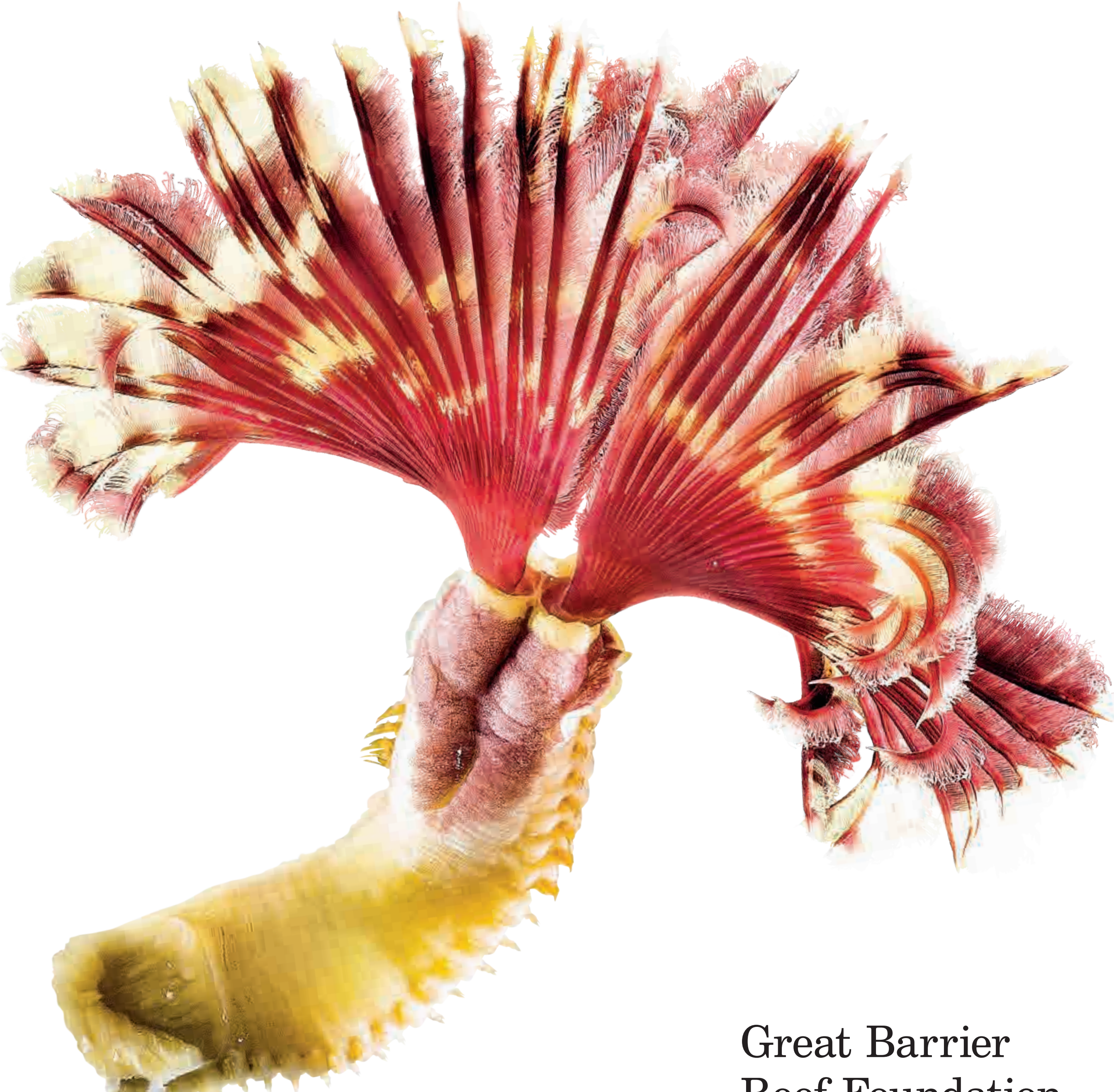
Resilient Reefs Successfully Adapting to Climate Change

Final report December 2017



Great Barrier Reef Foundation

Contents

1 Executive *Summary*

In July 2013, the Great Barrier Reef Foundation commenced the Resilient Reefs Successfully Adapting to Climate Change Program. The aim of this program was to provide knowledge and tools to inform management of the Reef in the face of a changing and increasingly variable climate.

Over this four-year period the impacts of climate change on the Great Barrier Reef have been on a scale never-before seen. Three category 4 or 5 cyclones and back to back bleaching events in 2016 and 2017 have resulted in a 50% decline in coral cover in the shallow regions of the Great Barrier Reef.

Without a doubt, the major achievement of the program has been delivery of two new tools for reefs – eReefs and a decision support tool tailored specifically for resilience-based management.

It is obvious now, more than ever, that we urgently need to develop and scale innovative new approaches, tools and solutions, to give the Reef a fighting chance in the face of unprecedented pressures. This has been the sole focus of the Resilient Reefs Program, made possible by a $12.5M grant from the Australian Government.

Through this program we have delivered more than 30 projects, partnered with 15 national and international research institutions, and matched every dollar received from the Australian Government with a $2.11 cash contribution from government, corporate or philanthropic donors and a $1 co-contribution from research institutions. We have shared the positive stories of hope arising from the program with more than 18 million people from around the world and collectively generated more than 37 publications in peer reviewed journals with 35 more in preparation.

We have substantially increased foundational data on the Great Barrier Reef through the release of the first open source coral genome library containing the genomes of nine cornerstone Great Barrier Reef coral species and their algal and microbial symbionts, and through the generation of the first whole-of-reef baseline for ocean acidification.

We have implemented four successful pilot projects ranging from a novel test for detecting stress in corals, to a surface film for shading reefs, to the cryopreservation of 15 Great Barrier Reef corals by applying the same techniques used for human IVF treatments.

Without a doubt, the major achievement of the program has been delivery of two new tools for reef management – a prototype resilience mapping tool for identifying reefs essential for reef recovery following a disturbance event, and eReefs which has already been used to develop water quality targets, generate the Reef water quality report cards, identify the rivers contributing most to crown-of-thorns starfish outbreaks, and assess the feasibility of novel reef interventions.

From its inception this program has centred on the needs of those who are charged with the management of Australia's iconic Great Barrier Reef. Through the new partnerships we have brokered, and the projects we have designed, we have succeeded in delivering outputs that are being used for reef planning, reporting, protection and management today.

All of these achievements have only been made possible through partnerships with brilliant reef scientists, dedicated reef managers, and our committed funders – corporate, philanthropic and government – in particular the Australian Government Department of Environment and Energy. The Great Barrier Reef Foundation has enjoyed working with all of you to deliver this program and we look forward to future collaborations to take these achievements to the next level for the benefit of coral reefs around the world.

2 new management tools
(eReefs, resillience-based management support tool)

3 new tools for monitoring reef health *(light thresholds for seagrass, semi-automatic monitoring of bleaching and disease, 3D habitat structure)*

3 new foundational data sets
(coral genome data, ocean chemistry data, Great Barrier Reef calcification rate data)

4 novel pilot projects
(surface films, metabolomic stress test for corals, larval re-seeding, cryo-preservation of coral gamets)

>3:1 return on investment – *every $1 of funding was matched with $3 of other funding*

12 PhDs

64 scientific, peer reviewed publications

14 Book chapters and reports

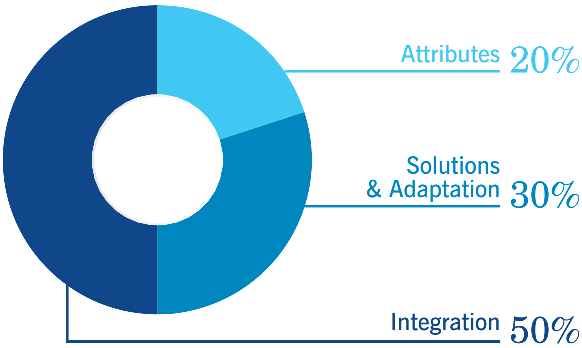
106 International conference presentations

2 Program *Outcomes*

The overarching objective of the program is to provide new knowledge and tools to inform Reef managers in the face of climate change.

Over the four years, the program has transitioned from a starting portfolio with a focus on attributes of a resilient reef (comprising 50% of a total of 16 Round 1 projects), to a final portfolio of large integrated projects with a clear management focus. Over the life of the program, 50% of the funding has been allocated to large, integrated and multi-institutional projects.

Relative proportion of allocation of funds for each portfolio stream



The following section provides outcomes of the Resilient Reefs Successfully Adapting to Climate Change Program on a project or thematic level with a clear line of sight to the original program objective.

2.1 New tools for monitoring

Management effectiveness and compliance require monitoring. You cannot manage what you can't measure and you can't enforce regulation if you can't measure impact. Monitoring forms a fundamental part of the management system for the Great Barrier Reef and will underpin the reporting against the actions and targets of the Reef 2050 Plan.

The Reef 2050 Integrated Monitoring, Modelling and Reporting Program (RIMReP) will guide the future of monitoring on the Great Barrier Reef. Through its development, it has been made clear that new methods and measures need to be developed and considered.

A range of novel monitoring, mapping and modelling tools have been developed under this program. Below are three examples of these projects, each focused on a specific tool, threshold or metric.

Coral Health: Bleaching and disease[1]

Principal investigator: Prof. Bill Leggat

JAMES COOK UNIVERSITY AUSTRALIA

Applied outcomes:

✓ A rapid, reliable and accurate impact and stress assessment tool

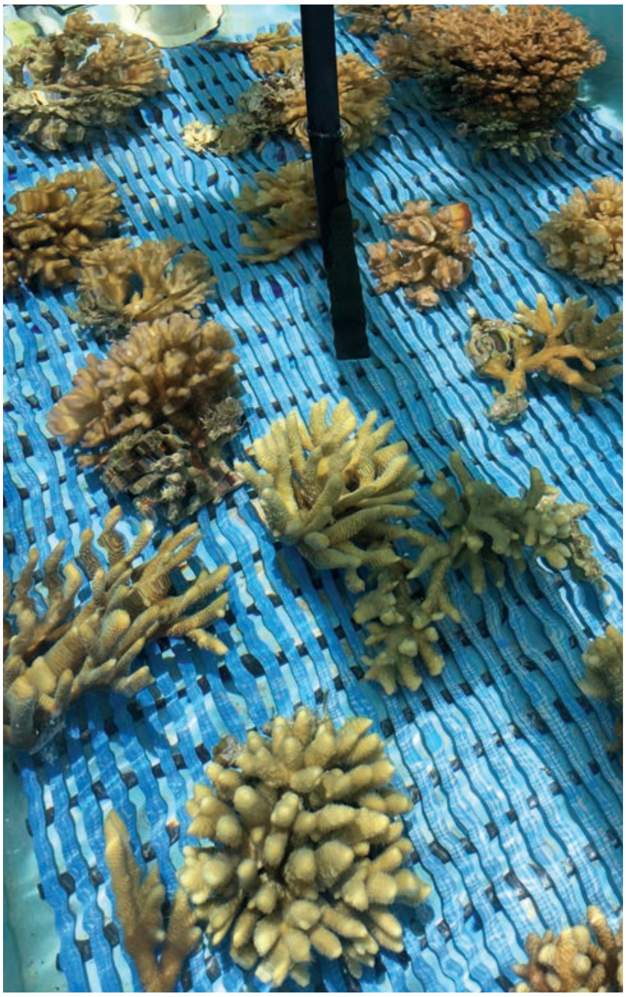
✓ Applicable across species once baseline levels have been established

Environmental metabolomics is opening new avenues for monitoring ecosystem health. It measures the impact of stress on organisms by directly measuring changes in metabolism. Use of metabolomics provides reef managers with rapid, reliable and accurate assessments of the amount of stress that organisms such as corals and seagrasses have been exposed to. The real power of metabolomics is that it can differentiate between specific stresses – for example stress due to poor water quality or stress from elevated sea surface temperatures present differently. This means you can measure an impact from a specific stressor, or specify what action to take to reduce stress following a specific response (for example stop dredging if the stress response is specific to sedimentation stress).

The team has deliberately taken an approach of developing sampling and analysis methods that are robust and field relevant. By doing this they have delivered a quick and accessible workflow that can be used by managers, rangers and development proponents without the need for sensitive, complex and expensive scientific equipment.

Results

- Developed a rapid, reliable and accurate impact and stress assessment tool.
- Method developed to be robust and field relevant.
- Metabolic response of corals to both CO_2 and temperature stress can be detected before any visual effects.



- Specific metabolic markers are associated with specific stressors, thus allowing the development of stress specific test kits.
- The method is applicable to both coral and seagrass and is likely to be applicable to any organism once baseline data is available.
- Capable of measuring sub-lethal stress and recovery.
- Can be used by proponents to monitor their environmental impacts.

Next steps

- GBRMPA have been involved in discussions around how to roll out this tool as part of their permit and compliance system.
- An ARC Linkage proposal will use an existing permit application to validate its utility.

[1] Round 1-4, total budget $350,000

Seagrasses – growth, diversity and localized effects on pH[2]

Principal investigator: Dr Catherine Collier

JAMES COOK UNIVERSITY AUSTRALIA

Applied outcomes:

✓ New metrics for seagrass health

✓ Incorporated into the Reef report card metrics

✓ Underpinning the seagrass model in eReefs

This research project tested the response of two seagrass attributes – growth and diversity – to environmental change (warming, ocean acidification, and water quality) and developed key indicators for the Reef Integrated Monitoring and Reporting Program (RIMReP).

Results

- Ocean acidification can increase the productivity of seagrasses in the short term. These effects are strongly influenced by water quality, where light limitation is the primary driver of decreased productivity.
- Lack of genetic diversity will reduce the capacity of seagrass populations to adapt under increasing climate stress and a possible loss of ability to set seed. All four seagrass indicator species had significantly reduced, or a total loss of, genetic diversity and increased clonality at the edge of populations' range.
- A number of indicators including water temperature, light and energetic status were identified for consideration in the Reef 2050 Integrated Monitoring and Reporting Program. These indicators are now being applied to measure change and to apply light (turbidity) thresholds. Water temperature indicators are also available for immediate implementation.
- Energetic status is a new and novel indicator, and is a precursor to a resilience indicator that has wide-reaching application including providing quantitative predictions for the Great Barrier Reef Outlook Report. Seagrass energetic status can be predicted from the seagrass climate change risk model and was developed from measured data on photosynthesis and respiration.

Next steps

- The seagrass model and the thresholds will be incorporated into the RIMReP.
- Research is continuing to further refine models and improve threshold predictions.

[2] Round 1-3, total budget $470,000

3D structures and coral community composition in a changing ocean[3]

Principal investigators: Prof. Maria Byrne, Dr Renata Ferrari, Assoc. Prof. Will Figueira

THE UNIVERSITY OF SYDNEY

Applied outcomes:

- ✓ New metric for reef ecosystem health
- ✓ Off the shelf 3D monitoring prototype
- ✓ A baseline data set of 3D habitat structure before and after bleaching

The structural complexity of coral reefs contributes greatly to their enormous diversity, providing a diverse and variable habitat for marine species. The more complex a reef system is, the more resilient it tends to be. Therefore, the ability to accurately measure and monitor the complex structures of coral reefs is a vital tool in the face of a changing climate.

This research project developed metrics and tools to monitor and investigate the correlation between coral reef habitat structure and ocean warming and acidification. The project also focused on evaluating the precision of both off the shelf and cheaper in-house tools.

Results

- A baseline data set of 3D habitat structure for the Great Barrier Reef was produced, covering a total of 36 coral colonies, 29 reef flats, 36 reef patches and 84 reef slopes.
- The relationship between coral morphology and habitat structure is strong and predictive and should be taken into account in coral reef monitoring.
- Solid data collection protocols for monitoring reef habitat structures were developed, including a ready-made, cost effective method that can easily be adopted by managers and research groups.
- Data collection methods that work on both reef flats and reef slopes, which require different imaging techniques and data processing, were developed.
- The effects of bleaching on habitat structure are vastly variable. Beyond the obvious impact of decreasing coral life, they may at times even increase structural complexity, as slow growing massive corals are replaced with early colonising, branching species in the first stages of recovery.

Next steps

- The 3D image capturing techniques are being used to add structural complexity to the Live Habitat Maps.
- 3D metrics are being considered for incorporation into RIMReP.

The foundational data from the Great Barrier Reef was collected before the 2016 mass coral bleaching event. The Lizard Island site is located in the worst affected area, thus providing an opportunity to investigate the effect of ocean warming on 3D habitat structure, including community composition and structural complexity. These data can be used to parameterise climate change models for coral reef habitat structure in a warming ocean.

Image: R.Ferrari

[3] Round 1-3, total budget $550,000

2.2 Ocean Acidification

Carbon dioxide (CO_2) in the oceans is in equilibrium with the CO_2 in the atmosphere. Atmospheric CO_2 is taken up by the seawater, where it forms carbonic acid and changes the seawater carbon chemistry. This process is called 'ocean acidification' (OA). Seawater acidity in the surface of the oceans has increased by 30% since the beginning of the Industrial Revolution. Rates of change will accelerate in the coming decades, as the buffering capacity of seawater becomes exhausted.

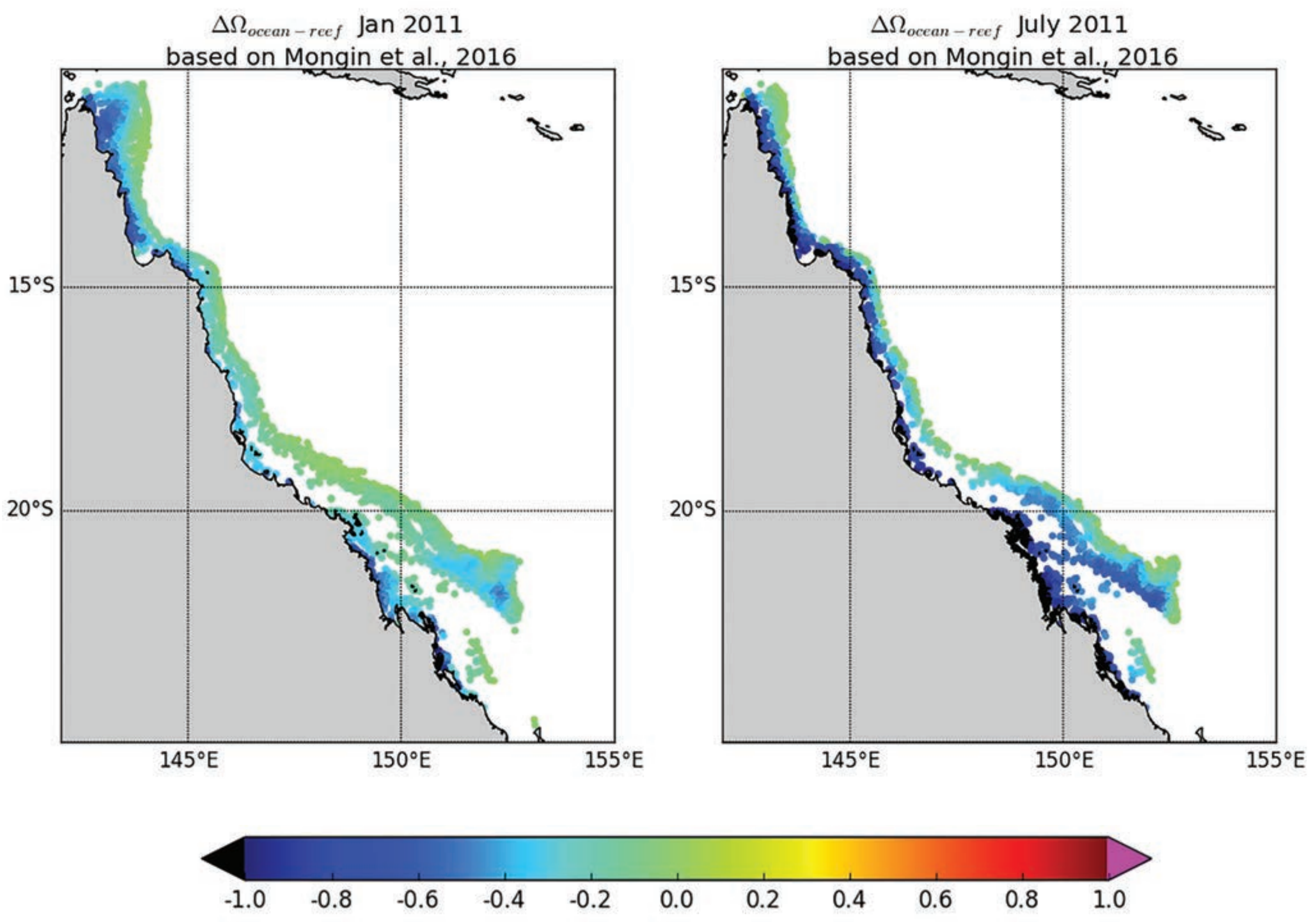
Although OA is a global issue, CO_2 concentrations in the seawater vary between regions, over time, and in response to other environmental factors (biological processes, temperature, salinity). Additional CO_2 is gradually removed from the atmosphere and the oceans through geological weathering and biological uptake, however this process will take many thousands of years.

Sensitivity to OA varies greatly between organisms. Some marine animals and plants, especially those with calcium carbonate skeletons or shells, are highly sensitive to small changes in seawater acidity. The ecological responses of marine ecosystems to elevated concentrations of CO_2 are still poorly understood. Today's high levels of CO_2 have already slowed rates of reef calcification on the Great Barrier Reef.

Unlike heat stress and more intense storms from global warming, OA is a chronic rather an acute disturbance, hence the damage that it is causing is not as graphic and visible as the damage inflicted by storms and mass mortality from heat waves.

Through the Resilient Reefs Successfully Adapting to Climate Change, over $2m has been invested into projects focusing on ocean acidification. This is the biggest investment into this research to date in Australia and has vastly improved our understanding of its scale and ecological impact on the Great Barrier Reef.

Figure 1: Coastal acidification on the Great Barrier Reef. Terrestrial runoff of nutrients leads to greater algal biomass and organic matter in the coastal and inshore Great Barrier Reef. Their respiration produces CO_2 that adds to the effects of the increasing atmospheric CO_2 in coastal systems. Amelioration of coastal acidification therefore can mitigate some of the stress from ocean acidification.



Foundational data programs – ocean chemistry

AUSTRALIAN INSTITUTE OF MARINE SCIENCE

CSIRO

Applied outcomes:

✓ Validation data for eReefs

✓ Ocean acidification data integration and visualisation

✓ Ecological response models

Ocean chemistry data was collected and analysed through three separate projects: Carbon budget[4], Carbon chemistry[5], and Future Reef[6]. The purpose of the Carbon budget project was to identify and characterise major drivers of carbonate chemistry to understand the Great Barrier Reef's vulnerability to ocean acidification, while the Carbon chemistry project and the Future Reef project both focus on collecting ocean chemistry data from stationary and vessel mounted systems. The Future Reef project is the only large-scale repeat CO_2 observing system on the Great Barrier Reef, using the Rio Tinto ship, RTM Wakmatha.

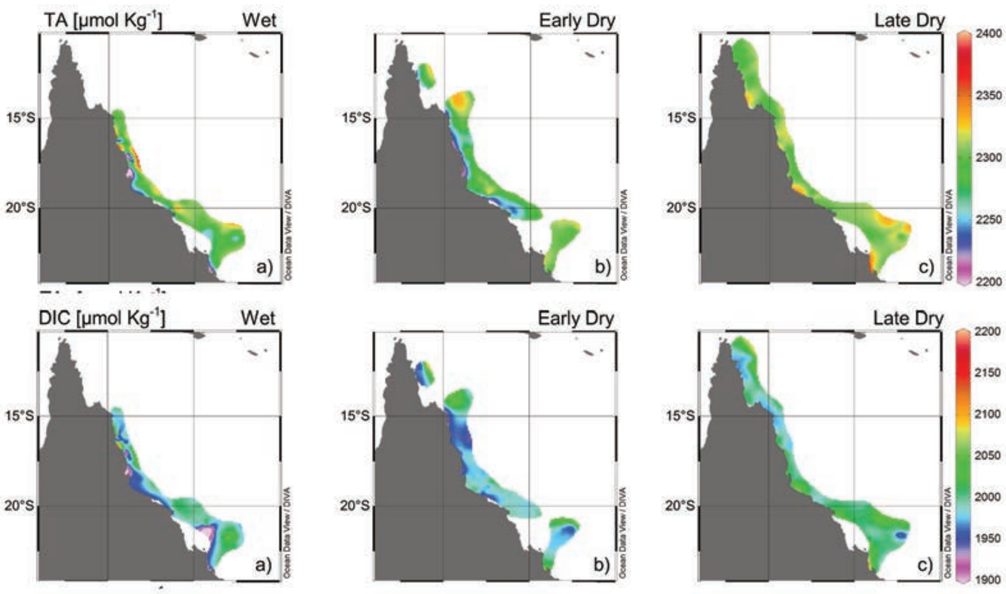
Results

- Ocean chemistry across the Great Barrier Reef remains positive for the growth of coral, providing an environment in which it can recover from events such as bleaching and cyclones.
- Ocean chemistry, and therefore the conditions for coral growth, differs greatly between seasons with the best growing conditions due to ocean chemistry in the summer.
- Inflow from the Coral Sea is a much stronger influence on the chemistry of Reef waters than outflow from coastal rivers.

Next steps

The instruments that have been installed and maintained through these programs will continue to collect data for AIMS and CSIRO and the data will continue to be made publicly available through existing platforms.

Figure 2. Maps of the distribution of total alkalinity (TA) and dissolved inorganic carbon (DIC) during the wet (December-March), early dry (April-July) and late dry (August-November) seasons.



[4] Round 1-3, total budget $270,000 [5] Round 1-4, total budget $755,000 [6] Round 2 allocations $50,00 + $1,095,017 from Rio Tinto

Crustose coralline algae (CCA) as indicators of ocean acidification and warming[7]

Principal investigators:
Prof. Guillermo Diaz-Pullido, Dr Emma Kennedy

Griffith UNIVERSITY

Applied outcomes:

- ✓ Baseline and new metric for calcification
- ✓ Monitoring prototype

In the long-term, ocean acidification is likely to be a significant impact of a changing climate on the Great Barrier Reef ecosystem. As more carbon dioxide from the atmosphere is dissolved in the ocean, the water becomes more acidic. Among other impacts, this decreases the capacity of corals to build their skeletons which create important habitats for other marine life. But the impacts will vary greatly across different reef habitats and locations, hence the ability to monitor individual reefs and gain early feedback on changes is vital.

Crustose coralline algae (CCA) are integral to coral reef growth and stabilisation. They also facilitate reef recovery by encouraging settlement of coral larvae.

This research project investigated whether CCA can be used as an early warning system for changes in ocean chemistry and temperature.

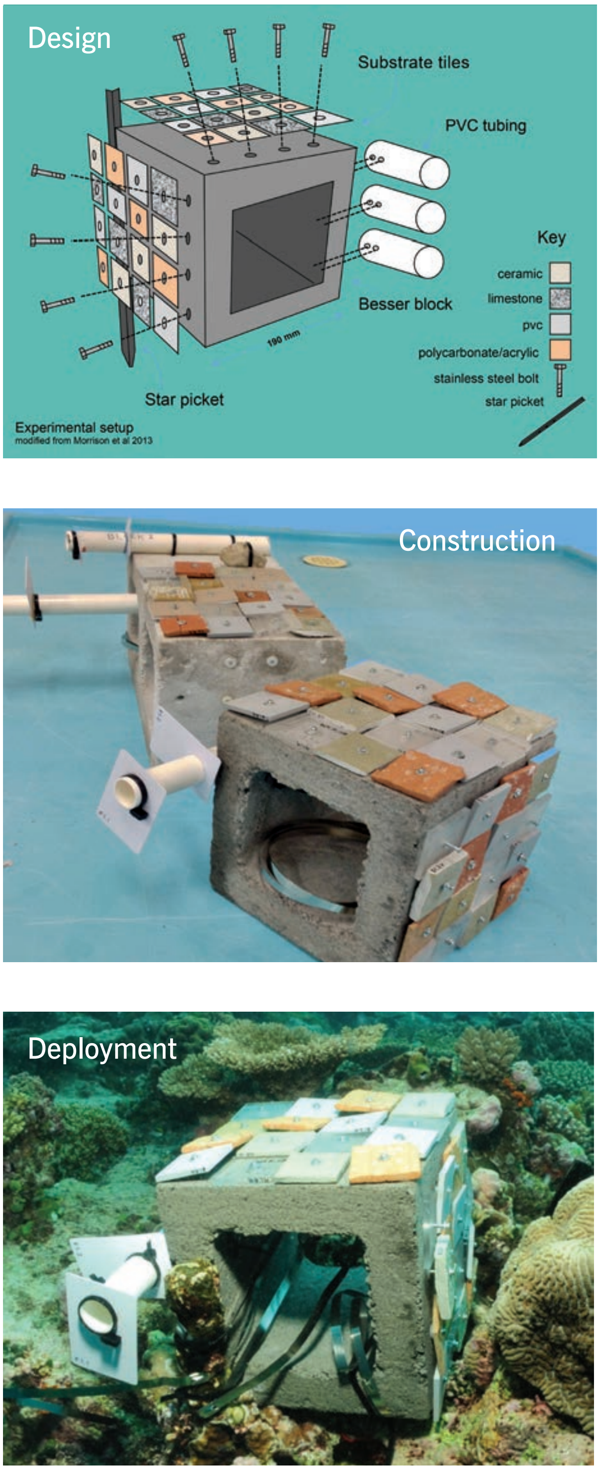
Results

- The first comprehensive baseline of coralline algae calcification rates for the entire Great Barrier Reef was established.
- New metrics for tracking climate change, including CCA growth rate and CCA community composition were identified.
- A cost-effective calcification monitoring device was developed, which can easily be incorporated into existing reef monitoring programs (Figure 3).

Next steps

This research forms part of the foundational knowledge around the use of CCA as a metric and the ecological role it plays in the coral reef ecosystem.

Figure 3: Calcification Monitoring Device

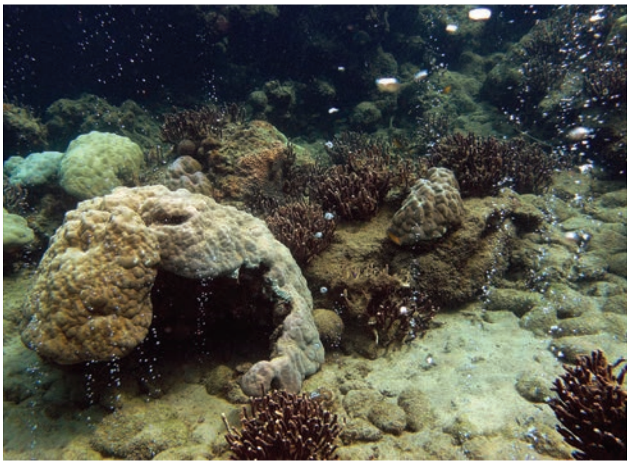


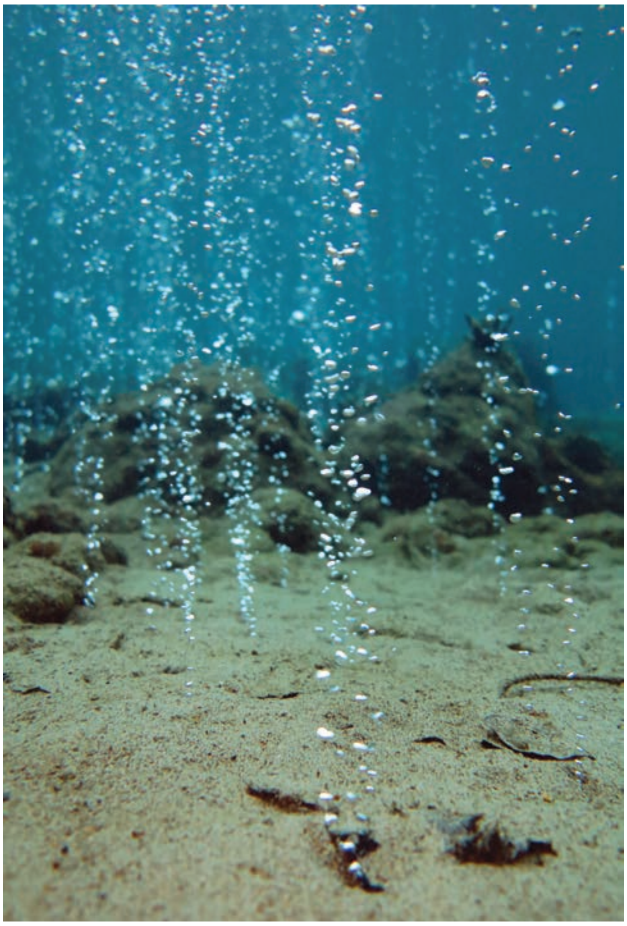
[7] Round 1-3, total budget $550,000

Carbon dioxide seeps: A collaborative study[8]

Principal investigator: Dr Katharina Fabricius

AUSTRALIAN INSTITUTE OF MARINE SCIENCE





Applied outcomes:

✓ Provided ecologically relevant thresholds for ocean acidification

Two natural volcanic carbon dioxide seeps in Papua New Guinea created a unique undersea laboratory to explore how coral reefs and ecosystems are affected by increased ocean acidification. The natural CO_2 gradients in the seawater simulate future high CO_2 conditions, allowing scientists to investigate the impacts on reefs like those found on the Great Barrier Reef. Comparing data on the spatial distribution of the most and least vulnerable taxa in the Great Barrier Reef will help pinpoint areas of greatest and least concern.

Results

The project's sub-projects each focus on a specific process or group of organisms.

- Coral recruitment: All coral larvae, regardless of origin, prefer to settle on surfaces that have come from a lower CO_2 environment.
- Zooplankton: Its nutritional quality remains the same but abundance is reduced under ocean acidification, so there is less food available to corals, fish and other planktivores.
- The stony coral *Galaxea fascicularis* consumes less zooplankton under ocean acidification even though the polyps exert the same effort and are the same size.
- Bioerosion: Data on rates of calcification (coral growth) indicate that erosion will out-pace calcium deposit when pH drops below 7.8
- Habitat structure: The total diversity in the habitat structures appears to be higher at the control than the high CO_2 sites. Preliminary data shows the chemical fingerprints from the sessile and motile communities differ in response to OA.
- Calcification/Echinoderm growth: Boring sea urchins grow faster at the high CO_2 sites, possibly due to greater food availability (more seaweed).

Next steps

The outcomes from this project will continue to generate new project ideas and opportunities and the research team is applying for various grants to continue this work.

[8] Round 1-3, total budget $282,500

Ocean chemistry data integration and visualisation

AUSTRALIAN INSTITUTE OF MARINE SCIENCE

CSIRO

Applied outcomes:

- ✓ Comprehensive understanding of the spatial and temporal impacts of OA and the ecological responses
- ✓ Baseline data and relevant thresholds for ocean chemistry
- ✓ Validation data for eReefs
- ✓ Ocean acidification data integration and visualisation
- ✓ Ecological response models

This component of the program provides a cross-platform comparison, analysis and visualisation of the existing carbonate chemistry data within the Great Barrier Reef to improve the understanding of spatial and temporal patterns. The data was also used to skills test the current biogeochemical model of eReefs, which was used to generate ocean acidification visualisations.

Results

- Today's high levels of CO_2 have already slowed rates of reef calcification on the Great Barrier Reef.
- The low carbonate saturation values observed inshore in the winter are approaching values that are considered marginal for healthy coral reef growth. However, reefs are still able to grow in all parts of the Great Barrier Reef, including the wet tropical inshore reefs where OA conditions are most critical.
- For the affected organisms of the Great Barrier Reef, respiration, but also photosynthesis and, to a lesser extent, calcification, is the biggest driver of change in today's seawater chemistry.
- Overall, the biota release more CO_2 rather than they take up through photosynthesis. This, together with the atmospheric CO_2, leads to a net CO_2 increase in the Great Barrier Reef seawater.
- Today's levels of OA may already be affecting the abundances of some calcifying algae and other reef organisms on the Great Barrier Reef.
- At increasing levels of OA, coral reefs are predicted to progressively lose their resilience, because OA affects many key processes and organisms. It leads to:
  - Declining reef calcification and accelerating reef erosion,
  - Declining abundances of crustose coralline algae,
  - Declining coral recruitment, reduced reef structural complexity and biodiversity,
  - Fewer benthic foraminifera (important producers of carbonate sand on some islands),
  - Increasing abundances of some fleshy seaweed.

Next steps

This was a one-off project to visualise outcomes from all ocean acidification projects under this program.

[9] Round 3-4 (total AIMS and CSIRO contracts): $550,667

2.3 Reef Futures Genomics consortium[10]

Genomics has a role to play in health, restoration and preservation and has played a pivotal role in the fields of human medicine and agriculture. However, we are still lagging on the foundational genomic data for corals.

Access to good quality reference genome data is crucial for any efforts to understand, and possibly accelerate, the capacity for coral to adapt or acclimatise to projected climate change scenarios. Over the past three years, the Sea-quence project, co-funded by the Great Barrier Reef Foundation and Bioplatforms Australia, has catalysed the generation of foundational reference genomic data for corals and their associated algae and microbial partners. These genome-scale baseline data are expected to underpin further fundamental and applied research.

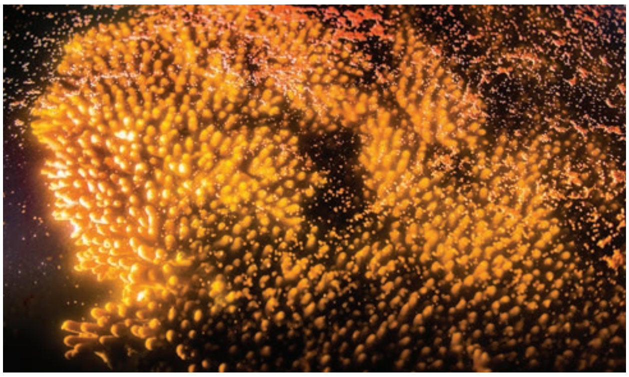
This project has built expertise in genome-scale bioinformatics in marine biology in general, and in coral reef studies in particular. It has been indispensable in enabling the consortium to develop and provide unique genome-scale data resources. The genome assemblies, annotations and analyses are a valuable resource for the Australian and international R&D community including coral biologists, field ecologists, genome scientists and reef managers.

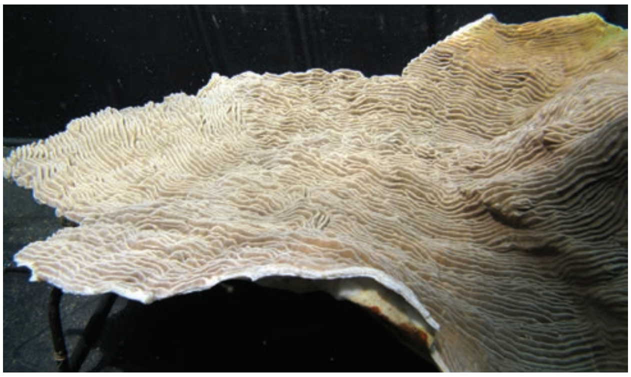
Through access to the assembled genomes of two corals, *Pachyseris speciosa* and *Acropora tenuis* the consortium researchers were able to do a deep dive into the levels of genetic differences found between populations along two environmental gradients on the Great Barrier Reef. For *P. speciosa*, this research extended into the Coral Sea, the Red Sea and Okinawa in Japan. The population genetic analyses revealed three distinct lineages of the species, of which one is unique to the Great Barrier Reef. The *A. tenuis* data confirmed a separation of the Magnetic Island population from other sampled populations, suggesting the existence of unique populations of high conservation status at this site.

Great Barrier Reef Foundation
Australian Government
Australian Institute of Marine Science
Australian Government Great Barrier Reef Marine Park Authority
BIOPLATFORMS AUSTRALIA
James Cook University Australia
جامعة الملك عبدالله للعلوم والتقنية King Abdullah University of Science and Technology
The University of Queensland Australia
Australian National University

Results

- Developed a method to allow the sequencing and separation of DNA from an adult tissue sample from a coral. Previously each component had to be sequenced in isolation to allow proper assembly, thus relying on DNA from sperm (which contains no *Symbiodinium* or associated microbial DNA); thus restricting the collection of material to a single, annual reproductive event.
- Sequenced the genomes of 9 cornerstone reef-building coral species, three algal symbionts and 57 microbial populations.
- Coral genomes vary in size as well as in number of genes. This complicates the analyses and assembly, but may be useful for studies of differences between populations or individuals.
- Completed coral, *Symbiodinium* and microbe genomes are of the highest reported quality of any published or reported coral genomes to-date.
- Identified three genetically distinct lineages of the species *Pachyseris speciosa.*
  - Developed a simple diagnostic assay to accurately separate these lineages.
- The genome of the associated algae (*Symbiodinium*) is smaller than originally thought, but the difference between different clades (types) is greater than expected. They can generate all their essential nutrients by themselves (not as dependent on the coral as previously reported).
- Assembled 52 coral associated, prokaryotic population genomes, which included microbes previously thought to be unique to marine sponges.
- Uncovered novel insights into the symbiotic relationships between the coral host and its associated microbes through complete holobiont sequencing of *Porites lutea.*
- Processes include recycling of nitrogen, phosphorous and sulphur within the system as well as more complex metabolic interactions between the coral host and its symbionts.
- A range of novel sequencing tools and assembly pipelines (automated computer programs) have been tested and developed.





Next steps:

- With the public release of the genomes, researchers from all over the world have accessed the data and are working on projects ranging from detecting species boundaries and developing genetic markers for stress tolerance to training a machine learning model to assemble genomes of complex, symbiotic organisms.
- With an increasing global focus on how to support coral reefs through climate change, gene-technologies are increasingly being considered as an option to improve stress tolerance. These methods rely heavily on foundational genomic data to be accessible.

[10] Round 1-3, total budget $990,000 (Sea-quence project) Round 2-3, total budget $100,000 (Coral genomes along environmental gradients)

2.4 Surface films to protect the Great Barrier Reef[11]

Principal investigators: Prof. David Solomon, Prof. Greg Qiao, Dr Emma Prime, Dr Joel Schofeild, Dr Andrew Negri

Cooperative Research Centre for Polymers — Solutions for a better world

THE UNIVERSITY OF MELBOURNE

AUSTRALIAN INSTITUTE OF MARINE SCIENCE

Applied outcomes:

✓ Possible local shading option to reduce coral bleaching

Research has shown that high light intensity is a significant co-factor in coral bleaching, increasing the severity of bleaching events. The rapidly warming waters that trigger severe coral bleaching tend to occur during calm, clear weather, causing increased light penetration. In a workshop focusing on novel approaches to reduce climate change impacts on the Reef, the concept of surface shade films was determined to be a feasible option for local mitigation of heat and irradiance. In 2008 the Tiffany & Co Foundation provided seed funding to initiate a project, led by the CRC for Polymers, to investigate this option. The idea was to develop an ultra-thin (a single particle) surface film to act as a shade cloth for the reef during bleaching conditions, thus aiming to reverse or avoid coral bleaching and reduce associated coral mortality.

During the initial phase, several approaches were investigated with the objective of achieving a 30% reduction in light intensity. One of three approaches that met the criteria was a particle monolayer of calcium carbonate, a particle that exists naturally on coral reefs. This approach was carried forward into phase II.

Calcium carbonate particle monolayers show an astounding 40% reduction in light intensity across all light spectrums, including ultraviolet light. Calcium carbonate is the building block of corals and other calcifying organisms, and as such the risk of adverse side effects are considered minimal.

Results

- Mono-particle film mixtures have been optimised to reduce light by up to 70% under initial laboratory conditions.
- Films maintain performance over 100 hours when tested on salt water (compared to 24 hours on fresh water).
- When tested over coral aquaria, set up under simulated bleaching events at the National Sea Simulator (SeaSIM), the mono-particle films were proven to be environmentally safe to corals, reduce light by 18%, and protect some coral species from thermal stress and bleaching.
- A 30% reduction of light has been achieved in laboratory conditions following the learnings from the SeaSIM trials.

Next steps

- A critical next step for this project is to improve the stability of the film in response to wave and wind action. This research is currently underway at the University of Melbourne.
- Testing efficacy of light reduction under natural sunlight.
- The Department of Environment and Energy has also expressed an interest in the project as a potential Reef Trust intervention.
- The Reef Restoration and Adaptation program proposes to have a dedicated program to conduct feasability studies of methods to control local environments, which would include this project.

[11] Round 2 and 3; total budget $100,000 (with $223,000 co-funding by the Tiffany & Co foundation)

2.5 Coral Larval Restoration on the Great Barrier Reef[12]

Principal investigator: Prof Peter Harrison

Southern Cross University

Applied outcomes:

✓ A method by which coral larvae, including naturally occurring spawn slicks can be used to re-seed degraded, larvae limited reefs

This project developed innovative techniques for coral restoration using enhanced coral larval settlement and recruitment to initiate ecological restoration of corals at Heron Island Reef.

The project was conducted during the 2016 and 2017 coral spawning and consisted of three stages.

1. Investigate the effect of larval density on survival and settlement rates of larvae and survival and growth of juveniles in an aquarium setting.
2. Field work to develop larval rearing and deployment techniques and to determine what the optimal concentration of larvae is to ensure maximum settlement and survival of the coral once deployed on the reef.
3. Long-term monitoring of surviving coral juveniles in the field.

Results:

- Higher densities significantly increase settlement – 4 times more larvae resulted in 15 times more settlement.
- Large scale rearing of coral larvae requires very large facilities as the concentration of larvae in the tanks has a big impact on larval health and survival (low densities are required).
- Collecting naturally occurring spawn slicks is extremely weather dependent and likely not a method that can be counted on as a source of larvae.
- The 2 x 2 m mesh tents successfully ensured larvae settled within the designated area.
- There is a total of 157 juvenile corals on the settlement tiles, corresponding to a survival rate of 3.8%, which is about what can be expected, so a very good result!
- Sites that were set up as ‘controls’, which had no larvae added to them, had no recruits, confirming that larval re-seeding will improve recovery rates on reefs with low densities of naturally occurring larvae (adult colonies to supply larvae).

Next steps

This program is being continued with funding from the Australian Government.

[12] Round 3 and 4: Total funds $10,000 (+$85,000 private donor)

2.6 Mapping networks of resilience using models, maps and long-term survey data

Resillience-based management requires access to decision support tools that translate long term trends into predicted reef trajectories through the integration of historical impact (exposures) and monitoring (decline and recovery rates) data. It also necessitates a capacity to define and identify key areas or populations that foster resilience at a local and regional scale.

The recently released Blueprint for resilience (GBRMPA) points to the need to create a network of resilience by targeting sites that will make the greatest contribution to the Reef's ecological and socio-economic resilience. This, in turn, requires detailed maps of the Reef, including current state as well as modelled prediction of variations in resilience and predicted impacts of future climate scenarios.

The Resilient Reefs Successfully Adapting to Climate Change program has funded a range of mapping and modelling projects that can be integrated to underpin such a decision support tool.

The Great Barrier Reef live habitat map[13]

Principal investigator: Dr Chris Roelfsema

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Applied outcomes:

✓ A satellite derived, dynamic habitat map

✓ A means to assess possible, and model current and future, coral cover on all 2,900 reefs of the Great Barrier Reef

Baseline mapping is recognised as essential information for terrestrial environments, providing the fundamental information required for all monitoring, modelling and management activities in the public and private sectors. To date this has not been done for the Great Barrier Reef due to the sheer number of predominantly submerged reefs, making satellite image analyses difficult. The Live Habitat Map project aimed to map geomorphic zonation and model benthic cover and develop a mapping method that could be applied to the entire of the Great Barrier Reef. During this program, the focus has been on the Capricorn Bunker Group and the Cairns management area.

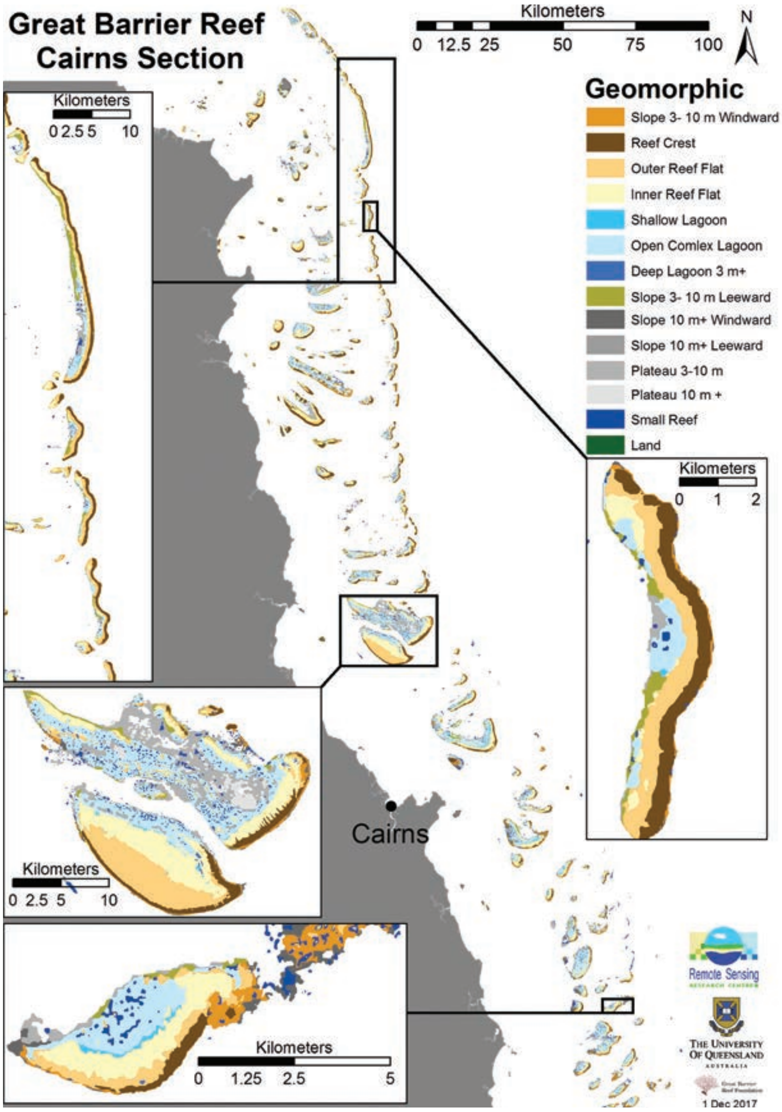
Results

- The study used a variety of input data for the mapping and modelling which included: satellite imagery, image-derived water depth, a wave exposure model, historical impact data and actual field data. From this the team developed and validated a mapping approach for geomorphic zonation, benthic cover and dominant coral cover types. This is the first time this type of mapping has been developed and successfully applied, and it has the potential to be applied to other reef systems.
- The project showed that comprehensive habitat mapping for the entire Great Barrier Reef is feasible using the developed methods. The required resources and approaches are now available.
- The live habitat map forms the foundation of the resilience hot spot decision support tool outlined below.

Next steps:

- A geomorphic and detailed benthic layer map for all 2,900 individual reefs of the Great Barrier Reef remains a priority need. These pilot projects have shown their value and have allowed the research team to improve their methods to ensure a top-quality product for the reef. With access to improved satellite imagery and excellent collaborative deals with the providers of corrected imagery and depth calculations, the team can produce the full Great Barrier Reef map for under $1m.

Figure 4: The geomorphic zonation of the Cairns management area



[13] Round 3 & 4, total budget $268,000 (+ $52,800 from Google)

CONNIE3: Dispersal on the Great Barrier Reef [14]

Principal investigator: Dr Scott Condie

CSIRO

Applied outcomes:

- ✓ Used in a range of ongoing research projects
- ✓ Used by the GBRMPA's COTS control program
- ✓ Pilot study for connectivity models in the resilience mapping project

Quantifying larval dispersal and reef connectivity is one of the greatest technical challenges faced by coral reef scientists and managers. For corals, crown-of-thorns starfish (COTS) and many reef fishes, larval dispersal occurs during early larval phases that cannot be tracked in situ over extended periods. Larval dispersal modelling therefore plays a key role in expanding our understanding of reef connectivity.

CONNIE (short for Connectivity Interface) is an online modelling and visualisation tool that allows users to explore dispersal patterns and connectivity based on a combination of realistic ocean currents and known physical, chemical or biological behaviours of dispersing substances or organisms. The interface can be found at www.csiro.au/connie/

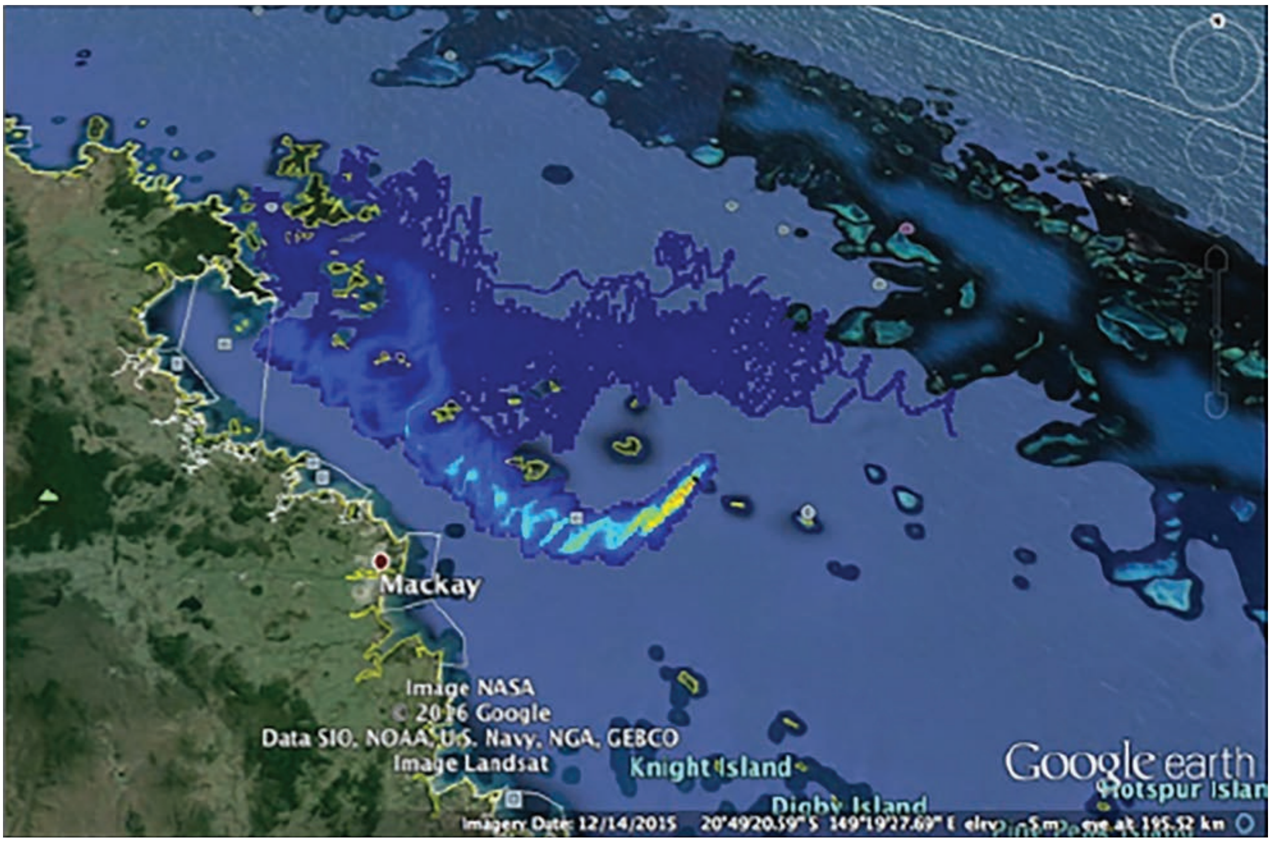
Results:

- Increased spatial resolution of the CONNIE model.
- Development of preloaded parameters for a set of substances and organisms.
- Improved representation of larvae settlement processes.
- More efficient generation and delivery of outputs such as modelled larval trajectories, dispersal distributions and connectivity statistics.

Next steps:

CONNIE will continue to be updated and utilised for the purposes stated above as new data and funding becomes available.

Figure 5. Modelled dispersal of crown-of-thorns starfish from a reef offshore from Mackay



[14] Round 2, total budget $61,037

Spatially realistic systems model[15]

Advance Queensland Innovation Project fellowship[16]

Principal investigators: Prof Pete Mumby, Dr Juan Carlos Ortiz, Dr Yves Marie Bozec, Dr Karlo Hock

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Applied outcomes:

✓ Modelling of coral cover trajectories to support decisions for resillience-based management

This project expands the Great Barrier Reef ecosystem model to explore the relationship between wave exposure and coral community composition to assess the impact of management interventions such as COTS control and water quality improvement on coral.

Results

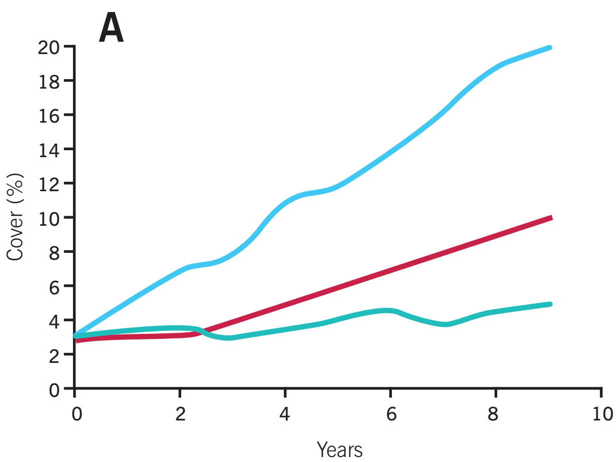
- The ecosystem model can accurately predict the recovery pattern of different coral community types.
- Wave exposure can be used to predict coral community composition.
- At low levels of wave exposure, ecological interactions are a stronger driver of coral community composition than wave exposure.
- Controlling COTS at key reefs could potentially enhance the recovery ability of reefs by up to nine times.
- Water quality strongly influences recovery potential of not only inshore reefs, but also reefs further off shore.

The ecosystem model, together with the Reef Habitat Map, eReefs and biophysical and genetic connectivity data, form the foundations of the resilience hot spot decision support tool and mapping project being implemented in collaboration with GBRMPA.

Next steps

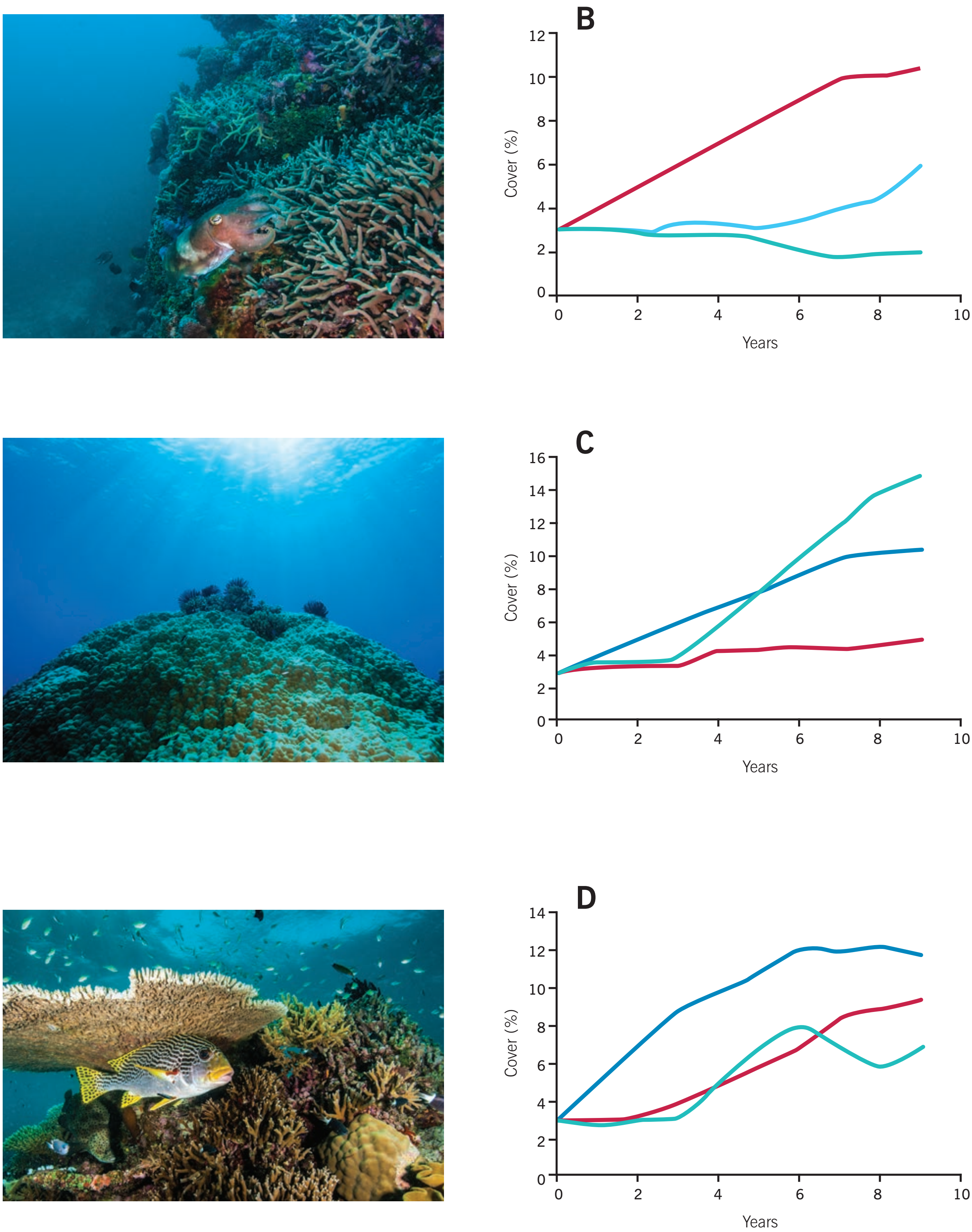
Following the integration of this program with the operational eReefs product, the Live Habitat Map and the AIMS modelling and mapping program (see Delivering a reef resilience plan for the Cairns management area p.22) the application of these models to the design of the Reef Integrated Monitoring and Reporting program became apparent. As a result, this project is now funded as a negotiated priority program through NESP for 2018 (Project 4.5 - Guidance system for resilience-based management of the Great Barrier Reef).

Figure 6. Ability of modified ecosystem model to represent the recovery of different community types after disturbances. A: Community dominated by plate corals Coloured lines represent model results for average cover of each coral type. Blue= plate corals, red= branching corals and green= massive corals.



[15] Round 2 and 4, total budget $270,247 [16] Round 3 and 4, Support to AQIP fellow, total budget $30,000

Figure 6. Ability of modified ecosystem model to represent the recovery of different community types after disturbances. B: Community dominated by branching corals, C: community dominate by massive corals and D: Mixed community. Coloured lines represent model results for average cover of each coral type. Blue= plate corals, red= branching corals and green= massive corals.



eReefs[17]

eReefs is a collaboration between:

Great Barrier Reef Foundation

Australian Government Bureau of Meteorology

CSIRO

Australian Government | Australian Institute of Marine Science | Queensland Government

Supported by Funding from:

Australian Government | Queensland Government

bhpbilliton | Science and Industry Endowment Fund | BMA BHP Billiton Mitsubishi Alliance

Applied outcomes:

- ✓ Inform water quality targets
- ✓ Develop scenario modelling
- ✓ Delivering visualisation products for water quality
- ✓ Provide modelled data to show impacts of management actions

eReefs is a collaboration between the Great Barrier Reef Foundation, Bureau of Meteorology, Commonwealth Scientific and Industrial Research Organisation, Australian Institute of Marine Science and the Queensland Government. In addition to funding from the Resilient Reefs Successfully Adapting to Climate Change program eReefs was supported by funding from the Australian Governments Caring for our country, Queensland Government's, BHP Billiton Mitsubishi Alliance, and the Science Industry Endowment Fund.

The research phase of eReefs was a six-year project that used the latest technologies to collate data with new and integrated modelling to produce visualisation, communication and reporting tools spanning from catchment to reef.

Results:

Products developed through the eReefs project include:

- Water Quality Dashboard.
- Scenario modelling suite.
- Forecasting modelling suite.
- Reporting and visualisation portal with data, graphics and animations for download.

Information about eReefs products and tools is publicly available at www.ereefs.org.au

Next steps

During 2017 eReefs transitioned into an operationalisation phase with funding from the Australian Government. A key deliverable from this new phase is to ensure eReefs is being utilised and maintained in an accessible format. It will also ensure that all additional research is carried out to support a required or requested operational product.

[17] Round 1-4: total budget $3,500,000 (+$8,576,000 cash contributions from other funding sources)

Delivering a reef resilience plan for the Cairns management region[18]

Principal investigators: Dr Mark Baird, Dr Scott Condie, Dr Ken Anthony, Prof. Pete Mumby, Dr Chris Roelfsema

Applied outcomes:

✓ Modelling of coral cover trajectories to support decisions for resillience-based management

The core activity of the project was to integrate existing maps, models, monitoring data, exposure and impact histories to deliver a spatially realistic representation of the current state of the reefs (at a reef by reef scale) in the Cairns management region. Coral cover, coral community composition and metrics of vulnerability and resilience were considered. The key challenge for this program was to integrate a range of models, maps and survey data to deliver a map and synthesis report of current state of reefs in the Cairns management area as of January 2017.

Results

The program successfully integrated outputs from eReefs, the Reef spatially realistic systems model, the Live Habitat Map, historical exposure data, the coral physiology model, existing survey data and eAtlas layers.

In addition to the status report, reef trajectories are modelled along the two 'extreme' Climate change scenarios (RCP 2.6 and 8.5[19]) and two water quality scenarios. Model predictions of connectivity are being validated using a reef wide genomics data set from a common, early colonising coral (*Acropora tenuis*).

The structured comparisons of model projections revealed a set of key findings.

- Implementing an effective crown-of-thorns starfish (COTS) strategy could become increasingly critical under climate change as reefs that escape climate impacts will become increasingly susceptible to COTS.
- Highly effective COTS control would mean higher coral survival and recovery to about 25% coral cover by around 2035. This can maximise coral stocks and potentially coral resilience before bleaching events become annual or semi-annual events.
- Even if global warming can be kept within 1.5°C above pre-industrial levels, the average coral cover on the Great Barrier Reef could decline regionally as we approach mid-century despite perfect COTS control and water-quality representative of pre-industrial levels. However, some reefs may sustain high coral cover through time.

These findings underscore the need for intensified conventional management but also highlight that new additional interventions may be needed. Spatial variation in reef resilience and/or susceptibility to exposures provides scope for sustained reef values locally and potentially in resilient networks.

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 Great Barrier Reef Foundation. Specifically, each institution has put forward elements of their flagship products to make this project happen: eReefs (CSIRO), regional coral and COTS model (UQ with contributions from AIMS and CSIRO), eAtlas (AIMS) and Live Habitats Maps (UQ).

Efforts are currently being made to visualise these outputs in a way that allows the uptake of additional data and models as things evolve. The prototype portal is an online visualisation tool developed within eAtlas (http://eatlas.org.au/gbrf/ngbr-coral-reef-resilience).

A web integration portal 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.

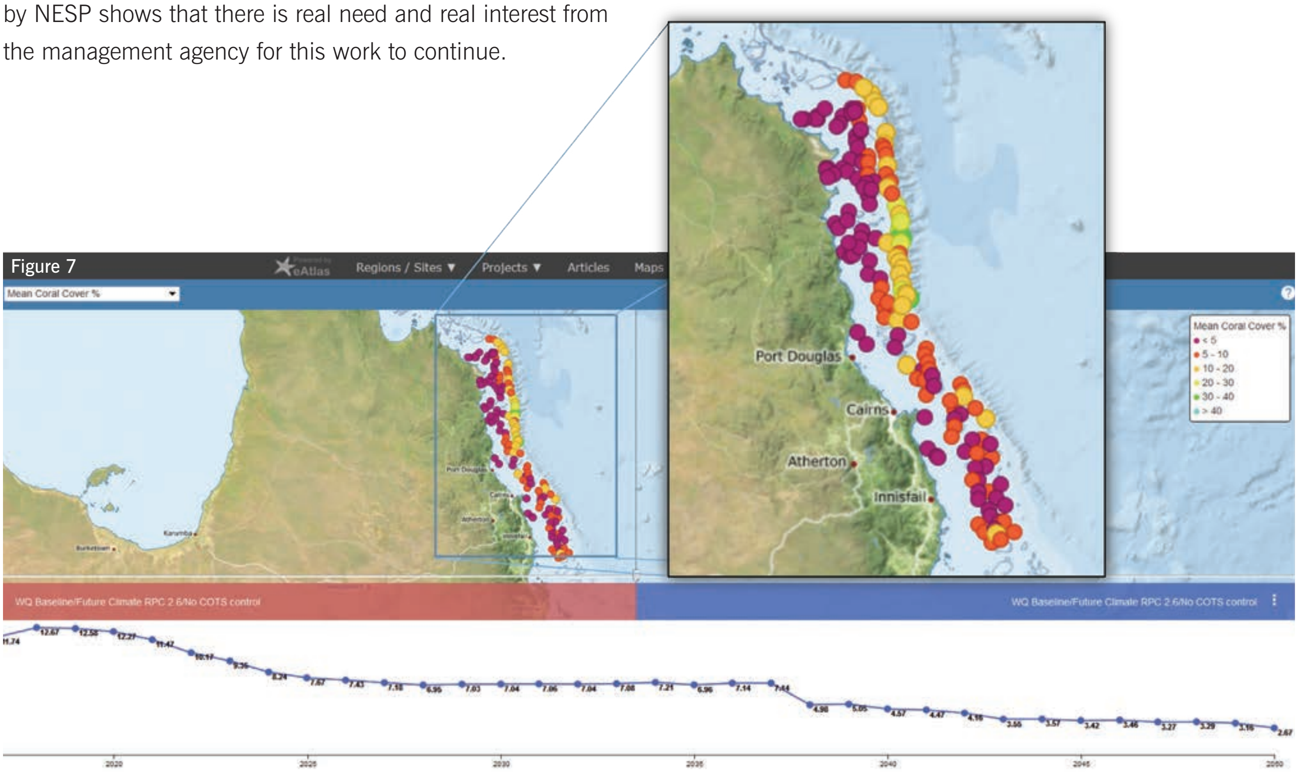
[18] Round 4, total budget $1,198,729 [19]Representative carbon pathways of radiative forcing in 2100 relative to pre-industrial values (+2.6, +8.5 W/m2). RCP 2.6 assumes that global annual GHG emissions (measured in CO2-equivalents) peak between 2010-2020, with emissions declining substantially thereafter. In RCP 8.5, emissions continue to rise throughout the 21st century

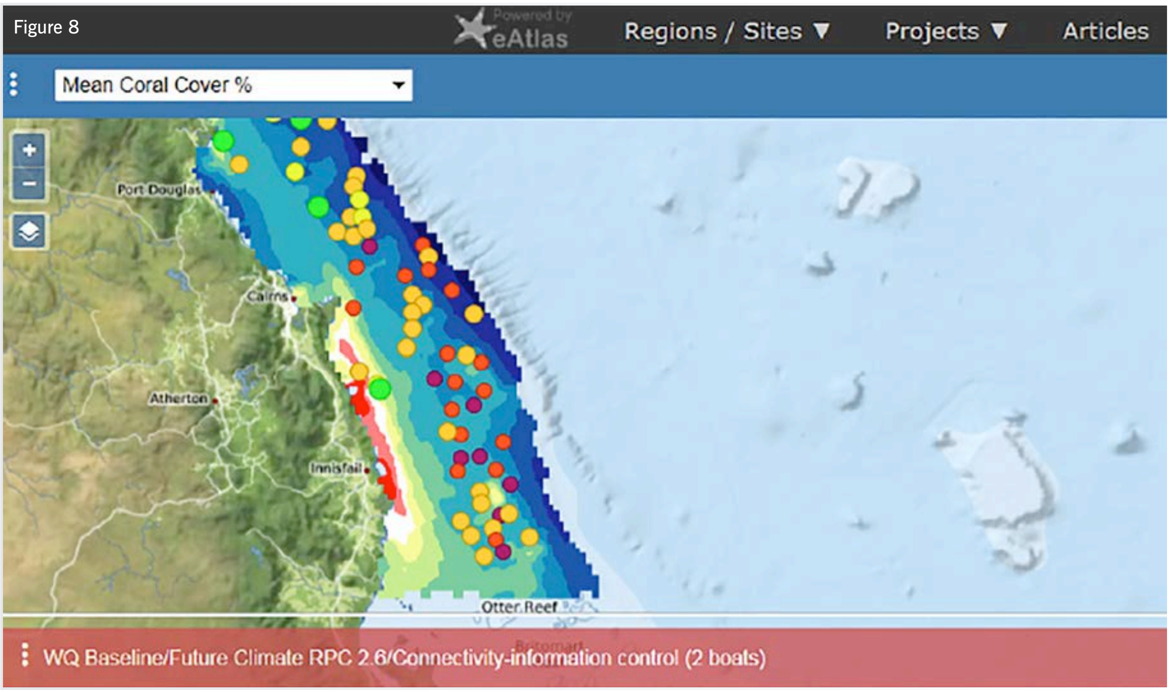
Next steps

The successful integration of this suite of models and maps has illustrated the potential for a range of similar products to become truly applicable and relevant as decision support tools. The key challenge is to build an integration portal that can and will be used by managers to inform decisions and to make strategic calls on priority actions. The continued engagement by staff at GBRMPA and the approved funding by NESP shows that there is real need and real interest from the management agency for this work to continue.

Figure 7: Example of projected coral cover for each of the 156 reefs averaged over time for the period 2017 – 2050 under baseline water quality and strong carbon mitigation (RCP 2.6) and without COTs control. The trajectory below shows average coral cover of all reefs over time.

Figure 8: Showing a synoptic layer of maximum chlorophyll for summer months under baseline water quality and strong carbon mitigation (RPC 2.6) and 2 boats doing COTS control using connectivity data.





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