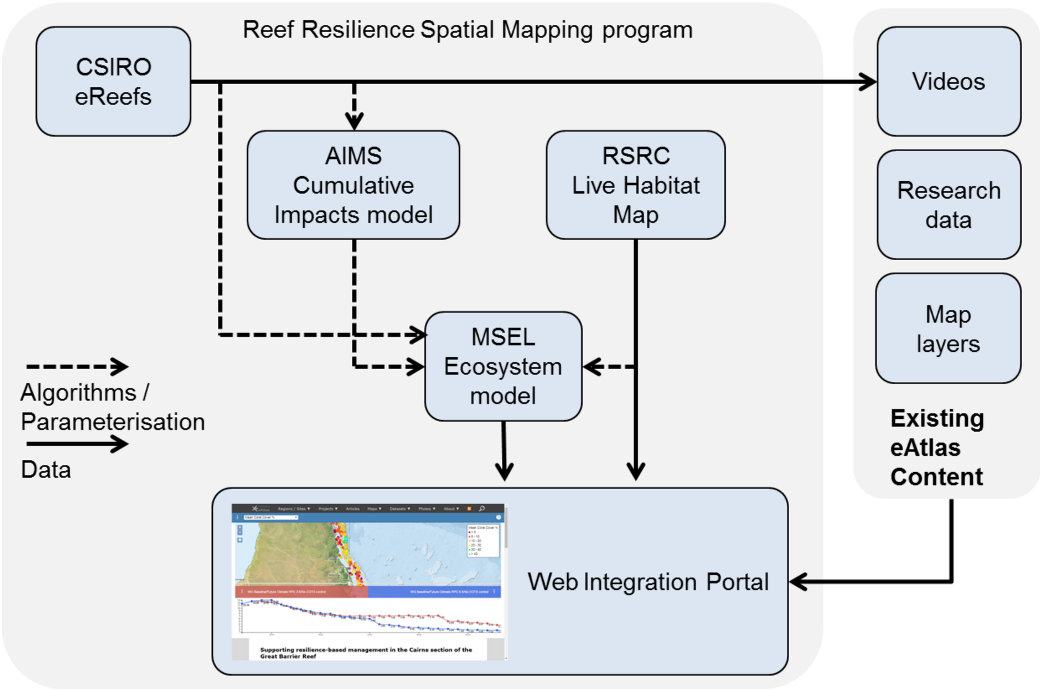
Live Habitat Maps were used to inform the selection of the 156 reefs used in the Resilience-Based Management Toolbox. The habitat maps can be selected among the environmental layers in then toolbox.

5. Architecture of the Resilience-Based Management Toolbox

The *RBM Toolbox* consists of four key elements:

1. Interactive, Web-Integrated Portal - WIP
2. Regional model of coral and CoTS meta-populations
3. Live habitat maps
4. Environmental input layers/exposures

In summary, the toolbox is centred on the regional coral and CoTS model, which uses inputs from the dynamic and spatial environmental layers of exposures (thermal stress, cyclone, observed CoTS outbreaks) as well as live habitat maps, and which are then integrated and displayed to the user via the WIP. In addition, the user can pull in additional resources from within eAtlas to create a mixture of model predictions and environmental layers that can support assessments of benefits vs risks of different management and thereby help inform spatial planning and other strategic management decisions.



We illustrate below how the toolbox works through examples, starting with the WIP as the interactive user environment. We then explain the role of different elements as we walk through examples.

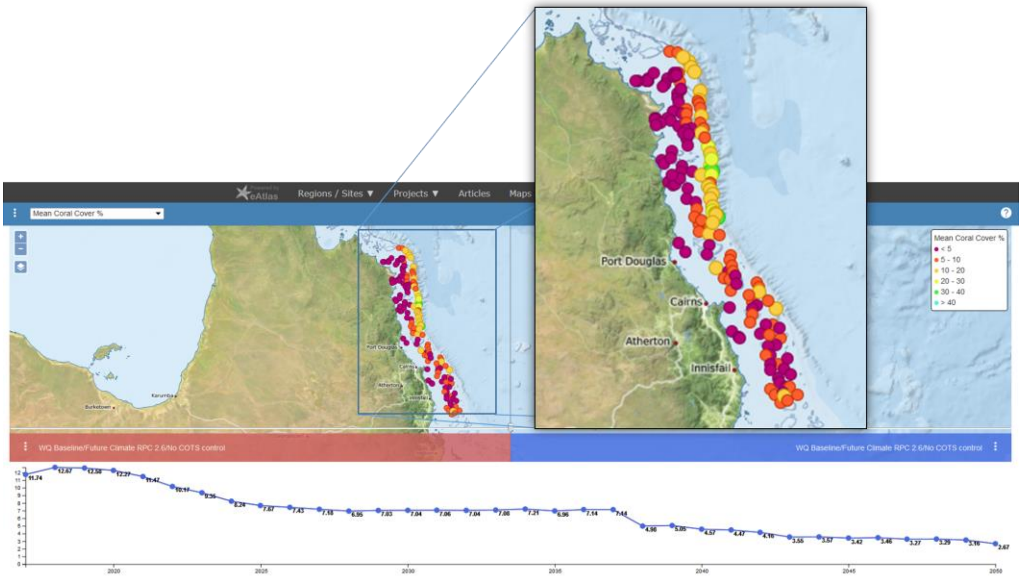
6. The Web Integrated Portal - WIP

The WIP is an online visualization tool developed within eAtlas, but which has a dedicated webpage developed for this project:

http://eatlas.org.au/gbrf/ngbr-coral-reef-resilience

The WIP integrates and displays spatial and temporal environmental, geomorphic and ecological data and models outputs. It is set up so that two coral model outputs can be shown simultaneously – as maps of reefs and exposure layers and as coral trajectories. This enables the user to directly compare effects of different CoTS strategies and/or different climate or water quality scenarios in space and time.

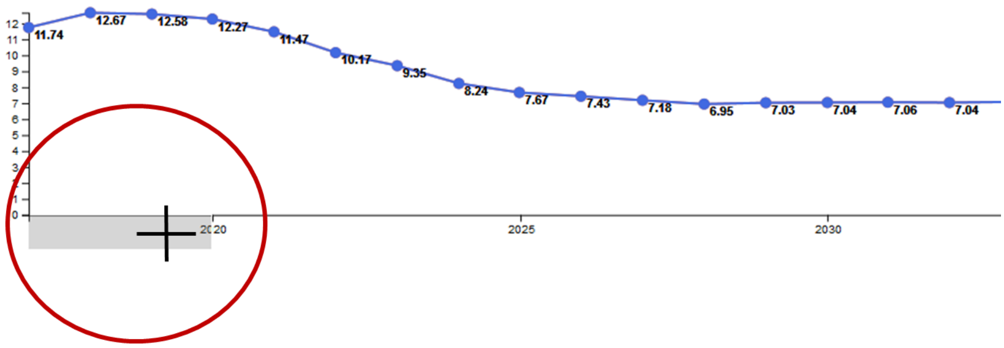
In the default setting, i.e. when the user accesses the webpage, a coral trajectory (i.e., total percent coral cover from 2017 to 2050) is visualised for the baseline water quality scenario under strong carbon mitigation (RCP 2.6) and without CoTS control.



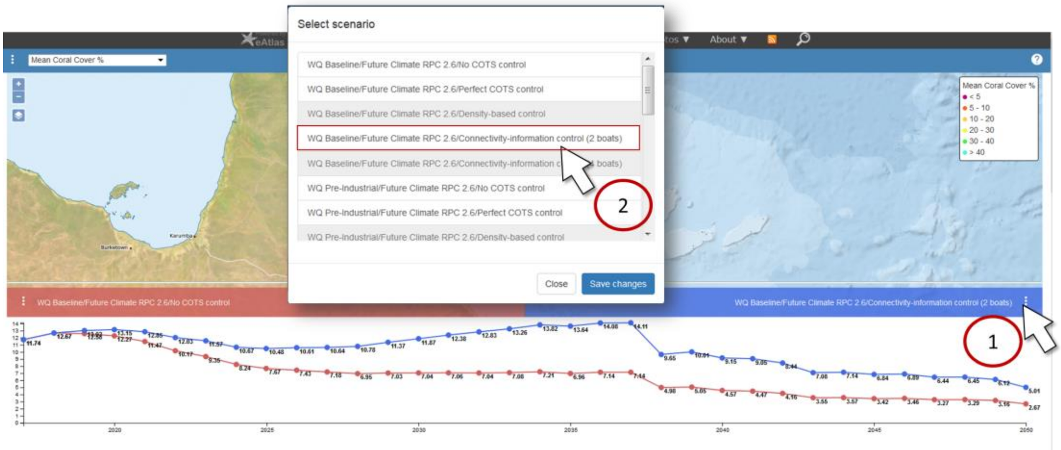
Here, the map shows the coral cover (in bins of 5 or 10%) for each of the 156 reefs averaged over time for the entire period. The trajectory below the map shows the average coral cover of all reefs over time.

The user can also select an individual reef (mouse click) or a group of reefs (ctrl + draw area with the mouse). The trajectory will update to display predictions for that reef or group of reefs.

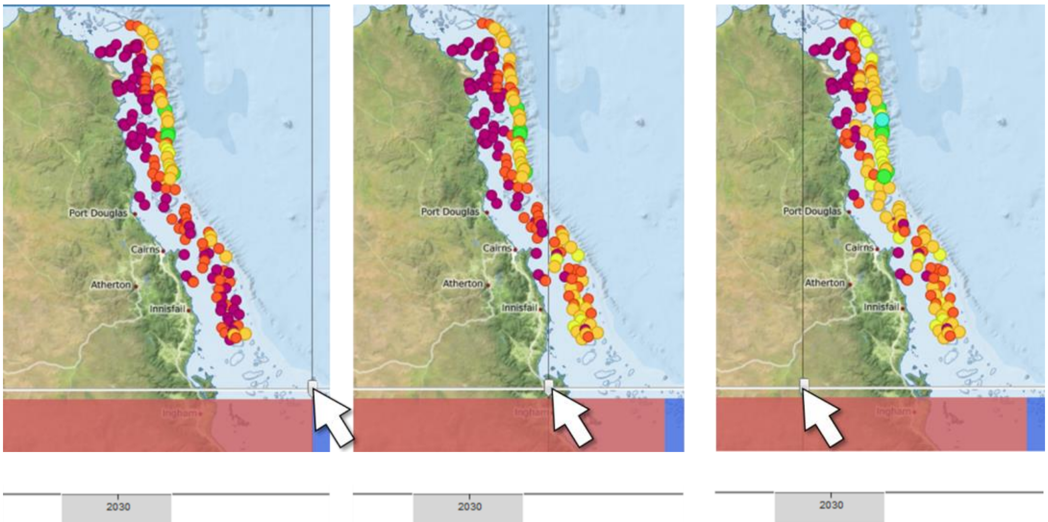
If a specific time period is of interest, for example 2017 to 2020, then that period can be selected directly on the time axis. This updates the map display of coral cover.



To compare coral cover projections under different CoTS strategies and/or climate and water quality scenarios, the user can pull those from drop-down menus on the far left or far right of the red and blue control bars below the map. In the example below we selected a CoTS strategy reminiscent of the efforts that are currently used by GBRMPA: a control program operating from two boats and which focuses on reefs that are key sources of CoTS larvae and also tend to have high density of adult CoTS - i.e. connectivity-informed strategy described in Section 12 below. This now generates a second coral trajectory so that the red line represents the no-control strategy and the blue line the 2-boat / connectivity-informed strategy.



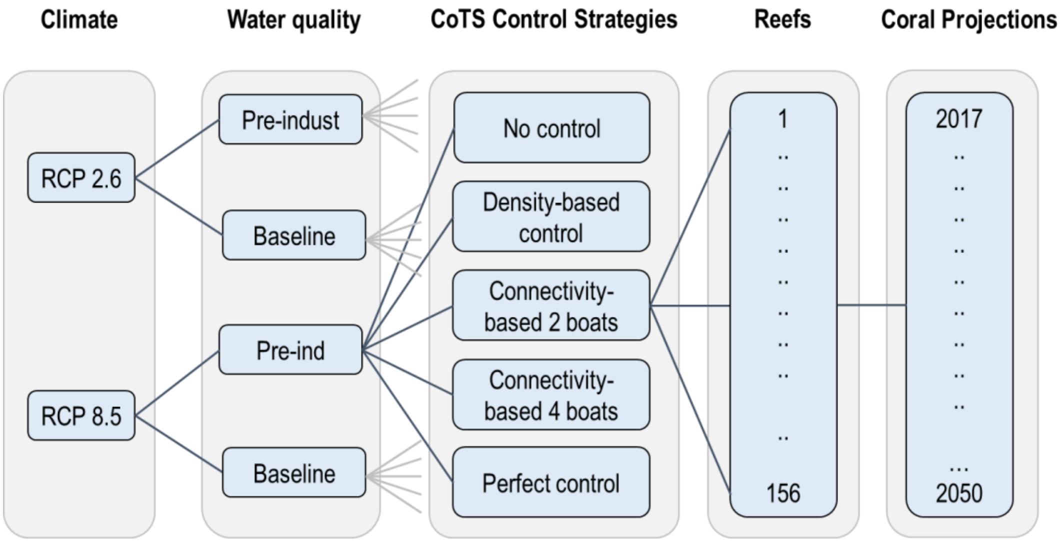
Again, if the manager is interested in mapping and comparing the consequences of these strategies for different coral reefs for a specific time period, then that period can be selected directly on the time axis. The spatial comparison is here done using the slider that splits the map area in two (vertically) as a sliding door. The layer in front represents the red scenario/strategy (no control) and the layer behind the 2-boat strategy – both for the period 2028-2032. Moving the slider to the left reveals the spatial texture in the model predictions for both strategies – in other words: some reefs remain at low coral cover regardless of effective CoTS control, some benefit from control (transition from red to yellow or green) and others sustain high coral cover with or without CoTS control. The latter is especially the case for outer-shelf reefs off Cooktown (Hock et al. 2017).



The above example is only for two CoTS control strategies: (1) no control and (2) CoTS control from 2 boats informed by connectivity. However, the toolbox allows the user to explore and compare predicted coral trajectories for combinations of two climate change scenarios, two water quality scenarios, and five CoTS strategies – a total of 20 combinations of reef trajectories.

In Section 12 we return to CoTS strategies in more detail to provide examples of how structured analyses of different strategy combinations (pairs) under different scenarios can be used to inform policy decisions, for example under the Reef 2050 Plan.

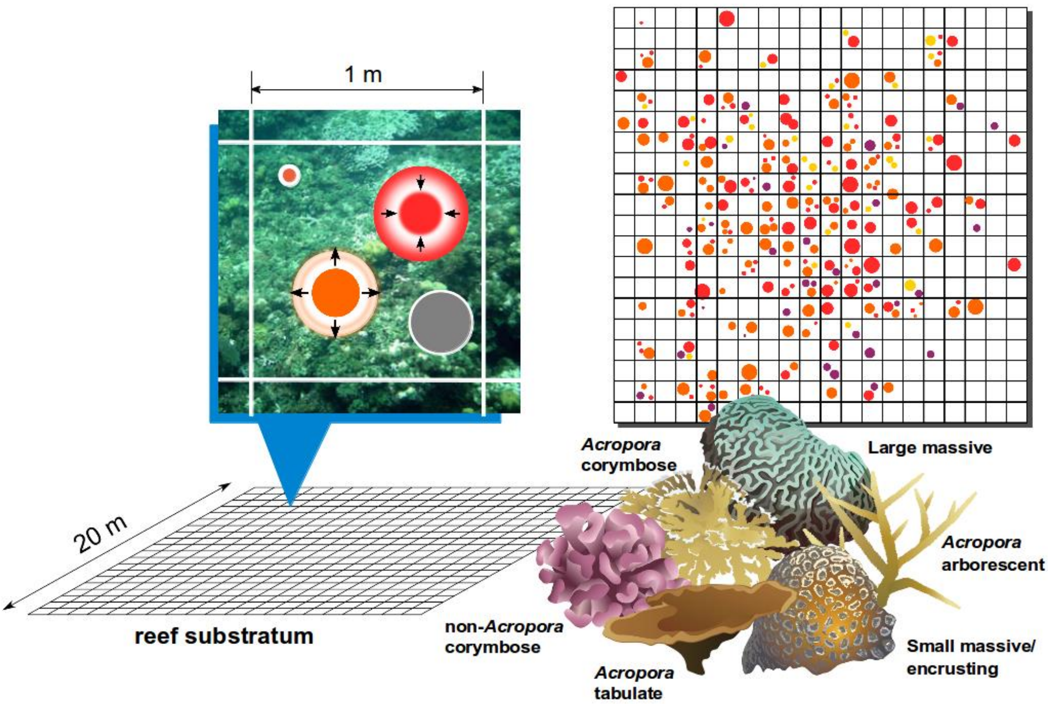
Importantly, because model projections of coral cover in this prototype consist of archived layers that the WIP makes available on demand by the user, management impacts of one strategy at one time point do not influence the scope of other management strategies at other time points. In other words – the impact of each strategy runs from 2017 to 2050 for all scenario and strategy combinations. In future versions of the toolbox, the model can be run live on demand by the user to explore flow-on effects of mixed strategies in time and space.



Summary lay-out of how the climate change (Representative Concentration Pathways, RCPs) and water quality scenarios and CoTS strategies are nested within the RBM toolbox. For each of the 20 scenario/strategy combinations, the model produced 100 simulations over the 2017-2050 time horizon and archived means and standard deviations for those simulations for each of the 156 reefs

7. The coral reef ecosystem model - *ReefMod*

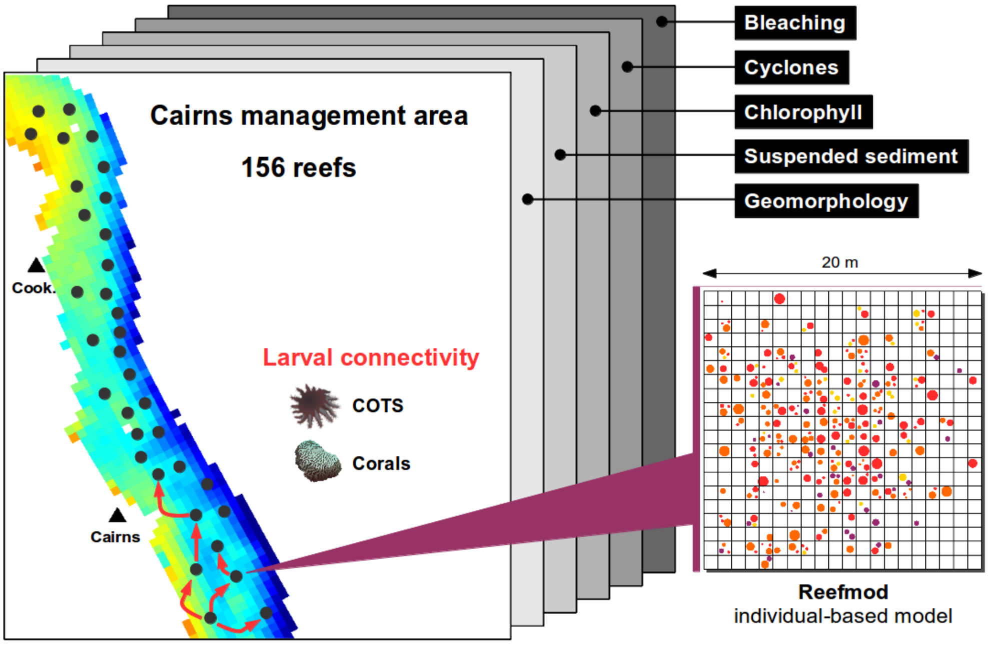
The core element of the RBM toolbox is a spatially-explicit model of coral communities (Mumby et al. 2007, Ortiz et al. 2014, Bozec et al. 2015) developed by the MSEL team at UQ and with contributions from AIMS around cumulative biological impacts. The model, broadly referred to as *ReefMod*, is individual-based and simulates the fate of coral colonies evolving on a regular square lattice representing a 20 x 20m horizontal reef substratum. In essence, the model grows coral reefs in a virtual, simulated environment using the principle of agent- or individual-based modelling. Each grid cell approximates 1m^2 of the reef floor, and can be occupied by multiple coral colonies of different species. The model integrates physiological, population-level and community-level processes for benthic reef assemblages in space and time using dynamic environmental exposure layers (past, present or future) as input. For the present application, we used a previous model parametrisation developed for the GBR (Ortiz et al. 2014) allowing the simulation of six characteristic morphological groups of *Acropora* (tabulate, arborescent, corymbose) and non-*Acropora* corals (corymbose, small massive and encrusting, large massive corals). A focus on *Acropora* corals is justified as they represent the key habitat-forming species on Indo-Pacific reefs and account for around 70% of the coral biodiversity in the region (Wallace 1999). The GBR model was augmented with explicit mechanisms driving the early-life stages of corals: coral reproduction, coral settlement, and growth and mortality of coral recruits. In addition, this new GBR model integrates a demographic model of CoTS (**Box 1**) to simulate the impact of CoTS outbreaks on coral populations.



Schematic representation of the reef ecosystem model (ReefMod). Individual coral colonies settle, grow, shrink and die in a virtual 20 x 20m environment as they do in situ. Demographic rates are specific to the six modelled coral groups.

In summary, each reef in the Cairns management region is represented by a *ReefMod* grid, and the 156 reef grids are connected through connectivity matrices of larval dispersal developed for CoTS and corals (Hock et al. in prep). In simulations, the dynamics of corals and CoTS are driven by demographic processes including recruitment, growth, reproduction and mortality. These processes are in turn linked to multiple environmental variables including warming, cyclones, water quality and hydrodynamics (i.e. connectivity).

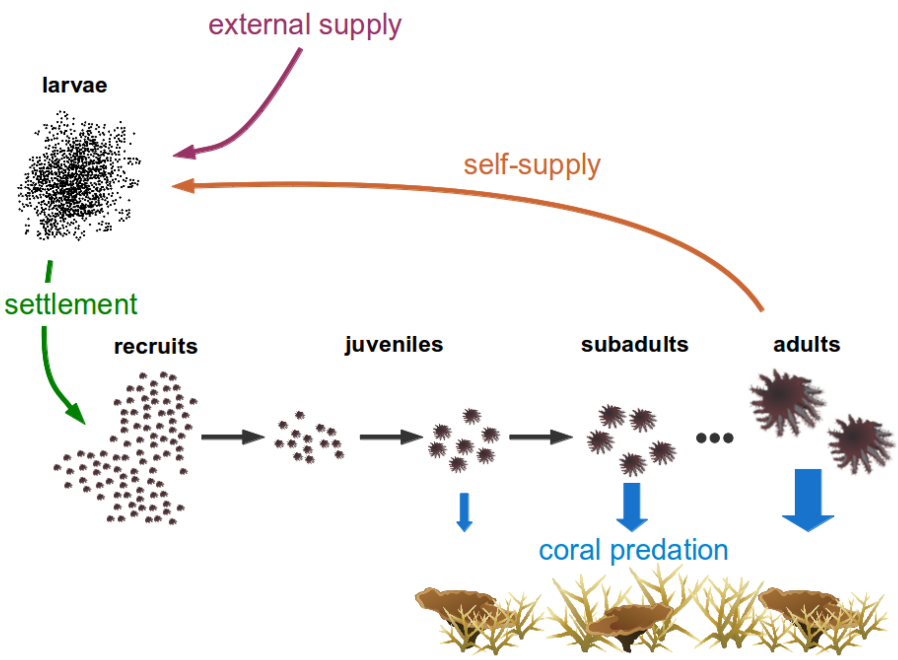
The model is spatially explicit in three ways: first by simulating the demographic processes of individual coral colonies and CoTS populations on a reef landscape, second by linking coral and CoTS demographics to their ambient environment (water quality on a given reef and exposure to cyclones and thermal stress), and third by connecting reefs in a network that represents inter-reef larval exchanges for both CoTS and corals.



Conceptual representation of the integration of the reef ecosystem model (ReefMod) into a regional model of connected coral and CoTS metapopulations with spatially-explicit environmental forcing.

Box 1. Integrating the population dynamics of Crown-of-Thorns Starfish

We developed a simple demographic model of the Crown-of-Thorns Starfish (CoTS) dynamics to simulate the propagation of CoTS outbreaks and their effects on coral cover. The model is structured by age (6-month age classes) and integrates age-specific rates of mortality, fecundity and coral consumption (e.g. Kettle and Lucas 1987, Keesing and Lucas 1992). CoTS release their gametes in summer (December-January) and the resulting number of larvae is affected by the ambient concentration of chlorophyll *a*. High chlorophyll concentrations promote the survival of CoTS larvae (Fabricius et al. 2010) and connectivity information determines the amount of CoTS larvae that are retained or distributed to other reefs. The stock of CoTS larvae available for settlement on a given reef is thus a function of local retention and external supply. The amount of corals consumed varies between coral species, and when coral cover drops below 5% the population of coral-feeding CoTS dies due to starvation.

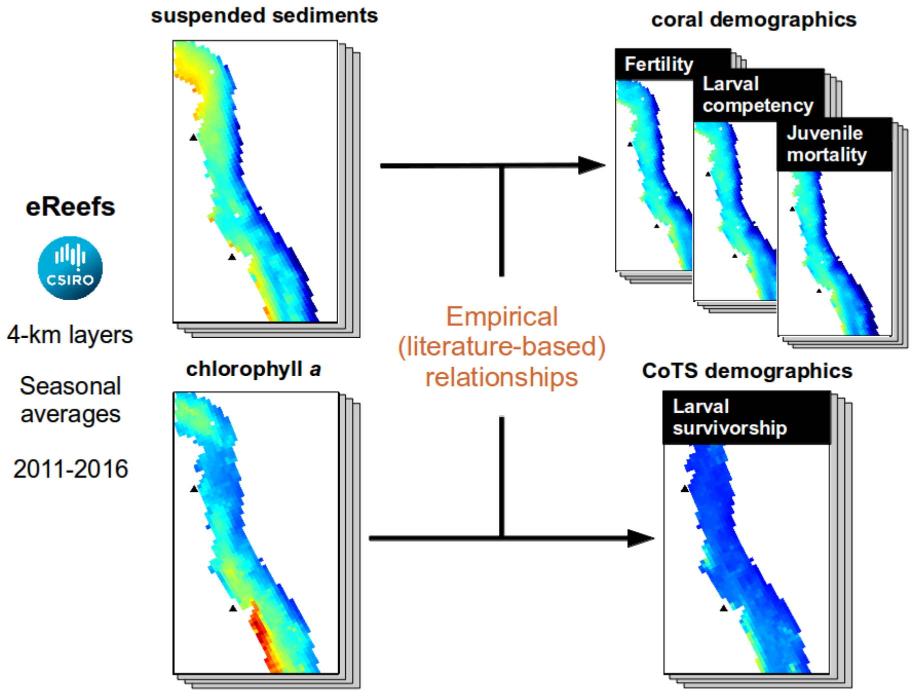


8. Model integration with dynamic spatial layers

Water Quality

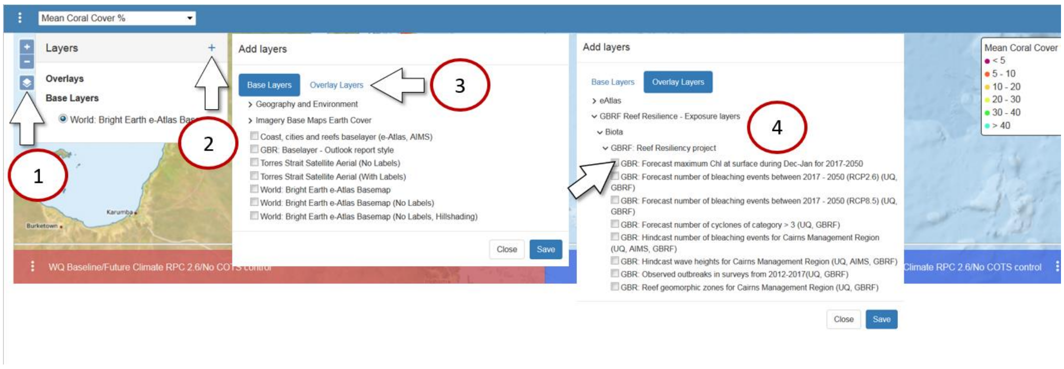
Nutrients, sediments and other pollutants run off from river catchments and episodically expose coral reefs to varying loads over varying spatial extents and timeframes (e.g., following extreme rainfall and river flood events). To capture these dynamics, exposure to run-off was assessed using the *eReefs* modelling platform developed by CSIRO. *eReefs* produces retrospective daily predictions of hydrodynamic and biogeochemical parameters at different depths.

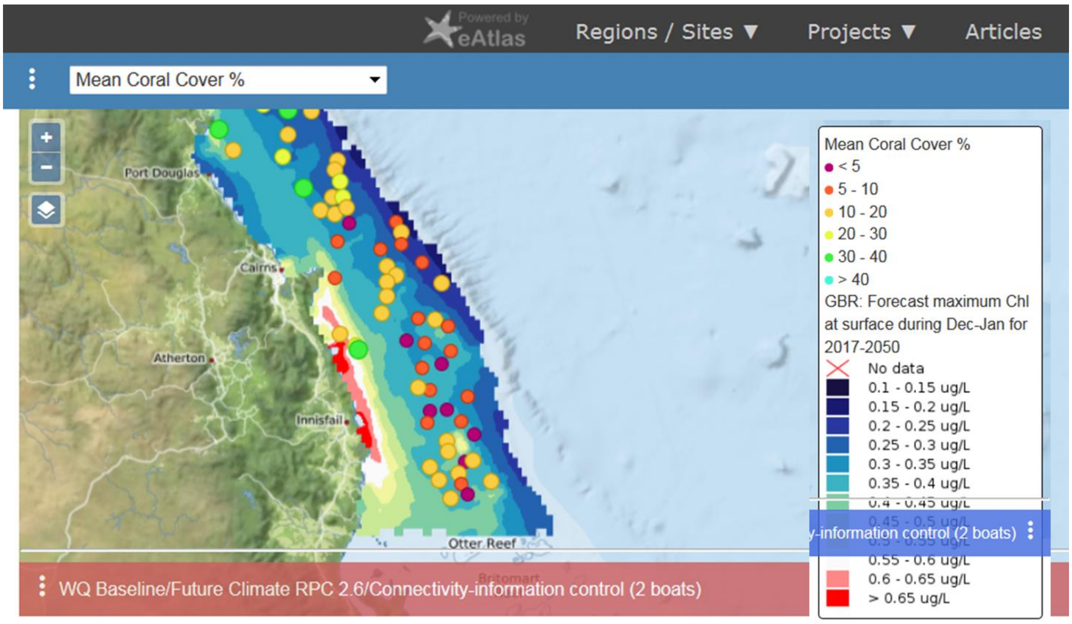
For the purpose of modelling coral and CoTS dynamics, we focused on two key water quality layers: suspended sediment concentrations (SSC, as seasonal averages) and surface concentrations of chlorophyll *a* (as summer maxima). Suspended sediment influences many aspects of coral biology, for example by shading corals in inshore waters (Anthony et al. 2009), lowering coral fertility, reducing future settlement success of coral larvae and hampering the survival of coral juveniles (Humanes et al. 2017a)(Humanes et al. 2017b). Chlorophyll *a* is assumed to influence the survivorship of CoTS larvae in the Cairns/Cooktown area (Fabricius et al. 2010), the latter referred to as the CoTS initiation zone.



Summary lay-out of how spatial and temporal dynamics of two key water quality variables (suspended sediment/turbidity and water column chlorophyll a) produced by eReefs were used as input into the regional coral and CoTS model. The stacking of layers indicate variation in time.

We used the dynamics of these spatial water quality layers to model coral and CoTS demographics for six consecutive years between 2011 and 2016. To examine the effect of different land-use scenarios, model simulations were run using pre-industrial and business-as-usual catchments loads for the years 2011-2016. We note that these two water quality scenarios in this version of the toolbox produce very similar layers of SSC and chlorophyll *a*. As a result, their differential impacts on coral and CoTS demographics is low.





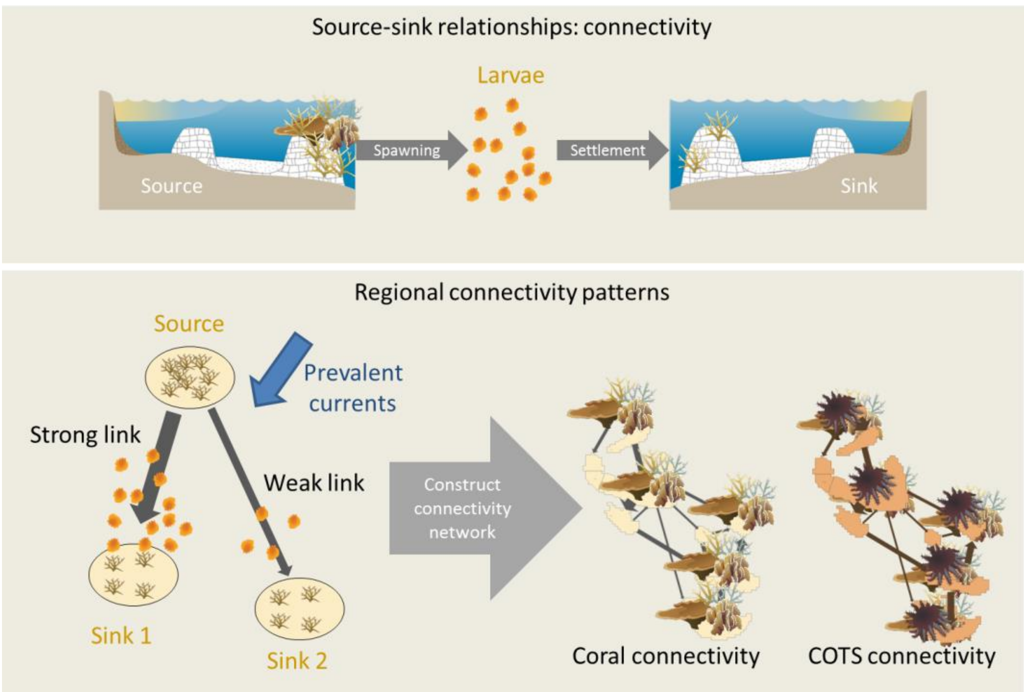
The figure above shows a synoptic layer of maximum chlorophyll *a* for the summer months. In the model, dynamic layers were used to inform CoTS outbreak likelihoods within the Cairns management area. In future versions of the RBM Toolbox, synoptic water quality layers for a given year can potentially be used to identify hotspots for CoTS initiation as the combination of (1) high water-column chlorophyll, (2) high coral cover and (3) high connectivity to downstream reefs.

CoTS outbreaks

Surveys of CoTS outbreaks have been ongoing in the Cairns regions since 2012. Two sources have been used to build a layer of past exposure to CoTS outbreaks:

GBRMPA's Field Management Program (FMP) and AIMS Long-Term Monitoring Program (LTMP). Manta tows from both sources were used to construct a yearly distribution of outbreaks on reefs. Operational thresholds used to determine the state of the reef (>0.22 adult CoTS on average per tow for incipient outbreak, >1 adult COTS on average per tow for active outbreak) (Moran and De'ath 1992, Pratchett et al. 2014) have been used to initiate outbreak populations on reefs. Since only a portion of reefs in the region was surveyed every year, CoTS population on reefs that were not surveyed in a given year were determined by the CoTS metapopulation model. On those reefs CoTS outbreaks may still emerge in the metapopulation model from the simulated population dynamics and larval supply from other reefs. As such, the CoTS exposure layer was a combined result of field observations from reefs for years where such observations were available, and the emergent model behaviour to fill the knowledge gaps for reefs that have not been surveyed.

Box 2: Connectivity simulations

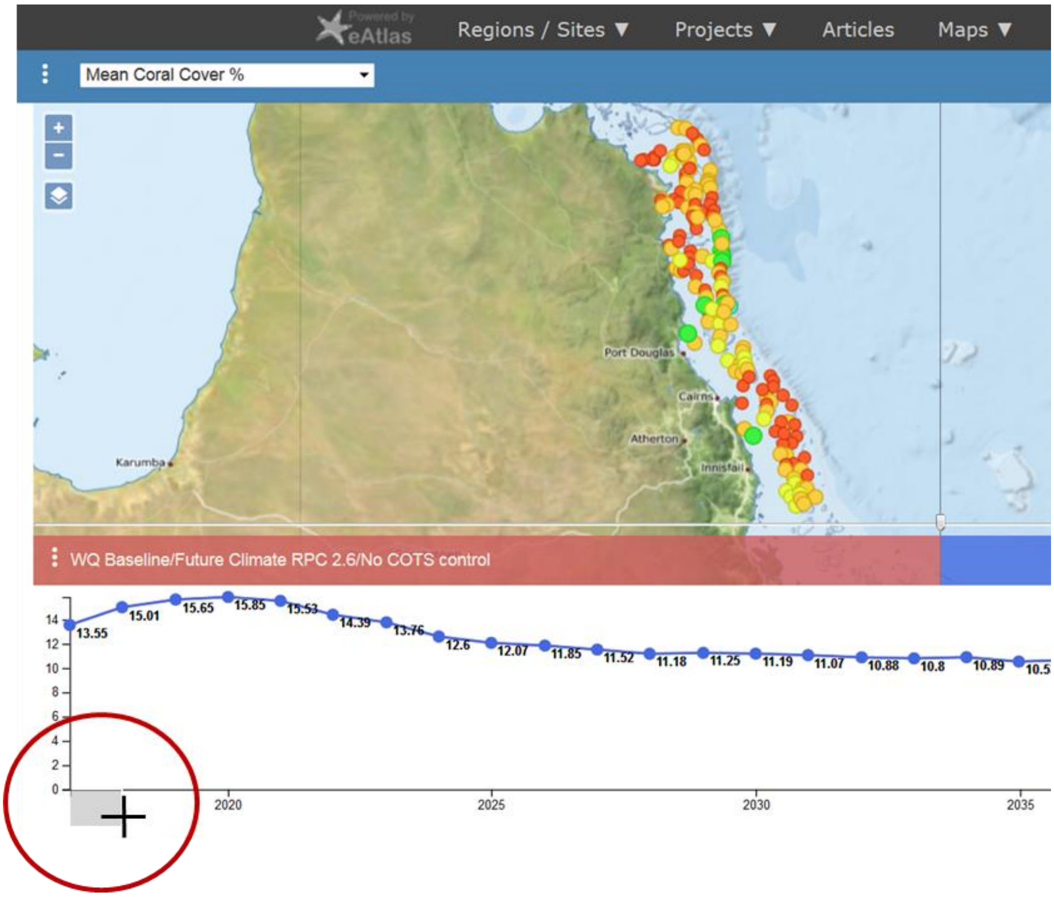


Dispersal of coral and CoTS larvae was simulated to determine the connectivity relationships among the individual reefs in the region which follows the framework published in Hock et al. (2014, 2017) and briefly summarised here. Larval dispersal was initialised by releasing the particles at spawning times, which were estimated from field observations for corals and approximated for CoTS (Hock et al. 2017). The spawning was simulated from dry reef polygons defined under the GBRMPA zoning plan (GBRMPA 2004). Dispersal of larvae released in the water column was then simulated with the Connie particle tracking tool (Condie et al. 2012)(see also www.csiro.au/connie2/ for a web interface) which uses eReefs hydrodynamic forces to generate a three-dimensional model of particle dispersal driven by ocean circulation. This model has hourly time steps and a spatial resolution of hydrodynamic forces over a 4km grid. Larvae that came within 1km of a reef polygon during dispersal would then contribute recruits to that reef, and these recruits were then added to the population dynamics models on that reef. The strength of connection between a source and a sink was determined by the number of larvae that reached another reef. This was further modified to represent time-sensitive survival and development characteristics of the modelled species (Connolly and Baird 2010, Pratchett et al. 2014, Hock et al. 2017), with the probability that a particle would successfully contribute to the population at a sink dependent on time between spawning and arrival at the sink reef. Larval dispersal was simulated for all reefs in the region in order to obtain regional connectivity relationships; however, only relationships between reefs that were mapped using live habitat maps were used in the metapopulation model. This process was then repeated for designated spawning times over the 6 years for which the hydrodynamic models were available (summers of 2010-11, 2011-12, 2012-13, 2014-15, 2015-16, and 2016-17). The obtained seasonal connectivity patterns were then coupled with outputs of water quality analyses for the respective years in order to simulate the relationship between connectivity and water quality on larval dispersal and settlement. These coupled connectivity and water quality patterns were then repeated in forecast simulations to represent future connectivity patterns.

9. Model hindcasting

To determine the current state of reefs across the Cairns region and the initial conditions for the forecasts, the model was run 100 times (replicate simulations) with spatially and temporally realistic regimes of water quality, bleaching, cyclones and CoTS between 2008 and 2017 (10 years). For each replicate simulation, the initial coral cover for a given reef was randomly generated from a normal distribution centred on a pre-defined average (standard deviation: 10%). Average coral cover at initial step (winter 2007) was derived from benthic data collected by the AIMS Long-Term Monitoring Program (LTMP) in 2006-2007. This dataset provided reef-wide coral cover for 26 reefs. The other 130 reefs were initialised with the mean coral cover reported for each management sector (Cooktown/Lizard Island, Cairns, Innisfail) and shelf position (inner-, mid- and outer-shelf reefs). Initial total coral cover for all reefs was distributed among the 6 functional groups following the average relative cover reported by AIMS LTMP on the inner-, mid and outer-shelf reefs in the region.

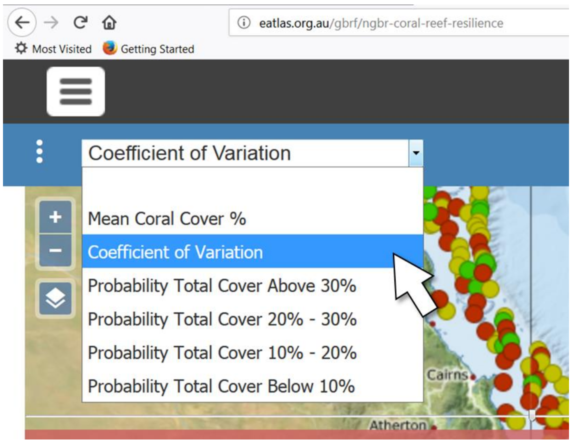
The current modelled state of all 156 reefs in the region can be visualized in the WIP by selecting the initial two years in the time series directly on the time axis (see below).



Validation of these hindcasting simulations is still in progress. To determine the extent to which our integrated regional model can predict coral cover in changing environments with confidence, model predictions will be compared against the coral trajectories monitored by AIMS LTMP for the period 2008 to 2017. We anticipate some discrepancies between observed and predicted reef state because location-specific habitats are not captured by our model parameter values (initial cover for 130 reefs based on regional averages). Some habitats may unexpectedly escape cyclone/cots/bleaching damages and some habitats may have been impacted by disturbances (e.g. coral disease) that went undetected. Also, CoTS control was not included in these hindcasts.

As the model develops further and local processes captured and used to continuously update and calibrate model functions, we expect that the predictive capacity of the integrated regional model will improve over time. This comparison between observed vs predicted reef state will imply running different hindcast scenarios whereby one stress is added at a time in order to inform about the most likely scenario of disturbance regime. Such scenarios may become available to managers and used as diagnostic tools to explore the mechanisms driving recent reef trajectories. For example, the model may pinpoint that a specific reef location likely escaped the recent bleaching events despite being predicted to occur based on exposure layers.

Importantly, the model simulates a level of uncertainty associated to the predicted reef state. Some of that uncertainty stems from stochastic processes such as cyclones, flood events, thermal anomalies. Parts of this uncertainty is artificially inflated because we used random values for initial coral cover at different reefs. Further, physiological as well as ecological processes such as bleaching risk, larval connectivity and recruitment are associated with uncertainty. This means that for model results to best inform decision-making, model estimates (averages) should be accompanied by their coefficient of variation determined from simulations. The coefficient of variation (standard deviation divided by the mean) can be selected from the main display menu (top left corner).



In Section 12 below we show how model predictions in conjunction with coefficients of variation can be used to inform statistical comparisons of the performance of different CoTS strategies under different climate and water quality scenarios.

10. CoTS control model

In the current version, CoTS control model is fully functional but not yet complete. Most notably, various decision-making processes that would determine how surveys should be performed in the region to gather valuable knowledge about the system have not been implemented yet. Also, the costs operating a control boat, and the ways these costs could be optimised, were not included in the control model at this stage. These and other further developments of the control model will be the major focus of future efforts under the NESP project on CoTS Integrated Pest Management (CoTS IPM). The current model is therefore not intended to be used as a decision-support tool for fine-scale tactical management of CoTS outbreaks, though it is expected that the current version would represent the foundation of the models that will aim to be able to support such decisions in the next few years. Rather, the current set of CoTS control scenarios can be used to compare the strategic importance of continued control efforts on reef futures, such as the improvement that could expected by continued CoTS control, as well as to provide the most comprehensive projections for future reef health which can support the GBR Outlook report. The current set of strategies are therefore designed to showcase how reefs should be selected for control once substantial effort has been invested to obtain knowledge about the system, and what kind of benefit can be expected when control is applied at specific regionally important locations.

Estimating control effort

Control effort was designed so as to mimic the major features that characterise real-world on-water management efforts of CoTS populations by dedicated control boats. Total control effort over a 6-month period was represented by the area that a boat could ideally cover for CoTS eradication in 6 months given the number of days a real-world control boat would typically spend on water doing the culls, providing an idealised 'quota' that can be controlled over this time. This number was then divided into individual voyages during which a control boat could visit a fixed number of reefs. The reefs were then controlled in the order determined by a prioritisation strategy before the next voyage. All boats used the same 'quota', that is, they could control the same area over a 6-month period, and additional boats simply meant that a larger area can be covered over the same time period.

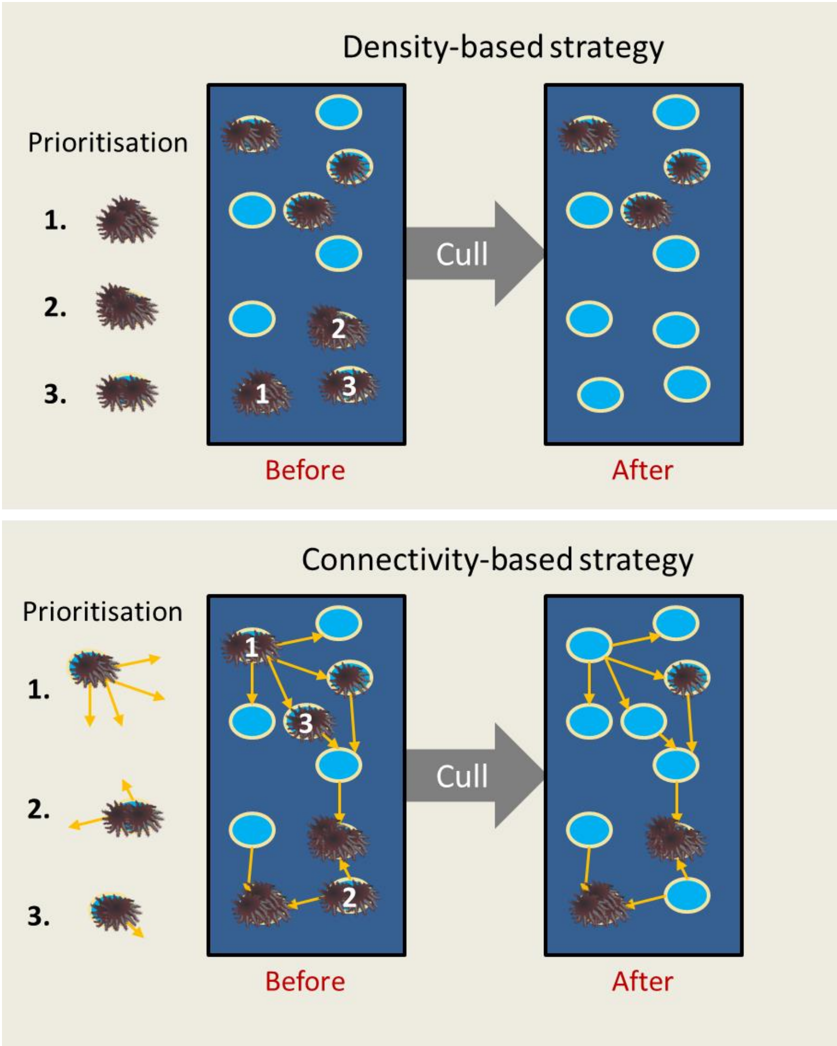
Strategies to select and prioritise reefs for control efforts

In order to demonstrate the utility of considering CoTS populations for making decisions about which reefs to select for control, the current version of the model featured complete knowledge of CoTS populations on individual reefs, that is, the state of CoTS populations was always known before decision were made on which reef to go to eradicate CoTS. If the knowledge about the state of the reefs was incomplete, it would be necessary to first decide how reefs should be surveyed before allocating control efforts. This adds a level of complexity that will be fully addressed as a part of NESP project on CoTS integrated pest management (IPM). However, it is important to emphasise that complete knowledge of CoTS populations is not expected to ever be available in real-world situations. Even so, it is a necessary starting point to determine how effective control strategies could be if key parameters about the system are fully known. Complete knowledge also allows some general rules to be tested in a relatively simple system – for example, if a strategy is not effective in controlling even with full knowledge of the system, it should not be considered further in the more nuanced explorations where knowledge must first be acquired through planned surveys.

The selection of reefs was based on one of the two prioritisation strategies:

1. A 'density-based strategy', under which the density of the populations on all reefs is known, but connectivity of reefs is not known. Reefs are then prioritised so that those with the highest density of adult CoTS are controlled first. Once a reef with the most adult CoTS is selected, the boat then proceeds to control CoTS on nearby reefs as well, regardless of density of adult CoTS on those reefs. This means that, while the strategy prioritises reefs with lots of CoTS by design, some effort may also be allocated to non-optimal sites. Although no strategy can be said to be realistic under conditions of a perfect knowledge about the state of the CoTS populations on all reefs, this strategy has some parallels to how control boats operate in real world where the boats tend to focus on reefs with lots of visible adult CoTS and also tend to visit other nearby reefs during the voyage.
2. A 'connectivity-based strategy' which takes into account not only the density of adult CoTS on reefs, but also the potential of those populations to export CoTS larvae. This follows a simple premise that a reef with a large population of breeding adult CoTS and lots of potential connections to other reefs will be able to introduce more larvae into the system, and should therefore be prioritised for control. This strategy always controls CoTS on reefs that have the highest

larval export potential and does not allocate any effort to nearby reefs unless they are also prioritised for their connectivity, in order to explore the limits of control with perfect knowledge and necessary but optimal allocation of –still limited – resources.

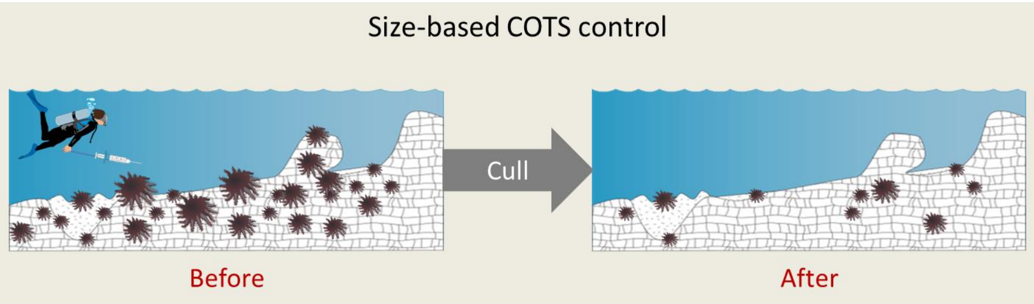


Once reefs were assigned priority scores using the selected prioritisation strategy, these scores were then used to compile a ranked list of reefs which provided the boats with a sequence of reefs to visit on an individual voyage. The boats would then proceed to cull a proportion of adult-sized CoTS on the selected reefs in the order of importance. Before the next voyage, the density of adult CoTS populations on each reef was updated to reflect the impacts of recent eradication efforts before planning the next voyage. Each boat would plan its voyage independently, but in such a way that the reefs it would visit did not overlap with the planned voyages of other boats (no visits to the same reef at the same time by multiple boats). This process would continue until all voyages for all boats in a given time period were completed.

In the current version, scenarios for each prioritisation strategy simulated CoTS control performed by more than one boat (in reality, there are currently 2 boats performing CoTS control in and around the Cairns region). Scenarios with 2 control boats were explored for both density-based and connectivity-based strategies in order to make their overall effort comparable, with the differences between outcomes coming from the way the reefs were prioritised for control. Scenarios with 4 control boats were also explored for the connectivity-based strategy to determine the effect of increasing the control effort while keeping the method to prioritise reefs, and indirectly also the level of knowledge about the system, constant.

In addition to the two prioritisation strategies, two other scenarios were also explored: a scenario where no CoTS control takes place, and an 'optimal control' scenario in which all adult CoTS on all reefs are reduced to 1% of their density at every time step (no boats explicitly modelled, instead CoTS populations are ideally and uniformly culled system-wide but not eradicated completely, which only removes them as a threat but not as a species). These two scenarios represented the extremes against which the effectiveness of the prioritisation strategies could then be compared. Specifically, no control depicts what kind of damage CoTS would do to the system if all control efforts were abandoned, while optimal control represents the maximum control impact we can expect to achieve with unlimited resources while still not eliminating CoTS from the system entirely - a sort of an ideal control outcome we should strive for with any control strategy.

The outcomes obtained with different control strategies under RCP 2.6 and baseline water quality are presented in Section 12.



Modelling CoTS removal from reefs

CoTS control on a reef selected for control was simulated as removal of a portion of its CoTS population. CoTS were culled by size class, and the cull efficiency per size class was guided by empirically determined size-dependent detectability (MacNeil et al. 2016). The proportion of the total CoTS population on a reef that could be culled was derived from approximate area that could optimally be covered in a day by a boat with a team of trained divers on board. An area that could be controlled by the divers was modelled optimistically: for example, it was implemented under the assumptions that each diver is maximally efficient while culling, that removing CoTS is only limited by detectability of individuals of a certain size, and that the area multiple divers could cover does not overlap. Even if the ability of the divers to cull CoTS was optimistic compared to what is possible in the field, this implementation nevertheless provided some indication of the limitations that would constrain the cull effort in terms of impact on CoTS populations, and also provides a null-model from which a more realistic model of diver behaviour and efficiency can be developed in the future. If the area of the reef was larger than what could effectively be controlled in a day by the diver team, the cull would continue on a reef for consecutive days until either the entire reef area was considered to have been subjected to CoTS control or the voyage came to its planned end. If there was still time remaining on the voyage plan after the reef was controlled, the boat would then move to the next reef on the priority list and proceed to cull CoTS on that reef. As noted, the reduction in reef's CoTS population as a result of a cull during the previous voyage would be taken into account before prioritising reefs for the next voyage.

11. Model forecasting – coral cover under future change

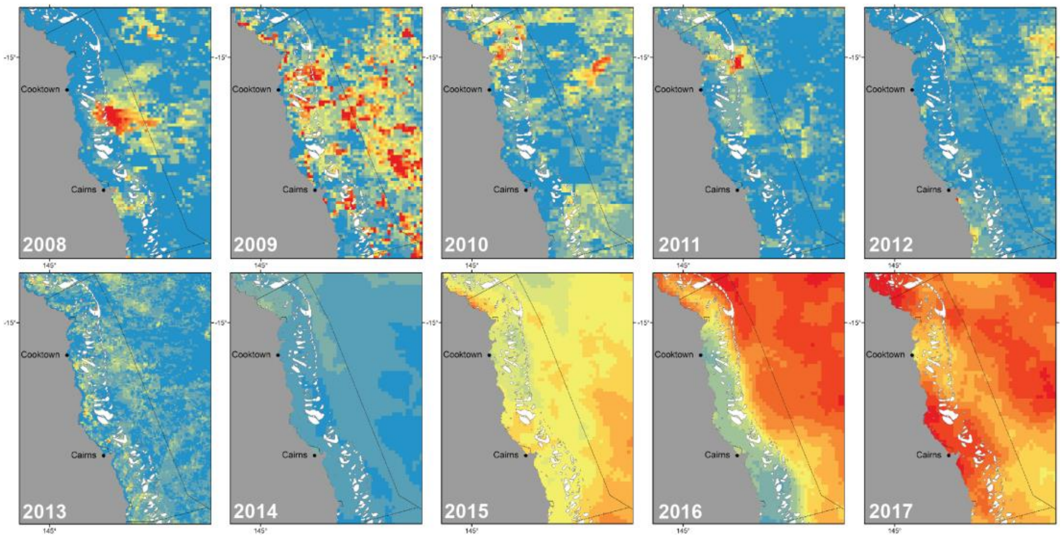
Here we explore in more detail the capacity of the model to produce forward projections of coral cover under climate change. Understanding this capacity as well as its limitations will be important for how results are used to inform medium- to longer-term policy decisions.

The RBM toolbox uses outputs of climate models in combination with hindcasting (which provides coral starting conditions) to produce forward projections of coral cover. This is necessary because *eReefs* only provides hindcasts of the physical and chemical marine environment on the GBR. The modelled future exposure layers were in this project limited to sea surface temperature. Some studies suggest that cyclones are predicted to increase under climate change in the south pacific region (Anthony 2016), but the signal is not clear from observations (Wolff et al. 2016). Because cyclones is likely to remain a significant disturbance on the GBR, however, we model future cyclone risks spatially using a new technique that blends historical data with modelled cyclone behaviour in the GBR region.

Projections of sea surface temperatures (SST)

To produce forward projections of SST, we used outputs from the UK Hadley Centre's Global Environmental Model HadGEM2-ES. Two contrasting climate scenarios from the IPCC's fifth Assessment Report were used: the strongly mitigated Representative Concentration Pathway (RCP) 2.6, and the un-mitigated RCP 8.5 (Pachauri and Meyer 2014). Degree heating months, which is a strong predictor of bleaching risk (Eakin et al. 2009), were extracted from temperature projections based on the method by (Wolff et al. 2015).

To produce spatially explicit bleaching forecasts as input into the reef model, we blended the historical spatial pattern in degree heating months (DHMs) to produce a regionally adjusted warming trend. The figure below shows annual spatial patterns of DHM from 2008 to 2017(capturing most recent bleaching events) and which we used in the hind-casting of coral cover. In forward projections we used these spatial textures to inform latitudinal and longitudinal differences in warming risks among reefs in the region, but then ramping up the regional warming trend according to the climate scenario (RCP 2.6 or 8.5). The temporal variation in heating seen during this decade was used also in the forecasts to account for this source of uncertainty.



Example of a time series of exposure maps used in hindcast simulations. The maps show maximum sea surface temperature. Three different sources of satellite data were used: Coral Reef Anomaly Data (CoRTAD) for years up to 2012 (Casey et al. 2015), ReefTemp for 2013 (Garde et al. 2014), and a new product by National Oceanic and Atmospheric Agency (NOAA) Coral Reef Watch after 2014 (Liu et al. 2014).

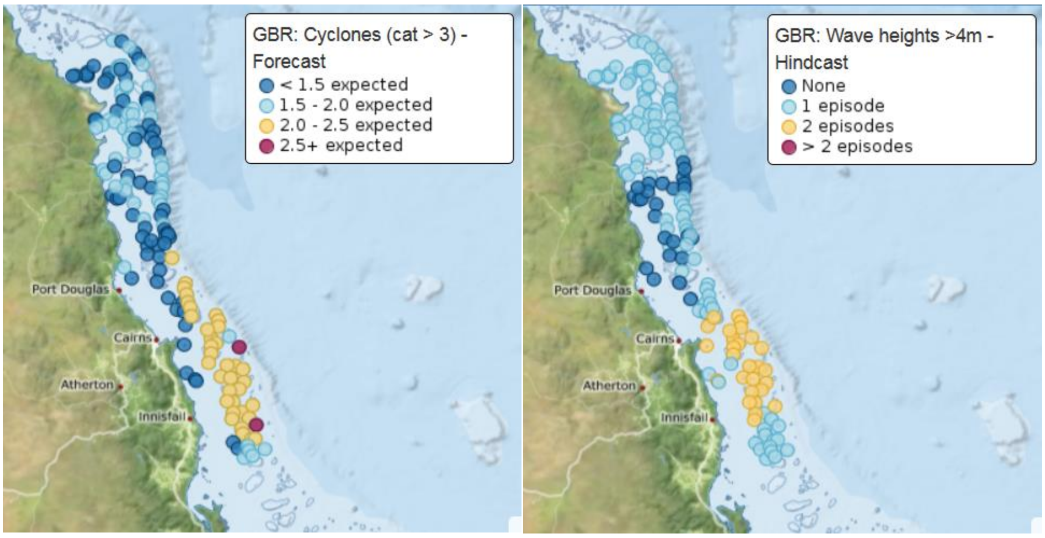
Cyclone forecasts

There is a strong spatial texture in cyclone risks on the GBR based on past observations (Wolff et al. 2016). We blended that historical texture with synthetic (simulated) cyclone tracks (Emanuel *et al.*, 2008) to produce a spatially explicit layer of cyclone risks to accompany protections of SST.

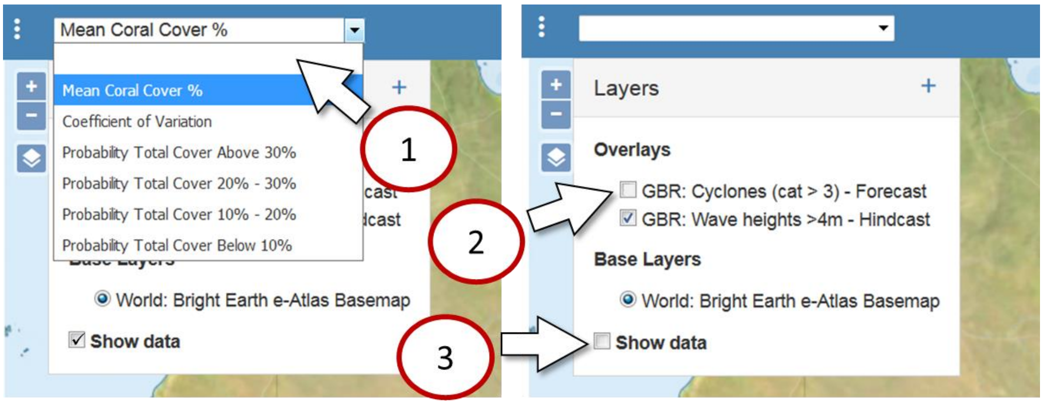
Cyclone behaviour is only a proximate cause of physical reef damage. A more ultimate explanatory variable is wave height, which can vary spatially depending on whether reefs are exposed to ocean waves or in the lee of other reefs or shallow water (Puotinen 2005, Fabricius et al. 2008, Game et al. 2008, Maynard et al. 2015, Mellin et al. 2017). To make this information available to the user, a hindcast layer of wave height is provided as part of the toolbox. The layer shows the frequency of wave heights exceeding 4 meters over the period 2008-2015. For future projections of cyclone-induced coral mortality, we assumed that this spatial pattern was preserved. The summary results in the panels below show that an area from Port Douglas to Cardwell is a hot zone for cyclone impacts (left panel), but that a narrower zone between Cairns and Innisfail represent the area most prone to damage (right panel).

We note an important caveat. Tropical cyclones are such stochastic events that the 2008-2015 window is unlikely to fully represent the cyclone risk in the region. For example, it includes TC Yasi but not TC Larry. While the blending of historical cyclones in this time window with the synthetic (modelled) cyclones fills in spatial gaps in the cyclone risk layer, there will still be tendency for the future to reflect the past.

Subsequent versions of the toolbox will use an expanded historical time window to inform cyclone forecasts.



To show these cyclone and wave height exposure layers in the RBM Toolbox without the overlay of coral cover, the coral data display can be switched off by deselecting "Show data" in the layer selector.



Future CoTS impacts

The current state of CoTS outbreaks was derived from the hindcast simulations of CoTS metapopulation dynamics. Future CoTS population dynamics was then allowed to emerge from the metapopulation models. CoTS metapopulation dynamics was also dependent on the overall dynamics of the system, primarily due to modified availability of coral on reefs due to impacts of cyclones and bleaching.

12. Outcomes of CoTS control strategies –worked examples

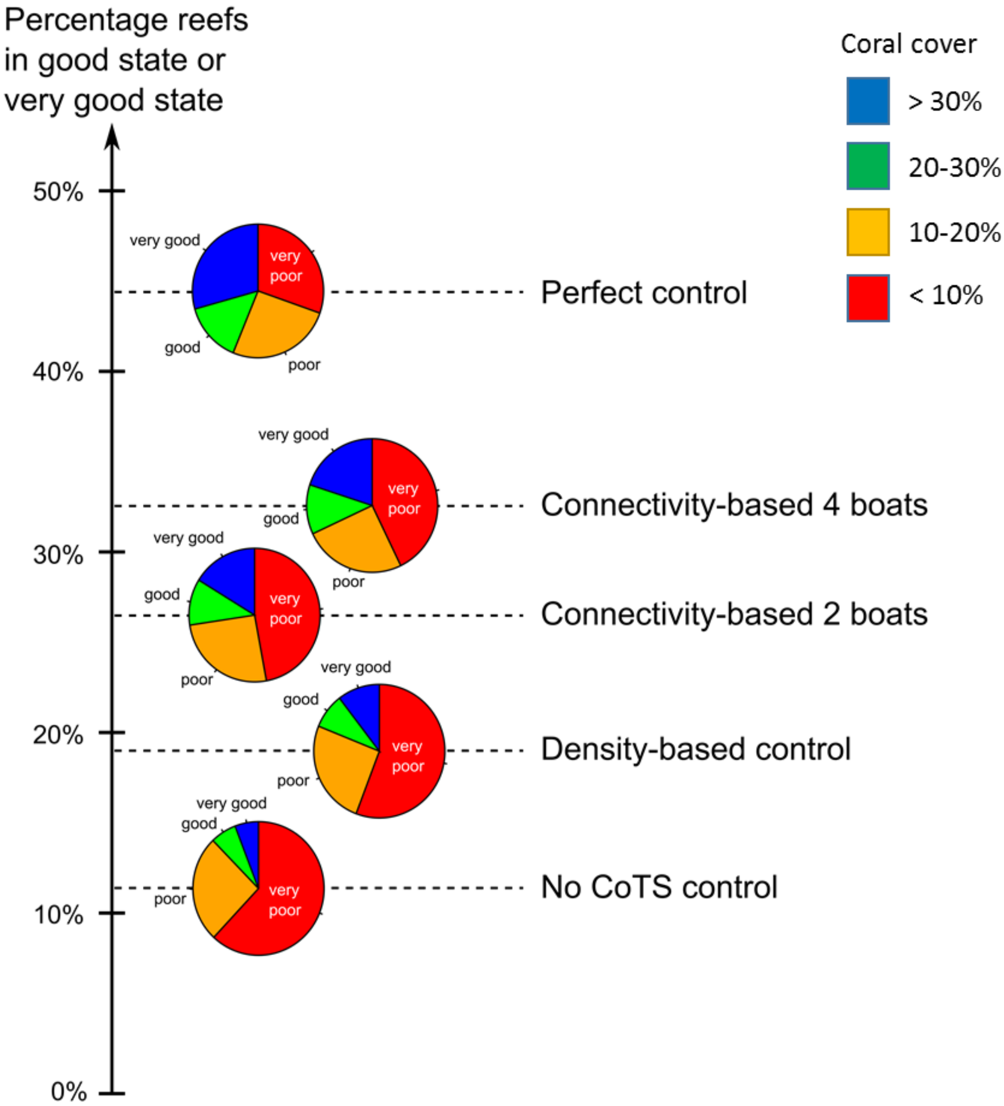
In Section 6 (*WIP introduction*) we provided initial examples of how the user can explore the consequences of two CoTS strategies for coral cover. Here we expand on these examples to help the user undertake more structured comparisons of the outcomes of different strategies. The examples are for illustration only and we hope to show that the *RBM Toolbox* is versatile enough to inform different avenues of enquiry – although keeping in mind that this version is restricted by a number of assumptions with respect to operation (e.g. archived, not live, model runs - see Appendix).

We have made five different control strategies available to the user ranging from no control to perfect control as the bookends, and with three intermediate strategies that represent versions of current practices (density based and connectivity informed control) operating from 2 or 4 boats. The 2-boats strategy is the current situation and we add the 4-boat strategy here to enable the user to ask questions about the expected gain in coral cover from adding another 2 boats to the control program.

The case of *No CoTS control* provides a "do-nothing" benchmark for all strategies in part to demonstrate the relative value or performance of a given strategy. Similarly, the *Perfect Control* strategy, where CoTS populations are suppressed effectively below outbreak threshold (Babcock et al. 2014) everywhere, represents the ceiling for the amount of coral cover that can be protected via CoTS control. Structured comparisons of the performance of all strategies, in concert with cost-benefit analyses, could inform investment decisions around whether the current control program should be upgraded or not.

Here we provide example comparisons among the different strategies under baseline water quality and the best-case climate scenario (RCP 2.6). Although RCP 2.6 might be optimistic in terms of real-world emission reductions (Rogelj et al. 2016), it helps to demonstrate the opportunities of effective COTS control strategies under carbon mitigation. Further we use year 2035 as our time horizon, effectively the mid-term milestone for the Reef 2050 Plan.

The figure below shows the result of an analysis of the proportion of the 156 reefs in the CMA that were maintained at different states of coral cover under different control strategies. The analysis cannot be performed easily with the current version of the RBM Toolbox, but we provide it here to inform discussions around what fraction of reefs can be kept in very good (>30% coral cover) or good (20-30%) under what efforts of control. We see this informing targeted control efforts in a spatial planning context.



When COTS are not controlled in the system, the proportion of reefs that are in good (green slices) or very good state (blue) drops to 12% by 2035 (bottom pie chart). In contrast, when COTS are controlled optimally (*Perfect control*) so that 99% of adult population is progressively removed from every reef at each time step leaving only small background populations, that proportion increases to 44% (top chart). This difference suggests that COTS contributes to the degradation of 32% of the reefs that would otherwise be in a very good or good condition even with other disturbance impacts (cyclones, water quality, mild bleaching) affecting the system.

Interestingly, optimal control does not appreciably affect the number of reefs that are in poor condition (26% of reefs with both no control and under optimal control, orange slices), suggesting that the impact of COTS manifests in reducing the prevalence of reefs that would otherwise have relatively high coral cover in the system. This is intuitive given that the COTS populations need coral to increase in density and develop into outbreaks. These model outputs therefore suggest that the primary outcome of COTS control will be to increase the prevalence of reefs in relatively good state among those reefs that would otherwise avoid the worst impacts of environmental stressors.

It is now possible to compare the effectiveness of the tested prioritisation strategies against these reference outcomes. Control using density- based strategy, which simulated the control by two cull boats both of which always knew about and prioritised the reefs with most adult COTS, provided marked improvement over the no control case. It does so by substantially increasing the number of reefs in good or very good state (only 19% for density-based control vs 12% for no control). Although the effectiveness of density-based control is not optimal, and in reality the impact of COTS control may be even lower since we are often unaware of where all outbreaks are located, this outcome suggests that, even with constraints, implementing COTS control will improve the state of the system and exhibit the trend towards higher number of reefs with moderate-to-high coral cover (the proportion of reefs in poor condition was again not appreciably affected).

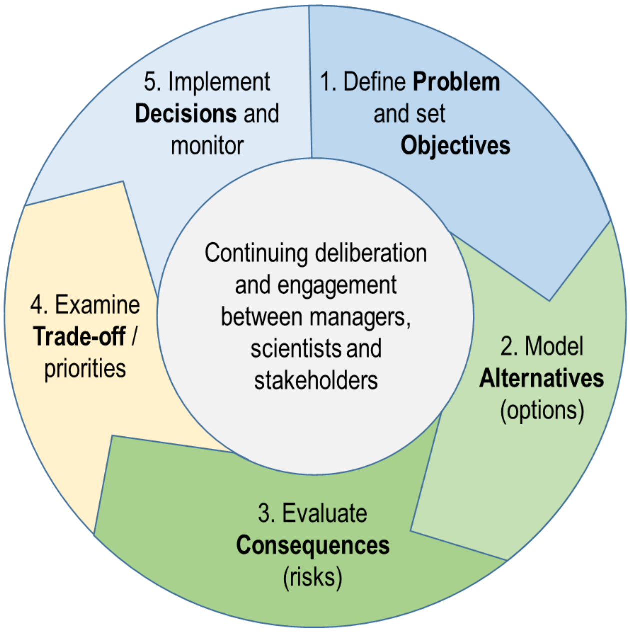
Although density-based control already resulted in an improved state of the system, it was outperformed by the connectivity-based strategy which used the same effort simulation of 2 boats. The connectivity-based strategy more than doubled the number of reefs in good or very good condition (27% for connectivity-based control vs 12% for not). This suggests that considering connectivity in prioritisation of reefs for control can be beneficial and lead to a better outcome for the system as more of the reefs with relatively high coral cover are preserved for the same amount of effort invested in control. The difference between the two strategies that use the same effort but different prioritisation scheme shows not only that concentrating effort at locations that matter is important to increase the effectiveness, but also what kind of information is needed to increase this effectiveness.

Even with connectivity taken into account, the impact of COTS control was still suboptimal due to other constraints such as limited number of reefs that can be visited in a 6-month time period. However, simply doubling the effort to 4 boats that all use the same connectivity-based strategy does not appear to be the answer, as the return for doubling investment is marginal (27% of reefs in good or very good condition for 2 control boats vs 32% for 4 control boats). It follows that simply increasing the effort while all boats continue to employ the same connectivity-based strategy does not appear to be the answer needed to increase control effectiveness, as some reefs are clearly missed even with 4 control boats, leading to a diminished return on investment. Therefore, to improve the outcome, either newly added or some of the existing boats would have to switch to another strategy to cover the reefs that have been missed by the connectivity –based strategy – most likely sinks that have poor connectivity are therefore not sufficiently prioritised. Such considerations will be explored in future versions of the control model under NESP projects on regional integrated pest-management strategies for COTS.

13. Using the RBM Toolbox to inform management decisions

The examples in Section 12 illustrate the richness of the problem and the relative benefits of different control strategies under best-case climate change. To use the *RBM Toolbox* as a basis for informing structured decision-making under a wider set of scenarios, we recommend that the user follows the stepwise process outlined in this section. It builds in on decision support practices used widely in decision sciences (Hammond et al. 1999, Gregory et al. 2012) and in particular in conservation planning

(Groves and Game 2016). In short, it builds on the steps in adaptive management, starting with a clear formulation of the management ***Problem*** and the setting of the fundamental ***Objectives***. It then explores ***Alternatives*** (management options) and evaluates their ***Consequences***. In a world of limited resources, ***Tradeoffs*** or priorities are examined before recommending a ***Decision*** followed by targeted ***Monitoring***. The key steps combine to form the useful acronym ***PrOACT*** (Hammond et al. 1999). This approach is already implemented by GBRMPA, and was demonstrated in a previous project supporting the Strategic Assessment of the GBRWHA (Anthony et al. 2013).



Schematic overview of the key steps in the structured decision-making process. The framework is adapted from Hammond et al. (1999) and Anthony et al. (2013).

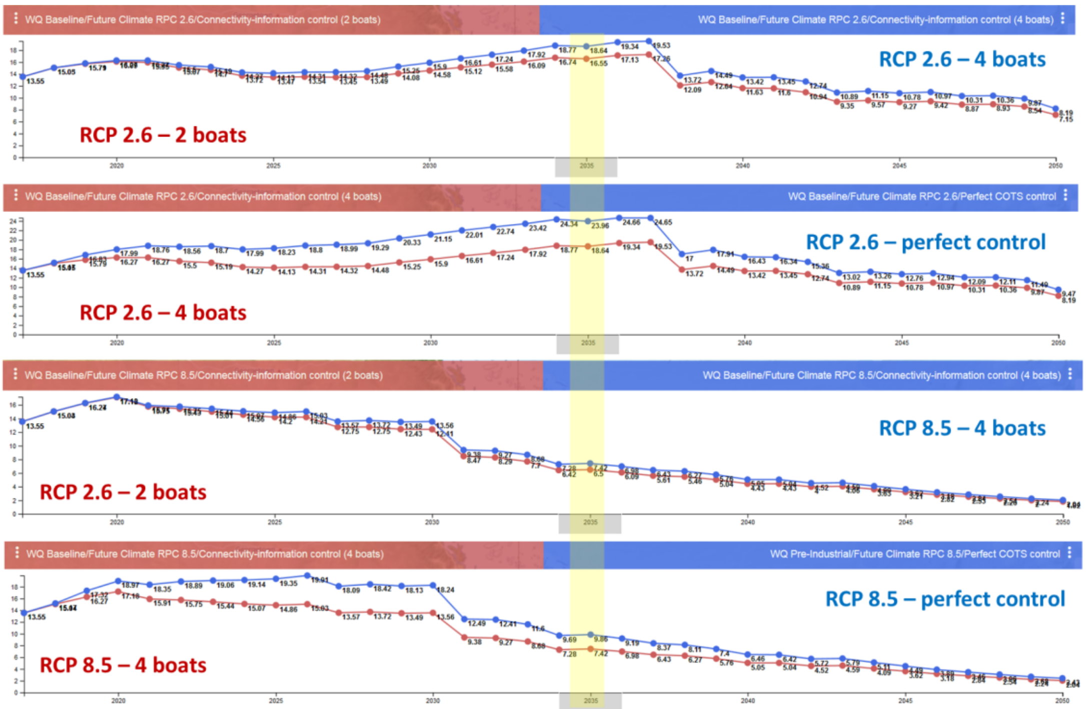
In the context of the structured decision-making steps above, the ***problem*** is to identify one or more strategies that best work to protect corals over a timeframe of concern. Above we discussed whether model analyses would support a 4-boat over a 2-boat, or whether efforts and investments should be made in a program that provides perfect control. A part of the problem is to understand the pay-offs (perhaps relative to investments) of these strategies under different climate futures and water quality scenarios.

Defining the timeframe is critical because we saw in Section 6 that impacts of climate change increase over time, and differences between CoTS strategies we explored diminish as we approach 2050. For the purpose of this example, let's say the key fundamental ***objective*** is to *maximize coral cover by year 2035*. A secondary objective would be to keep the costs of these strategies low. We do not include such cost-benefit analyses here, but suggest they can be made part of the structured decision-making process.

In the RBM Toolbox, we have already made model ***alternatives*** (strategy options) available for exploration so the user can compare these systematically. Because the two water quality scenarios in this prototype version show largely similar results, we use the baseline scenario only. This leaves six combinations of climate change scenarios and CoTS strategies to be compared (see table below)

Climate change	CoTS control strategies		
RCP 2.6	2 boats with connectivity info	2 boats with connectivity info	Perfect CoTS control
RCP 8.5	2 boats with connectivity info	2 boats with connectivity info	Perfect CoTS control

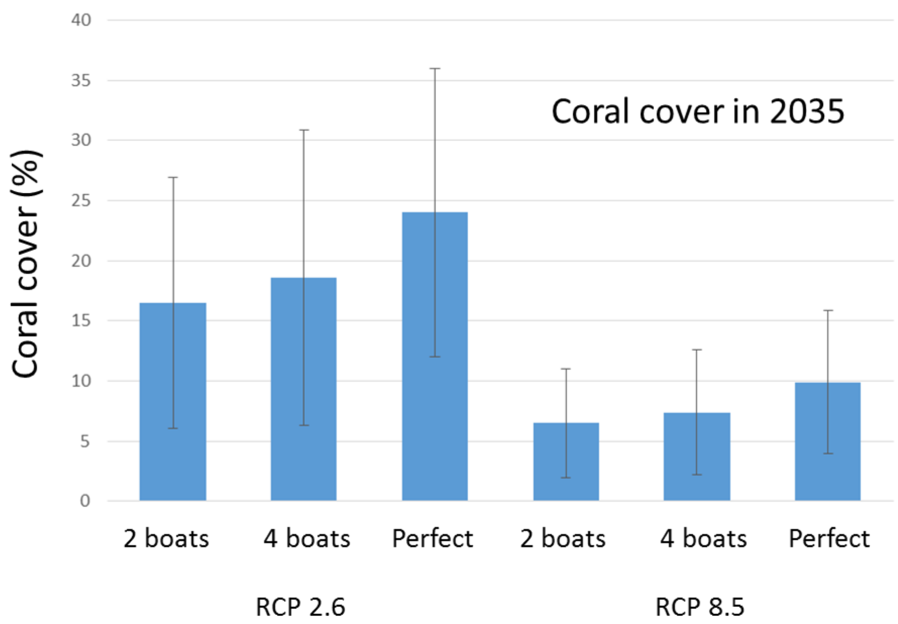
The next step is to summarise ***consequences*** – i.e. predicted coral cover for 2035 for the six different strategies/scenarios. As demonstrated in Section 6, pairwise strategies are selected from far left (red) and far right (blue) control bars in the WIP. We show the summary trajectories below (note that results of two 4-boat strategies are shown twice in the comparison). The yellow vertical bar indicates year 2035.



In version 2 of the *RBM Toolbox*, the user will be able to extract the summary data directly from the graphs or the map. In this prototype, however, summary data for year 2035 need to be transferred manually to a consequence table or a graph to enter into the decision analysis.

The bar graph below captures the summary results of mean coral cover and standard deviations for the 100 simulations of each strategy/scenario combination across all 156 reefs. The larger error bars arise from the fact that all reefs are included and which we demonstrated in the previous section to show large variations in responses to CoTS control. Therefore these results are not suitable for statistical analysis, but still inform on relative impacts at the regional level.

An important conclusion is that intensified CoTS control will provide returns in terms of increased regional coral cover (but here with unknown cost efficiency) and could mean the difference between ~5% and 10% coral cover under continued warming (RCP 8.5) by 2035. A similar analysis for year 2050 (end of the timeline in trajectories above) would show that the absolute impacts of intensified CoTS would diminish under both the mitigated and particularly the unmitigated climate change scenario.



Predicted coral cover for year 2035 for two climate change scenarios and three CoTS control strategies. Error bars are standard deviations for 100 simulations across all 156 reefs in the Cairns Management Area.

14. References

Anthony, K. R. N. 2016. Coral reefs under climate change and ocean acidification - challenges and opportunities for management and policy. Annual Review of Environment and Resources 41:59–81.

Anthony, K. R. N., J. M. Dambacher, T. Walshe, and R. Beeden. 2013. A framework for understanding cumulative impacts, supporting environmental decision-making, and informing resilience-based management of the Great Barrier Reef World Heritage. Final report to GBRMPA and the Department of Environment . Australian Institute of Marine Science, Townsville; CSIRO, Hobart ; NERP Decisions Hub, University of Melbourne and Great Barrier Reef Marine Park Authority, Townsville.

Babcock, R., E. E. Plagányi, B. Morello, and W. Rochester. 2014. What are the important thresholds and relationships to inform the management of COTS? CSIRO, Australia.

Bozec, Y. M., L. Alvarez-Filip, and P. J. Mumby. 2015. The dynamics of architectural complexity on coral reefs under climate change. Global Change Biology 21:223–235.

Casey, K., E. Selig, D. Zhang, K. Saha, A. Krishnan, and E. McMichael. 2015. The Coral Reef Temperature Anomaly Database (CoRTAD) Version 5 - Global, 4 km Sea Surface Temperature and Related Thermal Stress Metrics for 1982-2012 (NCEI Accession 0126774).

Condie, S., M. Hepburn, and J. Mansbridge. 2012. Modelling and visualisation of connectivity of the Great Barrier Reef. ... 12Th International Coral Reef ...:9–13.

Connolly, S. R., and A. H. Baird. 2010. Estimating dispersal potential for marine larvae : dynamic models applied to scleractinian corals. Ecology 91:3572–3583.

Eakin, C. M., J. M. Lough, and S. F. Heron. 2009. Climate, weather and coral bleaching. Pages 41–67*in* M. J. H. van Oppen and J. M. Lough, editors.Coral Bleaching: Patterns, Processes, Causes and Consequences. Springer.

Fabricius, K. E., G. De'Ath, M. Puotinen, T. J. Done, T. F. Cooper, and S. C. Burgess. 2008. Disturbance gradients on inshore and offshore coral reefs caused by a severe tropical cyclone. Limnol. Oceanogr. 53:690–704.

Fabricius, K. E., K. Okaji, and G. De'ath. 2010. Three lines of evidence to link outbreaks of the crown-of-thorns seastar Acanthaster planci to the release of larval food limitation. Coral Reefs 29:593–605.

Game, E. T., E. V. E. McDonald-Madden, M. L. Puotinen, and H. P. Possingham. 2008. Should we protect the strong or the weak? Risk, resilience, and the selection of marine protected areas. Conservation Biology 22:1619–1629.

Garde, L. A., C. M. Spillman, S. F. Heron, and R. J. Beeden MAppSci. 2014. Reef temp next generation: A new operational system for monitoring reef thermal stress. Journal of Operational Oceanography 7:21–33.

GBRMPA. 2004. Great Barrier Reef Marine Park Zoning Plan 2003. Great Barrier Reef Marien Park Authority, Townsville, Australia.

GBRMPA. 2016. Crown-of-Thorns Starfish Management Strategy and Contingency Plan. Great Barrier Reef Marine Park Authority, Townsville, Australia.

Gregory, R., L. Failing, M. Harstone, G. Long, T. McDaniels, and D. Ohlson. 2012. Structured decision making: a practical guide to environmental management choices. Wiley-Blackwell, West Sussex, UK.

Groves, C. R., and E. T. Game. 2016. Conservation planning - informed decisions for a healthier planet. Roberts and Company Publishers, Greenwoord Village, Colorado.

Hammond, J. S., R. L. Keeney, and H. Raiffa. 1999. Smart Choices: A Practical Guide to Making Better Decisions. Harvard Business School Press, Boston.

Hock, K., N. H. Wolff, S. A. Condie, K. R. N. Anthony, and P. J. Mumby. 2014. Connectivity networks reveal the risks of crown-of-thorns starfish outbreaks on the Great Barrier Reef. Journal of Applied Ecology 51.
Hock, K., N. H. Wolff, J. C. Ortiz, S. A. Condie, R. Kenneth, N. Anthony, P. G. Blackwell, P. J. Mumby, and S. Fraser. 2017. Connectivity and systemic resilience of the Great Barrier Reef:1–23.
Hughes, T., J. T. Kerry, M. Álvarez-noriega, J. G. Álvarez-romero, K. D. Anderson, A. H. Baird, R. C. Babcock, M. Beger, D. R. Bellwood, R. Berkelmans, T. C. Bridge, I. R. Butler, M. Byrne, N. E. Cantin, S. Comeau, S. R. Connolly, G. S. Cumming, S. J. Dalton, C. Kuo, J. M. Lough, A. S. Hoey, J. A. Hobbs, M. O. Hoogenboom, V. Emma, R. J. Pears, M. S. Pratchett, V. Schoepf, T. Simpson, W. J. Skirving, and B. Sommer. 2017. Global warming and recurrent mass bleaching of corals.
Humanes, A., A. Fink, B. L. Willis, K. E. Fabricius, D. de Beer, and A. P. Negri. 2017a. Effects of suspended sediments and nutrient enrichment on juvenile corals. Marine Pollution Bulletin.
Humanes, A., G. F. Ricardo, B. L. Willis, K. E. Fabricius, and A. P. Negri. 2017b. Cumulative effects of suspended sediments, organic nutrients and temperature stress on early life history stages of the coral Acropora tenuis. Scientific Reports 7:1–11.
Keesing, J. K., and J. S. Lucas. 1992. Field measurement of feeding and movement rates of the crown-of- thorns starfish Acanthaster planci (L.). Journal of Experimental Marine Biology and Ecology 156.
Kettle, B. T., and J. . Lucas. 1987. Biometric relationship between organ indices, fecundity, oxygen consumption and body size in Acanthaster planci (L.) (Echinodermata; Asteroidea. Bull. Mar. Sci. 41:541–551.
Liu, G., S. F. Heron, C. Mark Eakin, F. E. Muller-Karger, M. Vega-Rodriguez, L. S. Guild, J. L. de la Cour, E. F. Geiger, W. J. Skirving, T. F. R. Burgess, A. E. Strong, A. Harris, E. Maturi, A. Ignatov, J. Sapper, J. Li, and S. Lynds. 2014. Reef-scale thermal stress monitoring of coral ecosystems: New 5-km global products from NOAA coral reef watch. Remote Sensing 6:11579–11606.
Lough, J. M. 2012. Small change, big difference: Sea surface temperature distributions for tropical coral reef ecosystems, 1950-2011. J. Geophys. Res. 117:C09018–C09018.
MacNeil, M. A., C. Mellin, M. Pratchett, H. Sweatman, A. Cheal, I. Miller, J. Hoey, C. Fonnesbeck, Z.-L. Cowan, and K. R. N. Anthony. 2016. Joint estimation of Crown-of-Thorns (Acanthaster planci) densities on the Great Barrier Reef. PeerJ.
Maynard, J. A., R. Beeden, M. Puotinen, J. E. Johnson, P. Marshall, R. van Hooidonk, S. F. Heron, M. Devlin, E. Lawrey, J. Dryden, N. Ban, D. Wachenfeld, and S. Planes. 2015. Great Barrier Reef no-take areas include a range of disturbance regimes. Conservation Letters:n/a-n/a.
Mellin, C., Matthews, K. Anthony, S. Brown, M. Caley, D. Fordham, K. Johns, K. Osborne, M. Puotinen, A. Thompson, N. Wolff, and M. MacNeil. 2017. Bright spots of coral resilience on the Great Barrier Reef. PNAS (in prep).
Moran, P. J., and G. De'ath. 1992. Estimates of the abundance of the crown-of-thorns starfish Acanthaster planci in outbreaking and non-outbreaking populations on reefs within the Great Barrier Reef. Marine Biology 113:509–515.
Mumby, P. J., A. Hastings, and H. J. Edwards. 2007. Thresholds and the resilience of Caribbean coral reefs. Nature 450:98–101.
Ortiz, J. C., Y.-M. Bozec, N. H. Wolff, C. Doropoulos, and P. J. Mumby. 2014. Global disparity in the ecological benefits of reducing carbon emissions for coral reefs. Nature Clim. Change 4:1090–1094.
Pachauri, R. K., and L. A. Meyer. 2014. IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
Pratchett, M. S., C. F. Caballes, J. A. Rivera-Posada, and H. P. A. Sweatman. 2014.

Limits to understanding and managing outbreaks of Crown of Thorns Starfish (Acanthaster spp). Oceanography and Marine Biology: an Annual Review 52:133–200.
Puotinen, M. L. 2005. An automated GIS method for modeling relative wave exposure within complex reef-island systems: A case study of the Great Barrier Reef. Congress of the Modelling and Simulation Society of Australia and New Zealand.:1437–1443.
Rogelj, J., M. den Elzen, N. Höhne, T. Fransen, H. Fekete, H. Winkler, R. Schaeffer, F. Sha, K. Riahi, and M. Meinshausen. 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature 534:631–639.
Schleussner, C., J. Rogelj, M. Schaeffer, T. Lissner, R. Licker, E. M. Fischer, R. Knutti, A. Levermann, K. Frieler, and W. Hare. 2016. Science and policy characteristics of the Paris Agreement temperature goal. Nature 6:827–835.
UNFCCC. 2016. Paris Climate Agreement, http://unfccc.int/paris_agreement/items/9444.php.
Wallace, C. C. 1999. Staghorn Corals of the World: a revision of the coral genus Acropora. CSIRO Publishing, Collingwood.
Wolff, N. H., S. D. Donner, L. Cao, R. Iglesias-Prieto, P. F. Sale, and P. J. Mumby. 2015. Global inequities between polluters and the polluted: Climate change impacts on coral reefs. Global Change Biology 21:3982–3994.
Wolff, N. H., A. Wong, R. Vitolo, K. Stolberg, K. R. N. Anthony, and P. J. Mumby. 2016. Temporal clustering of tropical cyclones on the Great Barrier Reef and its ecological importance. Coral Reefs:1–11.
Wooldridge, S. A., and J. E. Brodie. 2015. Environmental triggers for primary outbreaks of crown-of-thorns starfish on the Great Barrier Reef, Australia. Marine Pollution Bulletin 101:805–815.

15. Appendix - Model details

Assumptions

- We model reef dynamics on 156 reefs identified by habitat mapping. The criterion for including reefs was based on how much habitat was observable from satellite imagery and therefore available to construct habitat maps. The largest reef excluded has a size of 0.17 km2. Here we modelled the coral reef slope (3-10m depth).
- Reefs that have not been mapped by the habitat maps/satellite imagery are not contributing to either coral or COTS metapopulation dynamics
- Past connectivity patterns for COTS and coral can be used to represent future connectivity patterns (we cannot predict future hydrodynamics)
- COTS larvae do not use reef cues to settle, e.g., do not preferably settle on reefs with high coral cover
- COTS on a reef disappears when coral cover drops below 5%, as it is assumed there is not enough coral resource to sustain COTS for the next 6 months
- Reefs have a constant level of self-recruitment for both coral and COTS; this self-recruitment level is the same for all reefs
- Both coral and COTS populations are limited to reef slopes (habitat that can currently be modelled by the ecosystem model); as a consequence, the model does not represent the entirety of the coral populations that might exist on a reef (e.g., corals that grow in deeper water); also, at the moment no COTS population reservoirs are assumed to exist in the deeper water
- Reefs operate under the conditions of full herbivory (i.e., macroalgae cannot grow)
- The state of the reef with regards to COTS, i.e. COTS population densities on individual reefs, is always known (complete knowledge of the system when it comes to COTS distribution and densities; survey planning to deal with incomplete knowledge not yet implemented in the current version)
- COTS are assumed to be distributed evenly across the available reef habitat (reef slope), i.e., aggregations and spatially heterogeneous distribution within a reef habitat are not explicitly modelled
- No effect of Green Zones or direct effects of COTS predators on COTS population dynamics were implemented in the current version
- COTS control efforts have not been used during hindcast simulations to determine the current state of the reefs
- The COTS control trips are not optimised for cost efficiency, only for impact; in other words, at the moment the control boats can reach all reefs with equal

ease and no travel or control costs are considered

- COTS control continues with the same intensity throughout the simulation runs, i.e., it does not stop or change if there are fewer outbreaks present in the system
- COTS culls are optimistically effective: a single sweep of the area by the divers removes all observable COTS; culling effectiveness is based on empirical estimates of COTS detectability (data on size-dependent observability of COTS from MacNeil et al. 2016), so no limiting effects of visibility, weather, habitat complexity, diver skills and expertise, etc. on cull effectiveness
- COTS control is optimistically efficient in terms of culling COTS ; although the parameters like the number of voyages per 6-month period and dives per voyage are based on actual AMPTO data, it is assumed that the divers are optimally efficient in their sweeps both as individuals and as a group (e.g., a single sweep by a diver kills all observable COTS over an area of the reef, no overlap in the ground the divers cover) and that boats can get anywhere with equal ease; also, all boats have the same capacity to remove COTS on all reefs
- The ruleset for picking which reefs to visit, i.e. COTS control strategy, stays the same during the simulation run (it does not dynamically/adaptively switch to some other strategy in response to changing situation in the field); reefs are selected in an adaptive fashion for a given strategy, in a sense that reefs are picked for control based on a set of rules that define a strategy (e.g. "first go to the reef that at this moment has the highest potential to export COTS larvae"), but those rules do not change during the course of a simulation run
- Thermal stress uses CoRTAD/CRW as background climatology for both hindcast and forecast simulations. The climatology has been updated to include the recent bleaching events. Spatial pattern of future bleaching events follows the general spatial pattern of past bleaching events, but intensifies in accordance with the climate model
- Only one climate model used to predict future thermal stress; therefore, there is no variability in outcomes that comparing different future climate models would provide
- Bleaching threshold in terms of DHW will not change in the future (i.e., corals do not adapt, which is a pessimistic assumption)
- In forecasting scenarios, both bleaching and cyclones can happen the same year while in reality a cyclone can disrupt an ongoing thermal stress
- Cyclone impacts on coral populations do not depend on reef's shape, wave exposure, or reef's position in a wider matrix (reefs may be sheltered by other reefs)
- Water quality scenarios are based on eReefs – therefore no changes in the amount of water that is discharged by rivers between pre-industrial and current scenarios, the difference is only in sediment and nutrient loads of

discharges

- For the hindcast scenario, impacts of cyclones were modelled following spatial predictions of sea state using a threshold of 4m wave height (model 4MW, Puotinen et al. 2016). This threshold corresponds to significant wave height, a very rough seas state able to move large reef blocks (Puotinen et al 2016). Predictions of the 4MW model was linked to coral mortality assuming a minimum 4m wave height is representative of a category 3. Future improvements might use layers of predictions for a range of wave height categories (4-6m, 6-8m, etc.) when. Less than 4m is no damage. We will revisit this to link empirically cyclone category, wave height and coral mortality.
- All reefs are assumed to have 5% sand cover, although surveys (AIMS 2008) show reef average biotic covers between 78-98%. Departures from the assumed 5% sand cover might explain some discrepancies between observed and predicted coral cover.
- For the forecast scenario, we use predictions of cyclone occurrence (different categories) based on the historical regime of cyclone in the region. Cyclone occurrences affect reefs independently
- For hindcast simulations, COTS populations on reefs were modelled using reported densities from FMP, Eye on the Reefs, and AIMS LTMP manta tow surveys (2012-2017).

Caveats

- The model in WIP is not interactive with respect to users being able to change future outcomes dynamically; i.e., it is not possible to change the state of, or the management approach to, specific reefs in order to see how this would change the future state of the whole system (e.g., WIP cannot be used to determine "what would happen if we focus COTS control on reefs A and B", because the WIP will feature pre-run scenarios); it is, however, possible to select individual reefs or groups of reefs to see their predicted future state and this future state will depend on the integrated processes that play out in the wider system
- Also, in its current state the model cannot be used to make decisions or provide estimates about the exact amounts of real-life resources that would be needed to achieve certain COTS control outcomes (i.e., the "how many boats are needed to control COTS right now?" question); it can, however, be used to see whether reducing COTS impacts would be even possible in the future given the listed set of assumptions – notably, that the control is very effective in removing COTS populations from reefs and that we have the full knowledge of the COTS population densities in the system – which is not a priori a given; the exact resources/number of boats can only begin to be addressed in any fashion resembling real world numbers once these assumptions are relaxed to be more realistic (i.e., we need surveys to determine the state of the reefs and better estimates how COTS are distributed on individual reefs outside of slope zones etc)

- The model cannot at this stage recreate the long-term spatial dynamics of COTS of the kind that some stakeholders may expect to see, e.g. future emergence of new (primary) COTS outbreaks in ~15-year intervals at the suspected initiation zones (e.g. south of Lizard Island); this most likely happens because of projected low coral cover in those areas as a result of environmental disturbances (which is also why designing the model to explicitly initiate the outbreaks in those locations does not result in the expected dynamics – COTS outbreaks are simply being initiated on reefs with no coral cover); this could be the case because some of the newly implemented impacts, parameters and/or processes need further tweaking; on the other hand, this could actually be what the future spatial dynamics will look like if the coral cover drops as predicted by the model
- The model predicts that in the future so many reefs will be depleted of coral by cyclones and/or bleaching that there would be few reefs with enough coral to could support COTS outbreaks; as such, the outcomes of different strategies that select reefs for COTS control tend to converge when the COTS distribution across the reefs is assumed to be known, because no matter how the reefs are picked for control it gets more and more likely that the right guess is made by picking one of the dwindling number of reefs that can support COTS
- Coral demographic rates are representative of mid-depth (5-15m) forereefs, so we only model reef dynamics on reef slopes (3-10m depth) because the area of reef substratum (hard bottoms) is not mapped below (the mapped strata corresponds to habitats deeper than 10m). We also ignore reef tops (0-3m depth) although hard bottoms on reef tops can cover extensive areas and thus significantly contribute to the dynamics of coral and CoTS meta-populations. Including reef tops will require a different parametrisation of coral growth and natural mortality, bleaching mortality and impacts of cyclones.
- Reefs were modelled at a coarse resolution since most exposure layers (cyclones, bleaching, chlorophyll and suspended sediments) have a coarse (4 km) resolution. Habitat maps were produced with a much finer resolution, so that reefs could be modelled at this scale provided that a specific parametrisation is made available. For the moment the only specific information at small scale (<100m?) is wave exposure which drives prediction of coral dominance, but there is currently no robust parametrisation of coral demographics that is representative of a changing hydrodynamic environment.